Acoustics and Audition

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Chapter Overview

During space missions, the sense of hearing is critical for crewmember safety and health, as well as for mission success. Detection and recognitions of sounds are positive factors contributing to successful communication, situational awareness, and localization of sound source. However, sounds that create annoyance or produce health effects are considered *noise*. High levels of noise can result in fatigue (due to disrupted sleep), performance decrement, and shifts in hearing sensitivity. In an aerospace environment, noise also can interfere with communications, reduce alarm audibility, degrade habitability, and present a safety risk. This chapter covers the basics of sound generation in spacecraft, noise measurement, and acoustic environments experienced by astronauts during space flight. It also offers a synopsis of hearing function and assessment, and the fundamental characteristics of noise sources and noise propagation. Auditory and non-auditory health effects from noise are discussed. Specifically, the impacts of acoustic conditions on habitability, interference of communication, and detection of key caution and warning alarms are described. Currently accepted noise criteria levels, which must be met on board a spacecraft, together with the hearing conservation programs are discussed (i.e., use of engineering controls and hearing protection). Future perspective and programs are briefly described.

Learning Objectives

1. Recognize the characteristics of noise and their potential impact on communication and operations during space missions.
2. Describe methods of monitoring hearing sensitivity on Earth and in space.
3. Describe measures used to mitigate the impact of noise on hearing and mission performance during space missions.

Introduction

The ability to communicate in space and hear alarms is a matter of safety, while protecting astronaut health is a prerequisite for accomplishing any space flight mission. All space-based communication systems are expected to accurately transmit and replicate speech, and other acoustic signals, to be easily heard by all crew members during extra-vehicular activities (EVAs), with individuals in other vehicles, or with mission control. While this may be true for the communication system, the underlying assumption is that the acoustic environment is conducive to successful communication and that the hearing acuity of crew members remains intact and capable of processing and understanding auditory inputs (Box 6.1).

Communication, therefore, is essentially no different in space than it is in any other work environment. Well, perhaps it is a bit different in that noise exposures in spacecraft may not be the same as those encountered by workers on Earth. This does not infer that noise is present at levels higher than that of terrestrial workers, but the unique confinements of space vehicles also impact on communication (between the Mission Control Center and among fellow

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Electronic supplementary material: The online version of this chapter (doi: 10.1007/978-1-4939-6652-3_6) contains supplementary material, which is available to authorized users.

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A.E. Nicogossian et al. (eds.), *Space Physiology and Medicine*, DOI 10.1007/978-1-4939-6652-3_6

Box 6.1
Noise exposures during space missions are unlike most occupational settings on Earth, since crew members are exposed to incessant noise 24 h a day, 7 days a week. While the International Space Station now contains "acoustic rest" locations, where noise levels are relatively low, there still remains a background noise in work areas that may exceed the set limit levels.

crew members), acute situational awareness, and rapid localization of sound sources. In addition, the body's response to microgravity may potentially alter the physiologic response of the ear. Further, our ability to assess hearing while in space is inherently different from conventional methods used in clinics.

In order to fully understand the implications of space flight on communication, it is important to review some basic concepts of audition and discuss the physical impact of the acoustical environment in which astronauts live. The acoustical envelopes of the U.S. Space Shuttle, the International Space Station (ISS), future space vehicles and habitats, and space suits used for EVAs are unique. This chapter reviews the impact of these acoustic environments with four key issues: (1) human health (both auditory and non-auditory effects from noise), (2) habitability, (3) interference on communication, and (4) detection of key caution and warning alarms. Each of these issues will be discussed in the following sections, with summaries of the metrics used to assess them.

Physical Dimensions of Sound

Acoustics

"Noise" is commonly referred to as any unwanted ***sound*** (Box 6.2). Astronauts, like everyone else, may find that some sounds are desirable (providing important signals or information), while other sounds are unwanted (and considered to be a "noise"). Not every individual may classify a given sound as a "noise," however. Astronauts have reported that they sometimes appreciate (to some extent) being reassured of nominal vehicle operation by the presence of sounds associated with normally operating equipment. On the other hand, other onboard sounds can quickly become aversive and annoying to humans, depending on a complicated interplay of physical acoustics and psychophysical auditory response.

While the physical parameters of sound can be measured by instrumentation, the human ear may not have sufficient resolution to accurately detect such parameters in all situations (Box 6.3). For example, a very small change in amplitude or frequency may be too small to be recognized by a human listener. Obviously, if a human's hearing sensitivity is not acute enough to perceive a sound, it might not be considered to be "loud," even if the physical intensity of the signal is high. On the other hand, a less intense sound might become an annoying noise if it occurs during sleep hours, seems dissonant because it contains an irritating tone, or persists for an extended period of time.

Box 6.2
Sound is defined as an oscillation of pressure propagating from a source, through an airborne or structure-borne medium with internal forces (e.g., elastic or viscous, like air or water) to a receiver (such as an ear or microphone).

Box 6.3
Sound can be described by three basic physical acoustical parameters: (1) ***amplitude***, (2) ***frequency***, and (3) ***temporal aspects of sound***. These characteristics each have a corresponding **psychophysical** correlate: **loudness, pitch**, and **sensitivity to change or timbre**, respectively.

Amplitude

The human auditory system has a large dynamic range of sensitivity; an individual with "normal" hearing may be able to hear a soft whisper or grass rustling in a breeze yet also tolerate sounds that are extremely loud (e.g., weapons fire, jet engine noise). Consequently, a logarithmic scale is used to describe the broad range of ***amplitude*** (Box 6.4) of these acoustic pressure fluctuations. The reference for the scale, 20 μPa, was chosen to be the smallest amplitude of pressure fluctuation detectable by a young adult male. Using the ***decibel*** (dB) scale, acoustic pressure fluctuations are reported in terms of ***sound pressure level*** (SPL), defined as 10 times the logarithm to the base 10 of the ratio of the time-mean-square pressure of a sound, in a stated frequency band, to the square of the reference sound pressure in gases of 20 μPa [1]. This reference (0 dBSPL) is considered to approximate the threshold of normal human hearing at 1000 Hz.

Because of the logarithmic representation of SPLs, the addition of two equal sound pressures is not a simple summation. Rather, it results in an increase in SPL of 6 dB if perfectly correlated and in phase. And, since the power in a sound wave is proportional to the square of the pressure, a

Box 6.4
Amplitude is reported in terms of ***decibels***, which report the ratio of the measured pressure to a reference pressure.

Box 6.5
In general, a human's ***subjective judgment of noise levels*** is not very precise; individuals can often accommodate to loud sounds.

doubling of ***sound power*** is equivalent to an increase in power of 3 dB. It is important to note that even though this is a doubling of sound power (or energy), this change is usually barely detectable by human hearing. For example, the crew once reported that when a module of the ISS lost power, the sudden reduction in noise levels made them very aware of how much noise is typically present. In addition, when a human subjectively judges that a sound level has doubled, the physical sound power's increase is actually closer to an order of magnitude (i.e., 10 dB) (Box 6.5).

Frequency

The perception of ***pitch*** is characterized by the ***frequency*** of sound, which can also be based on a logarithmic scale to more accurately interpret a human's response. The auditory frequency range has been standardized into octave bands and fractional-octave bands (e.g., 1/3 octaves). These ***octave bands*** are typically described by their ***center frequency*** (F_c), the geometric mean of the upper and lower band-edge frequencies (Box 6.6).

The human ear responds best to frequencies between 250 and 8000 Hz and is less sensitive to very low- and very high-frequency sounds. When using instruments to measure acoustic characteristics in a manner that represents human hearing, filters apply ***frequency weighting***. ***A-weighting*** is typically used when assessing the risk of noise-induced hearing loss (Box 6.7). The summation of acoustic energy that has been weighted in terms of an A-weighted overall sound pressure level is often referred to as simply the ***sound level***, in units of dBA. In contrast, the non-weighted wide-band sound pressure level, sometimes termed the ***overall sound pressure level*** (OASPL) in dB, is the figure of merit relating effects of impulse noise on the human hearing.

Another acoustics metric, the ***Speech Interference Level*** (SIL), is a used as a measure of the degree to which background noise interferes with (or masks) speech communication. The ***SIL(4)*** is computed by taking the average SPL (a simple average of decibel values) for the 500, 1000, 2000, and 4000 Hz octave bands. This metric can be used to estimate when "just-reliable face-to-face communication is possible" for various combinations of talker-to-listener distance and background noise levels, with normal, raised, very loud, and shouted vocal efforts, according to [2].

Box 6.6
Space flight acoustic requirements and metrics are based on standard octave frequency bands; i.e., ***octave band sound pressure levels*** ranging from 63 Hz to 8000 Hz (and sometimes to 16,000 kHz, which is very near the upper range of human hearing sensitivity).

Box 6.7
The most common weighting that is used in noise measurement is ***A-weighting***, which effectively cuts off the lower and higher frequencies that the average person cannot hear.

Temporal

Temporal aspects of sound can be manifested in several ways. For example, tonal and broadband sounds are very different and affect people very differently. Tones can tend to be irritating (such as those produced by a whining fan), whereas broadband noise can be soothing (like the sound of ocean surf). While this difference can be described in terms of amplitude and frequency, temporal patterns of sound can certainly become offensive (e.g., rattling machine parts).

More distinct temporal differences also determine the effect of the sound on the human ear. High-level impulse noise (such as a gunshot) may cause instant trauma to the ear and generate hearing loss. In this case, it is the peak OASPL that is important for determining a risk to hearing, as well as the duration of the overpressure wave.

In contrast, as noise durations increase from minutes to hours, such sounds are considered to be more of an impact on communication and habitability. However, when intermittent noise levels are 85 dBA or higher, the risk for temporary hearing loss becomes significant [3]. Levels of 115 dBA or higher may cause noise-induced hearing loss, even with short-duration exposures [4].

Of course, the temporal aspect of sound is also responsible for conveying the information contained within the sound. The ***vocal onset time*** (**VOT**) has been shown to be critical for distinguishing two similarly produced speech sounds (Box 6.8). For example, the voiceless gap between

Box 6.8
Speech is a clear example of this temporal aspect, since the human ear relies on features like the **VOT**, which is the length of the delay between the start of the speech sound and the beginning of the actual vibration of the vocal cords.

release and voicing for the phoneme /t/ has a VOT of 95 ms, while the VOT for the phoneme /d/ is only 25 ms. When these voiceless gaps are electronically manipulated (e.g., to a mid-point of 50 ms), the human listener becomes unable to identify the original phoneme correctly. In addition, temporal aspects of acoustics are critical to understand speech in the presence of background noise. Individuals with noise-related hearing loss often experience significant hearing difficulties when in crowds because of their reduced ability to process temporal cues; they report that they "can hear speech, but not understand it."

Mechanisms of Hearing

Human Auditory Sensitivity

Box 6.9
An ***audiogram*** is a graph that shows the results of a hearing test (or **audiometry**). When viewing the audiogram, remember that the audiogram only reports peripheral hearing status in terms of two acoustic parameters (i.e., amplitude and frequency) that we described above.

The young and normal human ear is capable of hearing frequencies ranging from roughly 20 Hz to 20 kHz. However, as shown in Fig. 6.1 [5], the human ear is most sensitive (depicted in the "threshold of audibility" curve) to sounds in the range of 250 Hz to 8000 Hz (which are, conveniently, most useful for hearing speech and other environmental sounds). When hearing sensitivity is measured with pure-tone audiometry, the threshold of human audibility is converted from dB SPL and reported in terms of ***dB Hearing Level*** (dBHL), where 0 dBHL represents the mean thresholds of a population of young, normally hearing adults. Since 0 dBHL represents such an average, it is possible for hearing threshold levels of some individuals to be reported as low as −5 dBHL; i.e., better-than-average hearing.

