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# HEARING ASSESSMENT ABOARD THE INTERNATIONAL SPACE STATION

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# HEARING ASSESSMENT ABOARD THE INTERNATIONAL SPACE STATION

by
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# ABSTRACT


## HEARING ASSESSMENT ABOARD THE INTERNATIONAL SPACE STATION

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This study undertakes to refine the understanding of the accuracy of a novel PC-based hearing assessment utilized aboard the International Space Station. During the design and construction of the ISS, time and funding constraints led to engineering compromise related to acoustics, resulting in a vehicle with excessive noise levels. To gain insight into crewmember hearing changes, a computer-based hearing assessment tool was developed, and was routinely administered by crewmembers and its data analyzed on the ground. In this study, data collected before return to earth was compared to standard pure tone audiometric data collected after landing, with the intent to demonstrate that these values were essentially identical, and that data collected onboard the ISS can be interpreted as if it were pure-tone audiometric data. However, statistical analysis of this data concluded instead that the onboard test tends to underestimate the hearing threshold, and should be further corrected or interpreted accordingly.

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# 1. INTRODUCTION

This study is a retrospective analysis of data collected aboard the International Space Station (ISS) to assess the hearing of crewmembers using a system which was proposed, developed and validated by the author. Due to the limitations imposed by operating in the space environment, this system is non-standard compared to formal pure-tone audiometry, which, more than 80 years after its introduction, remains the gold standard of hearing assessment. This study compares near-end-of-mission tests self-administered in space using this novel approach, referred to as OOHA (the On-Orbit Hearing Assessment), with pure-tone audiometry performed on the ground on a single group of 28 astronauts and cosmonauts with a goal to further validate and refine the method employed to perform the in-flight assessments.

Standard pure-tone audiometry has been routinely performed for decades on the ground before and after spaceflight on both U.S. and Russian spaceflights. However, efforts to perform in-flight hearing tests have been limited to the first Russian space station (Salyut) and a few early Space Shuttle flights. The decision to test only on the ground appears justified for short-duration flights given that hearing loss, when identified, has tended to be reversible for flights of a few weeks. Exposure to excessive noise levels during longer-duration flights (up to 14 months) has proven more problematic, in part because such exposure is continuous throughout the day without a period of quiet during which the ear can recover.

Threats to hearing are obviously not unique to the aerospace environment, and approaches to living and working in noisy terrestrial environments are well integrated into occupational health programs; these are referred to as Hearing Conservation Programs (HCPs). The goals of such programs can be simply stated as variations on three themes: removing the hazard, removing the worker and protecting the worker. Although an obvious solution is to remove the hazard by designing and building quiet spacecraft, this poses significant financial and logistical burdens that have not been overcome in any program to date. Staying on Earth and sending robotic spacecraft would remove the worker, whereas a compromise might be to have a quiet haven to which the worker could retreat from the noise to permit recovery. Yet another solution is to place a barrier between noise and crewmembers by using hearing protectors such as earplugs or muffs. However, these can limit communications, mask alarms or irritate crewmembers to the point that they are not used. Another option is to monitor crewmember hearing health on a regular basis to determine the efficacy of the other efforts. Given that some individuals are less sensitive than others to noise and can tolerate higher exposures without developing hearing loss, regular monitoring can help avoid overly stringent application of the other countermeasures. While all of these elements of hearing conservation have been implemented to some extent aboard the ISS, this investigation focuses on the latter, that of hearing assessment.

Due to the increased risk of noise-induced hearing loss posed by longer-duration missions, a laptop PC-based hearing-assessment tool was adapted for use aboard the ISS and has been in use for almost six years. While this test has proven useful and has driven clinical decisions, interpretation of the results has been constrained from the outset by uncertainty regarding the correlation between this test and standard pure-tone audiometry. During early usage of the test, medical specialists were skeptical of the results until confirmatory post-flight audiometry was administered. This study represents the first time in-flight data have been used to support the validity of this method and perhaps refine it relative to pure-tone audiometry. The hypothesis of this study is that the novel on-orbit hearing assessment (OOHA), as currently used, is a meaningful predictor of post-flight hearing function as measured with standard pure-tone audiometry.

# 2. SIGNIFICANCE

Human-rated spacecraft are designed with a great deal of attention to the maintenance of a hospitable environment for those living aboard. Pressure, temperature, humidity, oxygen and carbon dioxide levels and ventilation are all carefully balanced to maintain an earthlike atmosphere, and measures are taken to protect crewmembers from radiation and from the accumulation of wastes, toxins and microbes in the air and water. An unfortunate ramification of the operation of the systems required to handle all these functions, as well as those responsible for properly orienting the spacecraft and communicating with the ground, is the potential for excessive noise. Thoroughly addressing this potential in the design and construction phases of modules can lead to reasonable background levels. However, building the ISS to these specifications has proven too costly in terms of both money and time. As with other structural or functional elements, iterative compromise and downsizing have led to an acoustic environment on the space station that clearly has the potential to negatively impact sleep, communication, concentration and attention, and to threaten hearing function in both short and long terms.

The pathway to eventually quieting the ISS is a lengthy one; features added late in the design and construction phases are extremely expensive, even when these are addressed on the ground. Quieting provisions on the vehicle are ongoing and the noisiest portions of the vehicle are now less noisy, yet the costs of undertaking such efforts on an orbiting spacecraft have been staggering. Newer modules are more compliant with acoustics requirements. The approach in the meantime has centered on encouraging the liberal use of hearing protective devices (HPDs) of several types, the aggressive monitoring of the acoustic environment of all habitable elements of the ISS, and regular assessment of individual crewmembers' hearing acuity. Ground-based hearing conservation programs serve as excellent models to guide the use of HPDs, education and environmental monitoring in orbit, but hearing assessment of crewmembers has proven problematic in the past and present. Evaluations of the effects of spaceflight on hearing function have almost exclusively been limited to pure-tone audiometry performed before and after missions. And hearing assessments in space, when attempted, have been confounded by background noise.

Hearing loss aboard spacecraft obviously represents a tiny fraction of the overall problem of occupational hearing loss. Hearing loss caused by noise is a huge public health problem, with 30 million people exposed to hazardous occupational noise and 10 million with noise-induced hearing loss[1]. Young people seem to be particularly vulnerable, with reports that 15% of those between age 6 and 19 already show signs of NIHL, and that between 1971 and 1990, hearing problems increased 26% among those between 18 to 44 years old. By one researcher's estimate, preventing NIHL would do more to reduce the societal burden of hearing loss than medical and surgical treatment of all other ear diseases combined[2]. Among the recommendations of the U.S. Department of Health and Human Services' Office of Disease Prevention and Health Promotion Healthy People 2010 program, a number were related to hearing.[3] These included that the proportion of persons who have had a hearing examination on schedule, and who are referred by their primary-care physician for hearing evaluation and treatment be increased.

## ACOUSTIC PRINCIPLES

Physically, sound is a pressure wave that mechanically oscillates forward and backward as it propagates through air or other medium. It has measurable properties of frequency and amplitude. Characterization of pressure phenomenon in its many other manifestations is done using units of force over area, such as pounds per square inch or Newton/meters$^2$ (aka Pascals). In acoustics, these units are inconvenient because the range of sound intensity spans many orders of magnitude, from the lowest perceptible sound (20 microPascals or μPa) to the point at which sound waves become shock waves (>2 megaPascals), more than 100 trillion times the lower limit. Sound intensity is more readily expressed on the SPL (sound pressure level) scale, commonly using the decibel (abbreviated dB) to quantify the intensity of sound energy. The decibel is one-tenth of a bel, which is actually a logarithmically derived unit-less term (named after Alexander Graham Bell) which requires reference against a known standard. For acoustics, this is commonly 20 μPa, and a given pressure level in Pascals is converted to dB by multiplying 20 times the log of the ratio of that pressure level **p** to the reference level $\mathbf{p_0}$ as shown in the following formula: $\mathbf{SPL = 20 * \log_{10} ( p / p_0 )}$

This scale greatly simplifies comparisons between sound intensities, compressing the span of acoustic energy into a much more manageable range of less than 200 dB when referenced against the 20 μPa threshold, as shown in Table 1

| **dB (SPL)** | **Source (with distance)** |
|---|---|
| 194 | Theoretical limit for a sound wave at 1 atm environmental pressure |
| 180 | Krakatoa explosion at 100 miles in air (~2 megaPascals) |
| 168 | M1 Garand being fired at 1 meter |
| 150 | Jet engine at 30 m |
| 140 | Rifle being fired at 1 m |
| 130 | Threshold of pain; train horn at 10 m |
| 110 | Accelerating motorcycle at 5 m; chainsaw at 1 m |
| 100 | Jackhammer at 2 m; inside disco |
| 90 | Loud factory, heavy truck at 1 m |
| 80 | Vacuum cleaner at 1 m; curbside of busy street |
| 70 | Busy traffic at 5 m |
| 60 | Office or restaurant inside |
| 50 | Quiet restaurant inside |
| 40 | Residential area at night |
| 30 | Theatre, no talking |
| 10 | Human breathing at 3 m |
| 0 | Threshold of healthy human hearing; mosquito flying 3 m away (20 μPa) |

Table 1 Representative examples across a range of Acoustic Intensities[4]

The other major component of sound, frequency, is determined by the number of compression-rarefaction cycles as the wave is propagated thorough air. The frequencies that the young adult human ear is sensitive to spans the range between 20 and 20,000 cycles per second or Hertz (Hz), though this range contracts with age, particularly in the upper frequencies. The range between 300 and 4000 Hz contains most of the auditory content important in the reception of speech, while a typical piano ranges between ~30 to ~4000 Hz.

A thorough assessment of an acoustic environment at a given point in time would thus contain information on the sound pressure level at each frequency across the spectrum, typically grouping and summing this information for standard octave bands across which the frequency doubles, or tighter 1/3-octave bands. Such surveys are common to environmental and engineering assessments in many settings, including aerospace, and standards based on this approach are used for noise measurement and control. In 1971 limits known as Preferred Noise Criterion (PNC) curves were published[5], in which maximal levels across the spectrum were proposed as acceptable levels for ambient noise in different environments.

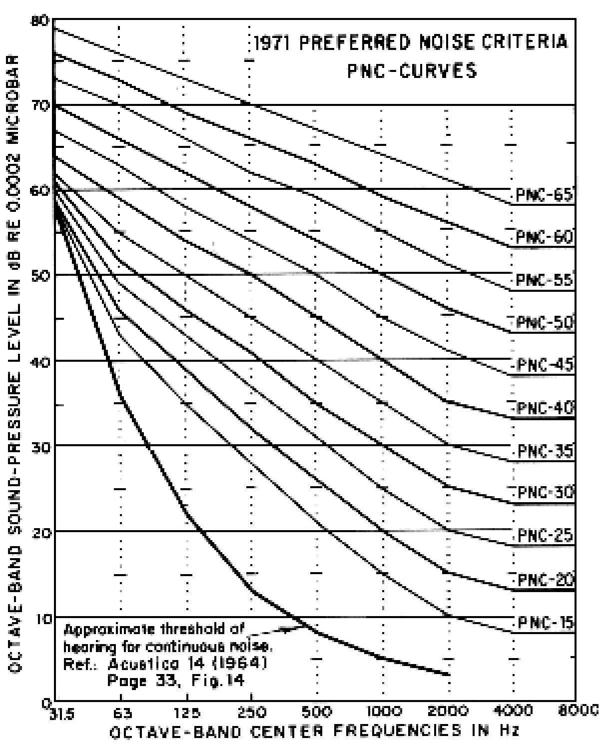



Figure 1 Preferred Noise Criterion Curves[5]

Shown in Figure 1 and in Table 2 with representative examples, these same criteria were used to help establish limits for the Space Shuttle and Space Station as covered in greater detail below, and will likely be employed for future vehicles.

| | PNC |
|---|---|
| Excellent listening conditions | <20 |
| Sleeping, homes, office, library or classroom | 25 – 40 |
| Large office, store, cafeteria and restaurant | 35 – 45 |
| Labs, engineering and secretarial space | 40 – 50 |
| Maintenance, equipment, kitchen or laundry room | 45 – 55 |
| Shop, garage, power-plant control room | 50 – 60 |

Table 2 Examples of environments at a range of NC levels[5]

Humans don’t hear all frequencies of sound equally well. The different components of the human ear serve to reflect or absorb sound energy of a given frequency, differentially transmitting and filtering how much sound actually reaches the inner ear to be processed into neural information. In the 1930s, Bell Labs engineers Fletcher and Munson[6] first accurately collected data showing the human ear's sensitivity to loudness at different frequencies. These were obtained by having multiple subjects compare sounds played through headphones at different frequencies and group them subjectively according to similar perceived volume. Plots of this data at different levels of perception ranging from “just heard” to “harmfully loud” are called equal loudness contours (or Fletcher-Munson curves), an example of which is shown in Figure 2. The curves reveal that the human ear is most sensitive to pure tones in the region of 3-4 kHz, which is also in the range of the resonance frequency for the external ear canal. Since all other frequencies are filtered out to a greater extent, sounds above or below this pitch range must be louder in order to be perceived as the same loudness.

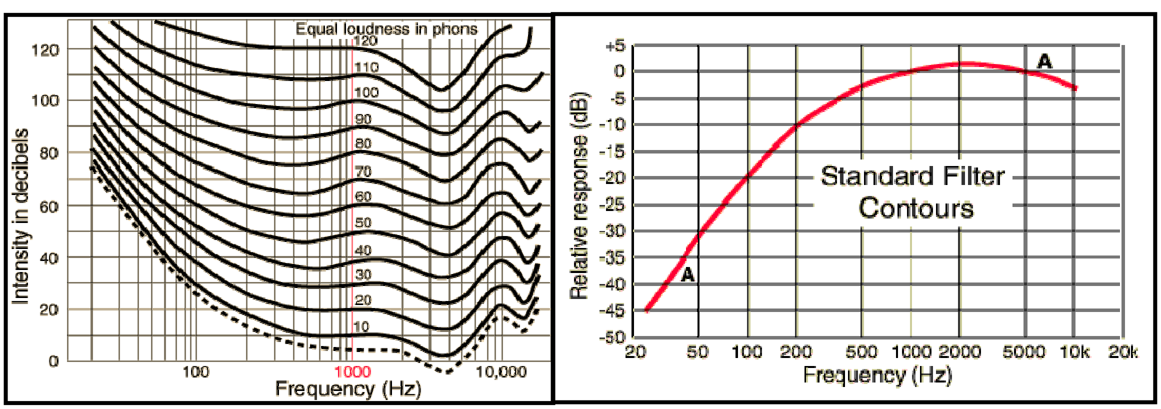



Figure 2 Equal Loudness Curves (Fletcher-Munson) and A-weighting correction curve

Tests of human hearing must take into account these averaged sensitivities at different frequencies and compensate for how they vary in normal subjects as well as those with pathology. Similarly, environmental measurement and monitoring must do the same, correcting for attenuation and masking that take place in all humans at the anatomical level. This effect is commonly taken into account using a correction based on curves known as A-weighting, commonly written as dBA. A-weighting is derived from an inversion of the 30-phon (or 30 dB-SPL) equal-loudness Fletcher Munson curve, also shown in Figure 2. Environmental data is often simplified using this scale to provide a composite value based upon equivalent energy content.

## BIO-EFFECTS OF EXCESSIVE NOISE

The varying acoustic environments through which people move as they work, rest or recreate can meaningfully affect health and performance in both far and near term. An extensive body of literature exists related to noise-induced hearing loss (NIHL) caused by occupational exposures, and the most studied principal outcome frequently being impaired hearing after years of exposure. The Occupational Safety and Health Administration (OSHA)[7] has well substantiated guidelines that apply to the workplace, which were used as starting points by those developing similar guidelines for spacecraft, but a principal limitation is that these were based on a typical 8-hour workday after which people went home to quieter environments. In the ensuing 16 hours, hearing ideally recovers, though of course some make personal choices that lead to higher exposure off-the-job than on. Little meaningful data exists on long term noise exposure without rest, though there has been increasing interest in this, especially by the military.

While NIHL represents one of the most serious outcomes, excessive noise in spacecraft has very important ramifications in the near term. Not only can astronauts suffer from headaches, irritation, fatigue, impaired sleep, and headaches which can all directly impact there performance of duties, but high noise levels can result in the inability to hear alarms or radio communication from ground controllers or to detect changes in the sound of equipment that could be malfunctioning. Speech intelligibility, already limited in some situations as crewmembers try to communicate outside of their native language, is further degraded in a noisy environment, leading to frustrating misunderstandings, and the need for raised voices, which can be tiring and cause throat discomfort and hoarseness. Even visual cues, which supplement auditory information as part of receptive language, are altered when crewmembers are not aligned. Inversion limits the ability to interpret lip movements; indeed, even facial recognition is degraded when a face is inverted with respect to the viewer.

## HEARING ASSESSMENT

Attempts to quantify hearing loss clinically date to the 1800s when whistles, tuning forks and vibrating strings called monochords were used in attempts to standardize stimulus intensity. Archaic as such approaches might seem, they continue to be used in modern clinical practice as screening tools. Many primary-care physicians routinely test hearing using tuning forks, and the Federal Aviation Administration annual testing of pilots' hearing is limited to what is sometimes called a spoken-voice test, demonstrating they can hear an average conversational voice in a quiet room, using both ears at six feet, with their back turned.

By the 1920s the first well-designed audiometer, the Western Electric A-1, was developed and since that time, the technology in electro-acoustics has continued apace with electronics in general. Driving these developments, however, noise hazards in our lives have increased dramatically relative to a hundred years ago, whether it's in military (artillery, aviation), occupational (production, construction), domestic (yard care equipment such as mowers, leaf blowers), or recreational (firearms, rock concerts or the ubiquitous iPod) environments. The goal of pure tone audiometry remains to identify the threshold below which an acoustic stimulus cannot be heard and to do so across various frequencies, comparing this to prior similar tests for that individual as well as to population data to rule out pathology. Where practical, this is done in a sound-proof room insulated from background noises, though hearing screening in doctor's offices and schools routinely is done using headphones alone. Test stimuli are presented via air conduction through a transducer, such as an insert earphone or supra-aural cushion headphone and consist of pure tones at octave levels typically ranging from 250–8000 Hz with the subject being asked to indicate when a stimulus is perceived. Rather than randomly presenting the stimulus at different intensity levels, most hearing tests employ an ascending method known as the modified Hughson–Westlake technique in which the intensity is decreased in 10 dB steps until no longer audible, increased in 5 dB steps until the tone can be heard, then lowered, alternating 5 dB increases with 10 dB decreases until a 50% response threshold is determined.

The results of an audiological evaluation are plotted on a graph called an audiogram. The audiogram conventionally depicts frequencies in Hertz (Hz) on the x-axis and intensities using a logarithmic decibel (dB) scale on an inverted y-axis, ideally with the reference upon which the decibel is scaled. Threshold hearing levels are plotted for both ears and for each frequency tested. As detailed above, the human ear does not hear all frequencies equally well, so to simplify the appearance of the data, standard audiometer-earphone combinations are corrected from a sound pressure level (SPL) scale referenced to 20 μPa to a hearing level (HL) scale that is an A-weighting of this scale.

# 3. SPACEFLIGHT NOISE EXPERIENCE

Spacecraft, both U.S. and Russian, have always pushed the limit in terms of acoustics. Literature on hearing loss in space was recently reviewed by Buckey, Hart et.al.[8], and is summarized below.

## UNITED STATES

### Mercury through Skylab

U.S. experiences during Mercury (mission durations of 15 minutes - 34 hrs), Gemini (1-12 days), and Apollo (6-12 days) were not problematic from a noise perspective, perhaps in part due to the relatively short duration of those flights.

The Skylab series of missions, representing the first foray into longer-duration spaceflight by the U.S., was started in 1973 with Skylab-1, which launched the unmanned habitat adapted from the fourth stage of a Saturn 5 booster. Three 3-man missions followed: Skylab-2 (28 days), Skylab-3 (59 days), and Skylab-4 (84 days). The station was about 4 times larger in volume than the Salyut station. Interestingly, the vehicle was pressurized to 5 psi, about ~1/3 of the sea level atmospheric pressure (14.7 psi) to which all other vehicles are pressurized. This was equivalent to living at 27,000 feet, but with an oxygen content of 66-73 %, a higher partial pressure of oxygen was available than on earth at sea level (170-188 versus 160 mmHg). Air at this decreased density transmits acoustic energy less effectively, so noise levels, though never measured, can be presumed to have been meaningfully less than vehicles operating at sea-level pressure. Crews noted reduced voice projection and difficulty whistling, in addition to feeling warmer due to reduced heat rejection and cooling more quickly after exercise and showers due to more rapid evaporation of moisture.

