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Status - International Space Station (ISS) Crewmembers' Noise Exposures

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ABSTRACT

Environmental noise in space vehicles, caused by onboard equipment and crew activities, has generated concerns for crew health and safety since early U.S. space missions. The International Space Station (ISS) provides a unique environment where acoustic conditions can be monitored while crewmembers from the U.S. and their international partners work and live for as long as 6 to 12 consecutive months. This review of acoustic dosimetry data collected to date reveals that the noise exposure limits of NASA's stringent noise constraint flight rule have been exceeded in 41% of these dosimetry measurements since ISS Increment 17 (2008), with undefined impacts to crew. These measurements do not take into account the effects of hearing protection devices worn by the crew. The purpose of this paper is to provide an update on ISS noise exposure monitoring approaches and hearing conservation strategies that include acoustic dosimetry data collected since the ISS Increment 55 mission (April 2018). Future directions and recommendations for the ISS noise exposure monitoring program will also be presented, including research initiatives aimed at better defining the impact of ISS noise on crew health and performance.

1. INTRODUCTION

This paper presents a summary and an assessment of the acoustic dosimeter data collected on the International Space Station (ISS) since Increment 55 mission (April 2018). It includes crew-worn noise exposure monitoring data collected during the daytime (work- L_{EQ16}) and nighttime (sleep-L_{EQ8}) periods and environmental noise exposure data, both collected on ISS. Crew-worn and environmental monitoring is performed by the trained crewmembers onboard ISS, with technical support provided by ground personnel. An overview of ISS' noise exposure monitoring and hearing conservation strategies along with details and descriptions of ISS modules have been previously discussed and presented elsewhere,[1-5].

Acoustic monitoring measurements made onboard the ISS are performed and the data is used to ensure a safe working and living environment for the crew, as well as to determine when actions are required in order to reduce the noise onboard the ISS. Details of the requirements used to monitor onboard ISS are briefly explained in the next section and in detail elsewhere,[5].

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2. REQUIREMENTS

Acoustic monitoring requirements are based on several ISS requirements documents and in the ISS Noise Level Constraint Flight Rule (JSC Flight Rule B13-152),[6]. The ISS Noise Level Constraint Flight Rule is based on 16-hour crew-worn work-period equivalent noise exposure level (LEQ16) and 8-hour crew-worn sleep-period equivalent noise exposure level (LEQ8) measured by the ISS acoustic dosimeters. The flight rule uses a 3-dB equal exchange rate and the World Health Organization noise guidelines for ground conditions,[7]. The Noise Hazard Inventory (NHI) was developed to use with this flight rule. The NHI is an inventory of noise levels and duration of exposures that can represent specific ISS locations and crew activities not already covered under specific crew procedures or operational controls. The NHI was first used during ISS increment 36 (July 2013) and has been used ever since. The NHI is reviewed and updated for every ISS increment.

3. NOISE MONITORING HARDWARE AND CREW TRAINING

3.1 Monitoring Hardware

Acoustic dosimeters (ADs) are instruments used to measure noise exposure over extended periods of time. There are three calibrated acoustic dosimeters onboard ISS at all times. Currently the Svantek 102A+ Acoustic Monitor model is being used on ISS. This Acoustic Monitor has been used since ISS Increment 53 (November 2017). See Figure 1. This Acoustic Monitor is a COTS product that meets Type 1 standards for accuracy per international standards for SLMs (IEC 61672-1:2013). This hardware is used as an acoustic dosimeter and a sound level meter. Detail hardware descriptions have been previously discussed and presented elsewhere,[5].

Figure 1. Svantek 102A+ Acoustic Monitor.

The crewmembers wear the ADs for a continuous 24-hour period to measure typical exposures to noise on ISS. The device is stored in a pocket or clipped to the crewmember's clothing. The microphone has a separate clip allowing placement on the collar or lapel so that it is in close proximity to the crewmember's ear. The AD is also deployed at static locations in ISS to collect noise exposure levels in predetermined locations. The data transfer and data download processes are outlined in Figure 5. As part of nominal on-orbit operations, the AD runs for approximately 40+ hour periods (24 hours for crew-worn and 16-18 hours for static locations). The battery change-out occurs during the 24-hour crew-worn sessions (right before the sleep-period) and also prior to the static location measurements. The collected AD data is then transferred to the Space Station Computer (SSC) via a USB, then to the server followed by a transfer to the Mission Control Center (MCC) and finally to the Acoustics Office for analysis, exposure assessment, data interpretation and reporting.

3.2 Crew Training

Environmental monitoring is one of the key tasks required by all crewmember onboard ISS in order to ensure a healthy and safe environment. On-orbit crew-time is a high demand asset for all operational tasks. Many environmental monitoring tasks are very time consuming and efficient procedures are used to minimize crew-time. The acoustic dosimetry monitoring task is performed by a trained crewmember. This crewmember deploys the dosimeters (either crew-worn or at a static location), downloads the data from all three dosimeters into the SSC and later stows the dosimeters back into the kit. This activity is performed once every other month. All crewmembers are trained to perform

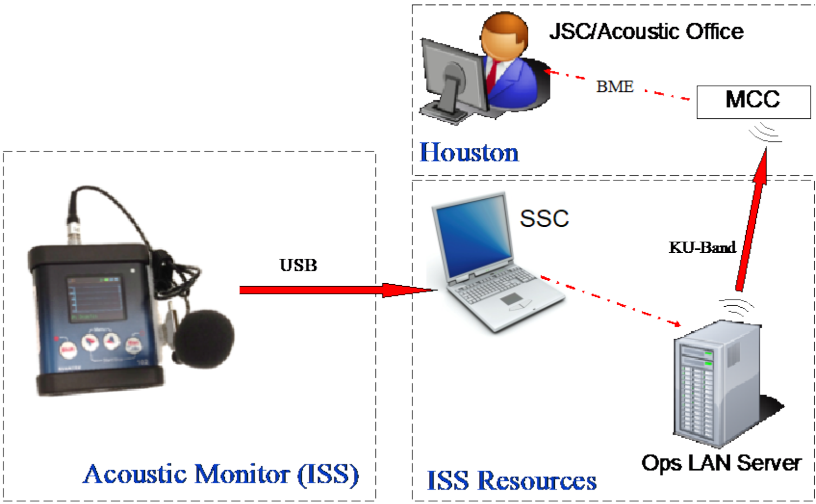

Figure 2. Acoustic Dosimeter Data Download Process.