Data from audiometric evaluations can be used to identify the degree and nature of the hearing loss (Box 6.9). Results can help determine if the loss is due to a disorder of the outer or middle ear, preventing the sound from reaching the cochlea at normal levels (a ***conductive hearing loss***) or something affecting the neurological response to sounds, either peripheral or central (a ***sensorineural loss***); or a combination of the two (a ***mixed hearing loss***). Such a determination, however, cannot be based solely on conventional audiometry (i.e., air conduction hearing tests done only with

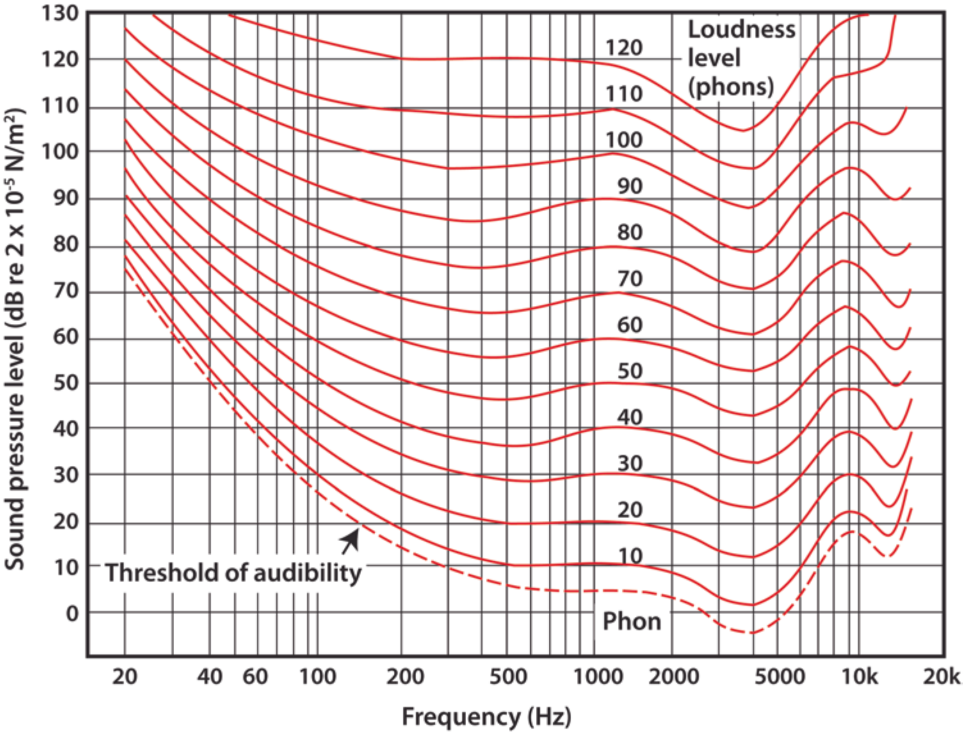


Fig. 6.1 Non-linear frequency response of human hearing to sound. Modified from [5]

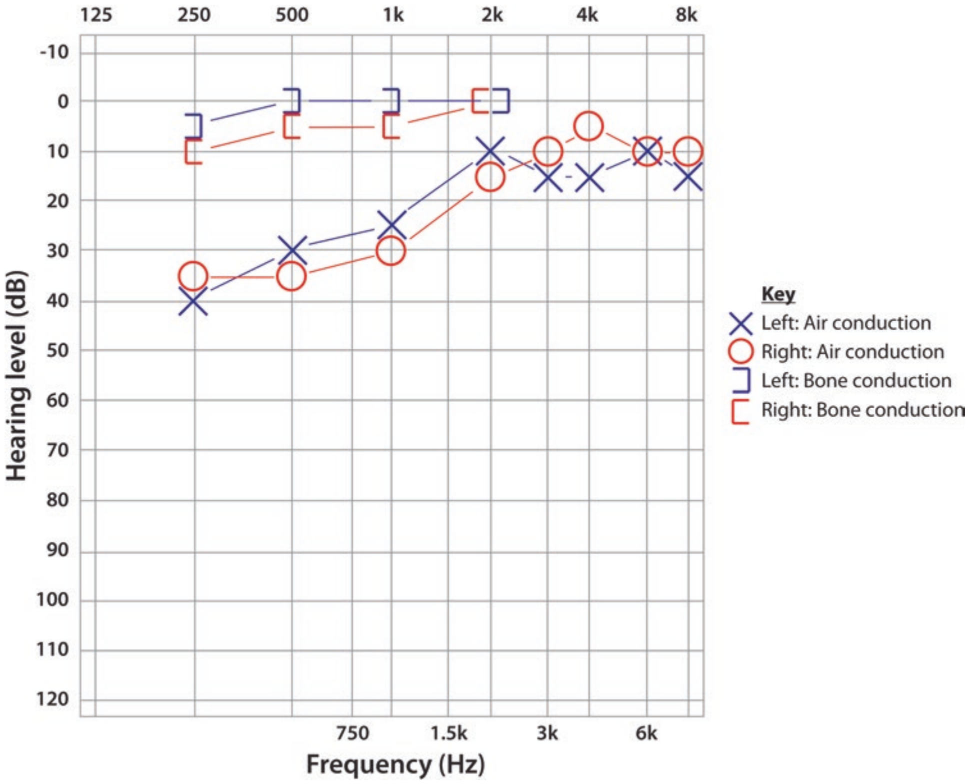


Fig. 6.2 An audiogram or graphic representation of hearing levels plotted as a function of intensity and frequency. This example shows a bilateral conductive hearing loss, with better hearing sensitivity for bone conduction (BC) than for air conduction (AC), in both ears

earphones and tones as stimuli); more advanced audiological tests are necessary to identify the underlying nature and the extent of the loss. The basic air conduction audiogram does not report the ear's ability to process temporal cues or speech understanding in quiet or in noise; more sophisticated audiological tests are required to assess these characteristics.

As noted previously, air conduction audiometry alone cannot identify the nature of the hearing loss. To confirm that a hearing loss is sensorineural in nature, bone conduction audiometry is conducted—using a transducer placed on the skull to present auditory stimuli directly to the cochlea, without routing sound through the external or middle ear. If there is no significant difference between thresholds obtained with air conduction and bone conduction audiometry, the hearing loss is considered sensorineural. If hearing sensitivity is normal for bone conduction stimuli but air conduction tests are abnormal (creating an ***air-bone gap,*** as depicted in the audiogram shown in Fig. 6.2), a conductive hearing loss is indicated.

When a hearing loss is recorded on an audiogram, the type of loss will often have a characteristic pattern (also called the ***audiometric configuration***) that can help in identifying the cause of the hearing loss. When hearing thresholds are elevated in the high frequencies (i.e., above 1 kHz) and of a sensorineural nature, the cause of the hearing loss is typically related to noise exposure, aging, and/or ototoxins (Box 6.10). When a conductive component exists, in addition to a sensorineural loss, the hearing loss is considered mixed in nature (as would be the case if someone with a noise-related sensorineural loss developed a conductive hearing loss due to middle ear infection). Mixed hearing losses can be exhibited as any combination of hearing loss in low, high and mid frequencies.

Box 6.10

Elevated low-frequency hearing thresholds may be caused by conductive pathologies (e.g., middle ear disorders) or sensorineural disorders (e.g., Menière's Disease), although excessive ambient noise in the audiometric test environment can elevate those thresholds, as well, by masking the low frequency stimuli.

A-Weighted Decibels (dBA)

As noted previously, the human ear does not respond equally to all frequencies, and weighting is typically used with sound level meters (SLMs) to represent human response, including the A-, B-, and C-weighting scales (Box 6.11). These weighting scales are shown in Fig. 6.3 [6]. The different curves are needed because the frequency response of human hearing is level-dependent, perceiving soft and loud sounds differently, as shown in Fig. 6.1. The weighting networks allow SLMs to approximate the response of human hearing.

Evaluation of risk for hearing loss during space vehicle launch abort is an example where the C-weighting scale should probably be used, but a lack of data relating dBC levels to hearing loss hinders this use.

Auditory Effects of Noise

Excessive noise exposure can result in progressive and permanent changes in human auditory function, depending on factors associated with the exposure (e.g., sound pressure level, duration, type of noise, and frequency), as well as the characteristics of the individual being exposed (e.g., susceptibility to noise damage, age, and prior history of hearing damage) [7, 8]. When excessive exposures to continuous noise result in a noise-induced hearing loss (NIHL), the loss is classically demonstrated as a bilateral, sensorineural hearing loss (Box 6.12). NIHL is first seen in high frequencies (e.g., above 2 kHz, with greatest hearing loss at 4 or 6 kHz, and better hearing at 8 kHz, resulting in an ***audiometric notch***). The anatomical damage from excessive noise exposure occurs in the cochlea, the site of the sensory cells for hearing, and more rarely, in the auditory neural pathways. As NIHL advances, the loss is demonstrated in the mid-frequencies, as well [9].

Besides a basic loss of hearing sensitivity, NIHL can also alter more complex auditory functions, like distortion due to loss of frequency and temporal resolution (essential to detect gaps in ongoing sound or hear speech in the presence of background noise). Auditory damage can also be linked to ***tinnitus***, a condition that causes people to hear ringing or similar sensation of sounds, which can impair concentration and interfere with sleep.

Exposure to intermittent or continuous noise that is greater than an 85 dBA ***time-weighted average*** (TWA) can lead to a measureable but temporary change in hearing thresholds, or a permanent change, depending on the intensity and duration of exposure. A TWA is a combination of

Box 6.11
A-weighted noise levels have been widely used in demographic and laboratory research to identify risks for noise-related hearing loss. Because of this extensive use, the A-weighted scale is sometimes used when the ***C-weighting scale*** (which is quite flat and, therefore, includes much more of the low-frequency range of sounds than the dBA scale) may be more appropriate.

Box 6.12
The ***risk of NIHL*** becomes an operational concern to space missions in that if crew members were to experience reduced hearing function, there would be negative impacts on mission safety and mission accomplishment (e.g., due to reduced speech intelligibility during EVAs, misunderstood communications between crew and ground, or inability to detect caution/warning alarms). In addition, NIHL has been shown to be additive to age-related hearing loss, yielding possible disability claims for occupational hearing loss post-flight.

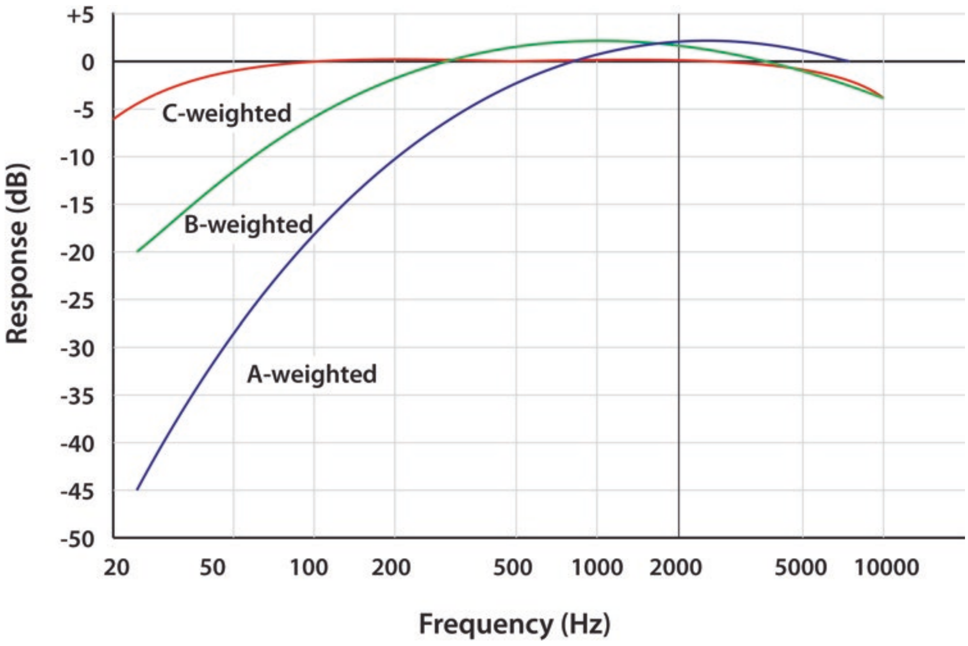


Fig. 6.3 A-weighting corresponds to human frequency response at low sound levels, B-weighting corresponds to human frequency response at moderate sound levels, and C-weighting corresponds to human frequency response at high sound levels. Adapted from [6]

sound levels and duration such that the average of the varying sound level over the exposure duration is equivalent to the level of a statistically stationary sound level over the same duration. If not specified (e.g., written as TWA_{8h}), the duration of a TWA is assumed to be 8 h. Exposure to 90 dBA for periods of less than 24 h may result in a brief decrease in hearing sensitivity at one or more frequencies. This ***temporary threshold shift*** (TTS) usually resolves within 24–48 h (Box 6.13). Greater noise exposures, caused by increased duration, level or combination of the two, may result in a permanent change in hearing at one or more frequencies and is known as a ***permanent threshold shift*** (PTS).

NASA's allowable limit [10] for terrestrial workers in occupational noise is equivalent to an 85 dBA exposure for duration of 8 h, using a 3 dB exchange rate. If the sound level is doubled (or increases by 3 dBA), the allowable duration is cut in half. (For instance, an exposure of 85 dBA for 8 h would be equivalent to an exposure of 88 dBA for 4 h). Levels on board the ISS are well below 85 dBA. However, crew members on the ISS are exposed to noise sources for several months during their missions, and sometimes for as long as 24 h a day, rather than just 8 h per work shift. This limited "acoustic rest" may present an increased vulnerability to NIHL [11].

A Damage Risk Criteria (DRC) is established to identify boundaries intended to protect the overall population of noise-exposed workers from NIHL (Box 6.14). These DRC are based on available scientific knowledge to determine which combinations of acoustic characteristics (e.g., level and duration of noise) are considered "hazardous" to health and chosen for noise standards for conventional ground-based occupational work environments.

Box 6.13
The degree, and longevity, of such a hearing shift is dependent upon the ***level*** and ***duration*** of the noise to which the person is exposed. If the individual is subjected to high-intensity noise level for a long enough time, a PTS is likely.

Box 6.14
The choice for ***Damage Risk Criteria***, when adopted in noise standards, is influenced by administrative decisions that consider such factors as the level of risk considered acceptable in a population, how much hearing should be preserved in an individual, and (to some degree) the costs of including individuals with marginal noise exposures.

In general, international noise standards agree that, as noise levels increase (above a certain level), the risk of a possible NIHL increases unless there is a corresponding decrease in the amount of time an individual works in that area (Box 6.15).

The ***Equal Energy Hypothesis*** (for noise-related hearing loss due to steady-state noise like that produced by fans and other equipment in space vehicles) assumes that two noise exposures with the same acoustic energy will generate the same amount of hearing loss [12]. Specifically, if the sound level is doubled (increased by 3 dB, since decibels are quantified logarithmically) and the duration is then reduced by 50 %, then the overall acoustic energy will not change (and the risk to hearing will not change).

The current U.S. federal occupational hearing conservation standards, outlined in the Hearing Conservation Amendment of the Occupational Safety and Health Act (OSHA) [13], identify the maximum permissible exposure level to be no more than 8 h at 90 dBA; greater exposures require mandatory use of hearing protection. In contrast to the Equal Energy Hypothesis, OSHA's standard uses a 5 dB, rather than a 3 dB, exchange rate.

OSHA's noise standard has not been revised since it was adopted in 1983, despite recommendations by the National Institute of Occupational Safety and Health (NIOSH) [14] and others for more conservative DRCs, based on contemporary noise research. These DRCs advocate, among other things, a recommended exposure level of no more than 8 h at 85 dBA (rather than OSHA's 90 dBA TWA), and a 3-dB exchange rate (rather than OSHA's 5-dB exchange rate).