Not surprisingly, no changes in pure tone audiograms were observed on post-flight testing following the 28, 59, and 84 day Skylab missions. Wheelwright et al.[9]

reported that the crewmembers of Skylab 4 had post-flight audiograms that showed a temporary threshold shift. However, clinic records were reviewed by Dr. Jonathan Clark[10] who found no evidence of hearing changes. In conversations with specialists involved with the post-flight medical assessment of Skylab crews, Dr. Clark was told that noise levels aboard the naval vessels used to recover Apollo and Skylab crews were themselves too noisy for hearing testing to be performed and may have contributed to any hearing changes.

## Space Shuttle

Despite relatively short durations of 2-16 days, Space Shuttle missions have clearly been associated with changes in hearing. Originally, noise limits for both the Orbiter and SpaceLab, a habitable research module that fits in the payload bay and connects to the mid-deck via the airlock, were specified using the NC-50 curve (see Figure 1), but when costs ran too high and time too short, the document in which these requirements were defined, the Orbiter Vehicle End Item Specification[11], was simply revised with higher limits. Currently the noise limits are 63 dBA on the flight deck, 68 dBA on the middeck, and 59 dBA in SpaceLab/Hab as shown in Figures 3 and 4.

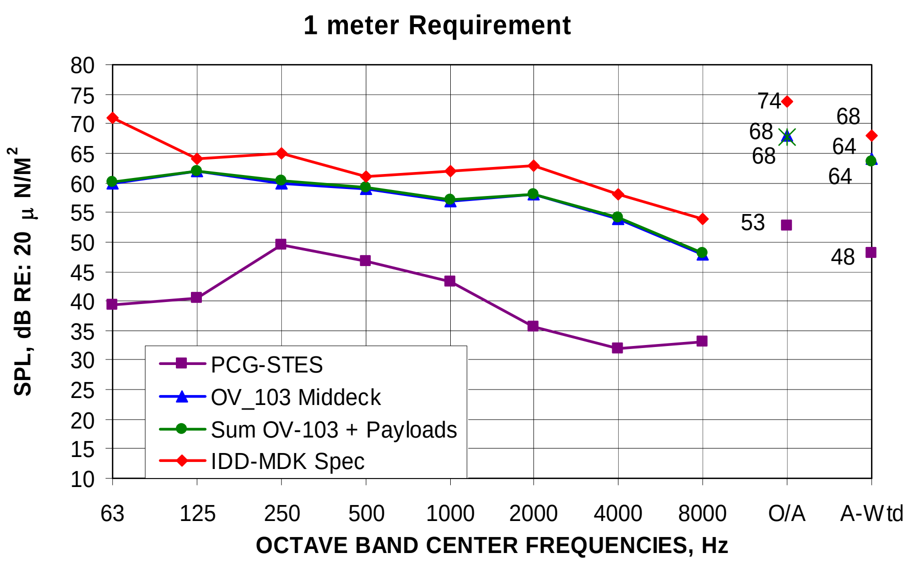



Figure 3 STS-114 (OV-103) Middeck Acoustic Noise[12]

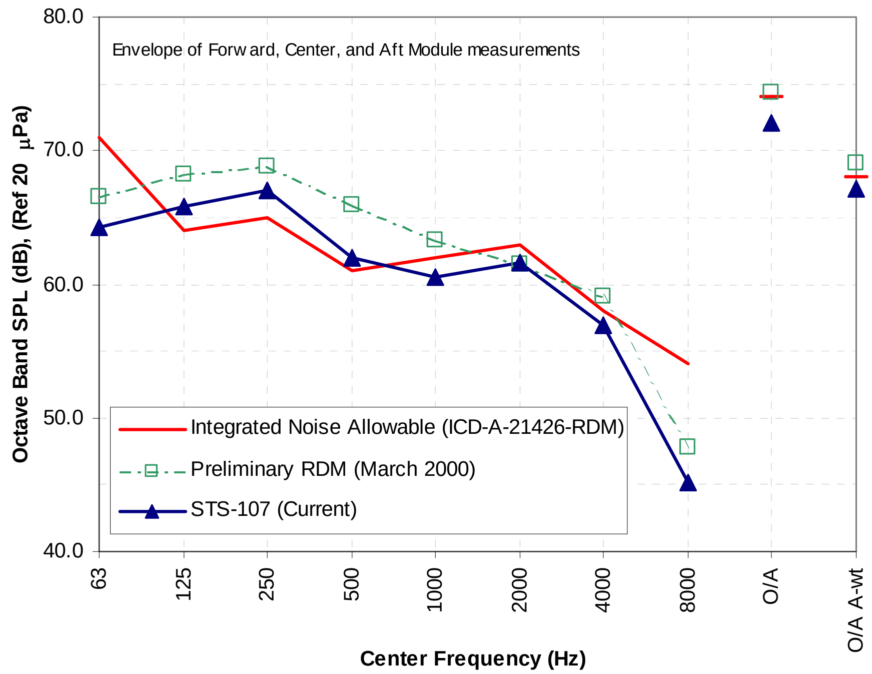



Figure 4 STS-107 Acoustic evaluation of SpaceHAB Research Module[13]

As seen in other programs, these limits are not infrequently exceeded, and commonly before a mission, documentation of exceedances and waivers are processed when it's determined that it's too late to change anything. One Shuttle mission in particular was notable for having relaxed requirements on noisy payloads in the research module in the payload bay. Excessive noise levels were compounded by crew behavior, one of whom was quoted as saying "It was so loud, I had to turn my Walkman all the way up to hear my music all day." Temporary threshold shifts were identified in this group on return. At that time, the suite of hearing protection devices (HPDs) available to crewmembers onboard the Shuttle was limited to two types of disposable foam earplugs and earmuffs designed for gun enthusiasts.

In 1999, the author worked to increase the available HPD options for Shuttle fliers by introducing custom molded musician's earplugs with interchangeable flat response filters rated at 9, 15 and 25 dB. These were subsequently made available to all members of the Astronaut Corps for occupational use in NASA's T-38 training aircraft, as well as for personal use.

Figure 5 Traditional HPDs used aboard the Shuttle and newer musician's plugs

A recent review of data compiled by JSC's Longitudinal Study of Astronaut Health program, designed to track epidemiologic trends of interest revealed that of 608 crewmember-flights over the first 20 years of Space Shuttle flights, noted that 17% returned with meaningful hearing loss (positive threshold shifts), and that 6% had permanent changes, as shown in Figure 6.

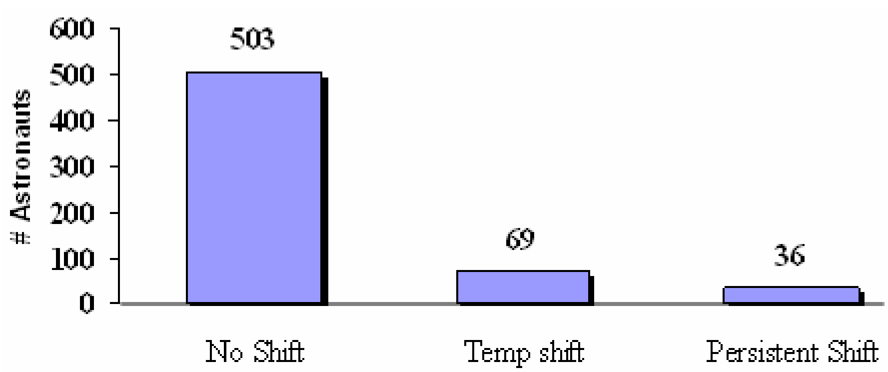



Figure 6 Hearing Changes after Shuttle flights STS-1 thru 108 (1981-2001)

**Mir / NASA**

Between 1995 and 1998, as part of preparations for the ISS, NASA contracted with the Russian Space Agency to send 7 astronauts to live and work aboard the Mir space station, each living with 2-5 Russian cosmonauts at a time. Mission duration ranged from 115 to 188 days. Onboard the Mir noise levels ranged between 58 and 72 dBA as measured by an acoustic dosimeter identical to that currently onboard the ISS, the Ametek Mark-1.[14,15] Data, shown in Table 3 are broken down by location to give a sense that there were relatively quieter areas, including the module in which U.S. crewmembers slept.

As an example, one of the astronauts (personal communication) offered details of his stay on the MIR. He slept on the Priroda module, where the sound was 58 dBA near a fan for radiation protection. In the Kvant 1 module the sound was a maximum of 73 dBA. This crewmember's acoustic dosimetry readings averaged from 62.3 to 68.3 dBA as averaged over a 24 hour period. HPDs were available including earmuffs which became uncomfortable after 30 minutes, and earplugs. He developed a sleep routine in which he wore foam earplugs for high frequency attenuation and an active noise reduction headset (Noisebuster Extreme) for low frequency noise for his eight-hour sleep shift. He related that high noise levels interfered with communications, and he had to press the earcups of his communication headset against the sides of his head to hear. He stated that high noise levels resulted in an inability to hear alarms over 20 feet away, that the treadmill operation was very noisy and that the continuous noise was worse than intermittent noise. Noise levels of 68-70 dBA caused headaches in the crew.

| core module | Min dB A | Max dB A |
|---|---|---|
| central control panel | 64.7 | 65.5 |
| work table | 67.7 | 70.9 |
| near galley | 65.7 | 65.7 |
| CDR's quarters | 66.0 | 66.0 |
| Eng's quarters | 64.5 | 68.0 |
| Kvant 1 | 68.9 | 69.9 |
| Kvant 2 | 70.4 | 72.3 |
| Krystal | 59.2 | 66.5 |
| Priroda | 58.7 | 63.1 |
| Overall Mir | 58.7 | 72.3 |

Table 3 Noise levels aboard the Mir Space Station

One of the 7 NASA-Mir astronauts suffered a Temporary Threshold Shift (TTS) as a result of long-duration spaceflight with subsequent resolution (See audiogram below in Figure 7). No data from cosmonauts flying at the same time were available. HPDs were not utilized by this crewmember, and estimates of the LEq24 for this crewmember was 67-70 dBA, based on noise levels for the various Mir modules and time spent in each. Of three NASA Mir astronauts without temporary shifts, LEq24s from 62 to 68 were estimated. No permanent shifts (PTS) were identified.

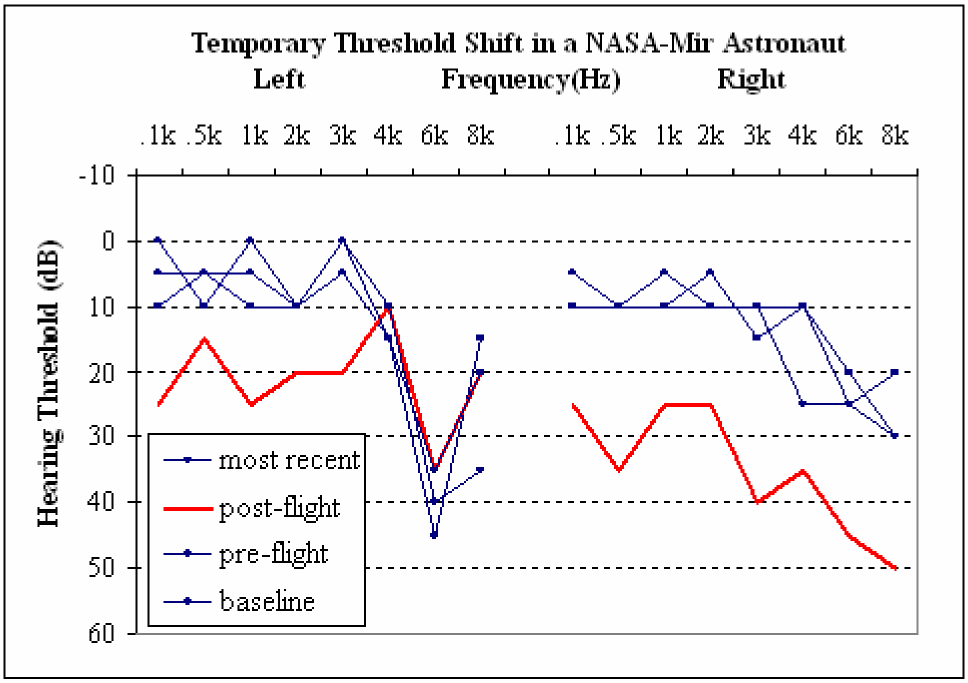



Figure 7 Temporary Threshold Shift in a NASA-Mir Astronaut

## RUSSIA

### Salyut and Mir Space Stations

The Russian experience is more illustrative of the problem, as they are much more experienced with lengthier flights than the U.S. As stated above, longer-duration experiences are more clearly associated with hearing loss, in part because the insult is ongoing for weeks and months rather than days, and no quiet rest period is available to allow recovery. Combined data[16] from 33 cosmonauts who flew on the Salyut 6, Salyut

7 and Mir space stations were summarized as follows: “While there are individual differences, changes in cosmonaut hearing may be described as involving changes in auditory sensitivity in the area of high frequencies (from 2.0 kHz and higher) for flights of 7 days to 1 year.” [17]. In private communication[18] with Dr Eduard Matsnev, ENT specialist at Moscow’s Institute of BioMedical Problems reviewing 30 years of Russian experience with long-duration spaceflight, it was stated that noise-induced hearing loss (NIHL) has led to disqualification of five cosmonauts from further spaceflight. He added that temporary threshold shifts had been reported in 100% of cosmonauts by one report and that PTS had been identified in 27/33 cosmonauts, with six of these in the extreme or profound range. As detailed above, one of the seven NASA-Mir astronauts suffered a temporary threshold shift as a result of long-duration spaceflight, with subsequent resolution.

These data suggest that in the Russian experience hearing loss after their missions is typically in frequencies in the 1-6 kHz range. Reports from the Salyut 6 space station note that the greatest post–flight threshold increases were in the high frequency, 4–6 kHz range[19]. Table 4 is excerpted from a summary paper of the Russian experience from Salyut 6, Salyut 7 and Mir states that "while there are individual differences, changes in cosmonaut hearing may be described as involving changes in auditory sensitivity in the area of high frequencies (from 2 kHz and higher) for flights of 7 days to 1 year.” [20,21]

| Subject | Duration (days) | 500 Hz | 1 kHz | 2 kHz | 3 kHz | 4 kHz | 6 kHz |
|---|---|---|---|---|---|---|---|
| 1 | 7 | 6 | 19 | 8 | 1 | 0 | -6 |
| 2 | 7 | 19 | 4 | 4 | -11 | -5 | 11 |
| 3 | 25 | 0 | 0 | 15-20 | 15-20 | 15-20 | 15-20 |
| 4 | 150 | 0 | 0 | 0 | 0 | 0 | 10-20 |
| 5 | 150 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 241 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 365 | 0 | 0 | 20-40 | 20-40 | 20-40 | 20-40 |
| 8 | 365 | 20-45 | 20-45 | 20-45 | 20-45 | 0 | 20-45 |

Table 4 Summary of published Russian/German post–flight audiometry data given as dB change from pre to post–flight threshold values

**Russian Ground-Based Studies of Long-Duration Noise Exposure**

In a 1965 study of human subjects published by Yuganov, 72 hour exposures of 72-74 dB resulted in raised hearing thresholds of 15-20 dB with resolution in 2-3 hours[22]. In a second set of experiments, Yuganov et. al., reported that 10 and 30 day exposures (using the same levels of noise exposure) resulted in threshold shifts of 20-25 and 25-30 dB with recovery taking place in 8-18 hours and 48-50 hours post exposure respectively. A characteristic feature distinguishing these investigations was the constant complaints throughout the experiment of the irritant and fatiguing action of the noise." Ward indicated that a 150-day continuous exposure of 82 dB SPL in a 1981 paper caused permanent hearing loss as well as hair cell loss.[23]

In 1967-1968, as part of Soviet ground-based evaluation of spacecraft life-support systems,[24] three healthy volunteers lived for one year in a mockup (Fig 7.5). After this experiment one subject returned to baseline hearing in four days, and another had a temporary threshold shift (TTS) that resolved over the following three weeks, while the third was left with a permanent threshold shift (PTS) with 20-45 dB changes between 2 and 8 kHz. Noise levels in this chamber were sloped from 92 dB at lower frequencies to 30dB at 10 kHz. In follow-up 30 years later, the first had normal hearing for his age while the other two had moderate and severe hearing loss in an NIHL pattern, prompting speculation on individual noise sensitivity as a predisposing factor to the development of NIHL.

# 4. HISTORY OF ON ORBIT HEARING EVALUATION

## SALYUT 7 SPACE STATION

The first well-documented attempt to perform pure tone audiometry aboard a spacecraft was undertaken as part of a joint Russian/East German cooperative project. The audiometer, "ELBE", show in Figure 8 was flown on a seven day Salyut 6 docking mission in 1978, and reported by Proehl in 1981[25], with use of this same device in subsequent Salyut and MIR missions. The in–flight data showed clear threshold shifts, particularly at the lower frequencies, which were not present on the day after landing. The authors attributed this to interference from noise levels on the station. No technical details on the audiometer are available, other than that it measured a frequency range of 500 to 6000 Hz, and no specifics on whether an ascending or descending method was used.


Figure 8 The ELBE audiometer flown aboard the Salyut space station[26]

## EARLY SHUTTLE HEARING ASSESSMENT

An audiometry-like test was also performed on three early Space Shuttle flights (STS 6-8), with 13 astronauts participating, including the principal investigator who flew on the first of these flights. The specifications, procedures and calibration scheme for this device, shown in Figure 9, as well as the dataset, are not available from either ground or flight testing. Comments from the crew, which included the principal investigator, Dr. William Thornton, were summarized as "Results are questionable. Audio evoked potentials are preferred to this method" and "procedures worked well, but differences in mission noise levels confounded results by causing threshold shifts. No evidence of increased intra-labyrinthine pressure was found."[27,28]

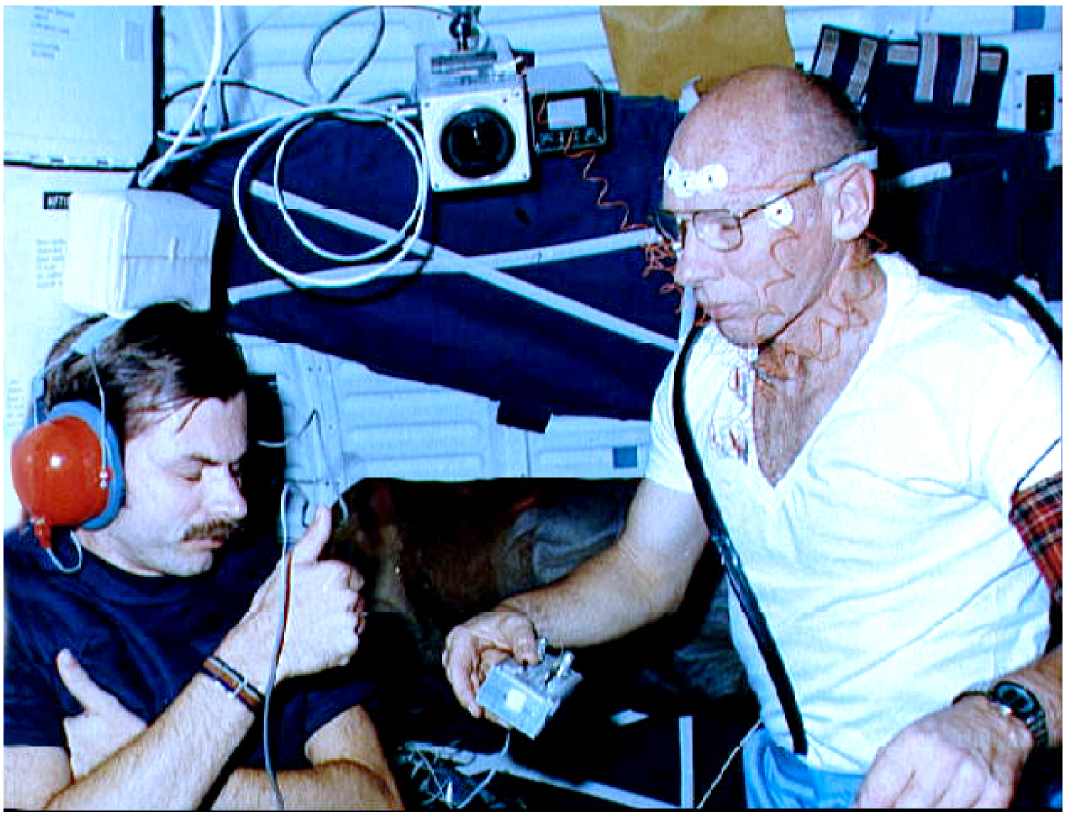


Figure 9 Astronaut Thornton administers a hearing test aboard Challenger during STS-8

# 5. ISS NOISE LEVELS

In the design and construction of the ISS, contractors were obliged to satisfy various standards and criteria. Ideally, these were to have been treated the same as any other environmental requirement—such as temperature, oxygen and carbon dioxide concentrations and radiation levels—to insure habitable living conditions. In practice, contractors on both sides seemed to have prioritized the requirements such that acoustic considerations were always the last to be taken into account. Requirements about noise were often left unsatisfied or were subject to waiver requests by the contractors doing the work. The following sections detail the specifications for the U.S. and Russian portions of the ISS, then the measurements from on-board which show how well these have been complied with.