AD measurements prior to flight. Training includes nominal operation of the AD hardware, software handling and operational and malfunction procedures. The crewmembers are also trained on how to use the different types of hearing protection devices (HPDs) available to them onboard ISS. The hearing protection devices (passive and active) that are available to the crewmembers include: disposable foam earplugs, custom (molded) earplugs, and active noise reduction (ANR) headsets,[8-10]. Several sizes of the disposable foam earplugs are also provided to and worn by the crewmembers, at their discretion, and then trashed.

4. DATA AND ANALYSIS

4.1 Acoustic Dosimetry

Acoustic dosimetry data is collected from crew-worn and static location measurements which is divided into several days (dependent on the number of crewmembers available during the Increment): (Days 1-2) crew-worn measurements and (Day 3) static measurements followed by the data download activity. The frequency of these activities is performed every other month, as previously mentioned. For the crew-worn activity, the crewmember dons the AD and starts the measurement before breakfast during the day of the planned activity. The crew-worn session concludes immediately before post sleep activities on the following day. The crew-worn session includes both, daytime and sleep-time periods (24-hours).

4.1.1 Crew-worn measurement

The crewmembers don ADs before breakfast on the day of the acoustic dosimetry activity for the duration of 24 hours to record the workday (LEQ16) and sleep- (LEQ8) period data. Post-sleep crew-worn data are deleted from the analysis reducing the total duration time period to approximately 24-hours or less. ISS noise exposure levels have been measured using a 3-dB time-intensity exchange rate, consistent with criteria recommended by the National Institute of Occupational

Safety and Health (NIOSH)[11] and the U.S. Department of Defense, and it has also been adopted internationally for use in hearing conservation programs,[12]. In this paper, all data, including the plots, will be presented using the 3-dB exchange rate unless otherwise stated.

An example of crew-worn AD logged data can be seen in Figure 3. The graph has been divided into work- (daytime) and sleep- (night-time) periods. The noise hazard level (85 dBA), the 16-hour LEQ limit (72 dBA) – directed to wear HPD, and the 60 dBA limit – crew recommended to wear HPD;

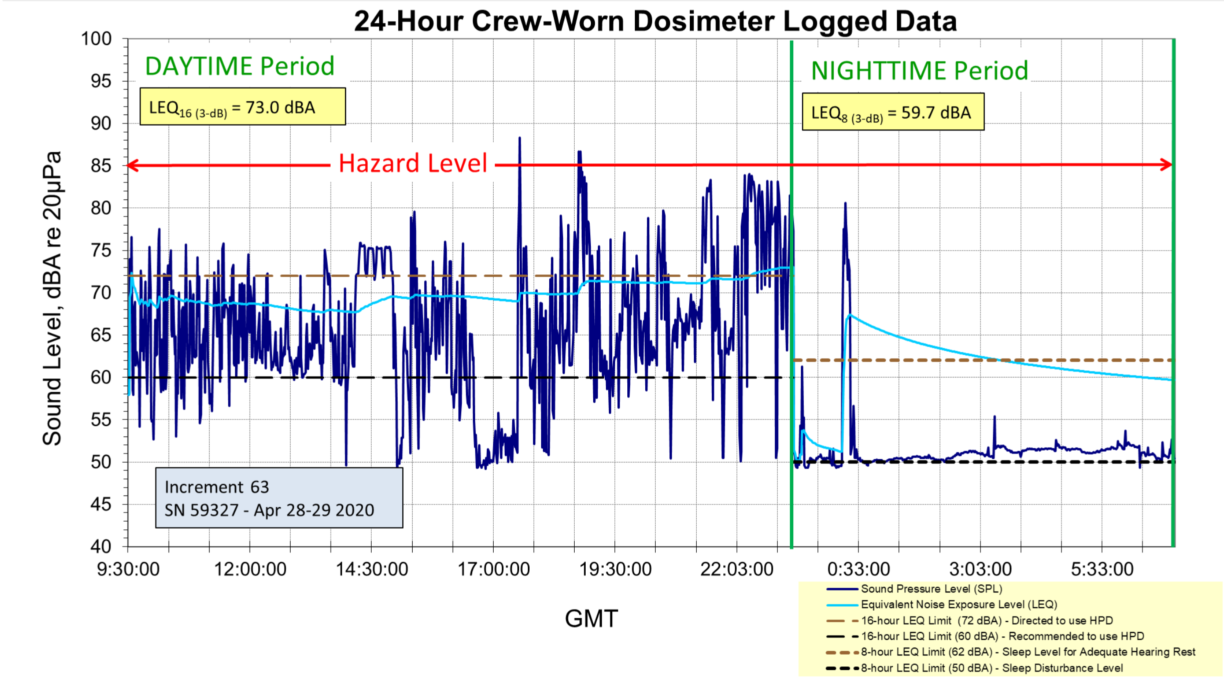

Figure 3. Crew-worn Acoustic Dosimeter Logged Data.
SOURCE: ISS Acoustic dosimeter data collected on April 2020, Increment 63.

have been identified in the graph. For this particular dataset, the equivalent noise exposure level (LEQ16) during the work-period was measured at 73.0 dBA. Based on the Noise Level Constraint ISS Flight Rule this crewmember was required to don HPD during noisy crew activities since the levels were above the 16-hr LEQ limit (72 dBA). However, use of HPDs was also required since the LEQ16 was above the noise hazard level at GMTs 17:32 and 18:47 during the work-time period. However, the flight surgeon can always recommend at any time to don HPD whenever the levels exceed 60 dBA based on the individual needs of the crewmember and the level and duration of the noise exposure and they are always available to the crewmembers on ISS, if needed. During the sleep-time period, the equivalent noise exposure level (LEQ8) was 59.7 dBA, above the sleep disturbance level (50 dBA) but below the sleep level for adequate hearing rest (62 dBA).