Wide variations are seen in human susceptibility to the effects of noise; it is possible for two individuals to develop very different amounts of hearing loss, even if exposed to similar noise exposure levels [15]. NASA has chosen to employ DRCs that are based on "most-conservative" criteria (similar to recommendations from NIOSH [14] and the World Health Organization [WHO]) [11], in order to protect all (not just some) crew members.

Sound levels in space flight vehicles and habitats do not typically reach the levels that would be of concern to OSHA. These levels range from approximately 45–80 dBA (excluding launch sound levels), and are generated largely by ventilation fans, motors, pumps, communication systems, environmental control systems, and science experiments (called "payloads"). Further discussion of the acoustic environment in space vehicles and habitats is provided in the next section.

Box 6.15
In summary, the risk of hearing loss caused by noise exposure is a function of the overall level of noise and the duration of exposure to that noise.

Box 6.16
Previous ***ISS Flight Rules for Noise Constraints*** had set the maximum 24-h noise exposure for a crew member at 65 dBA. But these flight rules have recently been updated to reflect the WHO's recommendations.

Box 6.17
In general terms, noise is classified as being of a "***continuous***" or "***non-continuous***" nature. Non-continuous noise can be further classified by the time-scale of the sound pressure level's duration (i.e., intermittent or impulse).

Stephenson et al. [3] found that individuals could work in noise levels less than 75–80 dBA for 24-h periods with no concern for a TTS or PTS. In addition, the WHO [11] has advised that 24-h noise exposures to 70 dBA or less will not cause hearing loss, even after a lifetime of exposure (Box 6.16). The new NASA flight rules [16], adopted in 2013, require hearing protection for exposures that exceed a work-time TWA of 72 dBA over a 16-h period. This corresponds to a 24-h noise exposure level of 70 dBA, taking into account that the 8-h noise exposure experienced during sleep is below 62 dBA. These new flight rules and their implementation will be further discussed later. NASA's Medical Operations Requirements Document [17] also requires the use of HPDs for any single exposure of 85 dBA or above.

Non-Auditory Effects of Noise

As discussed previously, noise is known to have adverse effects on hearing sensitivity. However, NIHL is not the only consequence of hazardous noise. Noise can also result in communication interruptions by interfering with, or masking, communications or alarms [18]. Noise can also result in sleep disturbances, fatigue [19], and reduced ability to concentrate on tasks [20].

Physical: Acoustics Environment

In order to define requirements and control space vehicle acoustic levels, the categories of noise sources must be defined. For space flight vehicles and habitats, the categories have been defined as follows:

A ***continuous noise source*** is a significant noise source that exists for a cumulative total of 8 h or more in any 24-h period (Box 6.17). A continuous noise source is typically a stationary (statistically invariant) or slowly varying source. This type of source usually defines the noise environment, determines the ability to communicate by voice, and is a main contributor to the habitant's noise exposure level and risk for NIHL.

An ***intermittent noise source*** is a significant noise source that exists for a cumulative total of less than 8 h in any 24-h period. Intermittent noise can have a negative effect on communication (for the duration of the noise), and may also contribute to noise exposure and NIHL.

One important example of intermittent noise during space flight is experienced during launch (and possibly during launch aborts), since the rocket and aerodynamic noise experienced during these phases of flight may be brief but have very intense levels.

To control the acoustic levels during nominal on-orbit space operations, continuous noise requirements were developed based on the Noise Criterion (NC) curves [21]. The NC curves, shown in Fig. 6.4, were originally established, based on subjective human testing, for rating indoor noise for areas such as public places, office buildings, restaurants, and schools, and are defined for octave band frequencies from 63 to 8000 Hz.

The NC-values of the curves were originally based on the SIL of each curve as shown in Fig. 6.4. However, the NC identifiers now differ slightly from the SIL levels because of the subsequent standardization of the octave band frequencies [21]. ANSI S12.65-2006 [2], describes the SIL 4-band method, SIL(4), and how it can be used to determine the impact of talker-to-listener distance and the level of voice power required to communicate, based on talker-to-listener distance and noise-level combination for which just-reliable face-to-face communication is possible. Just-reliable communications corresponds to an intelligibility score of at least 70 % based on ANSI S3.2-1989 [22]. Figure 6.4 also provides the relationship between NC, SIL(4), and the sound level (in dBA) metrics.

For the Shuttle Space Transportation System (STS), approval for an acoustic requirement was not reached before production of the first orbiter, but a goal of NC-55 was set relatively late in the program's development [18]. Since there was no acoustic requirement for the Space Shuttle during development, the noise levels ended up being higher than desired (Box 6.18) [18]. As a result, the addition of payloads, sound levels on at least 1 flight were high enough to disrupt communications, as discussed below. Figure 6.5 shows the estimated acoustic levels in the middeck of Space Shuttle flight STS-135, including the noise of the Shuttle *Atlantis* and its middeck payloads.

For the ISS, a continuous noise limit of NC-50 was mandated for U.S. Operating Segment modules. Additionally, the complement of continuously operating payloads within a module has been given an NC-48 allocation. This results in an implicit requirement of NC-50 + NC-48, which is approximately NC-52, for the composite noise sources (i.e., full-up

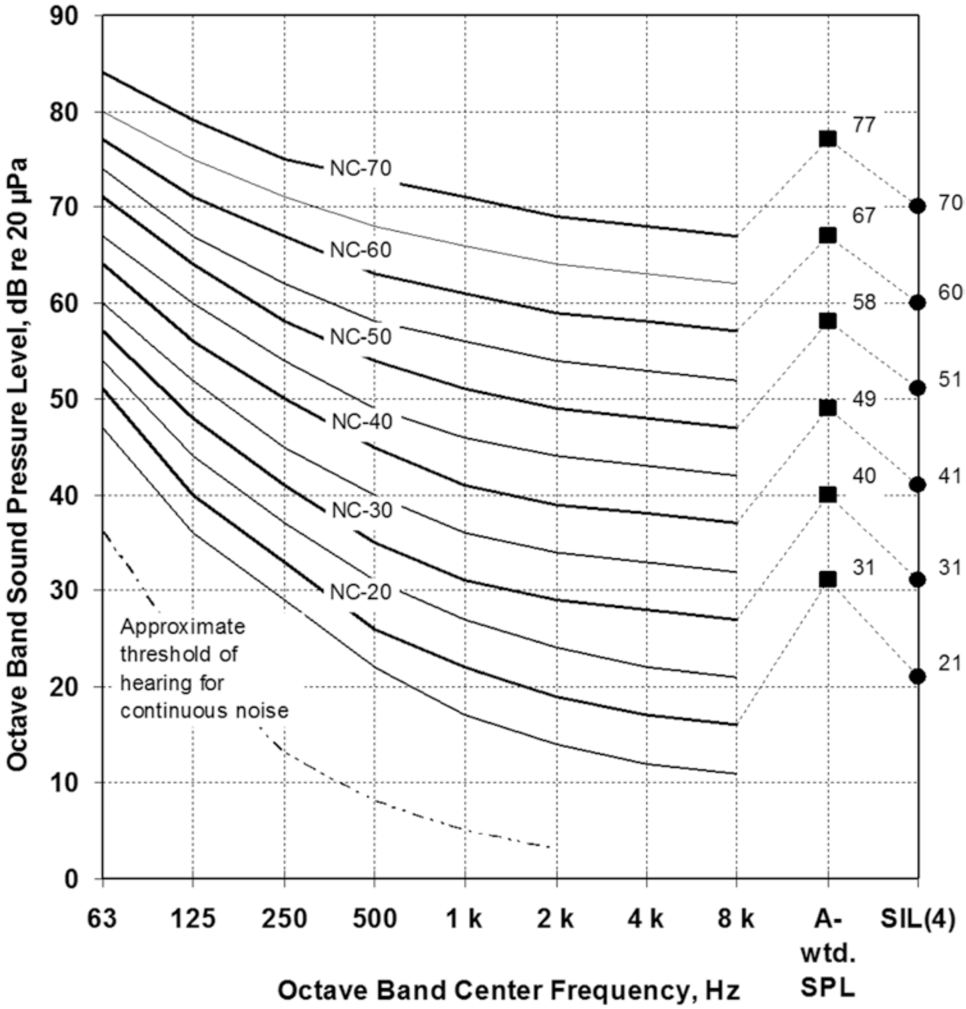


Fig. 6.4 Noise criterion (NC) curves. Corresponding A-weighted sound levels and speech interference levels are given for reference only. Courtesy of NASA

Box 6.18
Reports from one Space Shuttle Mission (STS-40) suggested that the ambient noise was sufficient to significantly interfere with routine face-to-face communications. To speak in a normal tone of voice, astronauts had to be within 0.2 m (0.65 ft) of one another [18].

systems) inside ISS laboratory modules [23]. Continuous noise requirements for lower-level hardware assemblies are set at lower acoustic levels; e.g., NC-40 for racks and government furnished equipment, NC-34 for aisle-mounted payloads, and a modified NC-32 for payload sub-racks.

ISS Russian Operating Segment modules have a continuous noise limit based on Russian standards, but is similar in level to NC-52 for frequencies above 1 kHz. The Russian continuous noise limits also include an A-weighted overall sound level limit of 60 dBA. Figure 6.6 shows the Russian and U.S. segment's continuous noise requirements (Box 6.19) [24].

Requirements for continuous noise levels in future space vehicles, including Multi-purpose Crew Vehicle, Commercial Orbital Space Transportation, and Commercial Crew Transportation vehicles, are also NC-52, including the noise produced by active payloads.

For intermittent noise, the allowable noise level is inversely related to the operational duration of the source. See Table 6.1 [24]. These levels and corresponding durations were chosen in a conservative fashion so that several intermittent sources could be operated simultaneously, and so that the effort to control when the sources were operated could be kept to a minimum.

Impulse noise sources are limited to an overall sound pressure level of 140 dB peak (Box 6.20) [13, 25].

Based on human needs, these acoustic requirements are fairly restrictive for the hardware developer. As a result, building hardware that meets these limits, in most cases, requires that the design process includes a noise control strategy that is initiated in the early design of the hardware and is carried throughout hardware development (Box 6.21).

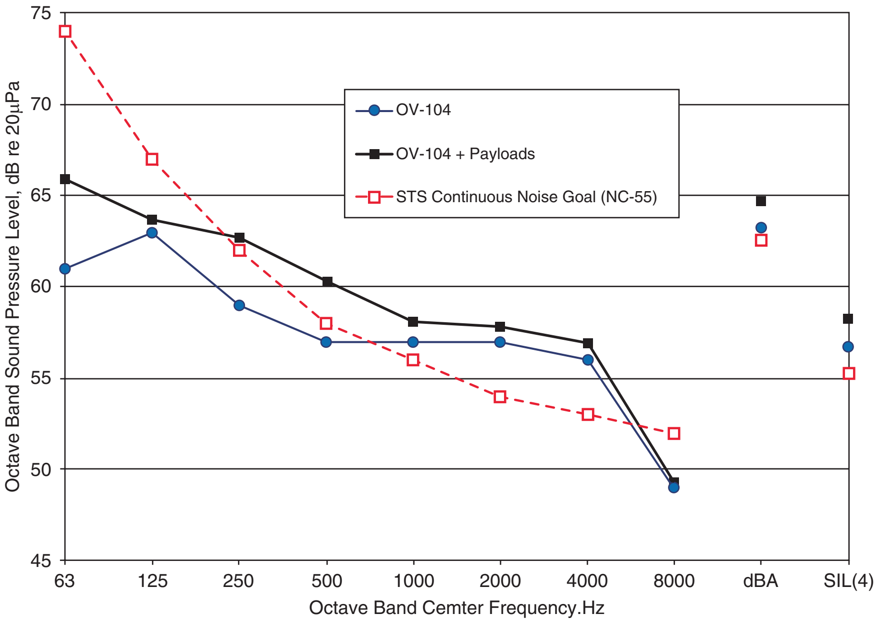


Fig. 6.5 Space Shuttle STS-135/Orbital Vehicle (OV) -104 predicted noise levels (Courtesy of NASA)

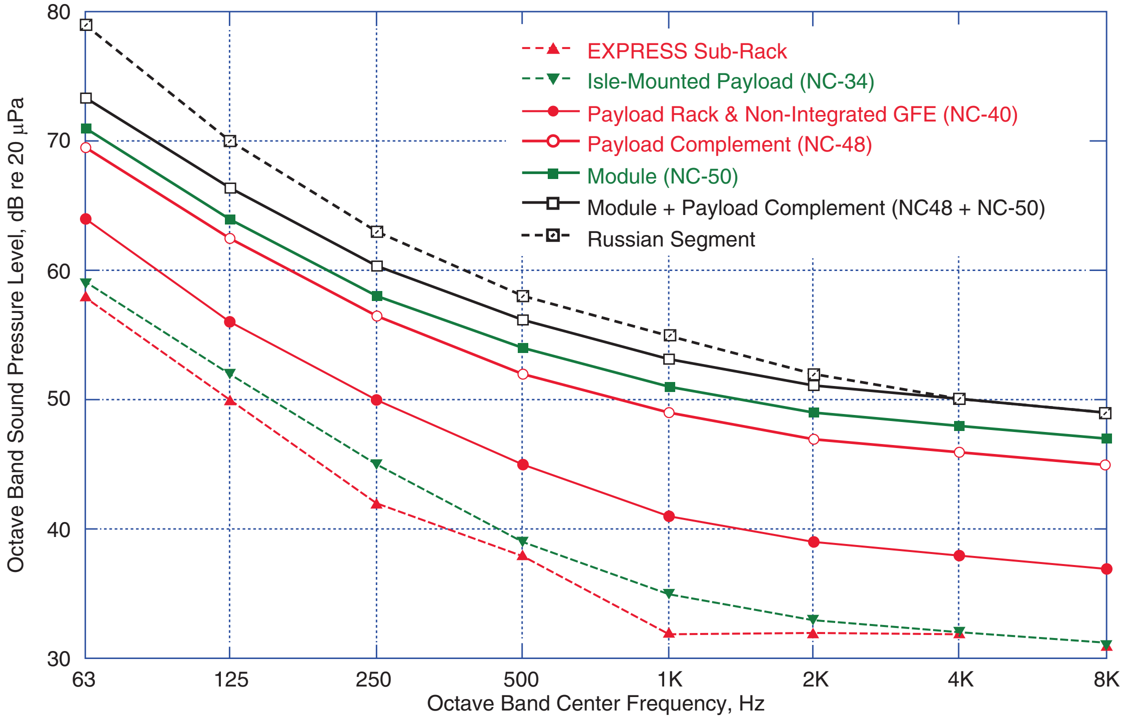


Fig. 6.6 ISS continuous noise requirements. Reprinted from Allen CS, Goodman JR. "Preparing for Flight – The Process of Assessing the ISS Acoustic Environment," *Proceedings of NOISE-CON 2003*. Washington, DC: US Institute of Noise Control Engineering, 2003

For modules, racks, and complicated hardware that include significant noise producing or rotating machinery, the development and implementation of an Acoustic Noise Control Plan is recommended (and sometimes mandated). Acoustic testing should be performed often so that trades can be made, and to avoid surprises late in the development phase. High acoustic levels realized late in hardware development can lead to significant cost and schedule overruns, and late mass and volume allocations may not be available. The methods of noise control are too many and detailed to describe here [26–29].