## U.S. ACOUSTICS DESIGN REQUIREMENTS

Acceptable levels of vehicle and payload noise are defined in a number of engineering documents[29] specific to the ISS, distinguishing between wide-band random noise, narrow-band noise and tones, impulse noise (as well as infra/ultrasonic noise) from the perspectives of hearing conservation, voice communication, annoyance and sleep. In these documents, which appear to have been derived from similar documents related to the Space Shuttle program, noise of constant sound levels of 85 dB(A) and greater are considered hazardous regardless of the duration of exposure, and use of hearing protection devices are declared necessary at this point, even for short-duration exposures. Interestingly, 85 dBA is a well-characterized line in the sand for occupational exposures during a full work day followed by 16 hours of rest. Maximum Continuous Noise—the summation of all the individual sound pressure levels from all operating systems and subsystems—is defined by one of a series of noise criterion (NC) curves that specify a maximal intensity at third-octave bands across the spectrum from 65 to 8000 Hz. ISS requirements specify two different NC curves for continuous noise: one for waking activities and a quieter specification for sleep environments, as shown in Figure 10). For the purposes of an environmental limit standard, continuous noise is characterized by octave-band SPLs at frequencies of 63, 125, 250, 500, 1000, 2000, 4000, and 8000 Hz, as summarized in the following graph for non-Russian elements of the ISS.

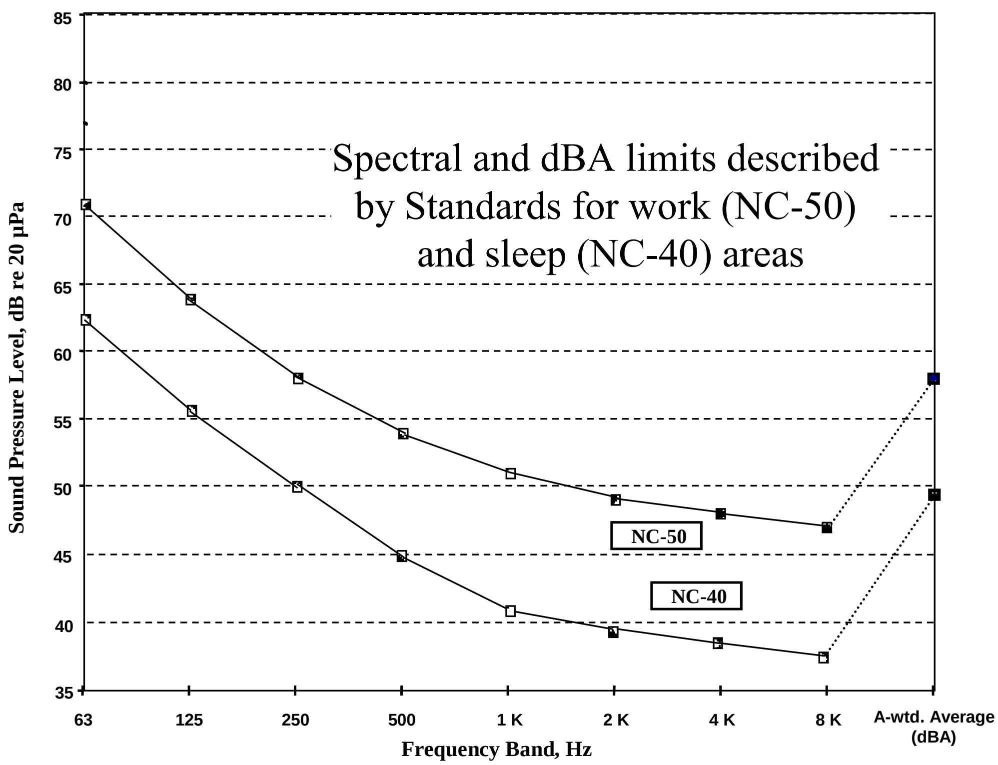



Figure 10 U.S. Spectral and dBA standards for work and sleep areas

The daytime environment is defined by the NC-50 curve. More intrusive narrow-band components should be ≥10 dB lower than the maximum sound pressure level of the octave–band which contains the component. Impulse sound (a change in SPL of >10 dB over <1 second) is not to exceed 140dB and should not occur during sleep periods. The sleep environment, defined by the NC-40 curve at the upper limit, is further characterized by a lower limit of NC-25 (not shown). To avoid sleep disruption, a background noise floor of this level can mask intermittent noises, similar to a fan or white-noise generator some people use to help them sleep. To further insure quiet during sleep periods, transient and impulse noise which exceeds the background by more than 10 dB is to be avoided.

## RUSSIAN ACOUSTICS DESIGN REQUIREMENTS

The Russian efforts related to the acoustics of their primary habitation vessel—the Service Module (SM) which launched in July, 2000—were constrained from the start by the fact that this module was originally designed to specifications for the Mir Space Station as a backup for that vehicle's Base Block. Thus, the SM was designed 15 years prior to its launch, and its construction began well before any acoustic guidelines from the U.S. or other ISS partners could be included. The result is that the SM, which houses the galley, two of three sleep stations, the central computers, the gymnasium, and the primary life support systems, is the loudest area of the ISS. Russian documents pertaining to the spacecraft design[30,31] divide noise into continuous wide-band (more than one octave width) and narrow-band noise. Wide bands are defined as full octaves, while continuous noise lasts longer than 8 hours. Limits for continuous wide-band noise are specified in the following Table 5.

| Flight duration over 30 days | Octave-band Sound Pressure Levels (SPLs) | | | | | | | | A-weighted SPL, 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 5 Russian Continuous Noise Limits

For comparison, the plot shown in Figure 11 indicates the disparity between the standards as set by the Russians, and those described above for continuous wide-band noise levels agreed to by the U.S. and the other International Partners.

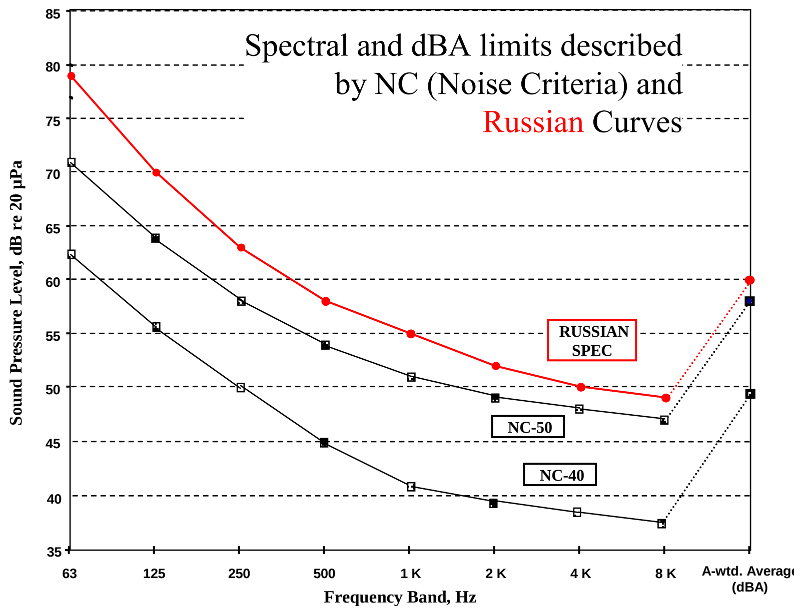



Figure 11 U.S. and Russian Limits compared

When intermittent noise (less than 8 hours) sources are present, they are constrained to levels that vary with their duration, so louder noises are tolerated for shorter periods of time, as shown in table 6 below.

| Maximal exposure time (hours) | Permissible increase in exposure levels (dBA) |
|---|---|
| 4 | +5 |
| 2 | +10 |
| 1 | +15 |
| 0.5 | +20 |

Table 6 Russian Intermittent Noise Limits

For both the U.S. and Russian specifications the acoustic contributions of voice communication (between themselves or with the ground) as well as recreational use of personal music or video players are not included in the environmental assessments. Crews are instructed not to speak or play music during on-orbit evaluations, which may lead to a underestimate of real noise levels, depending on the personal habits of that particular crew.

“Bio-acoustic” evaluation is stipulated in the Russian documents to be performed in habitable volumes of space vehicles with focus on the cosmonaut work and rest stations, as well as known excessive noise generators (exercise equipment, life support system pumps and fans).

Documents on both sides also include a mandate that hearing protection be available to provide aural isolation as needed (which many of the contractors use as an escape clause), and also stipulate how acoustics measurements are to be collected both during the design/construction and in-flight phases.

# 6. IN-FLIGHT MEASUREMENTS – THE ACTUAL ENVIRONMENT

The preceding section briefly addressed the specifications used to construct the various components of the ISS. As has been pointed out earlier, the contractors doing the actual design and construction under the supervision of the participating federal organizations (NASA, Russian Aviation and Space Agency, European Space Agency, Canadian Space Agency, Japan Aerospace Exploration Agency) representing the countries in this endeavor have had difficulty satisfying the requirements, resulting in a habitat that is, louder than acceptable based on crewmember health and performance.

The following section describes the instruments used onboard to measure the acoustic environment, then details the data collected as part of the ongoing work that crewmembers must do on a scheduled basis as part of an environmental monitoring strategy common to any hearing conservation program. It should be noted that these activities represent considerable crew time, effort and ground coordination, and that if the modules had been able to meet the requirements, the environment would not have even required testing onboard.

## ISS AUDIO DOSIMETER (IAD)


Figure 12 ISS Audio Dosimeter (IAD) used for spot checks and time weighted averaging

The ISS has several Ametek Mark I audio dosimeters used for both static and dynamic measurements. These are identical to the unit used aboard the Mir Space Station by U.S. crewmembers and are also on every Shuttle flight. These are designed to provide a summary measure rather than sound pressure level at specific bands of the noise spectrum, which is measured by the sound level meter (SLM). The utility of the dosimeter is that it can collect data over a specified time, and can provide information such as spot checks at single time and location or show peak or average levels over an extended period, typically 24 hours. The IAD is a commercial off-the-shelf unit with minor modifications – i.e. wrapping with a material that prevents potentially toxic volatile chemicals from off-gassing into the atmosphere of the vehicle, wrapping of the microphone cable with fire retardant Nomex material, and applying Velcro.

24-hour crew-worn measurements are the best estimate of actual at-ear noise exposures. Typically, astronauts will attach the audio dosimeter to their shirt collar as they move around the ISS. Noise levels for an entire day are sampled, with the understanding that whether or not it was a louder, quieter or average day is unknown. For the 8/12 hour sleep period, the dosimeter is reset and attached to the sleep station wall adjacent to the crewmembers head. Static measurements involve the placement of the audio dosimeter in various standardized locations for 16 hours. Both are typically done every other month. Table 7 is an example of data collected from both techniques.

| **Test Data Log** | **Date: 20-Nov, 1999 24-hour Measurements** | | |
|---|---|---|---|
| **Flight #:** Expedition 1 | **Time and Reading Comments / Observations** | | |
| Crewmember Worn: Kk | Lavg / Leq : | **69.6** | |
| | Start GMT: | 730 | |
| | Stop GMT: | 0630 | |
| Crewmember Worn: Gi | Lavg / Leq : | **71.5** | |
| | Start GMT: | 730 | |
| | Stop GMT: | 0630 | |
| Static Location: FGB 310 | Lavg / Leq : | **63.8** | Yuri's bunk area 2nd. Test |
| | Start GMT: | 1750 | |
| | Stop GMT: | 0825 | |
| Static Location: SM 435 | Lavg / Leq : | **70.4** | Panel just below SRVK in wardroom--main dining area |
| | Start GMT: | 1740 | |
| | Stop GMT: | 0825 | |
| Static Location: SM 332 | Lavg / Leq : | **63.8** | Shep's kayuta 2nd test |
| | Start GMT: | 2010 | |
| | Stop GMT: | 0825 | |

Table 7 Example of ISS Audio Dosimeter data

## SOUND LEVEL METER

Figure 13 ISS Sound Level Meter used for spectral analysis of modules and hardware

Spectral measurements aboard the ISS are made using a sound level meter based on a versatile hand-held analyzer platform, the Bruel & Klaer 2260 Observer. The unit is capable of full or 1/3 octave band analyses across a frequency range of 6.3 Hz to 20 kHz. Though this feature has yet to be used, the 2260 can be remotely controlled as a node on a wireless computer network, and could be operated by ground controllers, freeing up crewmembers for other activities. It is bundled with a Windows-based software package, Noise Explorer, that facilitates downloading data to the ground for analysis and reporting.

Two of these units were sent by NASA, one prime and one backup, for consolidation of the survey strategy across both the U.S. and Russian segments of the ISS. Early in Expedition 1, U.S. flight controllers were surprised when the cosmonauts were instructed to break out their own SLM. Though this turned out to also be a B&K 2260, it implied that the Russians would be doing their own assessments, a situation which has led to controversy about the extent of exceedances and how they should be mitigated.

Approximately every 2 months, a 2 hour acoustic survey of ISS is scheduled, resulting in a series of spectral measurements at dozens of locations. The SLM is also used once during each expedition or as needed to perform a detailed Engineering Acoustic Evaluation. This analysis is designed to collect information on the health and status of specific hardware systems e.g. life support systems fans and pumps that generate much of the noise onboard. A change in the acoustic signature of a piece of equipment could indicate a malfunction such as a worn bearing. Data from these sessions is covered in the following section.

## REPRESENTATIVE ISS SLM DATA

### U.S Laboratory Destiny

The U.S. Lab contains the core of the research resources of the ISS, as well as elements of the life support system, control of the robotic arms, most of the medical capability, exercise equipment and one of the three sleep stations. It has a modular design that permits rotation of it 23 racks to support different configurations. In this example from a recent acoustic survey, measurements in the Lab were taken at 7 locations, as seen in Table 8. In this and subsequent tables, frequency data as well as summary dBA value are provided for each location.

| Freq [Hz] | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| 63 | 54 | 49 | 52 | 51 | 52 | 53 | 56 | 59 |
| 125 | 56 | 50 | 52 | 53 | 53 | 54 | 58 | 56 |
| 250 | 50 | 51 | 53 | 54 | 56 | 57 | 59 | 55 |
| 500 | 48 | 53 | 54 | 54 | 56 | 57 | 57 | 55 |
| 1000 | 47 | 47 | 49 | 51 | 51 | 53 | 55 | 52 |
| 2000 | 46 | 48 | 49 | 49 | 51 | 54 | 55 | 54 |
| 4000 | 42 | 41 | 42 | 44 | 48 | 49 | 52 | 50 |
| 8000 | 36 | 37 | 38 | 39 | 42 | 45 | 47 | 45 |
| dBA | 52 | 54 | 55 | 56 | 58 | 60 | 61 | 59 |

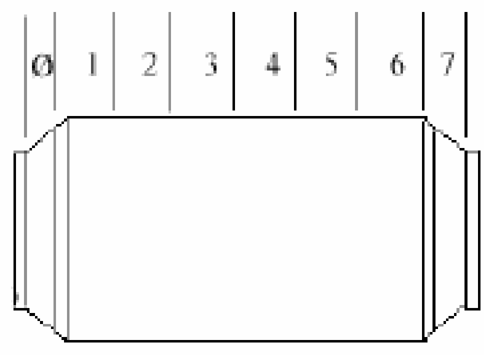



Table 8 Acoustic measurements in the U.S. Lab by location

## Temporary Early Sleep Station (TESS)

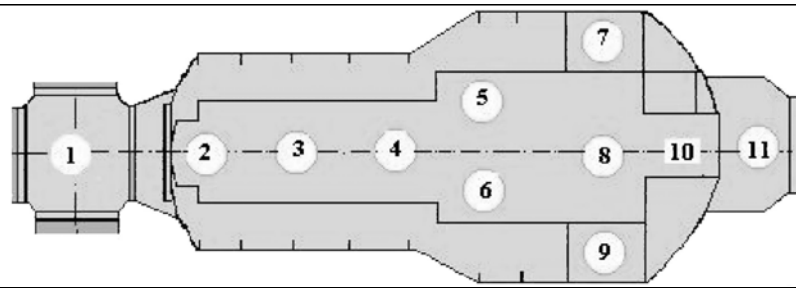
The Temporary Early Sleep Station shown in Table 9 is located in the front right of the U.S. Lab and deserves special attention, as it is the quietest area in the ISS. In addition to providing personal space for one crewmember, crewmembers perform hearing tests in the TESS, making it an analog to an audiometric enclosure. SLM measurements are taken in the TESS, with the door closed, at high (ear) middle and low levels. This site is also studied with the ISS audio dosimeter as part of 24 hour noise exposure assessments.

| Freq[Hz] | TESS low | TESS mid | TESS high | NC40 |
|---|---|---|---|---|
| 63 | 53 | 52 | 54 | 64 |
| 125 | 53 | 45 | 52 | 57 |
| 250 | 43 | 40 | 40 | 51 |
| 500 | 37 | 36 | 40 | 45 |
| 1000 | 31 | 34 | 44 | 41 |
| 2000 | 32 | 34 | 38 | 39 |
| 4000 | 24.0 | 26.0 | 32 | 38 |
| 8000 | 26.0 | 24.0 | 30 | 37 |
| dBA | 41 | 40 | 46 | 58 |

Table 9 Acoustic measurements in the TESS

## Russian Service Module (SM)

Zvezda is the structural and functional center of the Russian portion of the ISS. As stated above, it includes 2 sleep stations, systems for life support, communication, electrical power distribution, data processing, flight control, and propulsion. Measurements in the SM are taken at 13 locations as shown in (Table 10). The SM should satisfy the Russian Specification shown in Figure 12.




| Freq. [Hz] | 1 | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 11 | Russ Spec |
|---|---|---|---|---|---|---|---|---|---|---|
| 63 | 57 | 64 | 61 | 58 | 58 | 59 | 56 | 57 | 48 | 79 |
| 125 | 63 | 62 | 57 | 60 | 60 | 60 | 58 | 58 | 55 | 70 |
| 250 | 61 | 67 | 65 | 70 | 69 | 69 | 69 | 65 | 61 | 63 |
| 500 | 54 | 63 | 62 | 62 | 62 | 64 | 63 | 59 | 56 | 58 |
| 1000 | 59 | 62 | 61 | 63 | 62 | 63 | 63 | 60 | 61 | 55 |
| 2000 | 56 | 59 | 57 | 58 | 59 | 60 | 59 | 57 | 60 | 52 |
| 4000 | 49 | 53 | 50 | 52 | 52 | 53 | 53 | 53 | 55 | 50 |
| 8000 | 44 | 48 | 46 | 47 | 47 | 47 | 48 | 46 | 50 | 49 |
| dBA | 63 | 67 | 65 | 67 | 67 | 68 | 67 | 65 | 65 | 60 |

Table 10 Acoustic measurements in the SM by location

The SM was accepted to fly based on a commitment to develop and implement quieting provisions to lower noise levels. These are slowly being implemented by the Russian acoustics specialists as bearings are replaced, isolators added and mufflers and baffles placed. Meaningful changes are taking place, as shown in Table 11, but despite these efforts, the SM remains the loudest module of the ISS.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Exp 1 | 64.0 | 73.0 | 71.2 | 69.0 | 77.8 | 74.0 | 71.6 | 74.0 | 71.5 | |
| Exp 12 | 62.6 | 66.8 | 65.2 | 67.3 | 66.9 | 67.9 | 67.4 | 64.5 | 65.4 | 60 |

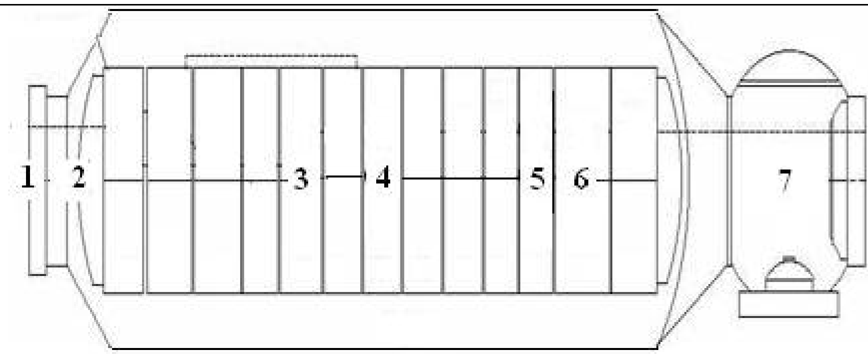
Table 11 Improved acoustic measurements in the SM over 12 expeditions

| Freq. [Hz] | Stbd Door open | Stbd Door closed | Port Door open | Russ-Spec for sleep |
|---|---|---|---|---|
| 63 | 63 | 62 | 66 | 71 |
| 125 | 61 | 57 | 59 | 61 |
| 250 | 60 | 59 | 60 | 54 |
| 500 | 54 | 49 | 56 | 49 |
| 1000 | 55 | 49 | 56 | 45 |
| 2000 | 50 | 42 | 52 | 42 |
| 4000 | 44 | 32 | 46 | 40 |
| 8000 | 37 | 10 | 40 | 38 |
| dBA | 59 | 54 | 60 | 50 |

Table 12 Acoustic measurements in the Russian SM Sleeping Compartment

**Russian Functional Cargo Block (FGB)**

The FGB, not shown, was the first module launched of the International Space Station. The FGB provides electrical power, storage, and propulsion to the ISS. Measurements were taken at 7 locations, with summary data shown in Table 13.




| KT1 | KT12 | KT13 | KT14 | KT15 | KT16 | KT17 | KT18 |
|---|---|---|---|---|---|---|---|
| 68 | 64 | 64 | 70 | 65 | 67.5 | 75-72 | 63.5 |

Table 13 Acoustic measurements in the Russian FGB[32]

**Docking Compartment (DC)**

The Russian Docking Compartment is similar to modules that were part of the Mir space station. It provides docking ports for the Soyuz and Progress cargo spacecraft, and is also an airlock through which crewmembers perform spacewalks. Measurements were taken at 3 locations (Table 14).

| Freq (Hz) | KT1 | KT2 | KT3 |
|---|---|---|---|
| 63 | 59 | 52 | 55 |
| 125 | 57 | 57 | 60 |
| 250 | 61 | 64 | 68 |
| 500 | 57 | 60 | 65 |
| 1000 | 59 | 62 | 66 |
| 2000 | 56 | 58 | 62 |
| 4000 | 48 | 52 | 54 |
| 8000 | 42 | 43 | 47 |
| dBA | 63 | 65 | 69 |

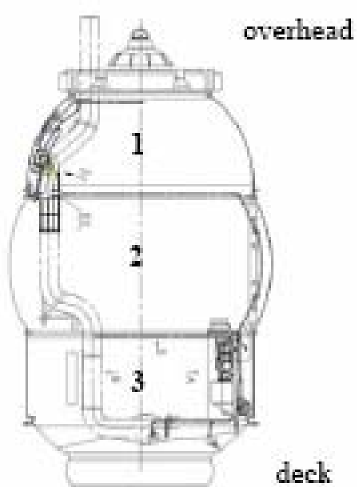



Table 14 Acoustic measurements in Russian Docking Compartment

**U.S. Node**[33]

The first U.S.-built component of the ISS, the Unity Node is a module with six connecting passageways and includes an exercise area and life support systems. It is also an area where large water containers are stored, and has been used as a shelter during periods of high radiation exposure. Visiting crews tend to favor it as an “overflow” sleep area. Summary data from the nodes is shown in Table 15.