Crew-worn acoustic dosimetry data on ISS have been collected since November 2001 (Increment 1). To date, the overall noise levels on ISS have improved and decreased from the higher levels first measured during the early years on ISS. However, there seems to be some ISS increments noisier than others, for example, as you can see in Figure 4; in 2009 (Increments 18-21), in 2010 (Increments 23-25), in 2012 (Increments 30-32), and more recently in 2018 (Increments 54-56) the noise levels are much higher than the other years. These elevated levels can be caused by dust clogged fans, noisy exercise equipment, experiment hardware, or specific noisy crew activities, etc. The high noise levels can increase the risks for degraded voice communications, and habitability (possible disruptions to crew sleep, interference with crew performance, etc.). After the clogged fans were cleaned, noise levels returned back to nominal levels and these were verified during the next acoustic measurement activities,[1-3]. General improvements in acoustic levels have also been observed on ISS due to noise mitigation efforts performed in the Russian Segment, as well as the

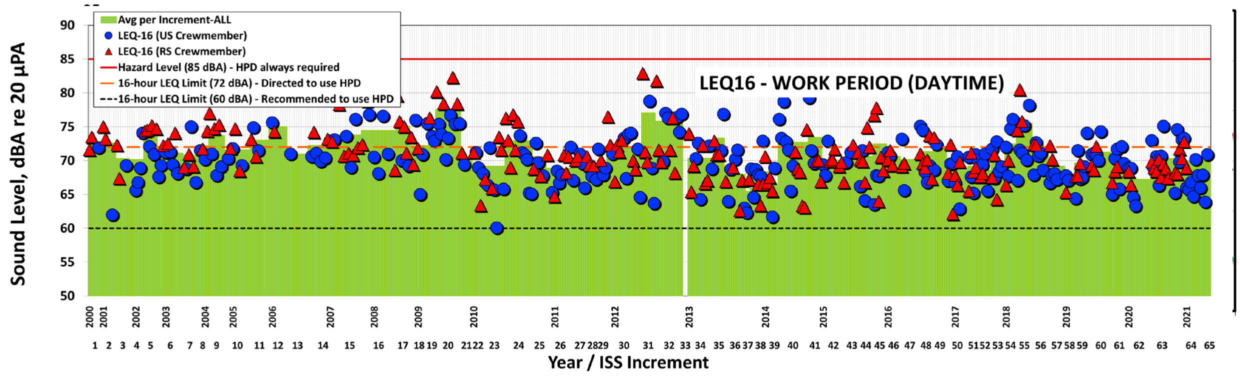

Figure 4. LEQ16 Crew-Worn Acoustic Dosimetry vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

addition of quieter modules and crew quarters as previously reported and discussed elsewhere,[13]. We have also observed the reduction of high noise levels associated with crewmembers running at high speeds in the treadmill since the installation of acoustic blankets in the vicinity of the treadmill. Since the addition of the acoustic blankets in 2016 (Increment 49), crew noise exposure to hazardous levels (85 dBA) associated to running on the treadmill have been decreased and eliminated. See Figure 5.

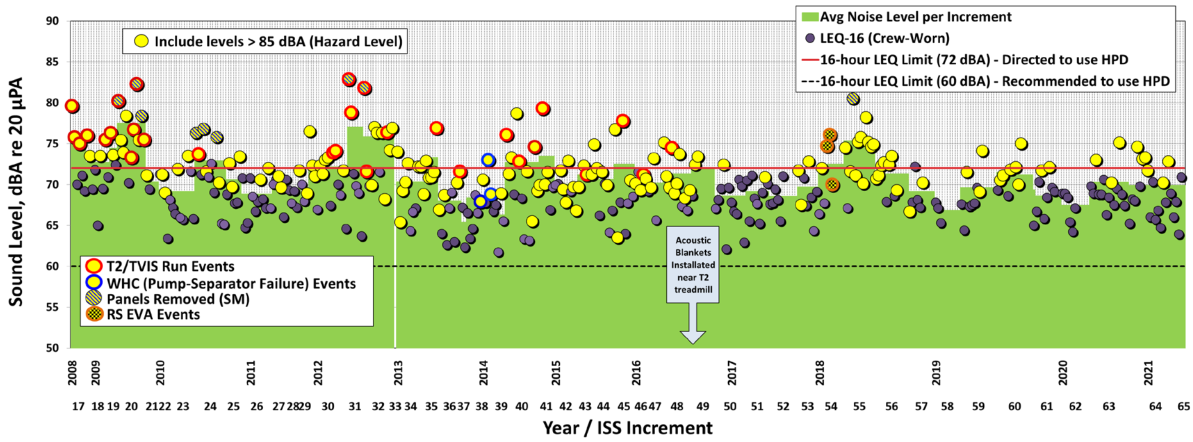

Figure 5. LEQ16 Crew-Worn Acoustic Dosimetry vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from July 2008 (Inc. 17) through March 2021 (Inc. 64).

The noise exposure level for the work-time period was dependent on where the crewmembers spent most of their time working and/or leisure and what activities or tasks they were performing. Crewmembers can either work in the Russian segment modules or in the U.S. segment modules (see Figures 6 and 7 for a data distribution of LEQ16 during work hours in the US and RS segments). As we compare the data distribution (LEQ16) from previous reporting years to the current reporting

