Status: Crewmember Noise Exposures on the International Space Station

José G. Limardo[1] and Christopher S. Allen[2]
NASA - Johnson Space Center, Houston, Texas, 77058

Richard W. Danielson[3]
Baylor College of Medicine, Houston, Texas, 77030

The International Space Station (ISS) provides a unique environment where crewmembers from the US and our international partners work and live for as long as 6 to 12 consecutive months. During these long-durations ISS missions, noise exposures from onboard equipment are posing concerns for human factors and crewmember health risks, such as possible reductions in hearing sensitivity, disruptions of crew sleep, interference with speech intelligibility and voice communications, interference with crew task performance, and reduced alarm audibility. It is crucial to control acoustical noise aboard ISS to acceptable noise exposure levels during the work-time period, and to also provide a restful sleep environment during the sleep-time period. Acoustic dosimeter measurements, obtained when the crewmember wears the dosimeter for 24-hour periods, are conducted onboard ISS every 60 days and compared to ISS flight rules. NASA personnel then assess the acoustic environment to which the crewmembers are exposed, and provide recommendations for hearing protection device usage. The purpose of this paper is to provide an update on the status of ISS noise exposure monitoring and hearing conservation strategies, as well as to summarize assessments of acoustic dosimeter data collected since the Increment 36 mission (April 2013). A description of the updated noise level constraints flight rule, as well as the Noise Exposure Estimation Tool and the Noise Hazard Inventory implementation for predicting crew noise exposures and recommending to ISS crewmembers when hearing protection devices are required, will be described.

Nomenclature

CQ	=	*crew quarter*
dB	=	*decibel*
dBA	=	*A-weighted decibel*
BME	=	*Biomedical Engineer*
ECLSS	=	*Environmental Control and Life Support System*
ER	=	*exchange rate*
GGR&C	=	*Generic Groundrules and Constraints Document*
GMT	=	*Greenwich Mean Time*
HPD	=	*hearing protective device*
IDRD	=	*Increment Definitions and Requirements Document*
IMV	=	*inter-module ventilation*
Inc.	=	*ISS Increment*
ISS	=	*International Space Station*
JEM	=	*Japanese Experiment Module*
JSC	=	*Johnson Space Center*
$L_{A,24}$	=	*24-hour equivalent noise exposure level*
$L_{A,PK}$	=	*highest instantaneous noise level*

[1]Deputy, Acoustics Office, Habitability and Human Factors Branch, 2101 NASA Parkway/Mail Code: SF3.
[2]Mgr, Acoustics Office, Deputy, System Management & Integration Branch, 2101 NASA Parkway/Mail Code: SF2.
[3]Mgr for Audiology/Hearing Conservation, Johnson Space Center, 2101 NASA Parkway/Mail Code: SD3.

$L_{A,T}$	=	*noise exposure level, actual crew wear times, T*
L_{EQ}	=	*equivalent noise exposure level*
L_{EQ8}	=	*equivalent noise exposure level (sleep-time period, 8 hours)*
L_{EQ16}	=	*equivalent noise exposure level (work period, 16 hours)*
L_{EQ24}	=	*equivalent noise exposure level (full-day, 24 hours)*
Lmax	=	*highest sampled sound level during the instrument's run time*
Lnight	=	*night noise exposure*
MMOP	=	*Multilateral Medical Operations Panel*
MORD	=	*Medical Operations Requirements Document*
MRID	=	*Medical Requirements Integration Document*
NEET	=	*Noise Exposure Estimation Tool*
NIOSH	=	*National Institute of Occupational Safety and Health*
NHI	=	*Noise Hazard Inventory*
OCA	=	*Orbital Communications Adapter*
OSHA	=	*Occupational Safety and Health Administration*
Rtime	=	*Run time (hour:min)*
SLM	=	*sound level meter*
SPL	=	*sound pressure level*
SSC	=	*Space Station Computer*
TeSS	=	*Temporary Early Sleep Station*
WHO	=	*World Health Organization*

I. Introduction

THIS paper presents an update on the status of the International Space Station (ISS) noise exposure monitoring and hearing conservation strategies previously presented,[1,2] as well as a summary and an assessment of the acoustic dosimeter data collected since April 2013. The strategy includes crew-worn noise exposure monitoring data collected during the work- (L_{EQ16}) and sleep- (L_{EQ8}) periods and environmental noise exposure data, both collected on ISS. Details and descriptions of ISS are presented elsewhere.[1,2] Crew-worn and environmental monitoring is currently performed by the trained crewmembers onboard ISS, with all technical support provided by ground personnel.