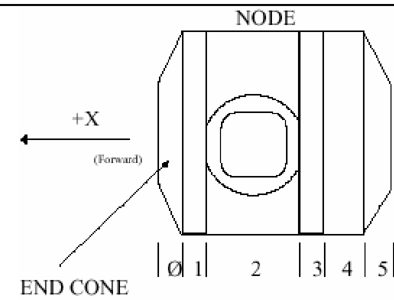
| Freq | 1 | 2 | 3 | 4 | NC-50 |  |
|---|---|---|---|---|---|---|
| dBA | 57.4 | 57.9 | 61.3 | 61.0 | 58 | |



Table 15 Acoustic measurements in the U.S. Node

**U.S. Joint Airlock**

The Quest Joint Airlock was originally to be the primary airlock for the ISS, from which spacewalks could be based using either the American or Russian spacesuits, though modifications permitting the latter capability have never been implemented. During spacewalks, significant noise is generated for short periods of time by pumps and valves, but in general it is a quiet place (Table 16) which crews regard as a haven from noise. It is also used as an overflow sleep area.

| Freq | 4 | 2 | 1 | NC-50 |
|---|---|---|---|---|
| **dBA** | 51.0 | 55.2 | 58.0 | 58 |

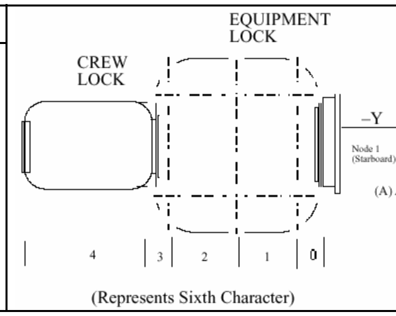



Table 16   Acoustic measurements in the U.S. Airlock

# 7. DEVELOPMENT OF OOHA
# (ON-ORBIT HEARING ASSESSMENT)

In early 2000 it became apparent that noise levels within the ISS would be higher than specifications allowed, and that the approaches mentioned above (hearing protection, timelining around noise, and powering down noisy equipment) were going to prove problematic for crew health and performance as well as scientific objectives. The most effective way to mitigate these seemed to be to develop a way to assess crewmembers' hearing while they were on orbit. As mentioned in previous sections, attempts to perform hearing tests aboard spacecraft had proven problematic and impractical. Concerns about hearing loss (fortunately temporary) in a U.S. crewmember aboard the Mir station, and uncertainty about the effects of long-duration noise exposure, as well as a desire to avoid constraining crewmembers with earplugs, led to a focused effort on overcoming the issues.

At this point, less than nine months remained before the flight of the first crew to the space station. It was realized that time was too short, and that the process of getting new hardware aboard the ISS was much too complicated. Aside from the cost of simply moving objects of a given mass and volume into orbit (currently several thousand dollars per pound), additional costs include thermal and vibration testing, off-gassing to remove volatile toxic gases, engineering drawings, processing and safety certification. Development of procedures can lead to order-of-magnitude increases in costs and take years rather than months. It was decided to take advantage of hardware already present onboard the space station to save cost and time. A review was initiated to examine everything available that might be used to perform any kind of hearing test onboard the station. It was clear that the following basics would be required:

- a means of introducing controlled and calibrated sound stimuli to one ear at a time
- a means of establishing the threshold which stimuli were perceived
- a relatively quiet place to perform the tests
- integration of the above with power, computing, training and scheduling constraints

- validation of the entire system from a biometric perspective

Initially, the possibility of using a CD player to function as an output device to deliver standardized stimuli was considered, but informal testing of the training versions of CD players the crews would be using revealed significant variations in their frequency response. Subsequently, the possibility of having the onboard laptop function as an audiometer was considered as a solution, one which was settled upon in the end. Initial efforts were limited to programming from scratch; although the author was limited by having worked previously only with the Apple Macintosh platform. The laptops then used aboard the ISS were found to have a sound card that could be directed to generate all the frequencies required to perform a standard audiogram and could do so across a range of sound-pressure levels necessary. However, in researching this and discussing with specialists providing hardware for our hearing-protection plan aboard ISS, a satisfactory commercial off-the-shelf product which has proven entirely satisfactory was found.

Previous arrangements had been made with Michael Santucci of Sensaphonics Hearing Conservation, Inc., in Chicago, IL, to supply custom-molded musician's earplugs with flat frequency filters to several Shuttle crews, and later for the entire Astronauts Corps as part of the newly implemented Hearing Conservation Program. NASA also contracted with this company to supply high-fidelity stereo ear monitors for ISS crewmembers for use with playback of recreational audio with CD and DVD players. These devices, called Prophonics ear monitors, are more thoroughly described in the later section.  In a conversation about the utility of his company's products in an onboard hearing assessment, Mr. Santucci mentioned colleague Tony Eldon, a professional sound engineer with interests in hearing conservation, who had developed a piece of software called EarQ.

Mr. Eldon's interest in developing this product stemmed from his work as a sound engineer for professional musicians, in which he'd realized that many of the people doing the same type of work were rapidly losing their hearing due to noise exposure on the job. In setting out to develop a tool to help adjust sound mixes to compensate for deficits in their own hearing, he was also able to offer them a means to recognize further deterioration in their hearing and do something about it. For example, if a sound man working for a live music group knows that he has a bilateral 60 dB hearing loss at 2000 Hz, he also knows that what seems the right amount of intensity in this range to him is too much mid-range for someone with normal hearing, so he must either correct for this or find another job.

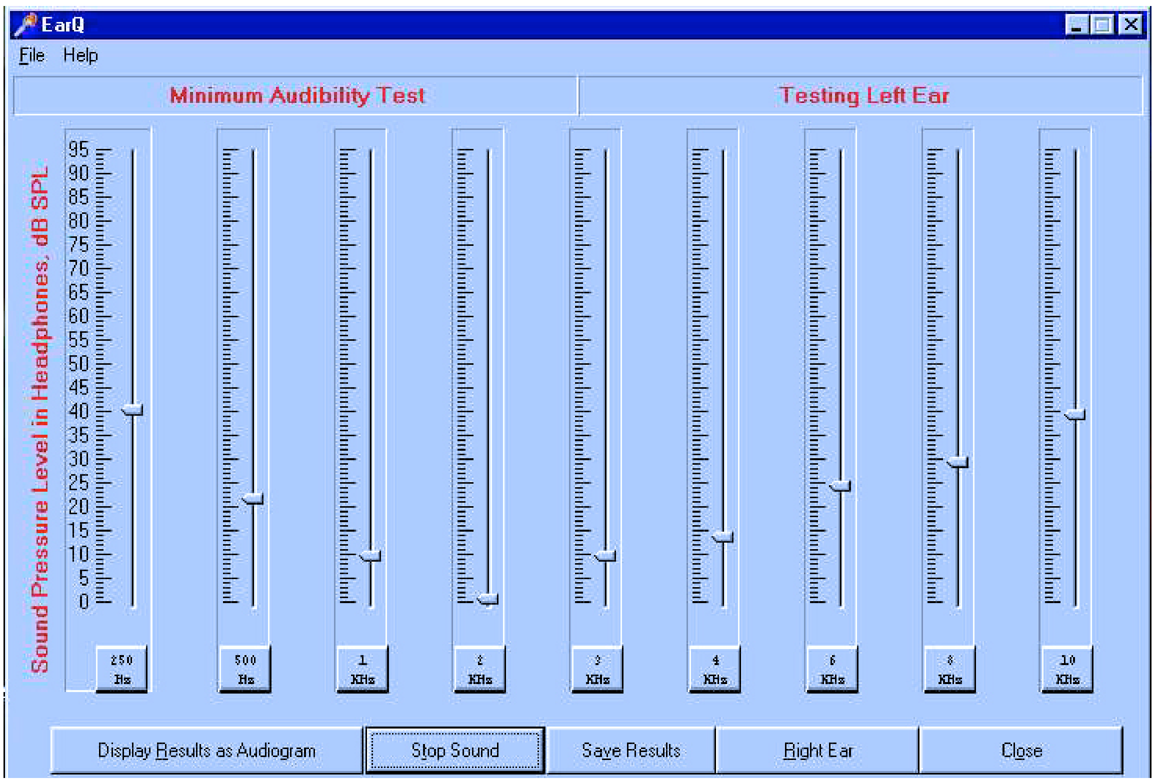



Figure 14 The EarQ Graphic User Interface

EarQ's interface, shown in Figure 14 is modeled after a sound engineer's mixing board or graphic equalizer. The initial version ran the frequency gamut of 20 to 20,000 Hz. Mr. Eldon's product, EarQ, provided something that would be easily adaptable for use on board the space station after some initial evaluations.

An early step was to establish that the software would run without problems on the laptop computers planned for use aboard the ISS, the IBM ThinkPad 760 XD. Training versions of this computer were already being used to test other software for inclusion in a suite of medical and exercise-related applications, so software engineers were quickly able to certify that EarQ had no incompatibilities with either the onboard computer itself or with other programs. Concurrently, we were running tests with EarQ on an identical computer to validate EarQ against a standard audiogram.

The initial validation was performed with no budget and limited scientific rigor using borrowed equipment and volunteer labor, as the process to jump start an effort like this through “proper channels” in a government agency can take months or years. Initial work was done in Building 45 at the Johnson Space Center in a reverberant chamber that was designed to simulate spacecraft modules in terms of their dimensions and acoustic properties. This is a five-sided chamber with hard surfaces designed to reflect noise in a worst-case scenario rather than absorb and muffle noise. A trained audiologist, Mary Sue Harrison, who had volunteered many hours of her own time to take ear impressions of astronauts for custom-molded earplugs, was kind enough to help with the effort by sharing her audiologic expertise and perform audiograms using her own portable audiometer (Maico MA27). The initial test was undertaken with five subjects, only two of whom had Sensaphonics ear monitors molded to their own ears. Due to the high expense of these products ($750/pair), the other 8 simply used poorly fitting ear monitors.

The subjects within the chamber were asked to self-administer the hearing testing using several different configurations, including the Sensaphonics ear monitors alone, Sensaphonics ear monitors underneath a Bose X headset with active noise-reduction operating, then the Bose X without the Sensaphonics earpieces, and, lastly, a standard portable audiometer. Inside the chamber we were able to perform the test in relative silence or in a noise field representative of the ISS, simulated by playing back a digital audio tape made previously in a mockup of the Russian Service Module at the Energia facilities outside Moscow. The sound in the chamber was adjusted to dBA levels matching those measured in the Energia mockup using a B&K 2260 sound-level meter identical to that currently used aboard the ISS. As shown in Figure 15, values obtained using EarQ in its native configuration ranged from 10-40 dB higher than values obtained using audiometry. These differences might seem disturbing at first, but at this point EarQ was being run in an uncalibrated state.

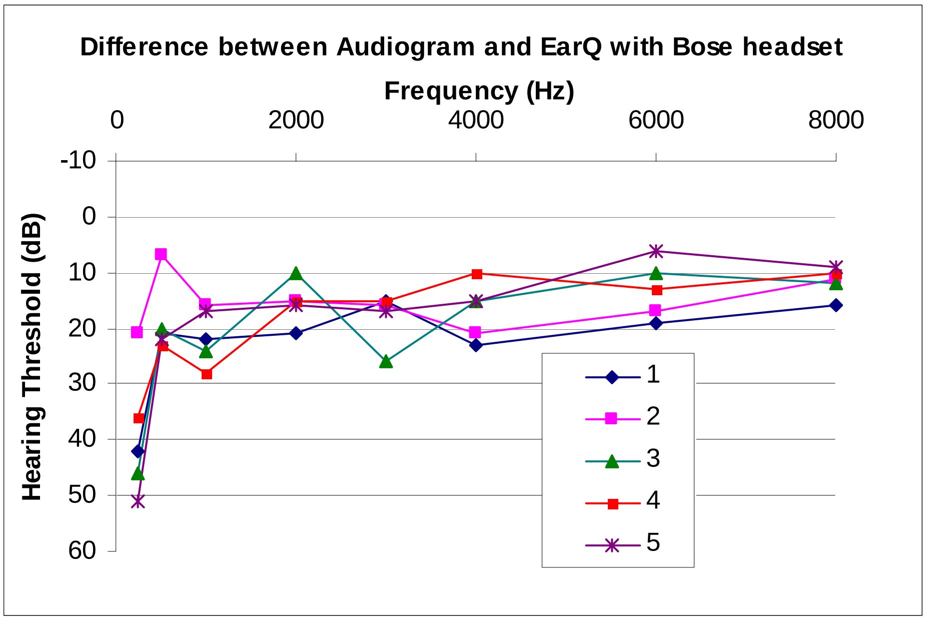



Figure 15 Difference between EarQ and portable audiometer values in ISS noise

Additional testing involved the two subjects who had Prophonics ear monitors custom-molded to their ears. These tests, which were performed in an anechoic chamber with background noise levels below 20 dB SPL, were done first using the audiometer, then using the EarQ software and Prophonics alone. Figure 16 shows a plot of this data, in which EarQ data was consistently 10-20 dB higher than the audiometric data.

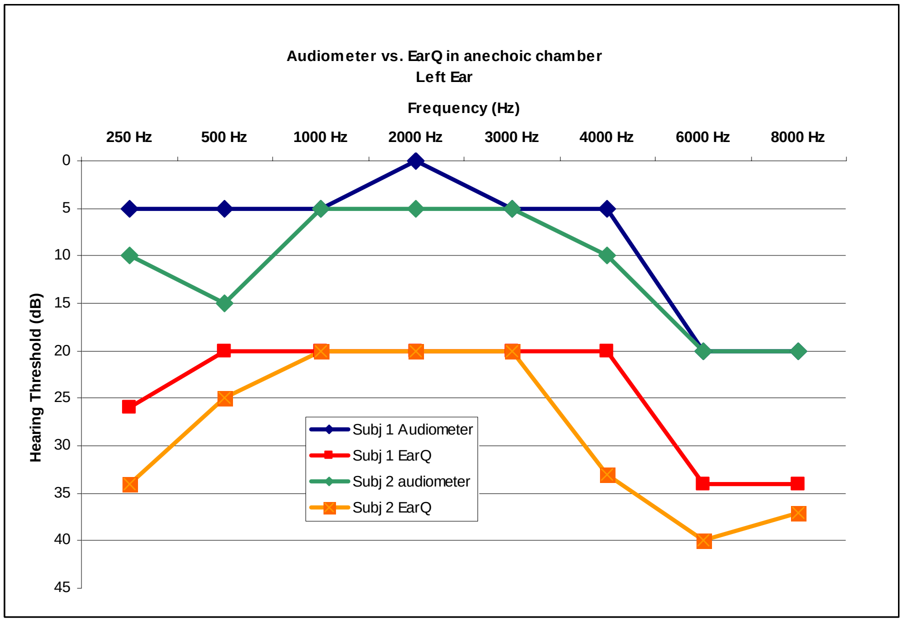



Figure 16 Plots of EarQ and portable audiometer values in quiet (anechoic) chamber

EarQ was designed to run on personal computers operating under the Microsoft Windows platform. Obviously, huge variation exists among PCs with regard to the pertinent specifications. Differences between sound cards installed in the computer, between proprietary drivers interfacing the computer's CPU with these cards, and differences between the computer circuitry connecting the cards with the output jack can all lead to different sound-pressure levels with a given indicated level on the EarQ screen. Likewise many different types of devices can be plugged into the computer to actually generate the acoustic stimuli (including headphones, ear monitors and earbuds), and each of these have a unique frequency response dependent on the impedance of the wire used, the design of the driver (speaker), the shape of the housing and a unique capacity to attenuate environmental noise.

The developer of the program designed the program to permit calibration of the display to correct for disparities inherent in the different combinations of hardware, using a simple text file containing values called offsets for each frequency. These can be added to or subtracted from the raw data value to adjust the output for the purposes of calibration. The most rigorous approach would be to measure the actual output from the headphone/ear monitor using a standardized method, attaching it to a microphone via a connector known as a 2cc coupler that acoustically models the ear canal. Another would be to match EarQ results against other hearing tests (i.e., audiogram).

In an even less-exact approach, absolute sound-pressure levels are not known, and a first test is used to document a baseline. Changes from this baseline in subsequent tests can be used to infer a change in hearing threshold. As quantitatively unsatisfying as the baseline approach seems, interpretation of data relative to baseline exams obtained after arrival on the ISS was the only way that hearing health was evaluated for the three years spanning the first seven expeditions.

After review of this data internally and with several outside audiologists, a proposal on how the system would be deployed and how data would be interpreted was submitted to managers charged with allocating funds for full implementation. Presented with data on the anticipated acoustic environment and faced with the alternative of having nothing in the way of hearing assessment for crewmembers, they agreed to budget money for development and revision of the software.

With formal agreements from the ISS program office to budget this effort, a number of modifications to the interface were implemented. For example, the initial product permitted assessment at 20 discrete frequencies across a range of 20 to 20,000 Hz (.020, .060, .125, .250, .500, .750, 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, and 20 kHz) with an SPL range of 20 to 95 dB. Traditionally, audiometry is assessed at 500, 1k, 2k, 3k, 4k, 6k and 8kHz dB HL, so EarQ was modified to indicate from 250 Hz to 10,000 Hz and with a sound-pressure level range of 0 to 85 dB SPL. We also had the EarQ default to saving files in a specific location in order to facilitate retrieval by the Mission Control for further analysis.

Consideration was given to data-display options during and after the test. In standard audiometry, subjects are blinded to the intensity of the stimuli; they simply indicate each time a stimulus is perceived, whether it is delivered manually by a technician, or automatically by a computer. Since this test is a self-administered, manual technique, the alternative of having the screen go blank, having crewmembers close their eyes, or even having another crewmember run the program were considered.

Discussions followed on how to handle the data after collection. Aviators and astronauts have a reputation of being defensive and private about medical data that could potentially impact their careers, so this proved a sensitive issue. Some felt that if a crewmember noted changes on his OOHA, he/she might choose not to share it with the ground and simply delete the file. Eventually it was agreed that crewmembers should be encouraged to use the test in addition to scheduled sessions and be able to recognize changes on their own, since they were the only ones who could do anything to limit their noise exposures. The fact remains, however, that this methodology cannot recognize results skewed by those wishing to exaggerate or hide a hearing loss.