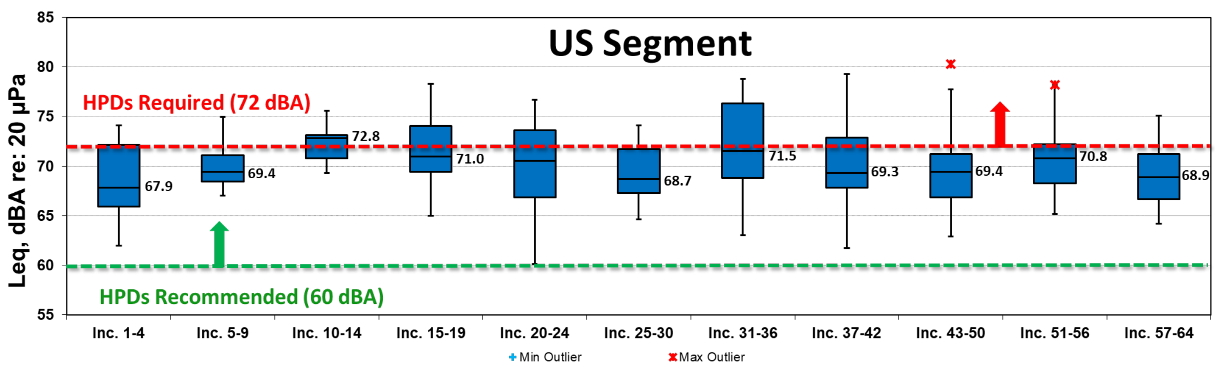

Figure 6. LEQ16 Crew-Worn Acoustic Dosimetry (US Segment) vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

years (ISS increments 57-64), the noise levels experienced by the crewmembers mainly working in the US segment were slightly lower (Figure 6: 70.8 dBA in Increments 51-56 vs. 68.9 dBA in Increments 57-64). The noise levels experienced by the crewmembers mainly working in the RS segment were also slightly lower from the previous reporting year (Figure 7: 69.5 dBA in Increments 51-56 vs. 68.7 dBA in Increments 57-64).

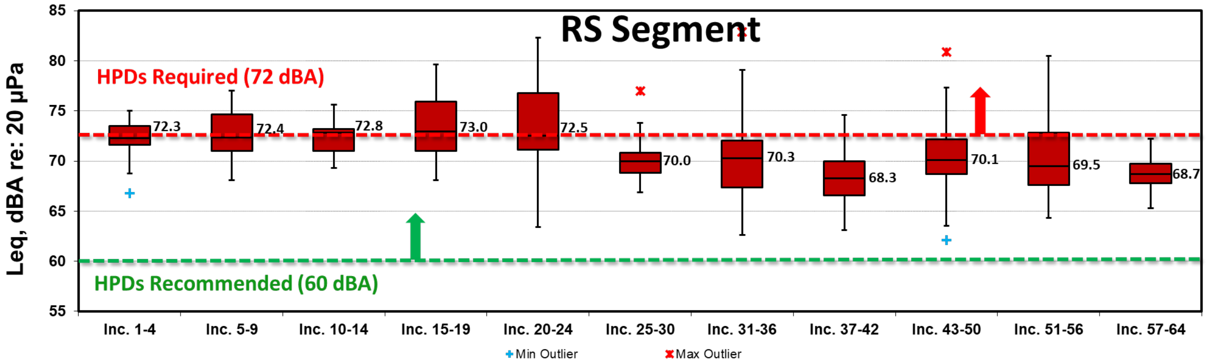

Figure 7. LEQ16 Crew-Worn Acoustic Dosimetry (RS Segment) vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

The crew sleep stations in ISS were designed to provide a personal, private area for a crewmember to rest, sleep, and work and also for personal activities. There is a total of six permanent sleep stations: two Russian sleep stations (kayutas) located in port and starboard locations in the Russian segment of the Service Module and the other four sleep stations (crew quarters) are located in the U.S. segment in Node 2. The ISS crew quarters (CQ) provide a quiet area for recovery (reduced acoustic stimulus to the ears) from daytime noise exposure levels. Noise levels in the RS segment crew sleep stations (kayutas) have previously (early ISS years) been a concern due to high noise levels; see Figure 8. Initially, the kayutas were designed with a porthole and a door, but the doors were removed on-orbit during Increment 1. Doors were later provided and installed to the kayutas,

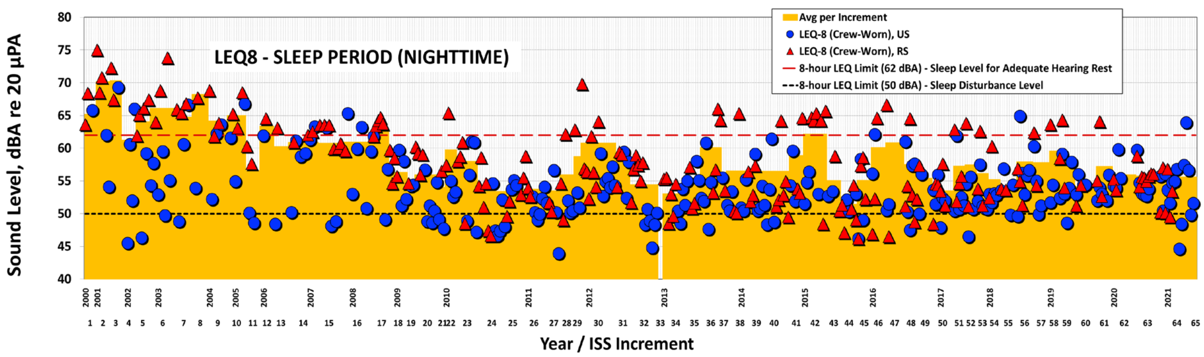

Figure 8. LEQ8 Crew-Worn Acoustic Dosimetry vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

along with other noise control mitigations added to Russian Segment hardware components and the noise levels were reduced in the Service Module. However, high noise levels still exist on certain occasions and it has been associated to crew activities and crew preferences. Some crewmembers will tend to sleep with the door opened, others with the fan operating in high speed, etc. When the crew sleep station door is opened, the module's environmental noise level can affect the levels inside the sleep station (impacting crew noise exposure during the sleep-time period). Different types and sizes of hearing protection devices are always available to crewmembers on ISS, if needed for sleep. The bottom-line is that both, U.S. and Russian sleep stations are adequately quiet when the doors are closed, providing auditory rest, and do not increase the risk for hearing loss. As we compare the data distribution (LEQ8) from previous reporting years, the noise levels experienced by the crewmembers sleeping in the US and RS segments were slightly the same from the previous reporting year, no significant differences were noted (Figure 9: 52.5 dBA in Increments 51-56 vs. 53.9

dBA in Increments 57-64) and (Figure 10: 54.6 dBA in Increments 51-56 vs. 55.5 dBA in Increments 57-64).