In order to verify that the space vehicle environment meets the continuous noise requirement, the contributions of all continuously operating hardware must be understood and

Box 6.19

Requirements for ***intermittent noise*** have been limited to certain types or classes of hardware to limit the number of hardware items operating at these higher levels. Examples include exercise equipment (treadmill and cycle ergometer), environmental monitoring equipment, and science experiments of wide variety such as centrifuges, combustion experiments, or autonomous positioning experiments.

Table 6.1 ISS intermittent noise requirements

Maximum noise duration	A-Weighted overall sound pressure level, dBA
8 h	49
7 h	50
6 h	51
5 h	52
4.5 h	53
4 h	54
3.5 h	55
3 h	57
2.5 h	58
2 h	60
1.5 h	62
1 h	65
30 min	69
15 min	72
5 min	76
2 min	78
1 min	79
Not allowed	80

Modified from Allen et al. [24]

Box 6.20

An ***impulse noise source*** is a source that creates a 10 dB or greater increase in noise which exists for less than 1 s. If this occurs at a sufficiently high level it may cause hearing trauma and possibly permanent hearing loss. At lower levels, this type of noise may produce a startle effect or wake a sleeping crew member.

Box 6.21

Elements contained in a ***noise control strategy or plan*** include selection of the quietest noise sources, early testing of noise sources (for noise and vibration), acoustic modeling of propagation paths (airborne and structure-borne) and reverberation, identification of predominant noise paths, system-level noise treatments (isolation, absorption), and component level noise treatments (barriers, mufflers, isolators).

included. The most important sources are verified and characterized by ground testing. However, hardware that is added at a later time must be measured in isolation, and then added to the composite environment using acoustic modeling techniques. Any "*exceedances*" to the requirements are addressed, either by implementing engineering noise controls or with operational/administrative controls. In certain circumstances noise *exceedances* are permitted with a "*waiver*" or "*exception*" to the requirements, if the risk is considered to be sufficiently small. Acceptability of the hardware for space flight regarding acoustic emissions is reviewed prior to flight as part of the Certification of Flight Readiness (CoFR) or Stage Operational Readiness Review (SORR) process [24].

In order to ensure the acceptability of the acoustic environment during the mission, and to detect any acoustic anomalies that are not recognized by the crew, the on-orbit acoustic environment is monitored by conducting routine ***sound level meter*** (SLM) measurements of the continuous noise levels in each module [30]. The SLM that is used to measure sound levels on ISS is shown in Fig. 6.7. Table 6.2 shows the typical average acoustic levels in the ISS modules. In some cases, module noise levels have improved over time, and also acoustic anomalies have been resolved by on-orbit addition of noise attenuation systems at the source [31]. Some of these are discussed briefly, below.

In addition to the measurements of continuous noise, each crew-member's exposure level is measured on-orbit with personal ***Acoustic Dosimeters*** (see Fig. 6.8). These instruments measure the time-weighted sound level (in dBA) over a 24-h time period, which is further analyzed for the approximate *16-hour work day* and *8-hour sleep period*. The dosimeters measure not only the continuous noise, but also any intermittent noise, as well as the influence of other common acoustic signals such as speech, alarms, or music. Measured levels are compared to allowable exposures as detailed in the Noise Constraints Flight Rules B13-152 [16].

The use of hearing protection, discussed further below, is only implemented when needed, as specified by these rules. Flight Rule B13-152 states, "If the 16-h crew work period Noise Exposure Level (LAEQ16) as measured by the ISS audio dosimeter or as predicted using the "*noise hazard inventory*" exceeds 72 dBA, crew members shall be directed to wear appropriate hearing protective devices (HPDs) during activities where high noise exposure levels are present. These activities and exposures will be identified in the "Noise Hazard Inventory." ***The Noise Hazard Inventory*** (NHI) is an operations product based on noise data and known crew activities that is used to communicate with Mission Control and the ISS crew to relay the information on when to wear hearing protection. This approach follows the task-based approach

Fig. 6.7 ISS Sound Level Meter (SLM), connected to Space Station Computer (SSC) for download (Courtesy of NASA)

Table 6.2 ISS continuous noise levels as of June 2013, in modules (upper) and in sleep stations (lower)

Module	NC-level	SIL(4), dB	dBA	Survey date	Normal level
Airlock	NC 41.6	39.3	46.9	June 24, 2013	NC 48.0
JLP	NC 42.5	42.6	49.2	May 1, 2013	NC 42.0
JPM	NC 46.1	45.9	52.7	May 1, 2013	NC 48.0
Cupola	NC 46.5	42.6	52.5	June 24, 2013	NC 45.0
PMM	NC 48.1	39.4	49.8	Aug 15, 2012	NC 48.0
Columbus	NC 48.1	43.2	51.5	Dec 7, 2012	NC 43.0
Node 2	NC 49.3	46.5	54.9	May 1, 2013	NC 49.0
Node 1	NC 50.4	47.8	54.9	May 1, 2013	NC 49.0
U.S. Lab	NC 51.6	49.7	56.6	June 24, 2013	NC 52.0
Node 3	NC 55.0	50.6	59.6	June 24, 2013	NC 56.0
MRM2	NC 59.4	54.4	63.3	Aug 15, 2012	NC 62.0
FGB	NC 62.4	55.2	64.7	June 24, 2013	NC 58.0
RSM	NC 62.5	54.7	64.0	June 27, 2013	NC 60.0
DC1	NC 62.9	59.4	67.7	June 27, 2013	NC 61.0
MRM1	NC 63.3	60.7	67.3	Jan 30, 2013	NC 65.0

Sleep station	NC-level	SIL(4), dB	dBA	Survey date	Fan speed
Deck CQ	NC-46.8	33.8	49.9	June 24, 2013	High
Stbd CQ	NC-47.1	32.8	50.0	June 24, 2013	High
Ovhd CQ	NC-47.7	35.2	49.7	June 24, 2013	High
Port CQ	NC-47.8	34.2	51.3	June 24, 2013	High
Stbd kayuta	NC-49.8	35.6	52.6	June 24, 2013	
Port kayuta	NC-58.9	36.8	57.9	June 24, 2013	

Courtesy of NASA

JLP Japanese Experiment Module Logistics Pressurized, *JPM* Japanese Experiment Module Pressurized Module, *PMM* Permanent Multipurpose Module, *MRM* Mini-Research Module 1 and 2, *FGB* Functional Cargo Block, *RSM* Russian Service Module, *DC* Docking Compartment 1, *CQ* Crew Quarters, kayuta (Russian crew quarters)

Fig. 6.8 ISS Acoustic Dosimeter, which shows a crew member wearing a dosimeter at the belt with the microphone clipped to his collar (Courtesy of NASA)

described by Li et al. [32]. For example, SLM measurements have shown that the treadmill, T2, produces sound levels of 85 dBA at the runner's head location. As a result, crew members are mandated to wear hearing protection when operating T2 above speeds of 10 miles per hour. The information in the NHI is derived from a ***Noise Exposure Estimation Tool***, which predicts crew noise exposure based on recent ISS acoustic data (SLM and Acoustic Dosimeter) and corresponding crew activities and locations. Results of Acoustic Dosimeter measurements, which do not include the effects of hearing protection use, are shown in Fig. 6.9. Each of the data points in Fig. 6.9 is the result of a crew-worn noise exposure measurement, and the green bars in the figure are the average of the noise exposure levels measured during that measurement session. Further discussion of crew noise exposure is included in references [33, 34].

The environmental monitoring data, SLM and Acoustic Dosimeter data, are used along with the predicted levels of new hardware to provide the CoFR and SORR statements prior to each ISS mission.

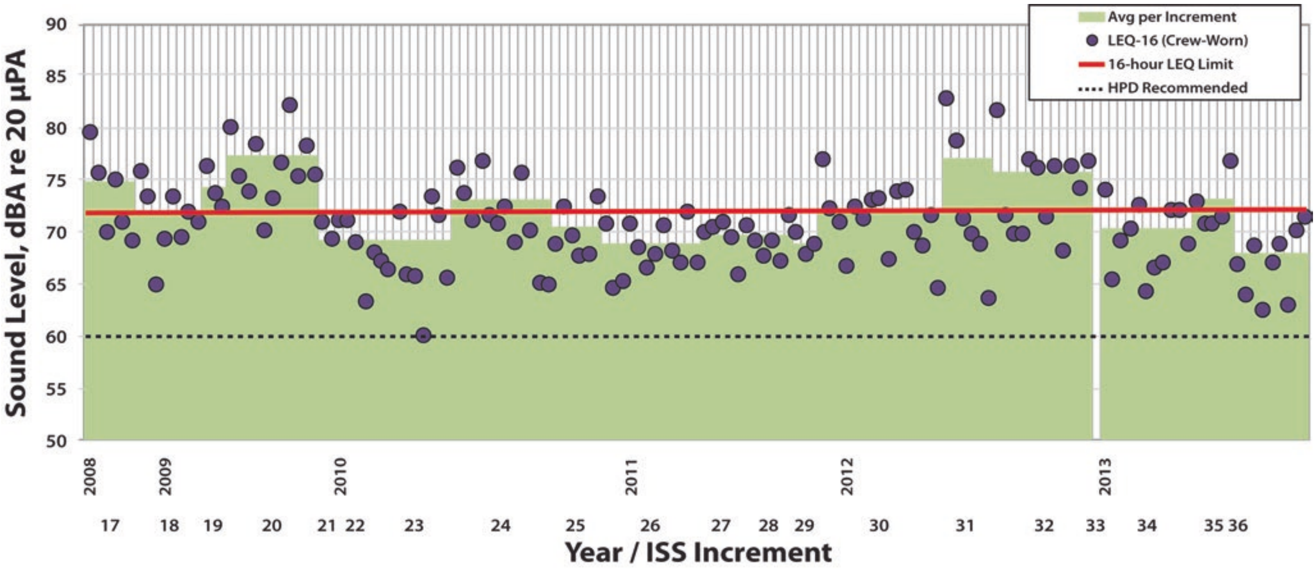


Fig. 6.9 ISS crew 16-h work day noise exposure levels from late 2008 to August 2013. Noise exposure reduction effects of hearing protection use are not reflected in this data since dosimeter microphone is pinned to shirt lapel (Courtesy of NASA)

A Historical Review of Acoustical Noise in Space Flight Vehicles

Noise levels that exceed acoustics standards have been a problem as far back as the Apollo missions. The ventilation fan in the Lunar Exploration Module had to be turned off in order to communicate with Earth because its high noise level interfered with the ability of the crew to hear the radio communications. Levels on the Russian space stations *Salyut* and *Mir* were high enough to generate many reported cases of temporary and permanent shifts in hearing sensitivity [35]. During the STS-40 mission on the Space Shuttle, noise levels in the low 70 dBA range caused severe communication problems between the crew and ground, as discussed later.

On the ISS, noise levels varied from module to module and also over time. That is, with the introduction of new modules or new equipment within a module, the noise levels varied. In some areas, e.g., in the Russian Service Module (RSM), noise remediation has improved the acoustic levels. In 2010, four new crew quarters were added, which provided four quiet locations for crew to get auditory rest [31]. Also, several of the added modules have low acoustic levels; e.g., U.S. Lab, JEM, COF, Node 2, and Cupola all meet their acoustic requirements. Finally, anomalies such as dust buildup on fan inlet screens and other surfaces caused increased noise levels from intermodule ventilation and crew quarters fans, which were resolved once the fans were cleaned [31].