Another inherent problem with this approach is that in the period of time between their last booth audiogram and their first on-board hearing test, a number of potential acoustic insults routinely take place, including flights in high performance jet aircraft, a launch aboard a Space Shuttle or Soyuz vehicle, and several weeks of living on-board the ISS. If their first OOHA is performed after a threshold shift has already developed, only further change will be recognized. With the damage already done but not recognized, it would not be known if a significant problem had developed until the crewmember returned and had abnormal post-flight audiogram months later.

Prior to flight, all crewmembers were introduced to the program EarQ, and were able to read through and perform the procedure using a laptop identical to that onboard and generic headphones. In addition to being familiarized with the procedure, in association with this training session, they were also given a briefing on the noise environment aboard the ISS, the hazards of NIHL, the available countermeasures (earplugs, noise cancellation headsets) and avoidance strategies.

During training, a certified audiologist was also present to take ear impressions, injecting a silicone-based material that hardens into a mold from which custom fitted ear monitors could then be made. This was accomplished in a manner well-standardized by hearing-health professionals and commonly used to make molded hearing aids, hearing protection devices and communications inserts. In this technique[34] after examination of the patient's ear, a vented dam (piece of foam with a small plastic tube attached) was inserted, followed by an injection of impression material. The dam serves a two-fold purpose, keeping impression material from moving too deeply into the canal and by allowing air to equalize through the tube as it is withdrawn, avoiding discomfort due to negative pressure. The dam generally adheres to the impression material and can be removed with the ear impression.

Ear impressions were made using a 50/50 mix of proprietary (Westone) vinylpolysiloxane base and vinylpolysiloxane catalyst that was either quickly blended by hand and injected with a syringe or simultaneously mixed and injected through an impression gun. Hand mixing and injection with a syringe was employed for Expeditions 1-6. Variation in this technique (e.g. the ratio of base to catalyst in the mix, the rate of mixing and loading of the material into the syringe or the pressure exerted on the syringe plunger) can lead to alterations in the characteristics of the final impression, affecting its overall quality and hence the finished product. In later expeditions such problems were minimized with the use of the same vinylpolysiloxane materials, automatically mixed and blended to the proper consistency as they are injected through a special mixing tip. After injection, as the material was curing, subjects were asked to move their jaw in chewing, talking and yawning motions to simulate the range of motions of the soft tissue. After several minutes of curing, the impression was carefully removed, minimizing the potentially uncomfortable vacuum effect in the ear. The ear was then inspected for retained impression material. In one case this was identified, but with a heavy training schedule, the crewmember had no time for removal and decided he’d have to return later in the day, a decision he regretted as the foreign body sensation was very distracting.

All ear impressions were overnighted to the Sensaphonics laboratory in Chicago, where the impressions were used as templates for the manufacture of the ear monitors, as well as other custom molded hearing protections. The ear monitors themselves can be thought of simply as very high fidelity in-ear headphones. Each earplug (shown in figure 17) has two sound drivers that can in combination more accurately reproduce the high or low ends of the spectrum, as do the woofer and tweeter of a conventional speaker cabinet. Two separate tubes direct the energy from the drivers through each ear monitor into the external canal, and a single shielded wire exits from joined at a 1/8' stereo plug, a common interface for computers, DVD and CD players, etc.


Figure 17 Prophonics 2X-S ear monitors with ED-9689-000 and BK-1613-000 drivers

# 8. IN-FLIGHT OOHA DATA

Figure 18 is a plot of all the raw OOHA data collected onboard station during the first 12 Expeditions. The 29 crewmembers who lived on the ISS during the period between November 2, 2000 and April 8, 2006 performed this test a total of 107 times on each ears, so 214 plots are presented. It is presented in part to give the reader an overall sense of what data from a typical session looks like (referred to informally as a "bowtie") prior to any data treatment. Subjective though it may have been, for the first seven Expeditions, subjects whose data conformed to this seemingly normative bow-tie distribution were considered to have intact hearing. Of interest, several of the outlying tracings were isolated for a given crewmember represented meaningful changes from baseline, which prompted counseling from their flight surgeons.

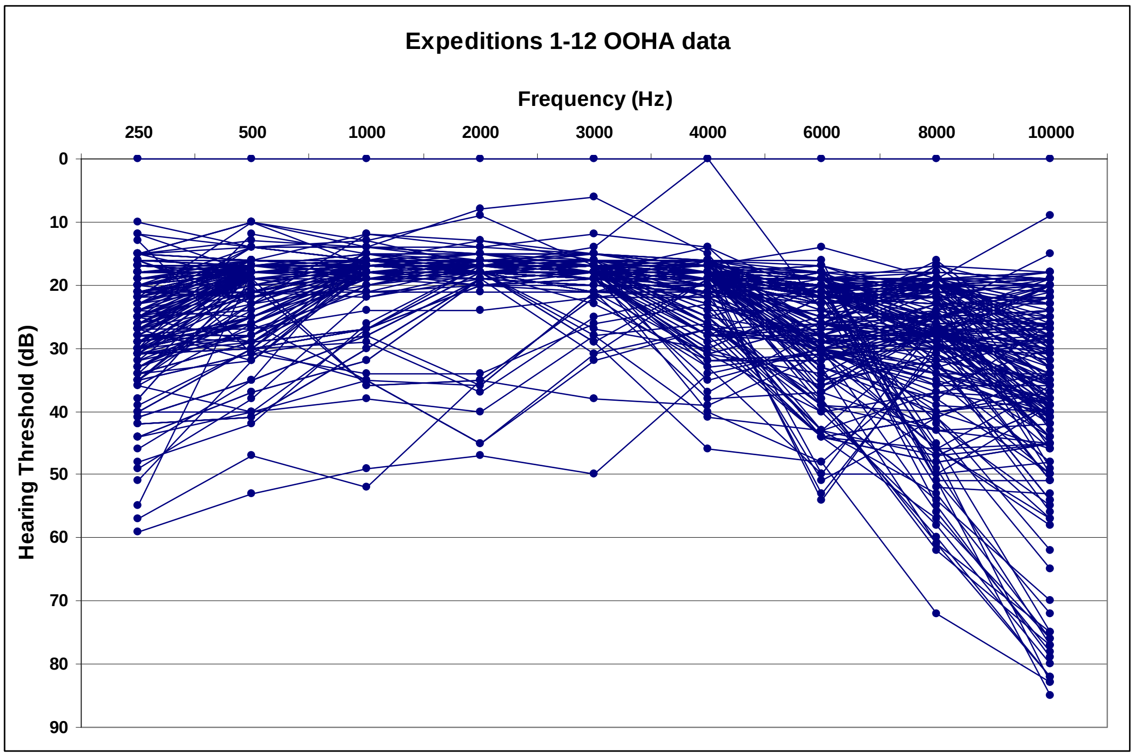



Figure 18 Composite plot of all OOHA data through Expedition 12

Figure 19 is a graphic which demonstrates the distribution of these tests through each of the 12 long-duration flights between October 1999 and April 2006. As can be seen in the diagram, considerable variation exists in the timing of in-flight testing between different expeditions. In most cases, crewmembers were scheduled to perform the test the same day, and in several cases where abnormalities were noted, a single crewmember was asked for repeat or follow-up tests. The number of test sessions per crewmember varied between 1 and 5, and averaged 3.5.

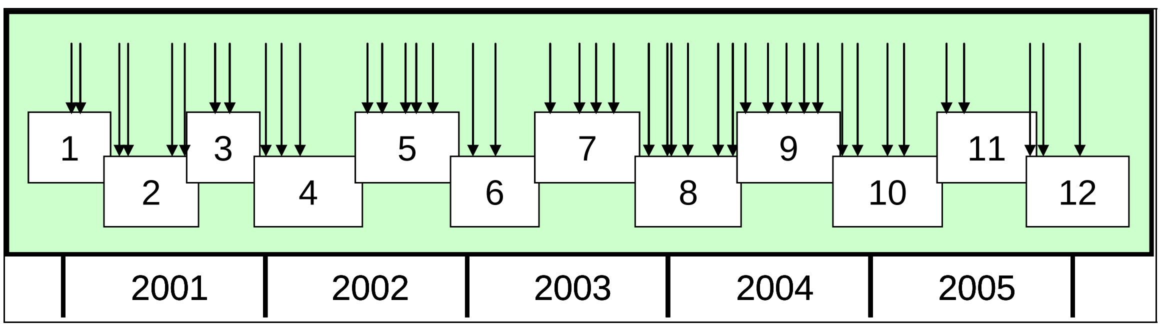



Figure 19 Timeline of OOHA testing across 12 Expeditions. Each arrow represents tests for all crewmembers aboard the ISS at that time

Currently, the On Orbit Hearing Assessment is scheduled to be performed within the first 3 days of arrival aboard the ISS, then once a month thereafter in conjunction with a station-wide survey of the acoustic environment with the Russian and U.S sound level meters. In reality, it is frequently crowded out of the timeline and has never been done earlier than 2 weeks into a mission. As described above, this has major implications to interpreting in-flight data without a pre-flight baseline OOHA test. For the first 7 expeditions, the first data take onboard was used as a baseline for subsequent tests, accepting the risk that NIHL due to launch and the ISS environment could develop before the first test and go unrecognized.

The procedures utilized by the crewmembers in training as well as in flight are summarized as follows. The assessment is performed by the crewmember him/herself in the Temporary Early Sleep Station U.S. Lab sleep station, a relatively consistent and quiet location as determined by sound level meter analysis. The Medical Equipment

Computer, an IBM ThinkPad 760XL loaded with medical software including EarQ is set up, the Prophonics earphones are donned and connected to the laptop, and a pair of Bose X Active Noise Reduction headphones are placed over the Prophonics to provide additional attenuation. Following calibration steps, the laptop screen displays a series of slider bars at frequencies standard to pure tone audiometry (.25, .5, 1, 2, 3, 4, 8, 10 kHz), and the subject manipulates the intensity of sound with arrow keys at that frequency until a minimum hearing threshold is determined. This is repeated at all frequencies for both ears. An optional display comparing hearing threshold with previous sessions is available to give immediate insight into hearing health, which can provide incentive to reduce noise exposure. A text file of the hearing threshold values in decibels of sound pressure level is saved and subsequently downlinked for analysis on the ground.

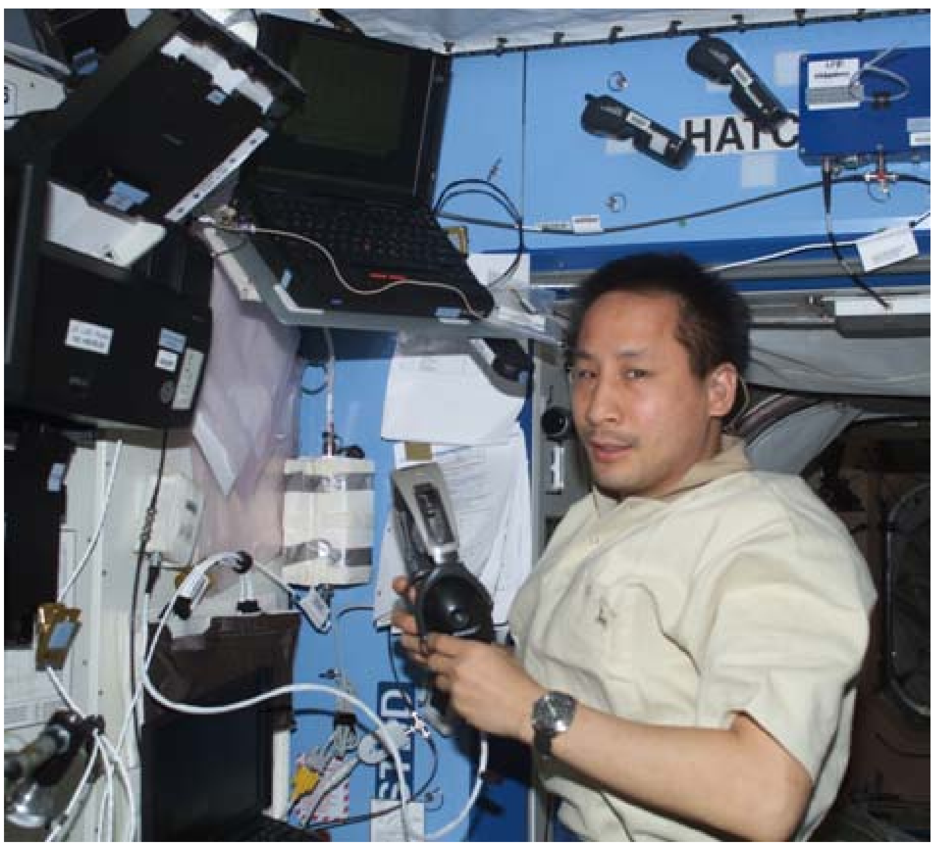


Figure 20   Astronaut Ed Lu performs the OOHA test aboard the ISS during Expedition 7

# 9. STANDARD AUDIOMETRY

The following section is a discussion of the second measure to be analyzed in this study. Pure tone audiometric data has been collected on astronauts and cosmonauts since the early days of spaceflight as a matter of routine as well as with a specific focus on spaceflight. In both U.S. and Russian programs, this was largely an extension of practices employed in the care of military aviators, in which comprehensive health evaluations take place annually. For NASA specifically, this approach has become formally codified in a number of clinical or operational documents.

Audiometric evaluations are performed as part of the initial medical screening of applicants to the Astronaut Corps, many of whom come from military and/or aviation backgrounds and present to NASA with well documented hearing health histories. Unfortunately, many of these individuals have a history of significant noise exposures related to aircraft operations and weapons systems, and otherwise highly qualified applicants have been turned away because of inadequate hearing acuity. Standards for selection of new astronauts are more demanding than for those already accepted, a function of the time and money invested in their training and flight experience. Experienced astronauts are also allowed a hearing asymmetry with a standard for a "good ear" and a "bad" ear. Astronauts are considered unable to meet hearing standards if they show a maximum dB HL loss at the frequencies shown in Table 17. Inability to meet hearing standards on the annual examination requires the voice discrimination test with a 95% or greater performance accuracy.

| | Frequency Hz | 500 | 1000 | 2000 | 4000 |
|---|---|---|---|---|---|
| Selection Standards | Both Ears | 30 | 25 | 25 | 50 |
| Annual Standard | Better Ear | 30 | 30 | 30 | 55 |
| (db HL) | Worse Ear | 35 | 50 | 50 | 75 |

Table 17 Hearing Standards for Astronauts[35]

Pre-flight and post-flight audiometry of astronauts and cosmonauts has been complicated to some extent by the realities of the logistics and timing of training, launch and recovery of ISS crews. If the highest priority was consistent methodology in the collection of audiometric data to isolate and measure the effects of spaceflight on hearing, we'd have a booth and an audiologist at the launch pad and landing site. Instead, three different systems have been used on the ground to collect data, following different schedules with different potential noise hazards between flight and measurement which could confound the data. Though these systems were each manufactured and are maintained in compliance with recognized standards (ANSI & ISO), their use, as opposed to a single gold standard, complicates the issue of interpretation of the in-flight data collected by the OOHA, given its non-standard approach. Brief descriptions of the systems used follows.

## RUSSIAN AUDIOMETRIC TESTING PROGRAM

The first International Space Station crew launched in late October, 2000 from the Baikonur Cosmodrome in Kazakhstan, Central Asia, aboard a Soyuz rocket. The training and preparation flow leading up to this and later launches from Baikonur were well rehearsed, as the Russians have been launching crews from this site aboard similar vehicles since Yuri Gagarin flew in the early 60s. Because of limited resources at the launch facility and, pre-flight audiograms are performed well before the crew travels to the launch site. This takes place at the same site in which the cosmonauts live and train, the Gagarin Cosmonaut Training Center in Star City, Russia outside Moscow.

Pre-flight audiometry is typically administered 4-6 weeks before launch. with possible noise exposures of significance taking place as they fly aboard Tupolev 154 passenger aircraft to Baikonur and of course, fly to space aboard the rocket. In some launch flows, the crews travel to Baikonur several weeks before launch for a suit fit check and inspection of the vehicle, then return to Moscow for a few days before flying back to the launch site 5-6 days before launch. For other crews, they leave earlier for the actual launch and perform the fit check and launch without a return to Moscow. The latter group thus has a single flight aboard these fairly loud (no data available) aircraft prior to launch, while the former has three flights, including one closer to launch. These 3-4 hour flights are louder than any continuous exposure they might encounter aboard the ISS, and have an unknown potential to influence hearing tests aboard the ISS. Hearing protection is available, but not encouraged, so is used by some crewmembers but not by others.

Post flight audiometry is routinely performed on R+3, or 3 days after return to earth. Landing day (R+0) is a day of meaningful noise exposures that are also in excess of what the crewmembers have tolerated onboard the ISS, with potential to influence post-flight audiometry. Once on the ground, they fly in a very loud (no data available) Russian Mil-8 military helicopter for 2-3 hours from the remote landing site in the steppe of Kazakhstan to one of the larger cities, then transfer to the same passenger aircraft used pre-flight for another 3-4 hour flight. Crewmembers are encouraged to wear hearing protection aboard both flights, but no data is available on compliance with this suggestion.

The Russians use a modern EYMASA Reduson CI-50 audiometric booth, manufactured in Spain, with an attenuation of 53db at 8000Hz. This is a double walled enclosure, with triple glass and anti-reverberation carpeting for additional isolation. It is certified by an accredited laboratory stating compliance with standards ISO 140, UNE-EN ISO 11957, ISO 717, UNE EN-ISO 13485 and 93/42/CEE. Attenuation data has been provided to NASA and reviewed by the JSC audiologist, who has been satisfied as to the quality of the enclosure. This unit is coupled with a Grason Stadler GSI-60 audiometer, a unit not uncommon in European and U.S. audiology clinics. This audiometer is in fact identical to that used at JSC beginning with Expedition 7. A dedicated audiologist is responsible for administering hearing tests under the supervision of Dr. Eduard Matsnev, an ENT physician who has worked with the Russian Space program for many years. Calibration practices were not provided but are presumed to be consistent with the modern equipment and training in evidence. The Russians cite ISO-8253, 1989 as the international standard they adhere to in performing audiometric evaluations. In a personal communication with Dr. Richard Danielson, data generated by equipment and protocols satisfying the applicable ISO and ANSI standards used by Russians and U.S. are interchangeable.

Figure 21 Testing enclosure and audiometer in Star City, Russia

## U.S. AUDIOMETRIC TESTING PROGRAM

Prior to Space Shuttle launches originating at Kennedy Space Center in Florida, preflight measurement takes place during a period up to 45 days prior to scheduled flight. All astronauts (both active, inactive and retired) have annual evaluations that include audiometry, and these can be used as a pre-flight evaluation if within 90 days of flight.[36] In the period between this study and launch, crewmembers have numerous opportunities for flights aboard NASA’s T-38 jet aircraft, including travel to Kennedy Space Center, typically 1 month before launch for a practice launch, and again about 4-6 days before the launch itself. In some cases, an alternative Gulfstream G-2 passenger aircraft is used for this travel. Acoustic data is available on these aircraft, but not presented. The issue is raised to make the point that meaningful variation exists between ISS fliers with regard to their noise histories that might influence test results.

Post-flight audiometry is performed using the identical protocol 3 days after return from space aboard the Shuttle, which lands at the same facility from which it launched. Typically travel from Florida to Houston occurs the day before the audiogram is performed, but in some flights, they return 2 days before the test. Efforts are made prior to testing to avoid additional noise exposure, but this is a period in which crewmembers return to Houston from the landing site in relatively loud aircraft, which can confound the results.

In the Flight Medicine Clinic at Johnson Space Center, astronauts and aircraft pilots have routine audiograms performed using the same equipment and procedures that are used to screen and diagnose all employees in need of hearing tests. These may be part of routine medical evaluations, as control subjects in ongoing epidemiologic studies of astronaut health or as subjects assigned to JSC's Hearing Conservation Program because of occupational noise exposures.

**Older System**

Pure tone audiometry is administered by a certified technician using a relatively older (see photo below), ANSI certified single-walled booth, the Industrial Acoustics 401A, and a more modern Tremetrics RA500 audiometer (also pictured below). The audiometer delivers acoustic stimuli via a pair of Telephonics TDH-39 supra-aural cushioned earphones. This audiometer was manufactured and calibrated to the ANSI S3.6 – 1996 standard for audiometers, and tests across a standard range of frequencies (500-8000 Hz). This system is checked on a daily basis using a Tremetrics OSCAR IV bioacoustic simulator. Annual microprocessor calibration of the Tremetrics RA-500, as well as the OSCAR IV was handled by an Audio Electronics, and more recently by Gordon N. Stowe & associates.

Since this system is also used to manage data for a large Hearing Conservation Program, the data from the RA-500 is ported out via RS232C ports through an adjacent networked computer to a server running the Hear/Trak database.