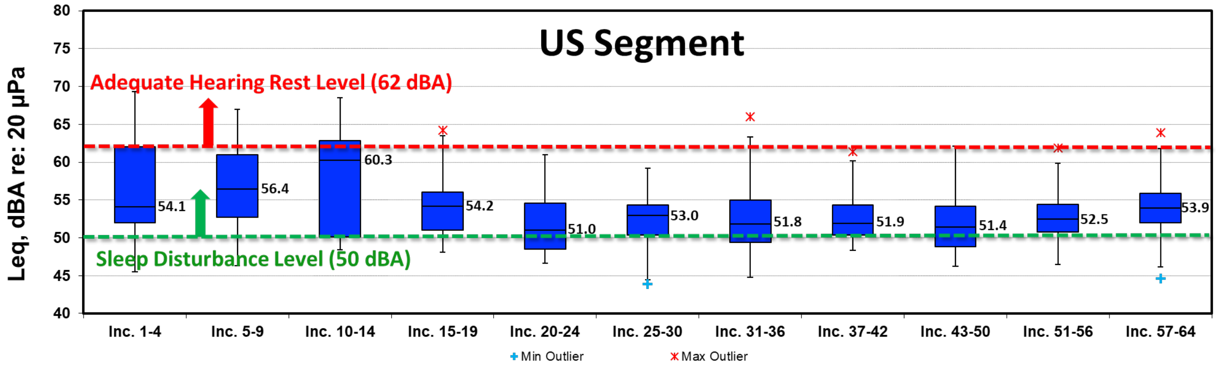

Figure 9. LEQ8 Crew-Worn Acoustic Dosimetry (US) vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

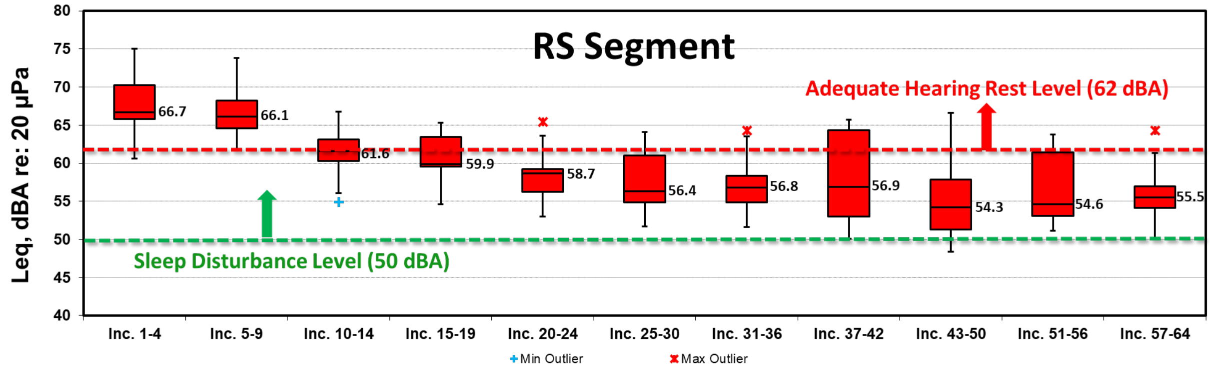

Figure 10. LEQ8 Crew-Worn Acoustic Dosimetry (RS) vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

After reviewing the dosimetry data collected on ISS since Increment 1 (2000), we can see that the data trend of the average work-time period noise exposure level for the crewmembers working either on the US or RS segments have remained consistently stable and below the 16-hour L_{EQ} limit (72 dBA) since the ISS assembly was completely built (after 2011). However, there were several ISS increments (2012: 30-32, 2014: 38-41, and most recently 2018: 54-57) where the average level was slightly above the HPD required limit. (See Figure 11). The dosimetry data collected to date

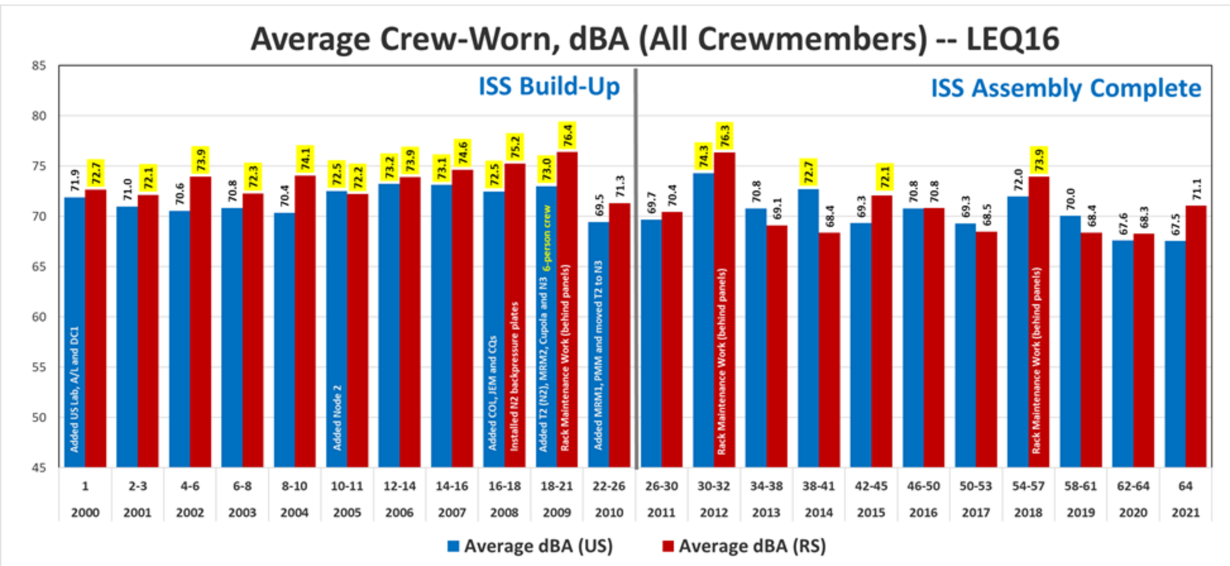

Figure 11. LEQ16 Crew-Worn Acoustic Dosimetry vs ISS Increment and Year.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

also indicates that the noise hazard exposure limit (85 dBA) have been exceeded approximately 41% of the time since ISS Increment 17 (2008), with undefined impact to crew. This measurement does not consider the effects of any HPDs worn by the crew. See Figure 12.