Space Shuttle

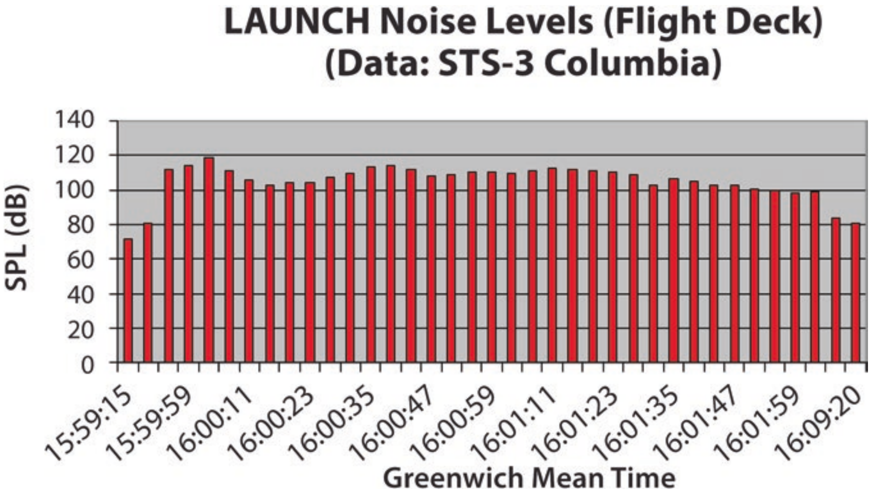
An important component of the Space Shuttle's noise was that which was produced during launch. Figure 6.10 shows noise levels measured during launch inside the flight deck during STS-3 [36]. The additional hearing protection provided by the space suit and helmet reduced maximum crew noise exposure levels down to approximately 103 dBA.

Once in orbit (roughly 8 min after lift-off), the level decreased significantly with the intent of achieving roughly levels not greater than 63–65 dBA. However, intentions were not always met, and levels on the flight deck were recorded at greater than 70 dBA [18]. During STS-40, levels as high as 73 dBA in the middeck and 75 dBA in the Spacelab (inside the orbiter's cargo bay) caused severe communications problems between the crew and ground. The unofficial catchphrase for the mission was "say-again!". Headaches were also reported to have happened during the mission, caused by the high noise levels [18].

The Space Shuttle Acoustics Working Group and the Astronaut Office determined that 70 dBA was the level at which hearing protection should be used [18].

Roller et al. reported the presence of temporary and permanent hearing threshold shifts among crew members after a Shuttle mission, based on a retrospective analysis of data collected on STS-40 [37]. They noted the absence of important tympanometric data on these individuals, which would have been very useful in ruling out the possibility of middle ear anomalies contributing to the apparent threshold shifts.

Fig. 6.10 Space Shuttle Orbiter internal noise, in the Flight Deck during the atmospheric launch phase as a function of time, analyzed using a 6-s time window. (*Source*: Nealis, "Acoustic Noise Analysis for STS-3," Internal NASA Report EE-2-82-016 (U), Flight Communications Branch, Tracking and Communications Division, June 1982 [36])



Alford et al., in a more recent comprehensive review of audiometric data from 618 crew members from Space Shuttle missions STS-1 to STS-129, compared audiometric data obtained in tests (conducted ~10 days before launch) and post-flight tests (conducted 3–5 days after return to Earth) [38]. These audiometric tests had all been done at the Flight Medicine Clinic at the NASA Johnson Space Center (JSC) under the supervision of flight surgeons until 2002, and then were supervised by an audiologist. Audiometric pure tone averages (PTA) were calculated as the mean of hearing levels in each ear, averaging *low frequencies* (500, 1000 and 2000 Hz) and *high frequencies* (3000, 4000 and 6000 Hz). The analysis of the larger population (from STS-1 through STS-139) did not reveal a significant difference between pre- and post-audiometric results, when comparing PTA data.

International Space Station

The first two modules of the ISS were joined together in 1998 and it has been continuously inhabited since 2000. During the early phase of ISS construction, before the U.S. Lab was launched, the crew spent most of their time in the RSM with sound levels mostly in the range of 67–73 dBA. During this time period, the acoustic environment was considered one of the top habitability concerns on the ISS. Since that time, efforts to reduce the on-orbit noise levels of the RSM have significantly reduced its sound levels. This is discussed further below. Many more modules were subsequently added to the ISS, and most of these have lower noise levels (Box 6.22).

Box 6.22
The addition of 4 quiet crew quarters (in Node 2), in addition to the two RSM Kayutas, has also been very beneficial to the crew. But in the early days of ISS construction it was necessary that hearing protection be worn by the 3-person crew for a significant portion of the day to protect the crew-members' hearing.

Goodman expressed concern that making HPDs readily available on the ISS would result in higher noise levels and the sense that HPDs could correct for any exceedances of the standards [23]. However, increased awareness and oversight for acoustics along with increased management support, including funding of a noise remediation contract to reduce noise levels in the RSM, helped to control noise levels on the station. Diligent efforts to apply and manage acoustic requirements and verification requirements for payload racks, sub-rack lockers, and aisle-mounted payloads, along with requirements for the full payload complement in each module, also helped to control the additional noise produced by payloads in the U.S. Lab, Columbus, and Japanese Experiment Module laboratories.

The ISS Acoustics Working Group and the Multilateral Medical Operations Panel Acoustics Subgroup were formed to work ISS acoustics issues, including setting standards for all international partners to meet and review/disposition requirement exceedances. With these measures, there is significant rigor applied to assuring standards are mostly achieved. As a result, hearing protection is no longer used as a crutch, but only as required on an infrequent basis (as dictated by the NHI) or as a crew preference.

Despite the substantial efforts to control hardware noise levels, the intended levels are not always met upon launch of the hardware. Thus, in an effort to protect the crew members, engineering modifications have, in some cases, been implemented on-orbit. One area where significant progress was made included acoustic remediation of the RSM. The RSM was designed to perform many of the functions

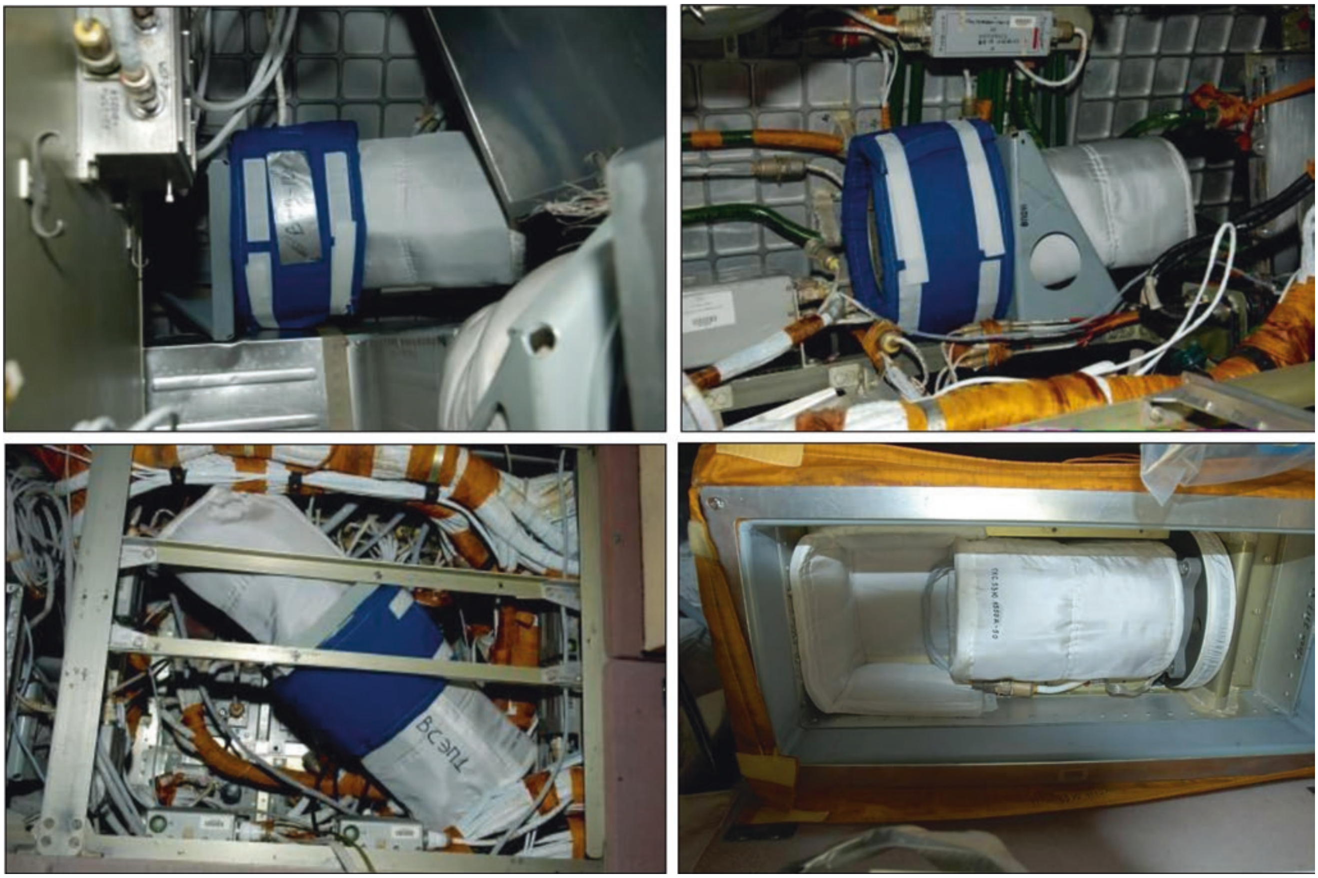


Fig. 6.11 Noise controls developed for Service Module fans (Reprinted from Allen CS, Denham SA. "International Space Station Acoustics – A Status Report," *Proceedings of International Conference on Environmental Systems 2011*. American Institute of Aeronautics and Astronautics, AIAA 2011-5128, 2011 http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100039608.pdf or http://arc.aiaa.org/doi/pdf/10.2514/6.2011-5128)

that were spread throughout the space station *Mir*, a significant amount of noise-producing hardware. Also, an agreement that legacy *Mir* fan technology would be used was made at high governmental levels. As a result, the initial sound levels in the RSM were in the mid- to high- 70 dBA range [39]. However, once in orbit, work to reduce the noise levels began immediately. Acoustic treatments were added to wall surfaces, and a noise enclosure was added to the CO_2 removal hardware (the "Vozdukh"). Inlet and outlet mufflers, vibration isolators, and acoustic wraps were added to many of the ventilation system fans. The air conditioner compressor and fluid lines were covered and new closeout panels were developed. These were developed by the Russian company Rocket Space Corporation – Energia (RSC-E) in cooperation with Russia's Federal Space Agency, Institute of Biomedical Problems, and NASA.

Figure 6.11 illustrates some of the noise controls implemented on RSM fans. Other controls included air conditioner and further Vozdukh acoustic treatments. Figure 6.12 shows a comparison of noise levels in the main part of the RSM from 2001 (Increment I) to 2013. Noise controls were also targeted to reduce the noise levels inside the ***Kayuta*** sleep stations, including fan vibration isolators, acoustic duct-liners, acoustic inlet louvers, register treatment, door replacement/modifications, and a fan-speed controller. Recently, a new ***quiet fan*** has been developed by RSC-E, using modern computational fluid dynamics (CFD) techniques, and this new fan model will replace two types of fans that are used at 30 different locations in the ISS. Use of this new fan has already been successful in reducing sound levels inside the MRM1 by as much as 10 dBA (see Fig. 6.13) and should provide further noise reductions in the RSM. Further details on the noise reduction effort and results achieved in the Service Module as a result of the noise remediation contract with RSC-E have been documented by Allen and Denham [31].

When payloads or other hardware produce significant acoustic emission exceedances, efforts are made to remediate the hardware prior to launch by incorporating noise controls; e.g., mufflers, barriers, acoustic blankets, etc. Goodman describes some of those efforts [23]:

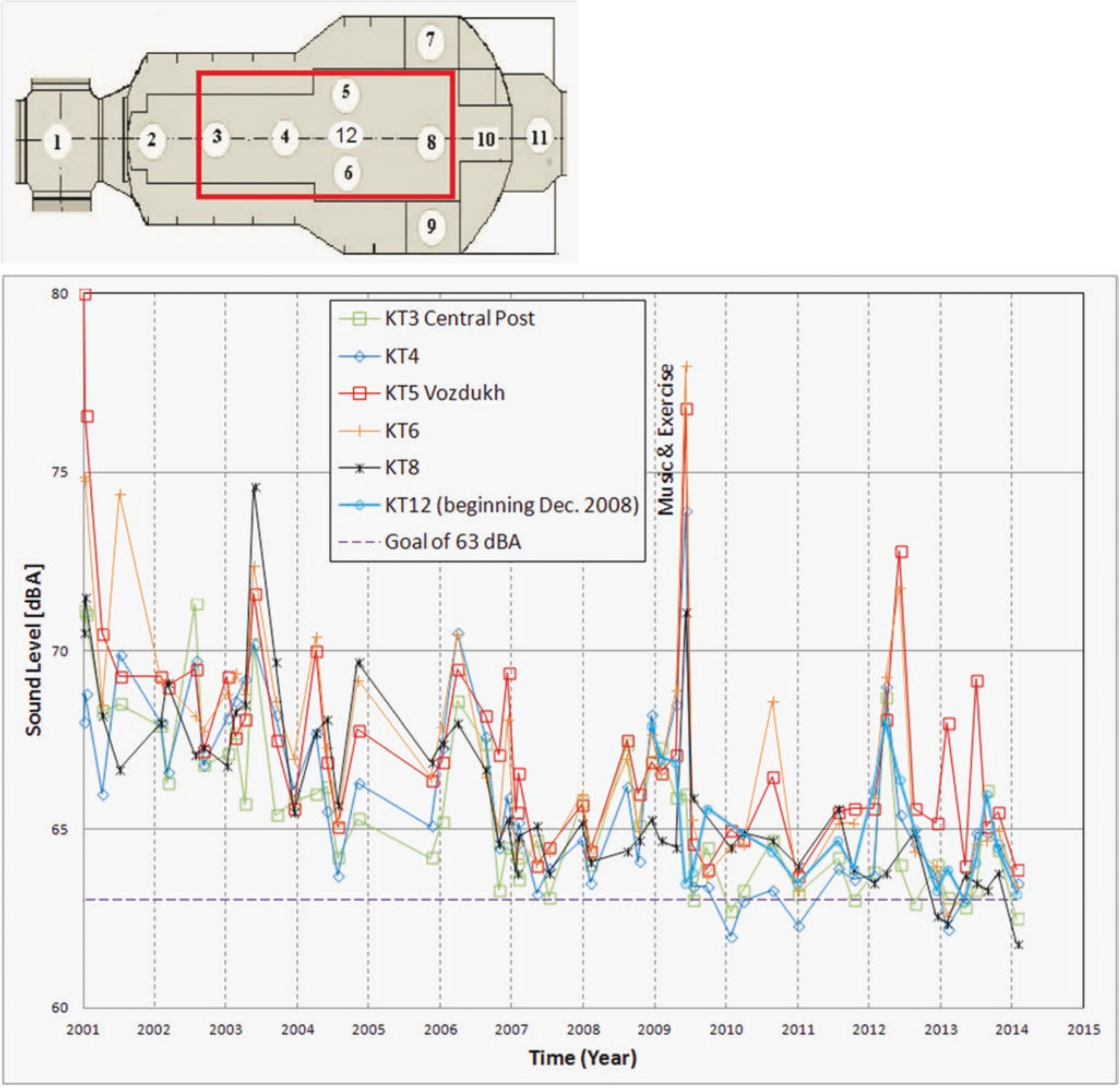


Fig. 6.12 Noise levels in main part of the ISS Russian Service Module (Courtesy of NASA)