Hear/Trak is a software suite that functions as an archival database and has features that help technicians determine test validity, identify threshold shifts, and aid in decision making about the effectiveness of hearing protectors or progress in reduction of a worker's exposures.


Figure 22 Enclosure, audiometer and calibrator employed in JSC's Occupational Medicine Clinic. The vintage logo on the booth serves to date this unit.

**Newer System**

The system described in the prior section remains in use for JSC's occupational population, as well as annual testing of astronauts. Halfway through the sixth ISS expedition an event occurred which impacted virtually every aspect of flight planning, including medical testing. On February 1, 2003, the Space Shuttle Columbia broke up on reentry over Texas, with the loss of all seven crewmembers on board. Prior to this event, aside from the launch of the first Expedition in October, 2000, new crews had gone up and returned aboard a Shuttle, with pre-and post-flight testing of long-duration Russian and U.S. fliers all taking place in Houston. As a result of the accident, the Shuttle fleet was grounded for more than 2 years, and responsibility for launching and recovering crews has been borne by our Russian colleagues. Thus, Expedition 6 which launched on a Shuttle with plans to return on another to Florida, was instead forced to land in a Soyuz capsule in Kazakhstan. Later Expeditions 7 through 12 launched and landed aboard Soyuz vehicles. From an audiologic standpoint and for the purposes of this study, this has led to crewmembers with different sets of pre-test noise exposures, different technicians or audiologists administering the tests, different hardware and different protocols, as well different ideas about data sharing and medical confidentiality.

Coincident with this paradigm shift, days before STS-107 was lost, Dr. Richard Danielson was welcomed aboard at JSC as the Flight Medicine Clinic's first audiologist, and within a year, had deployed a more modern suite of equipment in support of flight crew. Beginning in 2004, all mission related audiometry has been administered by Dr. Danielson. He is also integrally involved in educating crewmembers on spacecraft noise environments and hearing conservation principles, as well as training them in the use of the On-Orbit Hearing Assessment.

Dr. Danielson's suite uses a single-walled two-room custom enclosure manufactured by Eckel Industries of Canada, satisfying ANSI Standard S3.1 99 (Maximum Permissible Ambient Noise Level for Sound Rooms) and a GSI 61 audiometer, satisfying the 1996 ANSI standard for audiometer specifications (S3.6). This system is also routinely calibrated and checked on a daily basis with a Quest BA-202 “BioBetty” bio-acoustic simulator, (a more modern version of the OSCAR unit used in the older JSC system). Both the audiometer and the bio-acoustic simulator are maintained by Gordon N. Stowe on a routine basis.

Figure 23 More modern audiometer, enclosure and calibrator employed in JSC clinic

The arrival of a dedicated audiologist and the modernization of the JSC hardware was a distinctly positive development. However, for the purposes of this work, additional uncertainty was introduced with regard to methodology, raising the potential for confounding factors between post-flight data collected in the U.S. using the old system, the new system and the system used in Russia.

# 10. REFINEMENTS OF OOHA INTERPRETATION

After several expeditions, enough data had accumulated to recognize typical patterns and assure ourselves that the tests were valid onboard without a preflight baseline. Though aware of the lack of scientific rigor in this approach, for the first half dozen expeditions, we were able to distinguish normal audiograms from abnormal, recognizing NIHL and ENT pathology, and making clinical decisions and recommendations to crewmembers. These included increased use of hearing protection, noise avoidance, and in one case, treatment of Eustachian tube dysfunction with decongestants.

In 2003, a new audiologist arrived bringing along with his expertise and a budget permitting further validation and refinement of the interpretation of OOHA. A key step in this effort was to have a group of non-astronaut subjects fitted with the Prophonics ear monitors. Once the finished product returned, it was fit-checked by the audiologist. Following a two day period during which they were to avoid excessive noise, each presented to the clinic for audiometry and OOHA testing. A total of 10 subjects (including the author and the new audiologist) underwent standard pure tone audiometry in quiet, followed by administration of the EarQ test three times under simulated ISS noise conditions.

With the assistance of epidemiologists in NASA's Longitudinal Study of Astronaut Health, the EarQ data thus collected was then statistically processed using analysis of variance (ANOVA) at the frequencies which EarQ measures, assuming independence between the left and right ears. An $n$ of 20 was reached for each frequency. This analysis tested the null hypothesis that the mean of the first EarQ Trial 1 = mean Trial 2 = mean Trial 3, and concluded that no significant difference was observed between the values obtained by the repeated testing. This confirmed that EarQ is repeatable across tests.

Comparison of the EarQ data to audiometric threshold datawas made using a paired t-test to analyze the difference between mean EarQ and mean audiometry threshold, and the probability of that difference arising from chance. The standard error provides the variance of the mean difference to the "true" difference. The 10 kHz frequency datapoints were excluded in the comparison, as it is not tested in Audiometry. This test concluded that the difference between mean EarQ and audiometry threshold ranges from +10 to +19, with raw EarQ data always higher than the audiometric data. The frequency specific mean differences between the two tests, shown in Table 18 and Figure 24, has come to be referred to as ***offsets,*** and have been used as correction factors to adjust the raw values obtained onboard. This allows interpretation of these as if they were obtained using a pure tone audiogram.

| Frequency (Hz) | Mean Difference | Std Error | p-value |
|---|---|---|---|
| 250 | 19 | 2.06 | < 0.0001 |
| 500 | 19.32 | 1.93 | < 0.0001 |
| 1000 | 15.67 | 1.44 | <0.0001 |
| 2000 | 15.98 | 0.87 | <0.0001 |
| 3000 | 12.2 | 1.61 | <0.0001 |
| 4000 | 10.4 | 1.67 | <0.0001 |
| 6000 | 14.17 | 1.39 | <0.0001 |
| 8000 | 15.02 | 2.84 | <0.0001 |

Table 18 Results of the t-Test comparing mean EarQ thresholds in noise to pure tone audiometry in quiet (n=10)

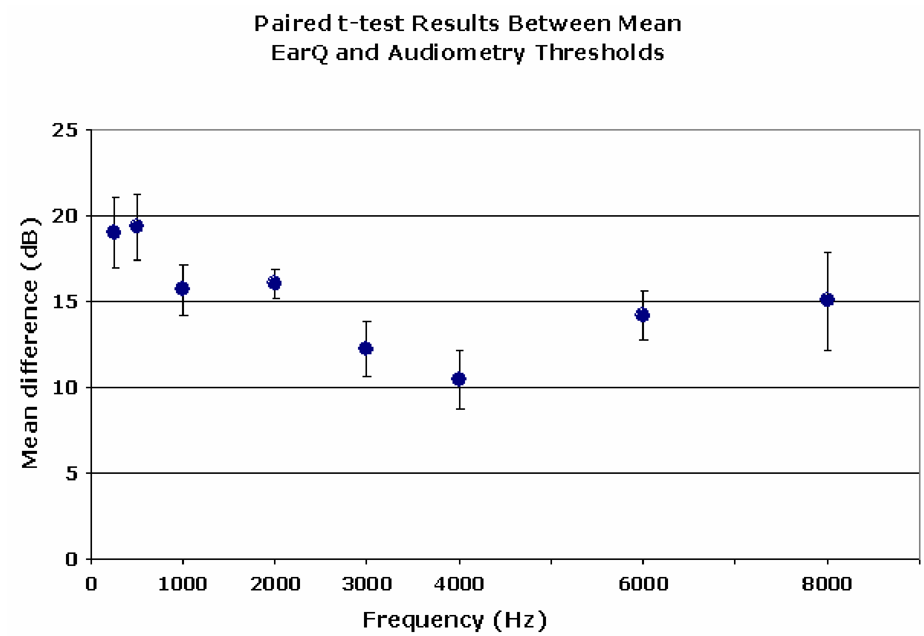



Figure 24 Plot of difference between means (± s.d.) of EarQ in noise and audiometry in quiet

This data was very important in that it was the first effort to validate EarQ with a statistically reasonable number of subjects, each performing the EarQ test in a manner consistent with the On Orbit Hearing Assessment. The most important difference from prior tests was that each subject used custom molded ear monitors for testing.

At the same time that the offset or correction factors were established, an effort was made to standardize the reporting format for both real-time interpretation and archival purposes. The convention for the display of audiometric data in the graphic form[37] includes placement of frequency data in Hertz (Hz) on a logarithmic scale along the abscissa and the hearing levels in decibels on a linear scale along the ordinate. It is typically scaled so one octave on the frequency scale is linearly equivalent to 20 dB on the hearing level scale. Figure 25 is an example of a proposed reporting form that can be automatically be generated by Microsoft Excel macros.

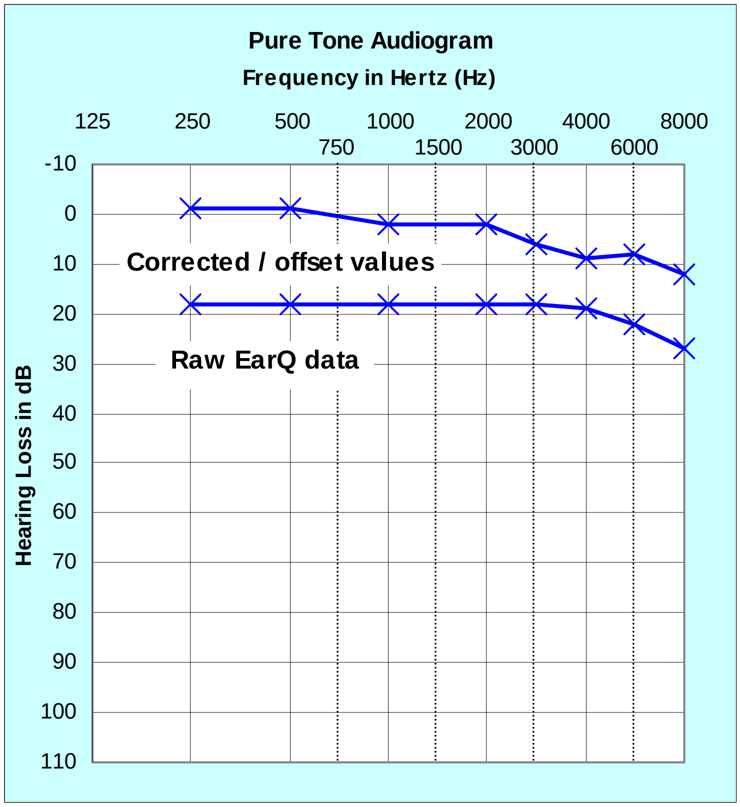



Figure 25 Standardized display used to report OOHA data

Currently, a OOHA test is evaluated and reviewed for consistency from several perspectives: i) compared to the first baseline OOHA, ii) corrected using the offsets derived from the 10-person sample and compared to pre-flight and iii) corrected using the offsets derived from an individual crewmembers pre-flight EarQ/audiometry session. Results from all of these are considered in the interpretation.

A previous discussion of calibration issues mentioned a third option, which remains elusive, primarily because it involves flying additional hardware with its own maintenance requirements. The calibration requirements for a standard pure tone audiometric setup, such as those in use at JSC have OSHA-mandated[38] scheduled calibration including daily functional checks as described above (using the OSCAR or Bio-Betty bio-acoustic simulator) and annual calibration of the audiometer-headphone combination using a sound level meter using a NBS 9A coupler at 70 dB. A means whereby crewmembers could actually test the output of their ear monitors onboard to verify the output could be done, as a sound level meter is onboard, but it would involve developing and testing not only an appropriate coupler for the Prophonics, but the procedures and crew time to train for and to perform these checks. At present, it is not anticipated that this will be undertaken.

# 11. ENT PATHOLOGY

Data from OOHA has also been used to drive medical decision-making. Indeed, this was the main justification for its development and implementation. Once reviewed on the ground, test results on several crewmembers have been interpreted to be consistent with NIHL, with a classic notch in the 4000-6000 Hz range. In these cases, the crewmember's flight surgeon was promptly notified of this development, and made a point to review the results with the crewmember at the next opportunity, typically during weekly Private Medical Conferences, and to reinforce adequate use of hearing protection devices. In most, but not all cases, crewmembers were compliant, and follow-up OOHA data would show improvement or resolution. Figure 26 is an example of one such transient deficit consistent with NIHL which resolved on subsequent testing.

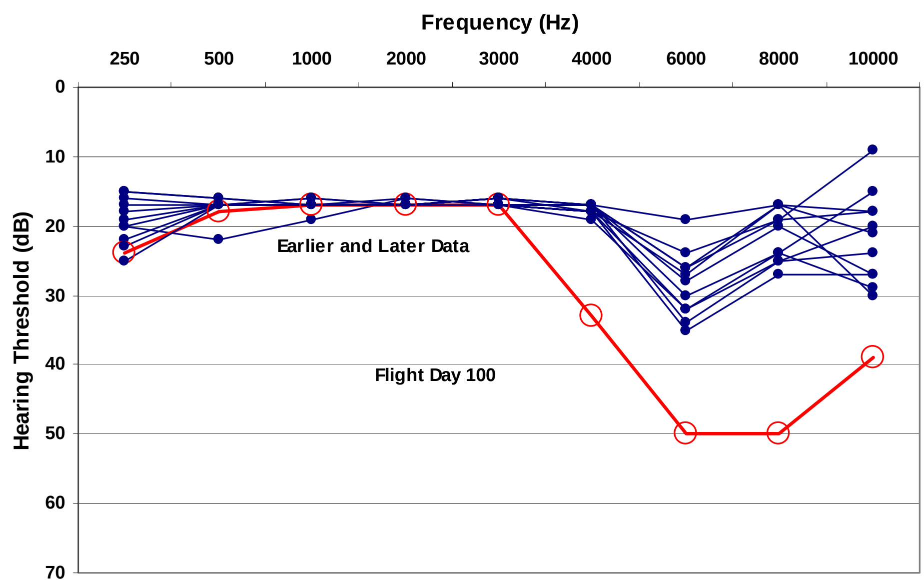



Figure 26 Transient Bilateral High Frequency Hearing loss

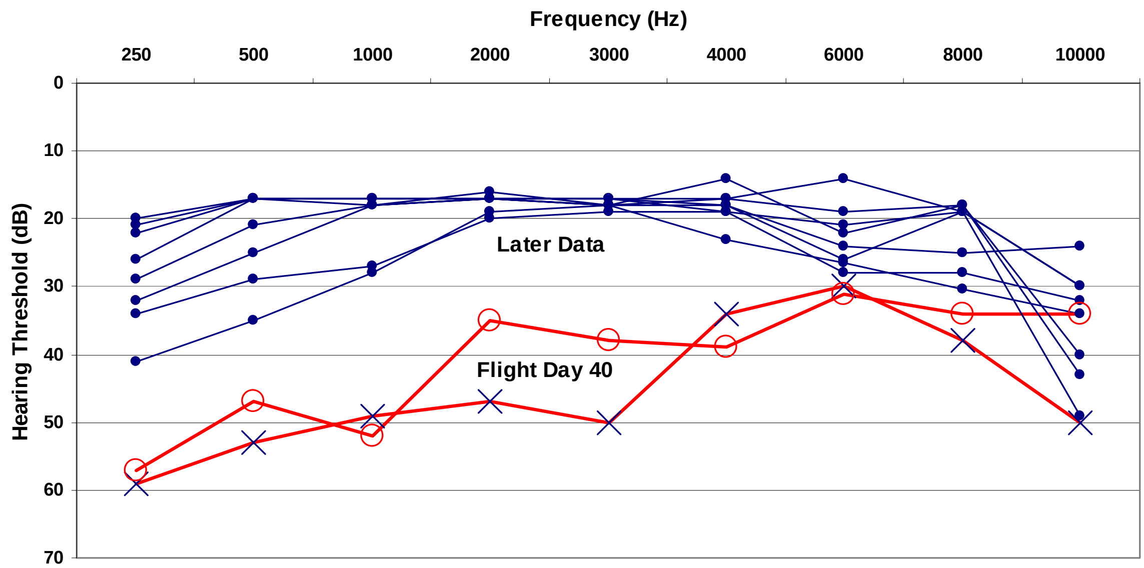



Figure 27 Transient Bilateral Low Frequency Hearing Loss

Another interesting observation was noted in a crewmember who demonstrated a bilateral low to mid frequency deficit during the first OOHA session that was inconsistent with pre-flight data, shown in Figure 27. No health problems had been reported before the test, but directed questioning with the study data led to the realization (or the admission) that the crewmember had symptoms of congestion, difficulty clearing ears and stated that "everything sounded like it was underwater." All complaints resolved after a week of decongestants, and a follow-up OOHA test was consistent with the "normal" appearing bow-tie. Because this subject's first test onboard was clearly abnormal, and it was prior to the use of offsets or baselining EarQ on the ground against pure-tone audiometry, concern remained until end-of-mission as to whether persistent changes had developed.

# 12. ANALYSIS/RESULTS

This remainder of this paper is a retrospective data analyses of data collected under the conditions, and using the methodology described above. It will examine the relationships between in-flight OOHA data and post-flight audiograms on 28 ISS crewmembers. Data from all the long-duration fliers aboard the ISS are included; as the entire applicable population is sampled, so no further discussion of sampling strategy or the applicability of the sample characteristics to those of the population are required. The data analyzed for this project was derived from two sets of measurements yielding discrete levels of measurement. That obtained on the ground using standard pure tone audiometry was expressed as multiples of 5 dB HL, so was considered less continuous than that obtained onboard using the EarQ software which reported changes of 1 dB (unreferenced). Additional analyses will assess interaction of other factors, such as nationality of crewmembers, location of landing (and hence first post-flight assessment) though these will be limited to descriptive review only.

Authorization for use of this data was granted by the Longitudinal Study of Astronaut Health Committee of NASA-Johnson Space Center's Space Medicine and Health Care Office, with the clear understanding that confidentiality will be completely respected and the data remain unattributable. Individually identifiable data was deleted or masked before being made available to others.

The central question addressed by this study was posed as “Are hearing test results on-board using the OOHA predictive of post-flight conventional audiometry outcomes?” The hypothetical position taken at the outset was that data from these two tests were the same, and the null hypotheses ($H_{0}$) was stated as: There are no statistically significant differences between crewmembers’ hearing thresholds for a given ear and frequency using the On Orbit Hearing Assessment (corrected) and conventional pure tone audiometry. Standard values for significance ($p<.05$) and for the probability of a type 1 error ($\alpha =.05$) were used.

The audiometric data from the first post-flight test was used without treatment; the values obtained using the , and no distinction was made between testing done in Star City, Russia or in either of the two U.S. configurations (older or newer). Data from each had to be entered into a Microsoft Excel spreadsheet by hand from printouts, including some of the Russian reports for which only graphical data with handwritten comments was available, requiring knowledge of Cyrillic. Recognizing the likelihood of a transcription error, this was done a second time for each crewmember, and the two spreadsheets compared for inconsistencies. For the purposes of this study, only the post-flight audiograms were required, but in the process of compiling all the data in one place, a fair amount of both pre- and post-flight information that had not been previously provided to the respective medical groups was distributed for interpretive and archival purposes.

The preparation of the OOHA data prior to statistical treatment was as follows. Raw data was taken directly from computer files saved by the crewmembers upon completion of each test and downloaded to the ground soon after completion. In addition to the EarQ data, each file included the crewmember's name, date and time the test was performed. The compilation of OOHA data over the last 5 years has resulted in a slowly growing database with potential differences in how files added to it were treated. Rather than risk data compromise resulting from inconsistent processing, the final dataset was rebuilt using raw original files, batch processing them only after the final subjects' data was available. Data for the raw values was then corrected using the offset values described above in the section titled Refinements of OOHA Interpretation. Initial analysis included an additional step in which the corrected data was then rounded up or down to the nearest 5 dB, but after discussion with a JSC epidemiologist, this step was dropped on the basis that it would be unnecessarily throwing away a degree of precision in my dataset.

The two datasets were then combined into a spreadsheet similar to that seen in Table 18, with entries for each ear of crewmembers that include their nationality and data from the two hearing tests, sorted by frequency. The offset-corrected OOHA values are denoted with an asterisk. Not shown in the table is data on the number of days between the last OOHA and the first postflight as well as the landing site.

Subsequent data analysis was done using the NCSS statistical package and was limited to descriptive statistics histograms, box-and whisker plots, the two-tailed Student's t-Test, and where necessary, it's non-parametric analog, the Wilcoxon Signed-Rank Test.