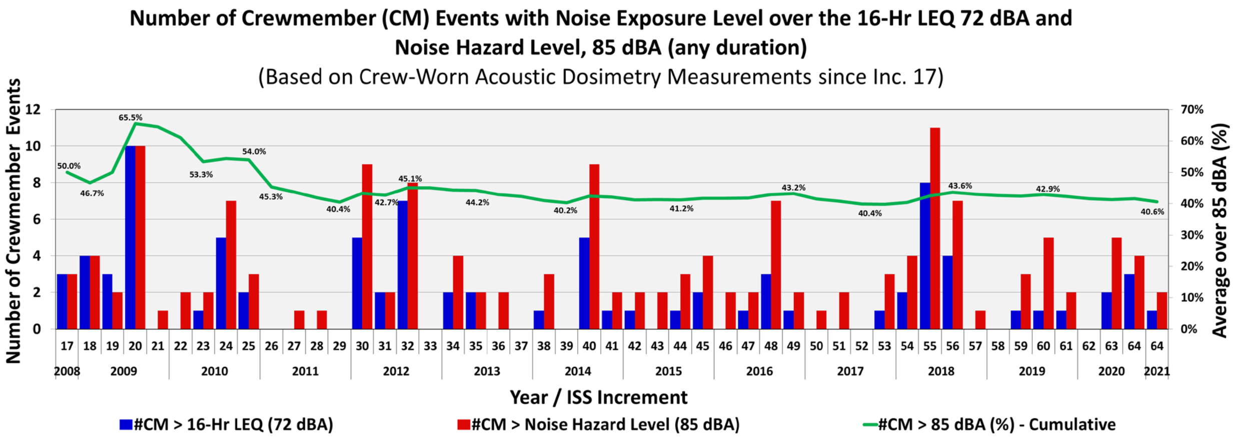

Figure 12. Acoustic Dosimeter Crew-Worn Measurement with Noise Exposure Level over 72 and 85 dBA
SOURCE: Acoustic dosimeter data collected from October 2010 (Inc. 17) through March 2021 (Inc. 64).

When reviewing the work period crew noise exposure data, we were able to identify approximately 93% of the noise sources that contributed to the crewmember's noise exposure levels when exposure levels were above the noise hazard level (85 dBA). This identification process was accomplished with the help of the Operations Planning Timeline Integration System (OPTimIS) tool, crew feedback and on-orbit noise surveys. OPTimIS is a tool used by flight controllers for mission planning and crewmember scheduling using an integrated timeline,[14-15]. We classified these identified events into six categories/activities: operations, maintenance, communications, exercise, crew activities and unknown events. See Figure 13. Based on the preliminary results, there are more high noise events related to crew activities, such as; mealtime, pre/post sleep activities, morning/after-

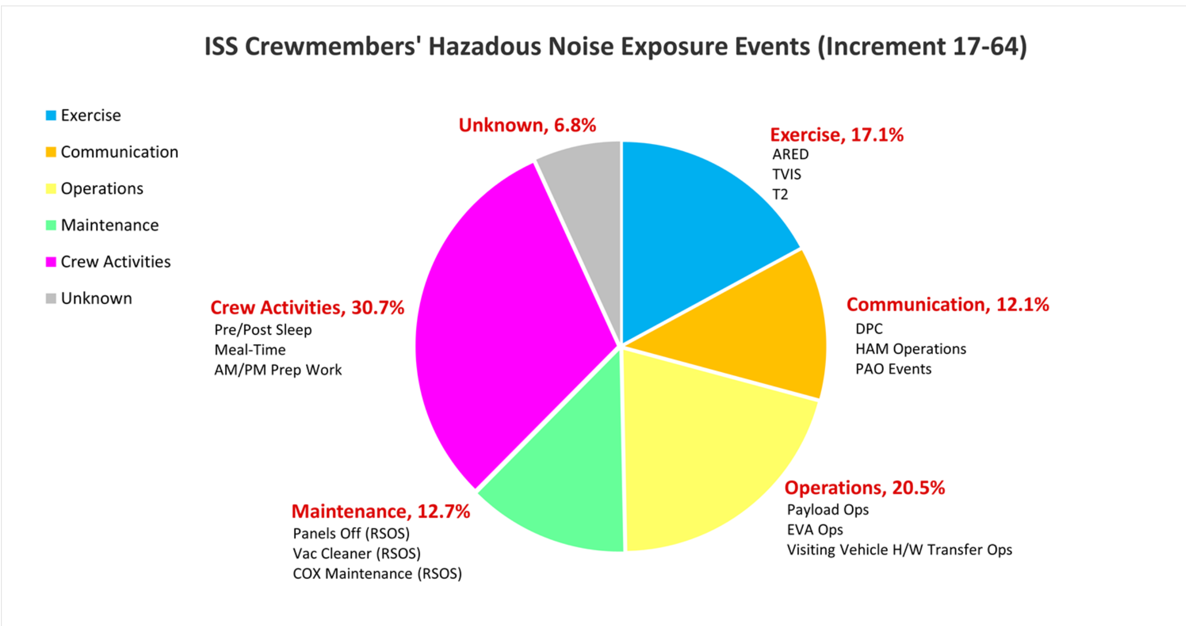

Figure 13. Distribution of noise exposure events during work-period hours (levels above 85 dBA).
SOURCE: Acoustic dosimeter data collected from July 2008 (Inc. 17) through March 2021 (Inc. 64).

noon prep work, and conferences (approximately 43%). These events are not necessarily hazardous but can increase the risks for degraded voice communications, and habitability in ISS. However, these findings are still very preliminary, further investigation is ongoing and will be reported in the future.