At times when hardware items are shown to be in need of design or consultant support, or in serious noncompliance, special focus and efforts are marshaled to help remedy the situation. Examples of these efforts are: quieting an Airlock Module depressurization pump and developing a heat exchanger muffler; developing muffler approaches for Express Racks and recommending their implementation; supporting efforts to quiet the Microgravity 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. [23]

As was stated previously, noise levels vary throughout the ISS. Table 6.2 shows the typical noise levels in the ISS modules, as of this printing. Typical average spectral Sound Pressure Levels are shown for the U.S. Segment modules in Fig. 6.14, and for the Russian Segment modules in Fig. 6.15. These reflect the complete construction of the ISS as well as the current 6-person crew configuration. In the U.S. Segment,

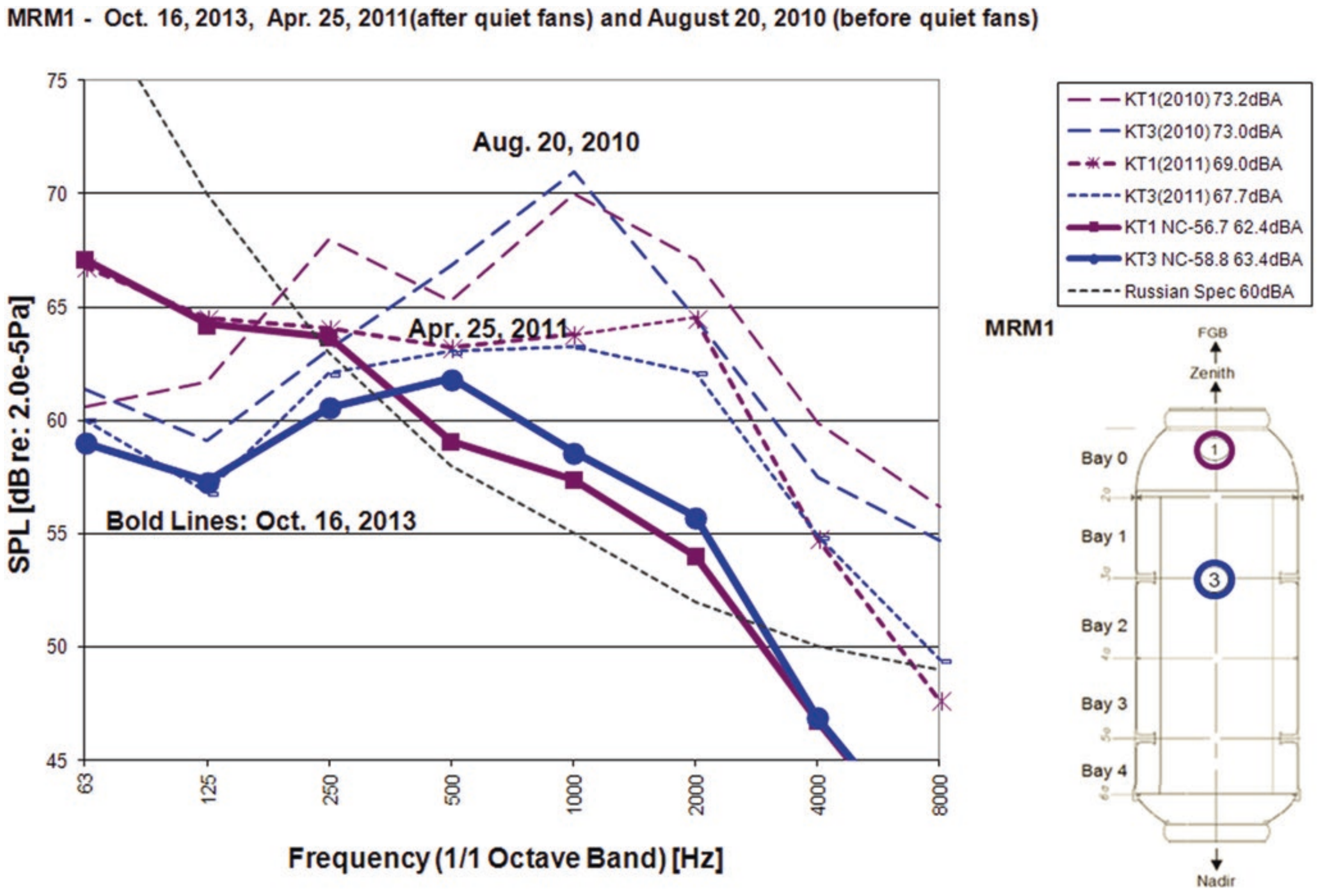


Fig. 6.13 Noise level reductions in MRM1 with implementation of Russian Quiet Fans. Two new fan replacements installed prior to April 25, 2011 measurement, and two more installed prior to October 16, 2013 measurement. One old-style fan remains to be replaced in the MRM1 (Courtesy of NASA)

work continues in an effort to reduce the levels in Node 3, which exceed its NC-52 requirement. The Urine Processor's (UPA's) Distillation Assembly (DA) is the loudest continuous hardware item in Node 3 and new sound blocking closeout panels are being developed to contain its noise. In the Russian Segment, noise reduction efforts continue with the replacement of loud fans with the new ***quiet fans***. Noise levels of the crew's sleeping quarters are also shown in Table 6.2 and spectral levels are shown in Fig. 6.16 [31]. Spectral levels in the Russian Kayutas are given in Fig. 6.17 [31], including levels prior to and after the noise remediation contract efforts, a 10 dBA reduction in each Kayuta. As a result of the new modules and crew quarters, as well as the on-orbit acoustic remediation, the overall noise environment on ISS has improved.

Hearing Conservation Programs and Hearing Protection

Each crewmember's auditory sensitivity is monitored, using conventional pure-tone audiometry, at least annually during flight physical exams and compared to a baseline audiogram that was recorded when the individual first became an astronaut. Data and trends are reviewed by an audiologist and flight surgeons at the NASA Johnson Space Center (JSC) to identify any shifts in hearing sensitivity since the baseline audiogram. When the crewmember is assigned to a mission, another set of audiometric tests are performed during preflight physical exams (usually 10–45 days prior to the mission) and post-flight physical exams (within 1–3 days after returning from space). The post-flight audiograms are

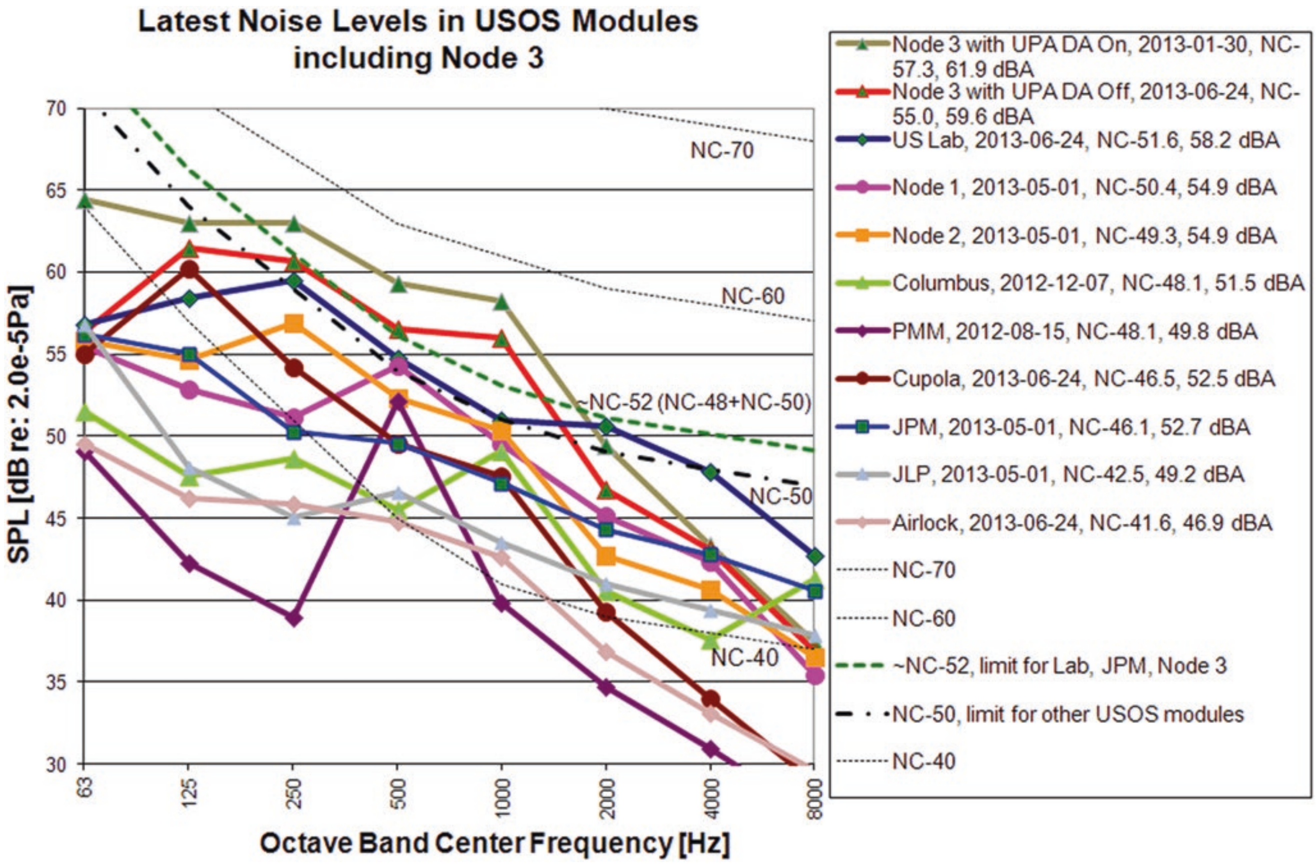


Fig. 6.14 Typical Average Acoustic Spectra inside the ISS U.S. Segment (Courtesy of NASA)

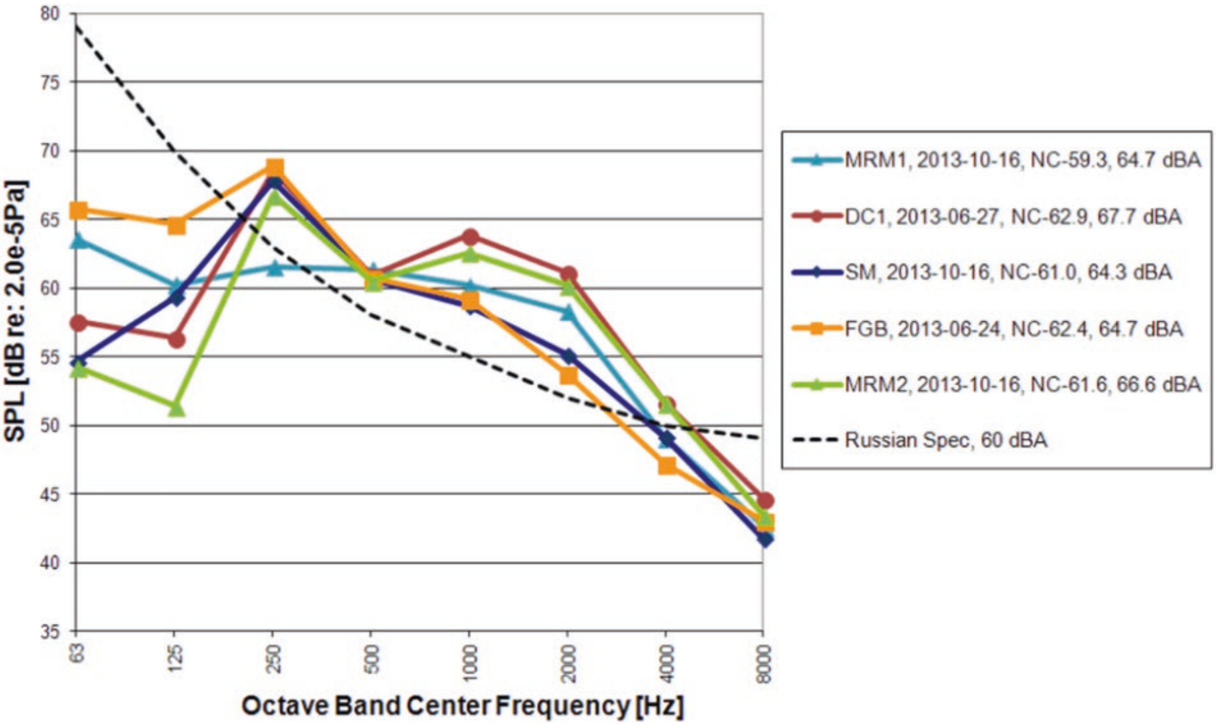


Fig. 6.15 Typical Average Acoustic Spectra inside the ISS Russian Segment (Courtesy of NASA)