## THE DATASET

Table 18 U.S. Last OOHA and first Post-Flight audiogram data

| Crewmember ID Left / Right | Nationality | 500 Hz | | 1 kHz | | 2 kHz | | 3 kHz | | 4 kHz | | 6 kHz | | 8 kHz | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | OOHA* | Audiogram | OOHA* | Audiogram | OOHA* | Audiogram | OOHA* | Audiogram | OOHA* | Audiogram | OOHA* | Audiogram | OOHA* | Audiogram |
| **3580 L** | **US** | -1 | 0 | 1 | 0 | 1 | 10 | 6 | 15 | 11 | 25 | 37 | 60 | 26 | 55 |
| **3580 R** | **US** | -1 | 0 | 2 | 5 | 2 | 15 | 7 | 25 | 20 | 25 | 8 | 45 | 12 | 50 |
| **5642 L** | **US** | -1 | 5 | 2 | 10 | 2 | 5 | 7 | 25 | 8 | -10 | 16 | 20 | 14 | 5 |
| **5642 R** | **US** | -1 | 5 | 2 | 15 | 2 | 10 | 7 | 15 | 20 | 10 | 8 | 15 | 12 | 5 |
| **1046 L** | **US** | -1 | 10 | 2 | 5 | 2 | 0 | 7 | 0 | 9 | 0 | 6 | 5 | 10 | 5 |
| **1046 R** | **US** | -2 | 10 | 2 | 10 | 1 | 0 | 6 | 0 | 8 | 0 | 6 | 10 | 7 | 5 |
| **7616 L** | **US** | -2 | 0 | 1 | 0 | 2 | 5 | 6 | 10 | 9 | 0 | 19 | 15 | 23 | 0 |
| **7616 R** | **US** | -3 | 10 | 1 | 5 | 2 | 0 | 5 | 0 | 10 | 0 | 6 | 5 | 12 | 5 |
| **1797 L** | **US** | 1 | 10 | 20 | 0 | 19 | 5 | 10 | 5 | 12 | 5 | 7 | 30 | 12 | 25 |
| **1797 R** | **US** | -2 | 5 | 1 | 15 | 2 | 10 | 7 | 15 | 22 | 20 | 17 | 50 | 31 | 45 |
| **5896 L** | **US** | 16 | 5 | 12 | 5 | 3 | 10 | 6 | -5 | 13 | 10 | 30 | 25 | 26 | 35 |
| **5896 R** | **US** | 2 | 5 | 1 | 0 | -1 | 0 | 6 | 5 | 18 | 30 | 30 | 25 | 31 | 45 |
| **2846 L** | **US** | -1 | 5 | 2 | 10 | 2 | 15 | 6 | 10 | 8 | 5 | 14 | 15 | 6 | 20 |
| **2846 R** | **US** | 9 | 10 | 0 | 5 | 0 | 15 | 6 | 15 | 8 | 10 | 22 | 20 | 16 | 20 |
| **1858 L** | **US** | 2 | 5 | 2 | 5 | 1 | 0 | 6 | 0 | 7 | 15 | 5 | 10 | 3 | 20 |
| **1858 R** | **US** | -2 | 15 | 1 | 10 | 1 | -5 | 5 | 5 | 7 | 20 | 16 | 15 | 9 | 0 |
| **6508 L** | **US** | -2 | 5 | 1 | 15 | 1 | 10 | 5 | 0 | 7 | 5 | 0 | 0 | 4 | 30 |
| **6508 R** | **US** | -3 | 10 | 0 | 10 | 1 | 5 | 6 | -5 | 8 | 5 | 4 | -5 | 18 | 20 |
| **8176 L** | **US** | 10 | -5 | 11 | 0 | 4 | -5 | 7 | 10 | 9 | 30 | 14 | 10 | 13 | 5 |
| **8176 R** | **US** | -1 | 5 | 2 | -5 | 2 | -5 | 6 | 5 | 9 | 0 | 7 | 20 | 5 | -5 |
| **5018 L** | **US** | 22 | 10 | 14 | 10 | 3 | 10 | 8 | 5 | 10 | 20 | 23 | 15 | 9 | 5 |
| **5018 R** | **US** | 13 | 5 | 2 | 10 | 2 | 10 | 7 | 0 | 10 | 5 | 17 | 20 | 15 | 5 |
| **2230 L** | **US** | -1 | 0 | 0 | 10 | -1 | 5 | 3 | 15 | 6 | 30 | 16 | 10 | 10 | 25 |
| **2230 R** | **US** | 5 | 0 | 2 | 10 | 2 | 10 | 6 | 20 | 9 | 15 | 6 | 25 | 5 | 20 |
| **4726 L** | **US** | 9 | 0 | 4 | 0 | 2 | 10 | 17 | 10 | 9 | 20 | 7 | 20 | 13 | 20 |
| **4726 R** | **US** | -1 | 0 | 2 | 0 | 2 | 0 | 6 | 10 | 18 | 20 | 13 | 40 | 13 | 35 |
| **8290 L** | **US** | 12 | 5 | 12 | 5 | 20 | 5 | 9 | 25 | 6 | 35 | 12 | 40 | 10 | 25 |
| **8290 R** | **US** | -2 | 0 | 2 | 10 | 2 | 10 | 9 | 10 | 21 | 30 | 26 | 40 | 22 | 35 |
| **6997** | **US** | -1 | 0 | 2 | 0 | 1 | 5 | 5 | 0 | 9 | 5 | 8 | 25 | 5 | 20 |
| **6997 R** | **US** | 3 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 16 | 0 | 26 | 20 | 43 | 15 |

Data shown each crewmembers' left (L) and right (R) ears, with identity coded

Table 18 (cont) Russian Last OOHA and first Post-Flight audiogram data

| Crewmember ID Left / Right | Nationality | 500 Hz OOHA* | 500 Hz Audiogram | 1 kHz OOHA* | 1 kHz Audiogram | 2 kHz OOHA* | 2 kHz Audiogram | 3 kHz OOHA* | 3 kHz Audiogram | 4 kHz OOHA* | 4 kHz Audiogram | 6 kHz OOHA* | 6 kHz Audiogram | 8 kHz OOHA* | 8 kHz Audiogram |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **9707 L** | **Ru** | 6 | 5 | 1 | 5 | 0 | 0 | 4 | 5 | 6 | 0 | 9 | 15 | 5 | 30 |
| **9707 R** | **Ru** | -2 | 10 | 1 | 10 | 1 | 20 | 5 | 20 | 9 | 0 | 6 | 0 | 6 | 20 |
| **5225 L** | **Ru** | 11 | 10 | 11 | 15 | 2 | 10 | 6 | 10 | 9 | 25 | 14 | 30 | 14 | 15 |
| **5225 R** | **Ru** | 10 | 10 | 2 | 10 | 1 | 5 | 5 | 5 | 18 | 10 | 15 | 15 | 13 | 10 |
| **1256 L** | **Ru** | -9 | 5 | -2 | 10 | 0 | 10 | 3 | 10 | 7 | 15 | 16 | 30 | 19 | 35 |
| **1256 R** | **Ru** | 12 | 5 | 2 | 0 | 2 | 5 | 6 | 0 | 7 | 5 | 5 | 5 | 14 | 5 |
| **4233 L** | **Ru** | -1 | 0 | 2 | 0 | 2 | 0 | 7 | 0 | 9 | 0 | 5 | 0 | 4 | 10 |
| **4233 R** | **Ru** | -1 | 0 | 1 | 0 | 2 | 0 | 6 | 0 | 9 | 10 | 8 | 15 | 27 | 15 |
| **6965 L** | **Ru** | -7 | 5 | -1 | 15 | 0 | 5 | 4 | 10 | 8 | 10 | 8 | 30 | 13 | 65 |
| **6965 R** | **Ru** | 10 | 10 | 4 | 15 | 0 | 10 | 5 | 15 | 15 | 20 | 29 | 45 | 22 | 55 |
| **6992 L** | **Ru** | -1 | 10 | 2 | 5 | 2 | 5 | 6 | 20 | 9 | 30 | 6 | 35 | 4 | 35 |
| **6992 R** | **Ru** | 8 | 15 | 8 | 10 | 8 | 5 | 10 | 10 | 23 | 30 | 17 | 20 | 20 | 20 |
| **2339 L** | **Ru** | -2 | 10 | -1 | 40 | -1 | 50 | 5 | 25 | 6 | 15 | 8 | 10 | 6 | 15 |
| **2339 R** | **Ru** | -1 | 10 | 2 | 25 | 2 | 45 | 6 | 25 | 18 | 0 | 13 | 15 | 13 | 15 |
| **3301 L** | **Ru** | -6 | 5 | -2 | 5 | -1 | 5 | 3 | 5 | 7 | 0 | 17 | 15 | 26 | 20 |
| **3301 R** | **Ru** | -2 | 5 | 2 | 5 | 2 | 0 | 5 | -10 | 8 | 5 | 14 | 5 | 21 | 10 |
| **4506 L** | **Ru** | 7 | 5 | 3 | 10 | 2 | 15 | 6 | 10 | 9 | 10 | 5 | 15 | 17 | 0 |
| **4506 R** | **Ru** | 3 | 0 | 0 | 10 | 0 | 10 | 5 | 5 | 12 | 5 | 29 | 15 | 32 | 0 |
| **8230 L** | **Ru** | -2 | 0 | 3 | 5 | 1 | 0 | 5 | 0 | 8 | 5 | 8 | 20 | 12 | 5 |
| **8230 R** | **Ru** | -5 | 0 | -2 | 5 | -2 | 0 | 0 | 0 | 4 | 20 | 16 | 30 | 41 | 20 |
| **3463 L** | **Ru** | -2 | 5 | 1 | 5 | 1 | 0 | 5 | 5 | 6 | 20 | 8 | 10 | 8 | 20 |
| **3463 R** | **Ru** | -3 | 0 | 1 | 5 | 1 | 0 | 4 | 0 | 7 | 5 | 5 | 10 | 2 | 60 |
| **9595 L** | **Ru** | 18 | 15 | 16 | 5 | 3 | 5 | 8 | 0 | 11 | 5 | 4 | 10 | 32 | 15 |
| **9595 R** | **Ru** | 6 | 15 | 3 | 10 | 2 | 5 | 6 | 0 | 9 | 0 | 11 | 0 | 1 | 10 |
| **1264 L** | **Ru** | -5 | 10 | 0 | 0 | 0 | 0 | 5 | 0 | 8 | 5 | 6 | 15 | 40 | 20 |
| **1264 R** | **Ru** | -1 | 15 | 2 | 5 | 2 | 0 | 17 | 0 | 36 | 0 | 34 | 0 | 17 | 5 |
| **4072 L** | **Ru** | 5 | 0 | 1 | 5 | 1 | 0 | 5 | 0 | 7 | 25 | 4 | 10 | 18 | 10 |
| **4072 R** | **Ru** | -1 | 5 | 1 | 5 | 2 | 5 | 6 | 0 | 8 | 35 | 12 | 30 | 16 | 25 |

Data shown each crewmembers' left (L) and right (R) ears, with identity coded

## RESULTS

The dataset shown above in Table 19 was analyzed first from a descriptive perspective. The following Table 20 and Figure 28 contrast data from the two methods by showing their arithmetic means and standard deviations at each frequency for all crewmembers, appropriate measures given the continuous nature of the dataset. These conveys a sense of how well OOHA predicts the first post-flight audiogram (within 6 dB), but provides only a measure of central tendency without addressing dispersion.

| Mean hearing threshold (dB HL and OOHA) | Frequency (Hz) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 500 | 1000 | 2000 | 3000 | 4000 | 6000 | 8000 |
| corrected OOHA means | 2.1 | 2.9 | 2.0 | 6.2 | 10.9 | 13.1 | 15.5 |
| corrected OOHA Std. Dev. | 6.5 | 4.5 | 3.6 | 2.6 | 5.7 | 8.6 | 10.1 |
| Audiometric means | 5.5 | 7.2 | 6.6 | 7.2 | 12.0 | 18.9 | 20.0 |
| Audiometric Std. Dev. | 4.9 | 7.0 | 9.6 | 8.6 | 11.3 | 13.6 | 16.2 |
| Difference between means (Audiogram - cOOHA) | 3.4 | 4.3 | 4.5 | 1.0 | 1.1 | 5.8 | 4.5 |

Table 20 Means and Std Deviation of OOHA (corrected by offsets) and Audiogram

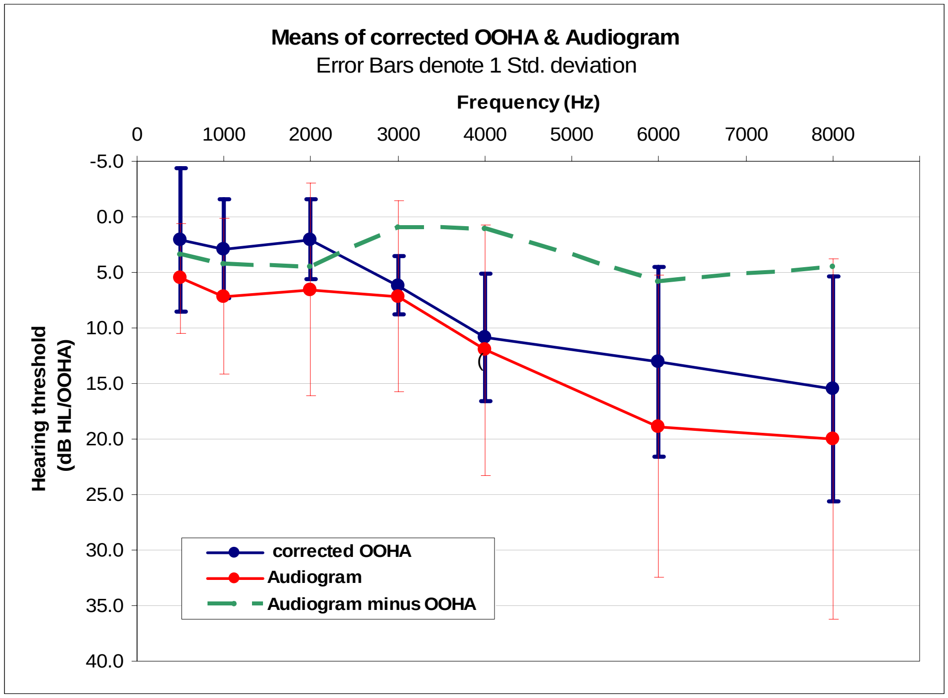



Figure 28 Means and Std Deviation of OOHA (corrected by offsets) and Audiogram

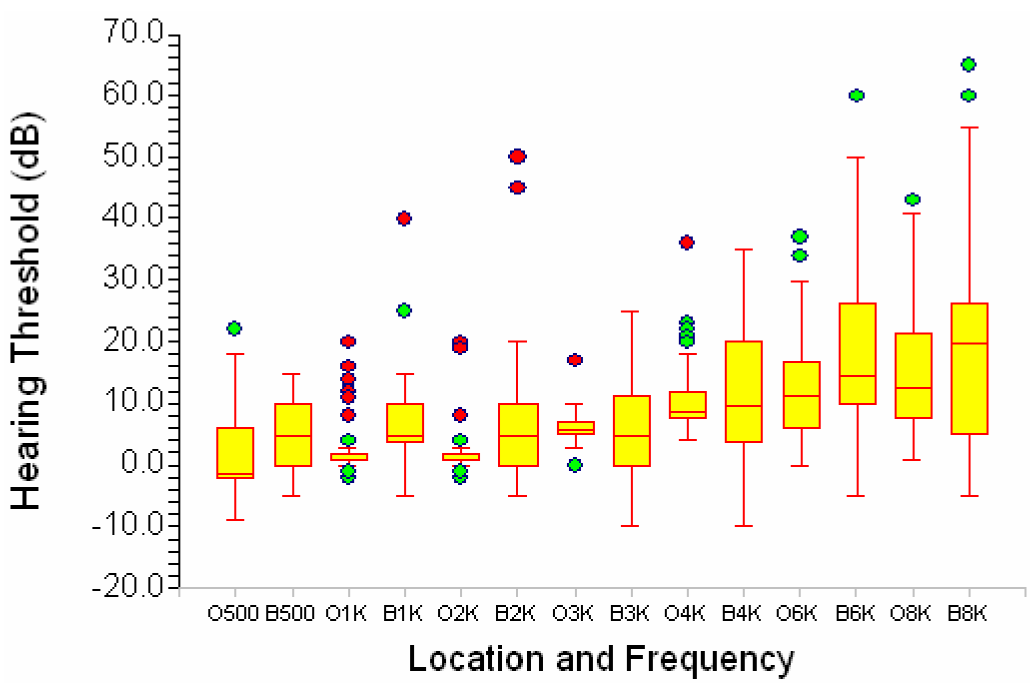



Figure 29 Box and Whisker plot comparison of corrected OOHA (O) and Booth Audiogram (B) data

Figure 29 displays a box-and-whiskers plot for the in-flight OOHA (O) and post-flight booth audiogram (B) tests at each frequency. Immediately apparent is that the 1, 2, and 3 kHz OOHA data appear different from the other frequencies in that it's much less dispersed, and the outliers are accentuated. This same tendency was noted in the raw data plots of all OOHA data shown in Figure 18, which shows a narrowed waist in the same 1-3 kHz range, with more variation at 500 Hz and above 4000 Hz, with progressive widening at 6000 and 8000 Hz.

This pattern of dispersion was initially confusing, but can be explained on the basis of several known phenomena. The first is the native frequency response of the healthy human ear, discussed above with reference to Table 2. Of the frequencies studied in OOHA and in standard audiometry (500-8000 Hz), the human hearing response is least sensitive at the low frequency and most sensitive in the midrange of 2-3000 Hz. Figure 30 is a graphic representation of the effects of two variables, age and pre-existing NIHL that can be expected to effect the outcome in a manner that was not controlled or corrected for in this study. The average age of this population of astronauts was 46 ± 5 yrs (s.d.) with a range between the youngest (37) and oldest (55) fliers of 18 years. As shown in the graphic on the left, on the basis of age alone, we expect variation in a group that spans two decades, more so in upper frequencies than lower. No attempt was made to distinguish astronauts or cosmonauts with NIHL from those without, but this condition is common in both groups, primarily due to their military and aviation backgrounds. As with aging, more variation is introduced in the higher than lower frequencies if this is not controlled.

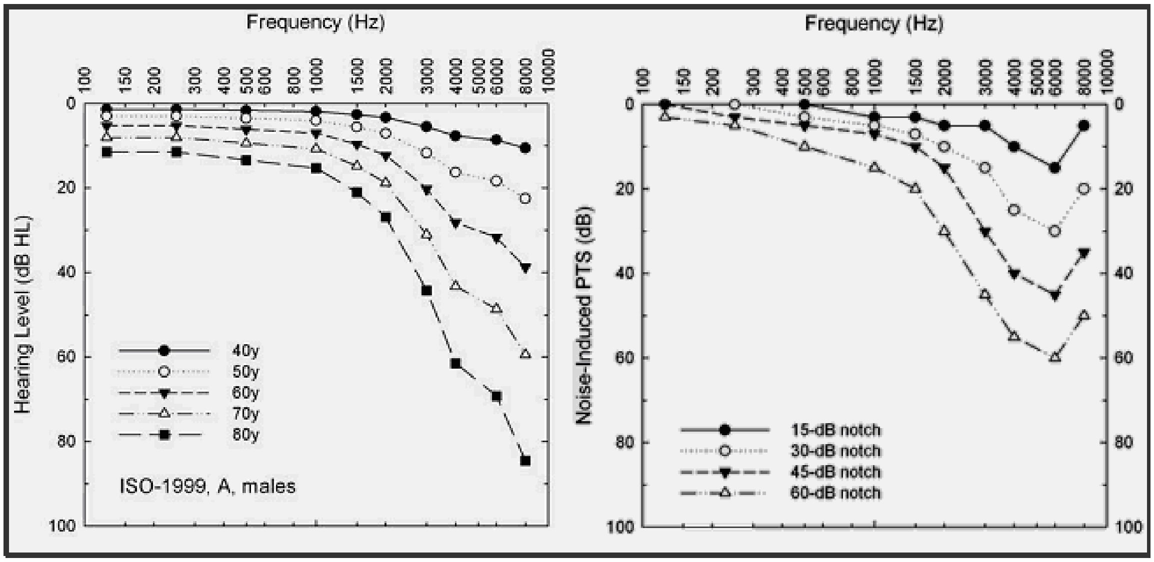



Figure 30 The effects of Aging (left) and Noise Induced Hearing Loss (right) on hearing response.[39]

Neither of these plots fully explains the higher degree of low frequency dispersion noted in the studies…the left side of the "bowtie". This is presumed to be an artifact of the testing environment, despite efforts to attenuate these frequencies both passively (Prophonics ear pieces) and actively (Bose X Active Noise Reduction headset), levels in these frequencies remain outside the standards for the enclosures in which the audiograms are performed. Audiograms are adjusted from SPL to HL by subtraction standards as published in the ANSI standard for audiometers,[40] standards which are based in part on the headphones through which the stimuli are generated and in part on the attenuation of the enclosures. For example, an enclosure in compliance with the ANSI S3.1[41] standard attenuates outside noise at 500, 1000 and 2000 Hz to less than 20, 27 and 28 dB SPL respectively. The Temporary Early Sleep Station, which functions as the booth, has noise levels of 40, 44 and 38 dB SPL at these frequencies.