As we look into the dosimetry data during the nighttime period, we can see that the data trend of the average sleep-time period noise exposure level (LEQ8) for the crewmembers sleeping either on the US or RS segments have remained consistently stable and below the Sleep Level for Adequate Hearing Rest Level (62 dBA) but above the Sleep Disturbance Level (50 dBA). However, the exposure levels during the sleep-time period for US crewmembers have been lowered most of the time than the levels experienced by the RS crewmembers. See Figure 14.

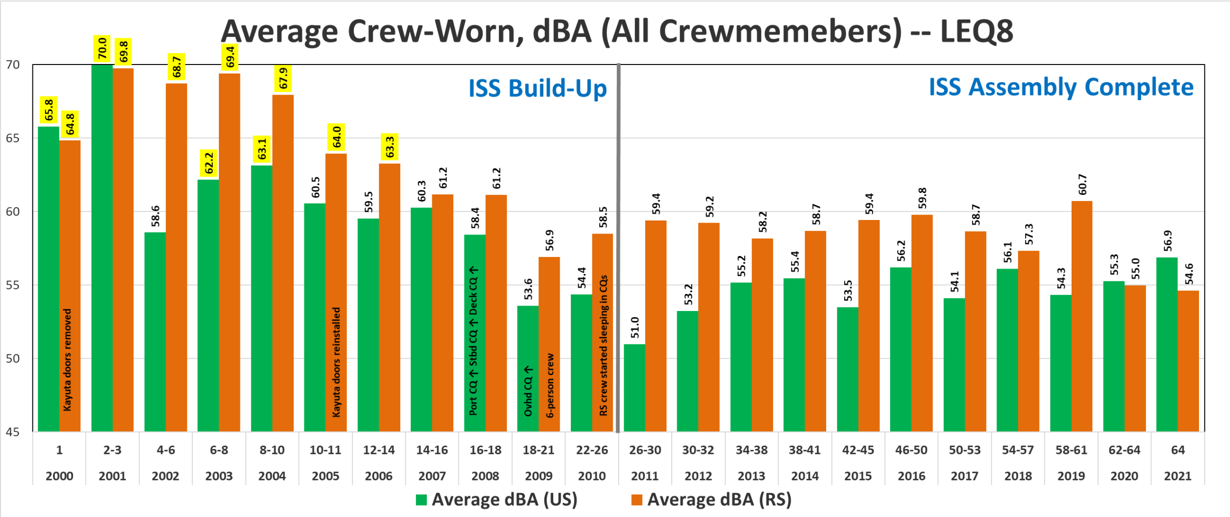

Figure 14. LEQ8 Crew-Worn Acoustic Dosimetry vs ISS Increment and Year.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

4.1.2 Static location measurement

After completing the 24-hour crew-worn measurements for all crewmembers, the dosimeters were then deployed at predetermined locations for approximately 16-18 hours for area monitoring. The ADs were cycled through each of the ISS pressurized modules or areas of concern, such as areas near exercise equipment, fans, etc. to help determine high noise levels which can affect crew noise exposure and help better understand the acoustic environment. These locations are defined in a "static-deploy plan" by the JSC Acoustics Office and uplinked to the crew on ISS before the activity is performed. Measurements have been recorded in various locations in the U.S. and Russian segments and the data trend analysis is performed.

The data-logging feature of the dosimeters have been proven to be an effective tool for assessing and evaluating continuous and intermittent sources of noise in the environment by providing time-stamped acoustic data and helping with assessment of the acoustic environment in ISS. If the measured noise level during a crew activity or task exceeds 72 dBA and is not documented in the crew procedures, then it will be included in the NHI and applicable hearing protection requirements will be documented for future crew task or activities.

5. CONCLUSIONS

This paper described the ISS noise exposure monitoring program as well as an assessment of AD data collected since April 2018 (Inc. 55) to March 2021 (Inc. 64). These data provided trending information with regards to the acoustic environment experienced by the ISS crewmembers during the work and sleep-time periods. Overall, there has been a substantial improvement in the acoustical environment on ISS since Increment 55 (2018). The measurements collected to date were highly dependent on the activities/tasks the crew performed during their stay on ISS, whether occupational or leisure, as well as environmental conditions on ISS. The identification of the hazardous noise events has also provided valuable information with regards to the crew's noise exposure assessment.

This information will help with the identification of crew activities or hardware performance that will require further investigation. The ISS crewmembers have several modules in which they can spend time working during the day and sleeping during the night. The acoustic monitors currently used on ISS have the capability to measure and log dosimetry data and many other acoustic parameters. As we continue to use OPTimIS and the crewmember's timeline is better understood with time stamps corresponding to the completed activities, we will be able to continue to associate the measured acoustic data with the actual crew activities and provide a better noise exposure assessment for our crewmembers.

6. FUTURE DIRECTION

Future acoustics research for long-term exploration missions should aim to relate ISS noise exposures to both, auditory and also non-auditory effects of noise, especially how acoustic conditions can affect hearing sensitivity, human performance, sleep and crew health on the ISS. We need to better understand how we can consider measuring noise in ISS with a subjective response. Considering using psychoacoustic factors such as masking level differences and loudness,[16]. Nevertheless, non-auditory health effects have been addressed as possible disruptions to crew sleep, interference with speech intelligibility and communication, possible interference with crew task performance, and possible reduction in alarm audibility; but they have not been formally investigated, with the exception of speech intelligibility and alarm audibility which controls on ISS are in place to minimize the effects. We need to further investigate if there are quantifiable non-auditory effects detected by the ISS crewmembers who live and work in space for up to 6-12 consecutive months and see how we can adapt these findings to future long-term exploration missions. To reiterate, non-auditory health effects are defined as "all those effects on health and well-being which are caused by exposure to noise with the exclusion of effects on the hearing organ"[17].