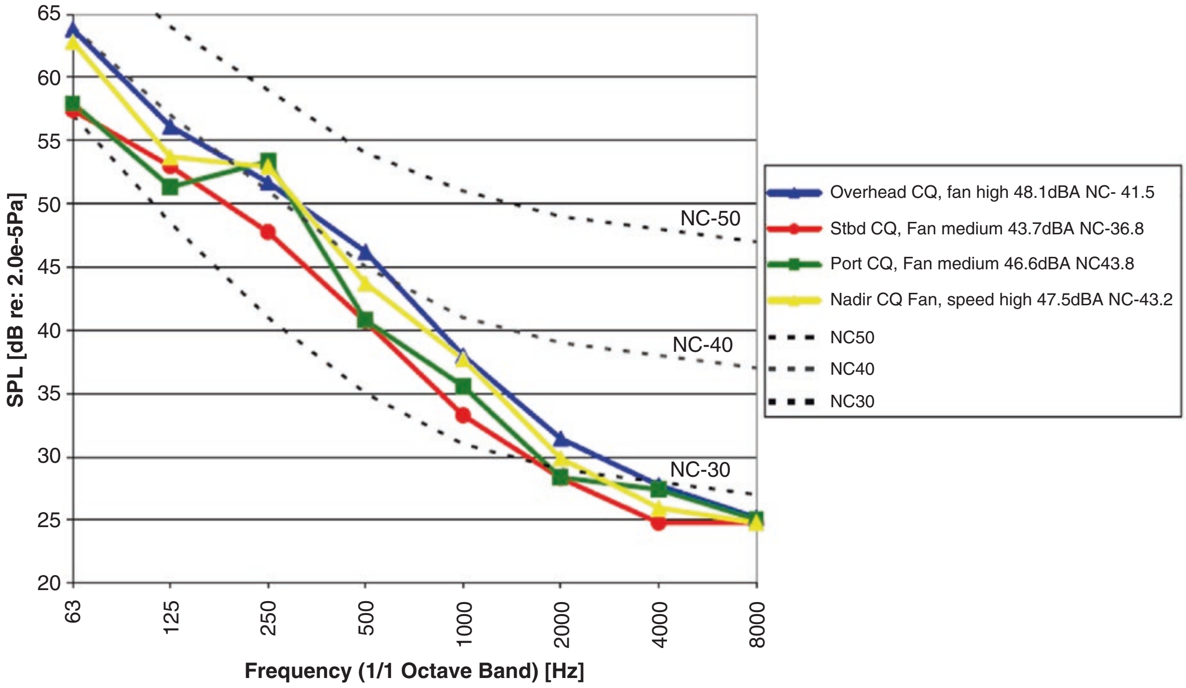


Fig. 6.16 Acoustic levels inside the new U.S. Crew Quarters (Reprinted from Allen CS, Denham SA. "International Space Station Acoustics – A Status Report," *Proceedings of International Conference on Environmental Systems 2011*. American Institute of Aeronautics and Astronautics, AIAA 2011-5128, 2011 http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100039608.pdf or http://arc.aiaa.org/doi/pdf/10.2514/6.2011-5128)

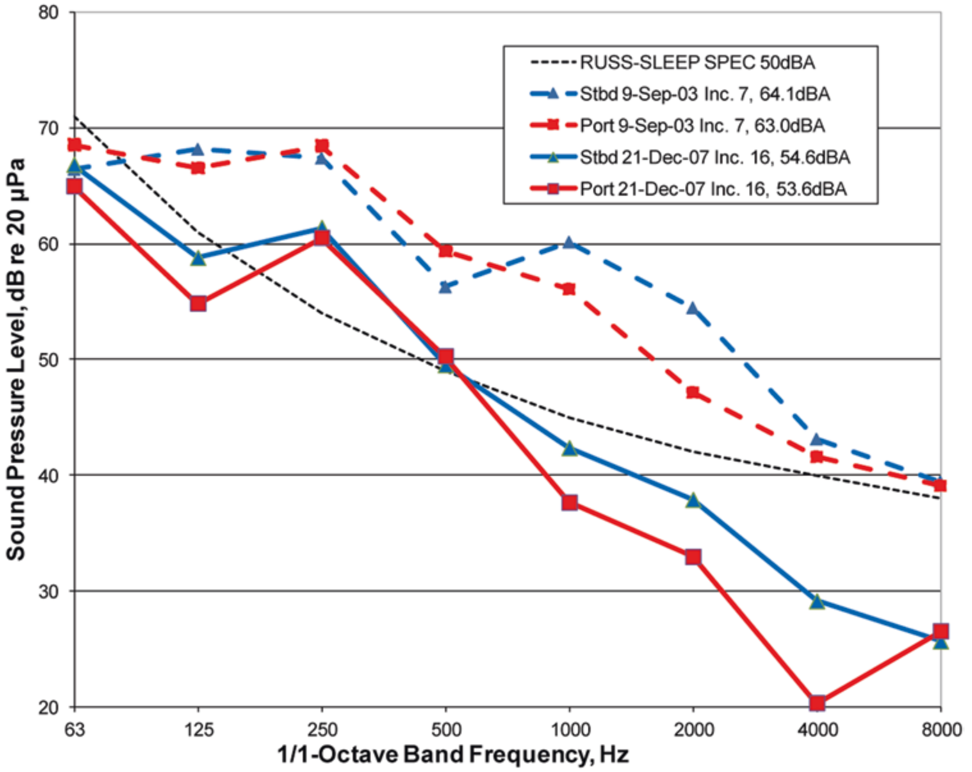


Fig. 6.17 Acoustic levels inside the Service Module crew quarters (kayutas), before and after remediation (Reprinted from Allen CS, Denham SA. "International Space Station Acoustics – A Status Report," *Proceedings of International Conference on Environmental Systems 2011*. American Institute of Aeronautics and Astronautics, AIAA 2011-5128, 2011 http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100039608.pdf or http://arc.aiaa.org/doi/pdf/10.2514/6.2011-5128)

Fig. 6.18 On-Orbit Hearing Assessment being conducted on the International Space Station (*Source*: Courtesy of NASA)

reviewed closely to identify changes in hearing sensitivity since the pre-flight audiograms that might indicate a space flight-associated change in auditory status. This review is particularly focused on indications of any shift (from the pre-flight baseline) seen in the audiogram's high frequency regions (i.e., 4000 or 6000 Hz, with better hearing at 8000 Hz). If such a change is suggested, additional follow-up evaluations are conducted by the audiologist.

In addition, a unique method of monitoring hearing thresholds is used on board the ISS. In this procedure, the ***On-Orbit Hearing Assessment (OOHA***), the crewmember determines hearing thresholds independently with a self-administered test (rather than being tested by someone else) (Fig. 6.18). The OOHA uses software on a space station computer that presents pure-tone stimuli via the computer's sound card and custom-made silicone ear monitors (which are worn under active noise reduction headsets to further attenuate ambient noise) (Fig. 6.19).

Prior to each mission, a baseline OOHA is performed in the JSC Audiology clinic during a pre-flight "fit-check" evaluation of the custom ear wear. On that same day, a conventional air-conduction audiometric test is also conducted to provide audiometric data acquired with conventional earphones, audiometer (calibrated to ANSI S3.6, 2010 [40]), and in an audiometric booth (that does not exceed ambient noise levels specified in ANSI S3.1 1999 [41]). The first in-flight OOHA is conducted on launch day 14 and is then repeated every 45 days thereafter. The raw OOHA data are then downloaded and routed to an audiologist, who converts these raw data to conventional hearing thresholds equivalent to conventional audiometry (using conversion data based on pre-flight testing), and interprets the OOHA results for flight surgeon review. If any indication of threshold shifts is observed, recommendations (e.g., increased use of hearing protection) are made.

Retrospective studies of audiometric data have suggested evidence of slight temporary and permanent hearing threshold shifts (at individual audiometric frequencies) among Space Shuttle crew members, following short-duration missions [38]. Fewer than 6 % of ISS crew members have shown an indication of "early flags" of hearing loss (Box 6.23) [42]. A recent NASA analysis of ISS increments 1–37 revealed that 6.8 % of the in-flight OOHAs suggested a mission-associated Standard Threshold Shift, using criteria of NASA JSC Flight Medicine Clinic (and similar to OSHA) when compared to the pre-flight OOHA. Abel et al. conducted a study of simulated ISS noise for 70 h and found no indications of TTS or PTS [43]. However, they noted that the impacts of noise and vibration during the launch of the Space Shuttle and/or the physiologic alterations induced by microgravity may have resulted in changes [37].

There are certain situations in which hearing protection must be worn on ISS (Fig. 6.20). For example, when operating pressure equalization valves, the sound levels may exceed the 85 dBA hazard level. As a result, hearing protection must be worn during this short-duration operation.

The levels of attenuation provided by these hearing protective devices range from 10 to 29 dB. While it may initially seem appropriate to seek "maximum" noise attenuation, there are potential risks of overprotection that might interfere

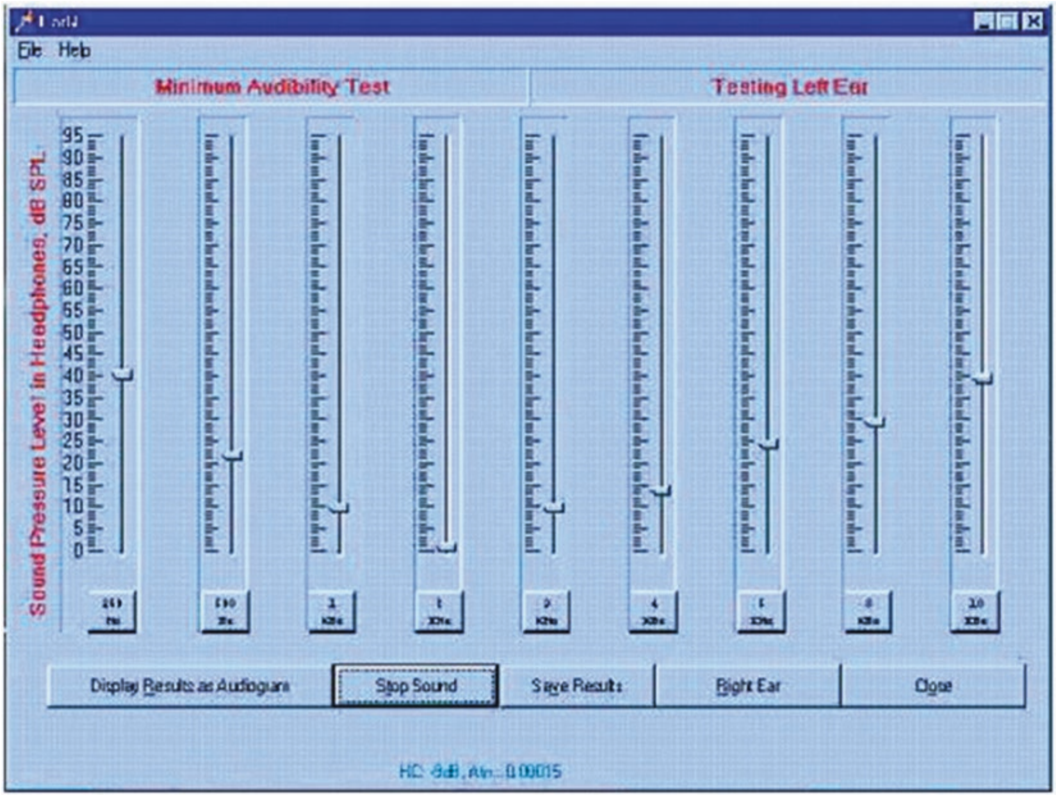


Fig. 6.19 Screen shot of OOHA test controls (Courtesy of NASA)

Box 6.23
Evaluation of data from both Space Shuttle and ISS missions obtained from the NASA ***Longitudinal Study of Astronaut Health*** (recently revised to the ***Lifetime Surveillance of Astronaut Health***) that, using conventionally accepted criteria for "early flags" of identifying noise-related hearing loss (that is, a 10 dB shift from baseline levels when averaging hearing thresholds at 2000, 3000 and 4000 Hz among U.S. ISS crew members, temporary hearing shifts have been seen in about 6 % of OOHAs, but none of the post-flight conventional audiometric tests.)

with speech understanding or detection of operationally important auditory signals. Consequently, hearing protection should be chosen with considerations of noise levels as well as user acceptance (e.g., comfort and performance), rather than solely using a manufacturer's labeled claim of noise attenuation (Box 6.24). Another form of hearing protection that has been flown is an HPD with ***active noise reduction (ANR***) of low frequency energy (below 1 kHz). This ANR offers a subjectively reduced level of continuous low-frequency noise (caused by fans and motors), while not attenuating human speech elements in high frequencies.

Astronauts are trained to be very conscious about the potential risks of hearing loss from exposure to high noise levels and, therefore, are accustomed to routinely using hearing protection during their aircraft training flights, as well as during non-occupational activities during their off-duty time at home. Consequently, they are well inclined to seek and use HPDs during their missions and often use HPDs during personal time and when sleeping. If the crew's preference for foam hearing protectors exceeds expected usage levels on the ISS, onboard supplies can run low, requiring unplanned requirements to manifest additional earplugs for shipment on next available ISS-bound vehicles. ANR headsets, originally manifested to reduce ambient noise levels for the OOHA, have been adopted as the primary headset for the Internet Protocol phone that is used during family, medical, and mission communications on the ISS.