## PAIRED T-TESTING

Data from the two tests was further analyzed using NCSS at each frequency, with the following outcomes.

For the lowest frequency, **500 Hz**, the means were within 3.5 dB. The differences were normally distributed, so the t-Test was appropriate. The null hypotheses (Ho), stating that the means of the two test were equal (OOHA = Booth), was **rejected** in favor of the alternate hypotheses that OOHA ≠ Booth, and that OOHA < Booth, and did so with a low p-value (less than .05) and high power (greater than 0.8).

At **1000 Hz**, the means were within 4.3 dB. The differences were NOT normally distributed, so T-test was inappropriate. The non-parametric analog of the t-Test, the Wilcoxon Signed Rank test was used to **reject** the Ho in favor of the hypotheses that OOHA ≠ Booth, and that OOHA < Booth  with a low p-value (less than .05).

For **2000 Hz**, as with the 1000 Hz data, the differences were not normally distributed, so using the Signed-Rank Test, Ho was **rejected** in favor of the hypotheses that OOHA ≠ Booth, and that OOHA < Booth, with a low p-value (less than .05).

The means for the **3000 Hz** data were within 1 dB, and the differences normally distributed, so the t-Test was appropriate. Ho was accepted, but with a high P value and low power.

The means of the two tests at **4000 Hz** were within 1.1 dB, and with normally distributed differences, so the t-Test was appropriate. Ho was accepted, again with a high P value and low power.

For **6000 Hz**, the means were within 5.8 dB, and the differences were normally distributed. On the basis of t-Test data, Ho was **rejected** for in favor of the hypotheses that OOHA ≠ Booth, and that OOHA < Booth, with a low p-value (less than .05) and high power (greater than 0.8).

Lastly, for **8000 Hz**, the means were within 4.5 dB, and the differences are normally distributed, so the t-Test was appropriate. Ho was **accepted**, but with a borderline p-value (less than .065) and low power (greater than 0.8).

In summary, the null hypotheses was rejected at each frequency when criterion of an adequate power (>.80) and statistical significance (<.05) were stipulated.

## ADDITIONAL QUESTIONS

In addition to the above analysis, strictly comparing the in-flight and post-flight test, the data were also reviewed from three perspectives to gain insight into how the variables inherent in the current process might be affecting the outcomes. With the central question of the study answered, these were cursorily reviewed at the descriptive level.

### Time Between In-flight and Post-flight Testing

As stated above, significant variation exists in the time between the last OOHA test onboard the ISS and the first post-flight audiogram. This is primarily a function of busy scheduling aboard the ISS, as in most cases crewmembers had a post-flight audiogram between days 2 and 4 after return, however 2 had to wait for 12 days, and another for 9 days before testing. On average, 62 days elapsed between the two tests ± 40 days (s.d.), with a range of 146, spanning from 17 to 163 days. In Figure 31, the 8 crewmembers who had an elapsed time between the two tests of less than 30 days, where separated from the remainder of the group. Meaningful differences between these two groups do not seem apparent, though it remains intuitively dissatisfying to compare data points from the two tests that are not as close as possible in time.

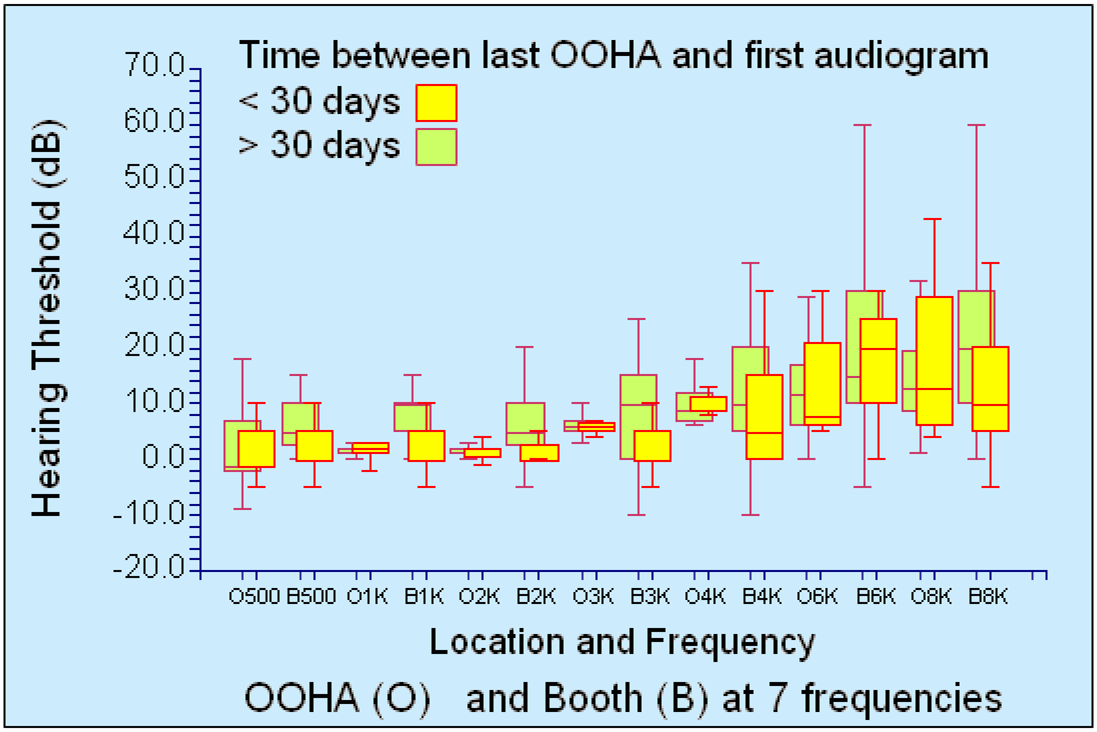



Figure 31 OOHA and Audiometry (Booth) by elapsed time between tests

**Nationality**

14 Russian cosmonauts and 15 U.S. astronauts have lived aboard the ISS as long-duration fliers. Figure 32 depicts how subjects from these two groups differed in terms of the measures used. For the purposes of this study, two groups do not appear to be meaningful different in terms of the distribution of their last in-flight test, their first post-flight test or the difference between the two.

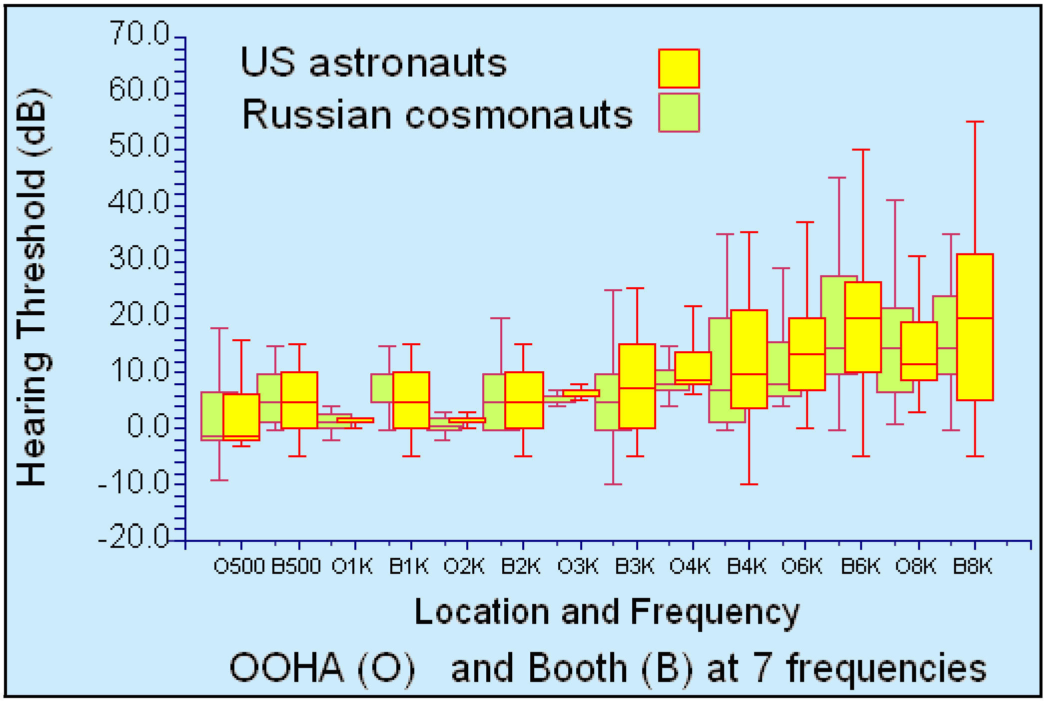



Figure 32 OOHA and Audiometry (Booth) by Nationality

**Return Vehicle and Landing Site**

15 crewmembers have landed at each of the recovery sites in Russia (Soyuz) and the U.S. (Shuttle). Those who returned on a Shuttle landed in Florida 2-4 days after leaving ISS, depending on weather conditions, whereas those returning on a Soyuz came home the same day they left the ISS. Noise levels aboard Soyuz are unknown, whereas those of the Shuttle are similar to the loudest areas in the ISS (see above). Additionally the Soyuz entry profile is more aggressive, normally peaking at 4.5 G's (though in one instance, 3 crewmembers were subjected to up to 9 G for a brief period) directed from back-to-front with significant decelerations generated by opening shock of the parachute and at impact with the earth. The Shuttle entry is gentler with peak of only 1.2 G, either back-to-front or head-to-toe (depending on whether or not recumbent seating is used) and lands gently like a jetliner. Once home, aircraft involved in the recovery and transport of the crews differ, translating into noise exposures that differ in terms of intensity and duration, and are followed by recovery times of different lengths prior to the first post-flight audiogram. Testing takes place optimally on R+3 days in both sites,

but uses different hardware and protocols. Mechanisms whereby these might directly or indirectly interact with hearing could include differential fluid shifting, microtrauma, in addition to the obvious differences in the development and resolution of temporary threshold shifts related to noise exposures. Figure 33 suggests that crewmembers who landed in Russia, regardless of nationality, had audiograms with less sensitive hearing in the upper frequencies than those landing in the U.S. No attempt was made to confirm with comparison to pre-flight tests to ascertain if this represented a decrement from a pre-flight baseline. Future analysis of the dataset might undertake to study this in the interest of protecting crewmembers' hearing from post-landing noise insult that could confound assessments aimed at understanding in-flight hazards.

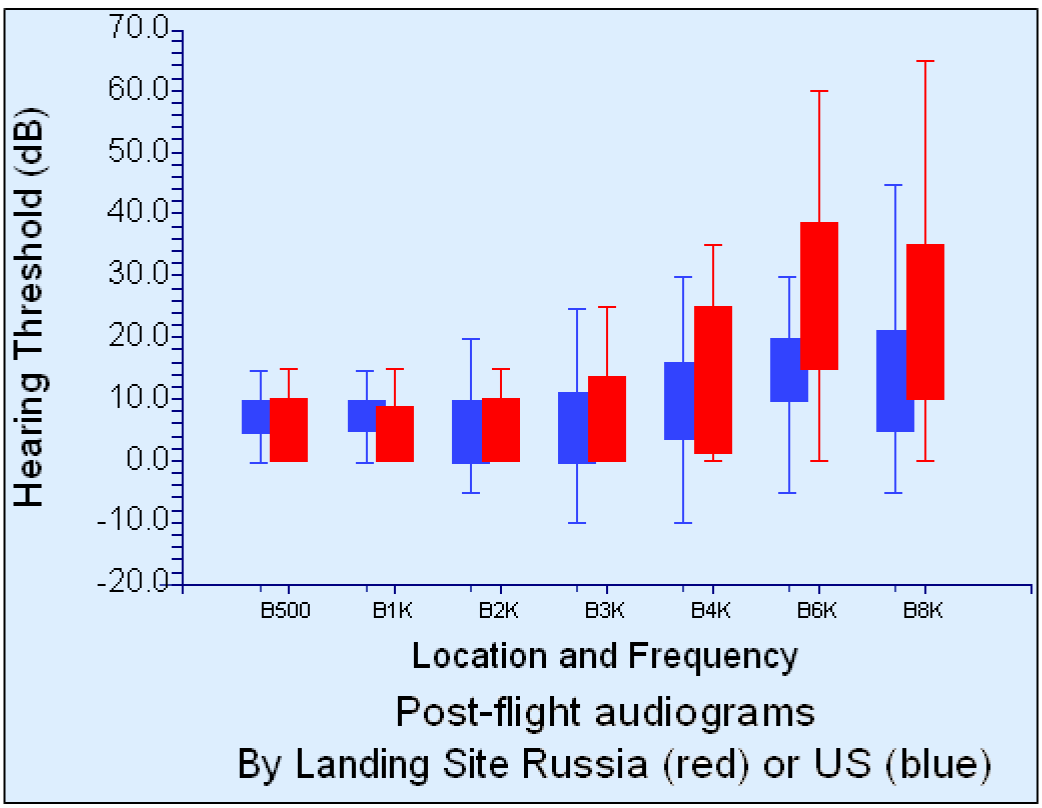



Figure 33 Post flight audiograms by landing location

# 13. FUTURE DIRECTIONS

As described above, since Expedition 8 (2004), raw OOHA data has been corrected at each frequency using the offsets derived from the previously described 10 subject-study comparing EarQ to standard audiometry, described on page 66. Unlike audiometric data, which is by convention in multiples of 5 dB, both EarQ data and the offsets are in units of 1 dB. Using the ascending method to establish the hearing threshold, as is done both for testing both in-flight and on the ground, a subject with a hearing threshold of 22 dB at a given frequency, can actually end up with a recorded value of 22 with OOHA. Since stimuli from an audiometer are in multiples of 5, the same subject will be tested at 20 dB (which he cannot hear) and at 25, (which he can hear), and a value of 25 dB will be recorded. Obviously this is rounded up by 5, rather than simply rounded to the nearest 5, as has been done with raw data. An option to further refine the OOHA data, which continues to consistently under-predict post-flight audiometry, is to round this data *up* to the nearest 5.

| Mean hearing threshold (dB) | Frequency (Hz) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 500 | 1000 | 2000 | 3000 | 4000 | 6000 | 8000 |
| corrected OOHA rounded *up* | 3.9 | 5.5 | 4.5 | 8.4 | 12.9 | 15.3 | 17.7 |
| Audiogram | 5.5 | 7.2 | 6.6 | 7.2 | 12.0 | 18.9 | 20.0 |
| Difference (Booth minus cOOHA) | 1.6 | 1.6 | 2.1 | -1.2 | -0.9 | 3.6 | 2.3 |

Table 21 Comparison of Audiometric Means with OOHA data corrected, then rounded UP

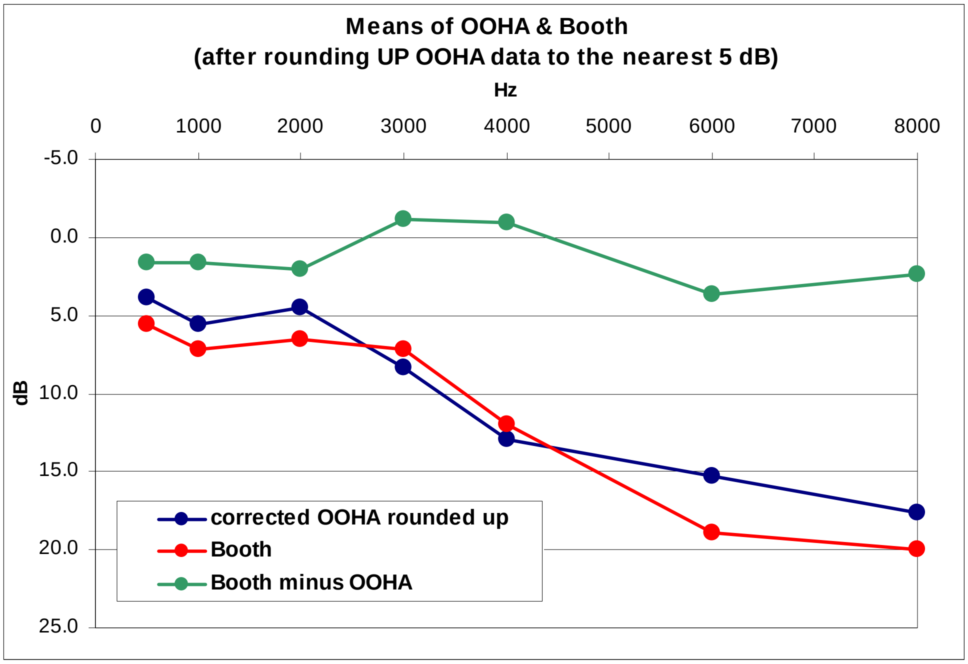



Figure 34 Comparison of Audiometric Means with those obtained with OOHA data corrected, then rounded UP

This option has not been analyzed in detail, but simply demonstrates how the means were affected. Descriptive graphics are shown in Table 20 and Figure 35 for comparison with Table 21 and Figure 34 above. The mean EarQ values, when corrected and then rounded up to the nearest 5 dB, are 2-2.5 dB closer to those obtained with audiometry when compared to those that are corrected then rounded up or down to the nearest 5 dB. It should be appreciated that these are likely trivial differences, well within overlapping margins of error for the two techniques.

# 14. CONCLUSION

Since the inception of the On-Orbit Hearing Assessment, it's been clear that this test is not the same as a pure-tone audiogram, the gold standard of hearing tests. A good deal of effort to date has gone into pushing the test closer to these guidelines, and an important question might be "How good is good enough."

When the author first began working on hearing issues for astronauts at JSC, the "state of the art" was typified by the Apollo era enclosures for testing in which audiograms were administered by paramedics and reviewed by staff who juggled these responsibilities with many others, and referred out into the community for most pathology. While this was not unacceptable, it was by no means represented the cutting edge people expect of NASA. Today, hearing health for flight crew is managed by a dedicated audiologist onsite with a fully modern diagnostic suite, whose experience includes managing patients in specialized (e.g. military, aviation) environments.

Similarly, 8 years ago acoustic predictions on the International Space Station, all still in pieces on the ground, were drifting higher and higher above specifications, and beyond flying ear muffs and foam earplugs, no plan for protecting or evaluating the individual hearing health of astronauts existed. Today, the 13$^{th}$ crew is aboard the ISS, and of the 12 long-duration crews flown so far, none have returned with sustained meaningful hearing loss. Importantly, some of those crewmembers were diagnosed with significant changes in-flight using OOHA, and were advised to limit exposures in ways that perhaps spared them a permanent decline in their hearing. On that basis alone, the adage "close enough for government work" comes to mind.

However, the results of this analysis suggest that while OOHA data is similar to standard pure-tone audiometry, it varies in important ways. The hypothesis of this study was that at all 7 frequencies tested, OOHA data and audiometry data would be essentially the same. As used today, OOHA tends to under-predict hearing thresholds, though by less than 5 dB for each frequency.

Intervening noise exposures are an obvious confounder, as the time between the last OOHA and the first post-flight audiogram averaged ~2 months and ranged between 17 and 163 days. In-flight noise, as well as noise related to aircraft used in the recovery and transport of crewmembers could play a role. Auditory physiology, peripheral or central, could also be postulated to change as a result of fluid shifts as crewmembers move from microgravity to the 1-G environment. Analysis of OOHA data at several frequencies is also suspect due to many outliers, and at most frequencies, OOHA data varies less than standard audiogram data. These observations are almost certainly artifacts of the software, hardware or procedure crewmembers use to generate the data. Additionally, the post-flight audiometric data was collected using three different methodologies and hardware complements. The assumption was made that no meaningful differences existed between data from the one Russian and two U.S. setups, almost certainly not true. Each of these could potentially qualify the findings and represent a weakness of this study.

Doubtlessly, the shortcomings of the OOHA technique need to be kept in mind for those managing the hearing health of astronauts and cosmonauts living aboard the ISS, especially as the environment changes with added modules, a larger crew complement, and different payloads. While it appears that newer modules will be closer to specifications and overall noise levels will decline, monitoring strategies of both the environment and the crewmembers should be continued, since both personal dosimetry data and OOHA demonstrates that noise levels are high enough to cause changes in more sensitive crewmembers.

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Stephen Hart was born on November 14, 1957 to John Alexander and Cynthia Sawyer Hart. He grew up in Galveston County, attended college and medical school, and post-graduate training in Texas. He is currently employed at NASA's Johnson Space Center, where he works as an operational Flight Surgeon supporting Astronauts flying aboard the Space Shuttle and the International Space Station.

**Educational Background**

1970-75 Clear Creek High School, League City, TX.

1975-79 Baylor University, Waco, TX. undergraduate study in anthropology and pre-med curriculum.

1979-82 University of Texas at Austin. BA in Anthropology with physical and cultural emphasis, as well as pre-med curriculum.

1984-86 University of Texas, Master's candidate in Microbiology, focusing on retroviral amplification in mouse mammary tumor virus, and on the pathogenic mechanism of bacterial endotoxins at the molecular level.

1986-90 Texas A&M College of Medicine, College Station/Temple, TX.

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