6.1 Noise and Sleep Disturbance

Research studies have shown that noise exposure has physiological effects, such as disruption to normal sleep cycle (longer to fall asleep, shortens deep and REM stages, daytime fatigue, insomnia, etc.), as well as next day after-effects (excessive daytime sleepiness, tiredness, reduced productivity, poor job performance, and possible risk of accidents, etc.),[18-22]. Sleep disturbance is influenced by characteristics of the noise itself (low-frequency, intermittent or even tonal) and also on the individual being exposed, such as age (as people get older, they spend less time in the deep sleep, Stages III-IV). Shiftwork is also a risk factor for sleep disturbance and other health effects. The biggest industrial catastrophes, such as the Three Mile Island, Bhopal, Chernobyl and Exxon Valdez disasters, have occurred during the night shift. The shift schedules, fatigue and sleepiness were cited as major contributing factors to each incident,[23]. The equivalent crew noise exposure levels (LEQ8) experienced by the ISS crewmembers during the sleep time period ranged from 42 to 75 dBA, as seen on Figure 8. The sympathetic nervous system (vegetative arousal) is activated within 45-55 dBA and the awakening threshold is around 60 dBA, which is within the noise levels experienced by the ISS crewmembers.

6.2 Noise and Annoyance

Guski has proposed that noise annoyance is partly due to acoustic factors and partly due to personal and social moderating variables. Annoyance brings feelings of disturbance, aggravation, dissatisfaction, concern, bother, displeasure, harassment, irritation, and nuisance, discomfort, etc., some of which combine to produce the adverse reaction,[24]. According to the literature, annoyance is a response to noise rather than an auditory perception of it. It is mentioned that noise is more likely to be annoying if it's random in nature, high pitched, and it occurs during the sleep time period. Annoyance is classified as subjective; noise is likely to be annoyance if one perceives to be not necessary. Data suggest that the threshold for annoyance is from 50-55 dBA. The background work-time period noise levels experienced by the crewmembers on ISS are way above the threshold level for annoyance. According to Persson-Waye et al., prevalence of annoyance and disturbed concentration and rest was significantly higher among the persons exposed to low-frequency noise as compared to controls,[25-26]. Similarly, low-frequency noise was rated as significantly more annoying than broad-band noise at the comparable A-weighted sound pressure levels,[27]. Likewise, loudness and tonality both have a significant influence on noise-induced annoyance,[28]. Noise sensitivity as compared to personal factors, had the most significant role to noise annoyance,[25-26, 29-30]. Melamed et al. also reported that use of hearing protection devices was related to noise exposure level, but more so to high noise annoyance,[31].

6.3 Noise and Human Performance

The effects of noise on human performance depends on the actual task which is being performed by the worker and it can affect each worker in a different way. This effect can be explained by the "Inverted-U Model" also known as the Yerkes-Dodson Law, where peak performance is achieved when workers experienced a moderate level of pressure. But when they experience too much or too less, their performance declines,[32]. In this model, noise is considered to act as a biological stressor. The nature of the noise: sound level, spectrum, temporal (continuous or intermittent), speech intelligibility, etc. also effects human performance; as well as personal/individual factors of the worker. The effects on human performance can be perceived in tasks that require reading comprehension, attention span, problem solving, memorization, and even communication with co-workers and or alarm audibility. Several studies have been performed where the nature of the noise has affected human performance and productivity. For example, Kyriakides and Leventhall reported that low-frequency noise can affect productivity, and Persson-Waye et al. and Bengtsson et al. also reported that low-frequency noise can interfere with proof-reading tasks,[33-36]. It was also found that intermittent and treble noise reduces human performance,[37-38]. With regards to background speech intelligibility and noises from human activities, researchers have found that it impairs short-term memory, working memory tasks, and reasoning ability, and also disrupt tasks representing office work,[39-46].

Most of these non-auditory health effects described above can be described in a stress model as shown in Figure 15. This figure shows the principal reaction scheme used in epidemiological noise research for hypothesis testing,[47]. It simplifies the cause–effect chain, that is: sound – annoyance (noise) – physiological arousal (stress indicators) – (biological) risk factors – disease – and mortality (the latter is not explicitly considered in the graph). The mechanism works "directly" through synaptic nervous interactions and "indirectly" through the emotional and the cognitive perception of the sound. It should be noted that the "direct" pathway is relevant even at low sound levels particularly during sleep, when the organism is at its nadir of arousal. The objective noise exposure (sound level) and the subjective noise "exposure" (e.g. annoyance) may serve independently as exposure variables in the statistical analyses of the relationship between noise and health end points. There is a need to systematically assess causal factors, so that recommendations can be provided to mission planners, habitat designers, and trainers for exploration missions. Need to know if noise exposure is a causal factor or an environmental contributor to non-auditory health effects such as, sleep loss, annoyance, and human performance during long-duration space missions.

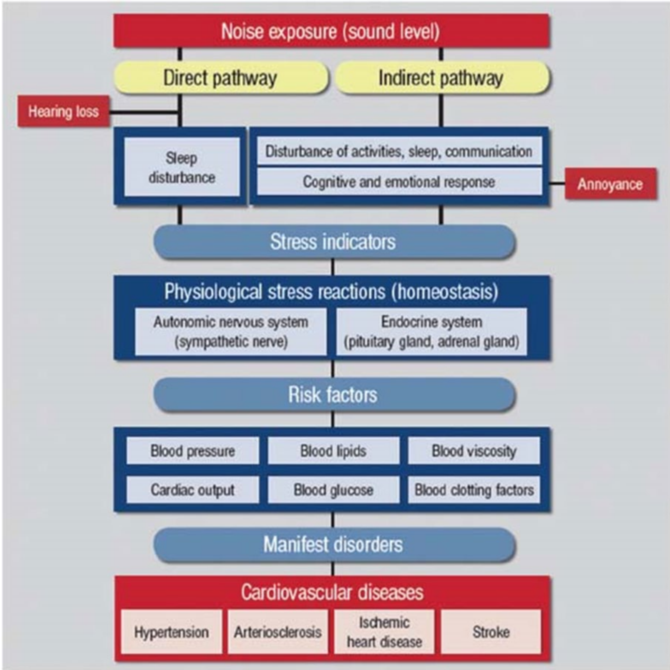

Figure 15. Noise Effects Reaction Scheme.
SOURCE: Adapted from Babisch, 2002.

7. ACKNOWLEDGEMENTS

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