Alarm Audibility

Another important acoustics-related issue regarding manned spacecraft operations is the need for the crew to hear alarms (Box 6.25). On the ISS there are three types of audible alarms that are broadcast throughout the station, ***Class I – Emergency***, ***Class II – Warning***, and ***Class III – Caution***. These alarms are tonal in nature, but differ by frequency and

Fig. 6.20 Examples of hearing protective devices used on the ISS. (**a**) Disposable foam earplugs, which attenuate more high frequency sounds than low frequency sounds. (**b**) Custom-made silicone earplugs (often referred to as "musician's earplugs") and filters that attenuate sounds (by 15 or 25 dB) uniformly across all frequencies. (**c**) Custom-made silicone ear monitors, which have two high-fidelity speakers, used to attenuate ambient sounds while producing acoustic stimuli for the On-Orbit Hearing Assessment, and also serving as hearing protectors to reduce noise levels of loud treadmill equipment, allowing crew members to reduce the volume levels of music while exercising. (**d**) Active noise-reduction (ANR) headsets, which attenuate more low frequency sounds than high frequency sounds. When ANR headsets are coupled with microphones, crew members also use this headset to communicate with their internet protocol (IP) phone conversations (Courtesy of NASA)

Box 6.24

Passive hearing protectors typically provide more attenuation in high frequencies, which can cause wearers to feel that speech seems subjectively "muffled." As a result, crew members are also offered custom "musician's" ear plugs that have a flat attenuation across all frequencies, in order to reduce noise levels while not distorting perceived acoustic characteristics.

Box 6.25

The important feature of an audible alarm, in order for the alarm to be heard above the background noise, is the ***signal-to-noise ratio (SNR)*** of the alarm signal above the background noise. Other effects that also need to be taken into account include the ***upward spread of masking***, effects of hearing protection use, and the effects of hearing loss among crew-members. When these effects are combined with the SNR, it is said that the alarm signal must exceed the crew member's ***effective masked threshold*** by a certain amount.

temporal characteristics. For example, the Emergency alarm, used in the cases of depressurization, fire, or toxic release, is a 2 kHz tone that is on/off at approximately 0.5 s intervals, whereas the Caution alarm is a steady tone at approximately 500 Hz. The Warning alarm is a tone that alternates between 2 kHz and 500 Hz frequencies at approximately 0.5 s intervals. It is critical that the crew members are able to hear and respond to the Emergency alarm immediately.

NASA has recently adopted ISO 7731 (2003), which takes into account all of the factors listed above [44]. This standard relates the ***critical band theory of human hearing*** discussed by Kryter to typically used octave and 1/3 octave band frequency resolutions [45]. An alarm signal must exceed the masked threshold of the critical band by at least 15 dB in order for the signal to be audible and elicit the attention of the receiver. This corresponds to required signals that are at least 10 dB above the masked threshold expressed in octave bands or 13 dB above when expressed in 1/3 octave bands [46, 47].

A third option is also given in ISO 7731 (2003) [44], which does not require a frequency analysis. This option is for the A-weighted Sound Level of the alarm signal to be at least 15 dBA above the A-weighted Sound Level of the background noise. This will produce a louder alarm, so this option is the alarm requirement now used to awaken sleeping astronauts.

ISO 7731 also provides simple methods, either for octave band or 1/3 octave bands, to take into account the upward spread of masking, a fact of human hearing that low-frequency sound will mask higher frequency sounds depending on the intensity of the masking noise [45]. Regarding hearing protection use, if not for the upward spread of masking, the background noise would be attenuated by the same amount as the alarm signal, resulting in no net change in ***SNR*** when using HPDs. However, since the level of attenuation provided by

HPDs varies with frequency, and is usually less effective at low frequencies, the attenuated background noise may have more low-frequency content relative to the high frequencies, thereby accentuating the upward spread of masking effect. Examples are given in ISO 7731 that describe how to account for hearing protection use; this method is used by NASA when reviewing the alarm audibility situation on ISS.

Examples are also given in ISO 7731 on how to account for audibility when the listener has hearing loss. This is usually not an issue for alarms on ISS, since the alarm signals are limited to 2 kHz or below and crew members do not typically have hearing loss at these low frequencies.

Another consideration is that the alarms should not be excessively loud. If alarm levels are too high, they could cause the crew to become startled, thus causing confusion and delaying their response to the emergency [46]. In order to avoid this problem, alarm levels on ISS are limited to not exceed 95 dBA.

An acoustics issue with alarms on ISS can arise when there is no alarm speaker located in a module (or more typically, a visiting vehicle). Most of the modules that make up the ISS have two ***Audio Terminal Units (ATUs)***, which broadcast the alarms within the module. But some modules and most of the visiting vehicles (e.g., Automated Transfer Vehicle, Hydrogen Transfer Vehicle, Space-X Dragon, and Orbital Cygnus vehicles) do not have an ATU within the vehicle. To allow alarm audibility in these modules/vehicles, the alarm signal propagates through the hatch from the adjacent module. And since there is a significant attenuation when the signal passes through the hatchway, the signal intensity entering the vehicle is reduced. This puts more importance on meeting the continuous (background) noise requirement in that module or visiting vehicle, in order to have an acceptable alarm SNR or separation above the crew member's effective masked threshold.

Future Clinical Concerns

Impacts of Extra-Long Duration Missions

The number of astronauts who have participated in long-duration missions (i.e., 6 months) is relatively small. Approximately 140 crew members have participated in these missions, whether on board the ISS or NASA-*Mir*. Until May 2009, the maximum crew size of the ISS at any one time was 3. Later, 6 or more crew members per increment have lived and worked on the ISS. And, beginning in 2015, 2 crew members were assigned to a year-long mission on the ISS. NASA is just now starting to be able to acquire the data necessary to adequately assess the impact of missions of this length on hearing function. Assuming that missions travel beyond low Earth orbit (LEO), particularly for transit to other planetary objects, the length of the mission may extend well beyond 6 months. Unless noise levels can be reduced to and maintained at those defined in NASA standards (e.g., NASA Standard 3001) [25], astronauts will continue to be exposed to levels that, over time, may be hazardous—in this case, a very long time. Additional work is needed to assess the impact of current noise levels. Furthermore, this will continue to challenge the engineering community to ensure that, while constructing even more sophisticated and complex systems for human space transportation and habitation, noise levels are maintained at or below specified standards.

Health Effects of Noise on Crew Sleep

Sleep, or more precisely the lack of sleep, is a potential concern for crew health and safety about the impact of sleep disturbances on mission activities, attempting to identify what factors may be the cause and how they may be mitigated. NASA has conducted studies using a device called an ActiGraph to monitor the sleep/activity cycles of crew members, correlating sleeplessness against factors that may disrupt sleep (Box 6.26) [48]. As was noted earlier, noise has a number of non-auditory impacts on individuals, including disturbing sleep. Employing this type of technology in future studies may help NASA better characterize the risk, and determine the effectiveness of noise reduction efforts.

The Role of Ototoxins

Exposure to certain chemicals, either alone or in concert with noise, may result in hearing loss [49, 50]. The training and mission activities of astronauts may put them in contact with some potentially ototoxic chemicals (e.g., xylene, diesel fuel, kerosene fuel, jet fuel, JP-8 fuel, n-hexane, mercury, organic lead, and hydrogen cyanide). Therefore, in addition to assessing noise data, it will be important to track exposures to known ototoxic chemicals to help determine the possible concomitant or synergistic effects on hearing.

Box 6.26

The ***ActiGraph*** is a small device, based on accelerometer technologies, that is traditionally used to monitor human motion against the force of gravity. It is very sensitive to changes in the state of activity of an individual, thus able to sense a change from sleep to wakefulness.

Radiation and Central Nervous System Health Concerns

Chapter 7 provides a detailed description of potential hazards from space radiation, including the central nervous system (CNS). Human and animal subject studies describing the impact of space radiation on hearing are not well documented, even though numerous investigations into the therapeutic radiation treatments on both central and peripheral auditory structures [51–55] indicate significant negative effects on both pure tone thresholds as well as auditory brainstem responses. The investigators claim that damage could occur from the Eustachian tube to the auditory brainstem pathways, thus resulting in conductive, sensorineural, or mixed hearing losses.

Case Study

Learning Objective: Review the Current Approach to Hearing Conservation on the ISS

In the Spacelab (a laboratory module flown on the U.S. Space Shuttle missions: see also Chap. 1), the crew's callouts needed to be repeated; "Say again" was the phrase often repeated. Inability to understand normal speech and communicate with each other was reported by the crew as a major frustration during working in the laboratory. Levels in the Orbiter Crew Module during STS-40 also were high, reaching daily averages as high as 71–73 dBA as compared to 73.5 dBA through 75.5 dBA in the Spacelab. The high levels in the Orbiter were due to two payloads in the mid-deck. The crew was very irritated during operations and sleep periods, and reported headaches, attributed to the high noise levels experienced during the mission. Another report documented more details about the STS-40 noise levels and crew comments, and reiterated the recommendation that NC-50 should be met in areas where speech communications were required and NC-40 for sleep periods. The report also documented that 85 % of the crew noted that noise interfered with their ability to concentrate and relax. In the STS-50 mission, noise levels in the Orbiter middeck values measured at 60 dBA and the flight deck values measured 64 dBA. The crew commented that the flight deck and mid-deck noise values were acceptable. Fifty percent of the crew reported that noise interfered with concentration and relaxation [18].

As stated by NASA "The ISS presents a significant acoustics challenge considering all of the modules and equipment that make it an on-orbit laboratory and home with long-duration crew occupation. The acoustic environment on board the ISS has become one of the highest crew habitability concerns. The acoustics mission support function, including training, mission control support, and data analysis, is necessary to monitor crew exposure and ensure that the crew members' hearing is not at risk. Without accurate on-orbit data, all preventative ground efforts are rendered ineffective. Mission monitoring and support is critical to the control and mitigation of acoustic noise on the ISS. ISS Acoustics preserves crew members' hearing and provides for a safe, productive, and comfortable noise environment."

In order to protect the crew from continuous exposures to high noise levels, low noise areas are used for periodic rest. Current protocols for hearing conservation on the ISS include:

1. Noise level monitoring
2. Astronaut periodic in-flight hearing tests
3. Rest/sleep area isolation and muffling, without impeding the air flow and heat exchange (Fig. 6.21)
4. Personal noise protection equipment (ear plugs, ear muff with/without noise cancellation capability) (Fig. 6.20)

Review the efficacy of the aforementioned preventive measures and discuss possible engineering solutions to reduce noise at its source such as: fans, equipment, vibration in metal cylinders, etc.

Using both specially fitted earplugs and noise cancellation devices has shown a reduction of dBA of approximately 15 dBA Should the crew wear the ear plugs in addition to the communication earmuffs to better discern speech while performing complex tasks with the assistance of the ground support crew? Can ear plugs lead to external otitis and what precaution should the crew members take to prevent infections during repeated wear?

Self-Study Questions

1. In-flight and post-flight audiometric surveillance should include hearing threshold shift information. Describe the approach on how to measure these shifts and communicate the results to the astronauts.
2. What are the best practices for hearing conservation in space flight missions? Compare hearing conservation programs employed on ISS with more conventional hearing conservation programs used in the military and industry.
3. Were there any cases of hearing loss reported in the U.S. or Soviet/Russian programs following long-duration missions?
4. This chapter describes several different forms of describing acoustic metrics. Describe how these different metrics are measured/calculated and how the ISS programs uses them to protect crew health and safety: dBA, dBC, dBSPL, SIL(4), dBHL, TWA, NC.

Fig. 6.21 Padded sleep area used in the Space Shuttle and the ISS (Courtesy of NASA)

5. What acoustic measurements are best made with a *Sound Level Meter*? With an *Acoustic Dosimeter*? What information is provided by each of these devices and how would flight surgeons and acoustics experts use the data?
6. Describe some strategies (both administrative and engineering) that have been used to reduce noise levels on the ISS for crew health, safety and habitability.
7. Besides being a risk for hearing loss, why would acoustic issues be a concern for crew health and safety during their long-duration mission?

Key Points to Remember

1. The ability to communicate in space and hear alarms is a matter of mission safety on space vehicles.
2. Unlike terrestrial settings, space mission environments expose crew members to noise with little acoustic rest.
3. Sources of noise in the ISS include life support systems (such as fans), experimental and system equipment, and secondary reflections from metal surfaces (i.e., reverberation).

4. Crew sleep compartments on the International Space Station are designed to be low-noise areas, where the crew can relax during the off-duty hours and sleep with minimal disruptions.
5. Crew members are encouraged to wear personal hearing protective devices, as they choose, to reduce annoying sound sources.
6. Based on scientific evidence of the risks of hearing loss, NASA's flight rules use Noise Damage Criteria that are more conservative than those of the U.S. Occupational Safety and Health Act for conventional occupational workers.
7. A Noise Hazard Inventory, based on noise data and known crew activities, is used to communicate information to the ISS crew on when to wear hearing protection on the ISS.
8. Excessive exposure to high levels of noise may result in a bilateral, sensorineural hearing loss that is first seen in high frequency regions (i.e., 4000 or 6000 Hz, with better hearing at 8 kHz), resulting in an "audiometric notch" in an audiogram.
9. The level of noise within habitable modules are influenced by sounds emitted from individual racks and payloads, so hardware sometimes needs to be quieted prior to launch by incorporating noise controls.
10. If no temporary threshold shifts are seen after a given noise exposure, that noise exposure is not expected to cause a permanent threshold shift.
11. Individual susceptibility to the auditory effects of noise varies widely among individuals.

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