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. Acoustic requirements are documented in the Medical Operations Requirements Document,[3] the Medical Requirements Integration Document,[4] the Generic Groundrules and Constraints Document,[5,6] the Increment Definitions and Requirements Document[7] and the Noise Level Constraint ISS Flight Rule (JSC Flight Rule B13-152).[8] The ISS Noise Level Constraints Flight Rule is based on 16-hour crew-worn work-period noise exposure levels (L_{EQ16}) and 8-hour crew-worn sleep-period noise exposure levels (L_{EQ8}) measured by the ISS acoustic dosimeters. This flight rule sets forth the hearing conservation standards according to the type of activity and duration (16 hours of crew work period and 8 hours of sleep period) and is based on noise exposure levels measured and calculated (from sound levels and corresponding exposure durations) using a 3-dB equal energy exchange rate (ER). In order for the Acoustics and Audiology offices at Johnson Space Center (JSC) to assess the noise levels and to take the necessary protective measures, a Noise Hazard Inventory (NHI) was developed and provided to the ISS Mission for use in conjunction with this flight rule. The Flight Surgeons/Biomedical Engineers (BMEs) are in charge of monitoring compliance with these rules. The JSC Acoustics Office provides the increment-specific NHI for each ISS increment. The NHI is a database of sound pressure acoustic data developed from ground and on-orbit measurements of hardware that is used by crewmembers while working and living on ISS. The NHI provides a correlation between noise exposure and identified activities as well as locations to allow informed recommendations for when the crew should wear hearing protection. This correlation is based on a calculated 16-hour work-period noise exposure level. All currently provided hearing protective devices (HPDs) are appropriate for use and reduces noise exposure sufficiently. In addition, the data obtained from the noise measurements is analyzed to help determine sources of excessive noise and to indicate the need for future noise mitigations. The NHI reduces the risk for noise-induced hearing loss, and helps improve voice communications by avoiding unnecessarily mandated hearing protection use. The NHI is used for implementing the acoustic flight rule that is based on a "task-based" hearing conservation approach. The plan is to collect time-specific crew location and activity information during the nominal monthly crew acoustic dosimetry session. Any crew activity or task with noise levels exceeding 60 dBA is included in the NHI to help mitigate current and future (long-term) crew noise exposure risks. Use of appropriate HPDs may also be required as a result of the noise exposure analysis, including exposure sound levels and durations. If the L_{EQ16} is higher than 72 dBA, then the crewmembers are directed to wear appropriate HPDs during the activities where high noise exposure levels are present. These activities and the noise exposure levels are identified in the increment-specific NHI. However, if the L_{EQ16} is above 60 dBA, the flight surgeon recommends to the affected crewmember use of appropriate HPDs based on the individual needs of the crewmember and the level and duration of the noise exposure. These activities and the noise exposure levels are also identified in the increment-specific NHI. Adherence to these guidelines should keep the sound energy levels to which the ear is exposed at an acceptable level. In order to keep continuous background levels low, NASA and the Johnson Space Center's Acoustics Office have developed and implemented acoustic requirements that must be met for hardware and payloads to be certified for spaceflight and operation on ISS.[9]

A total of three acoustic dosimeters are onboard ISS at all times. The acoustic dosimeter currently used for monitoring ISS noise exposures is a Quest model NoisePro DLX-1®. Detailed explanations on the dosimeter's features and capabilities are documented in Ref. 1. This instrument is used to obtain crew-worn and static acoustic dosimetry measurements. To obtain crew-worn (personal) noise exposure data, the crewmembers wear the acoustic dosimeters for a continuous 24-hour period (including during the sleep-time period), to measure typical noise exposures as they perform nominal tasks and move throughout various locations on ISS. The device is stored in a pocket or clipped to the crewmembers clothing and its microphone is clipped on the crewmember's collar or lapel so that it is in close proximity to the ear. For environmental noise exposure data, the acoustic dosimeter is then placed at specific fixed (static) locations on ISS. Placing the dosimeter in these designated locations have helped characterize the internal acoustic environment of ISS, and assisted in the implementation of effective countermeasures which reduced or eliminated crew exposure to high noise levels and the need to don HPDs. All crewmembers are trained, prior to flight, in acoustic dosimeter measurement techniques. This training includes nominal operation of the acoustic dosimeter hardware, software handling and operational and malfunction procedures, as well as options for HPD use on ISS.

II. Data and Analysis

Acoustic dosimetry data were collected from crew-worn and static location measurements. During nominal sampling days, the acoustic dosimeter activity was divided into four days; crew-worn measurements for all six crewmembers (days 1, 2), static measurements (day 3), and data download activity (day 4). These activities are performed every other month. For the crew-worn activity, the crewmember dons the acoustic dosimeter and starts the measurement before breakfast during the day of the planned activity. The crew-worn session concludes immediately before post-sleep activities the following day. The crew-worn session includes day-time (16-hours) and sleep-time periods (8-hours). For the static measurement session, the crewmember deploys the acoustic dosimeters at predetermined locations. The static locations include specific areas in the modules or in the vicinity of specific hardware for conducting assessments and evaluations of its performance. These locations are preselected by the JSC Acoustics Office in coordination with our Russian acoustic counterparts and are rotated throughout the ISS modules for trending purposes. During this reporting period in May 2014, a crewmember called down to report that while changing out the batteries from one of the acoustic dosimeters there was corrosion in the battery compartment. The crewmember was then instructed by ground personnel to bag the dosimeter as a Hazardous Material Level 2 and stow for return. Since then, all acoustic dosimeter activities have been performed with just two operational dosimeters until the new replacement dosimeters arrive later in spring 2015. The acoustic dosimeter activity has been extended one extra day (from four to five days) to compensate for the non-functional, battery corroded acoustic dosimeter.

After completing the crew-worn and static measurements, the data is then transferred from all dosimeters to the Space Station Computer and downlinked via the Orbital Communications Adapter. The following paragraphs will discuss the crew-worn and static location measurements, along with the analysis of the data collected during the time period April 2013 through March 2015.

A. Crew-worm measurement

The crewmembers donned acoustic dosimeters before breakfast on the day of the acoustic dosimetry activity for the duration of 24 hours to record the work-day (L_{EQ16}) and sleep- (L_{EQ8}) period data. Post-sleep crew-worn data was deleted from the analysis reducing the total duration time period to less than 24-hours. An example of the equivalent noise exposure levels (L_{EQ}) along with other data collected from the acoustic dosimeters are shown in Table 1. Since the approval of the revised Noise Level Constraint ISS Flight Rule,[8] ISS noise exposure levels have been measured using a 3-dB time-intensity ER, consistent with criteria recommended by the National Institute of Occupational Safety and Health (NIOSH)[10] and the U.S. Department of Defense, and it has also been adopted internationally for use in hearing conservation programs.[11] In this paper, all data, including the plots, will be presented using the 3-dB ER unless otherwise stated.

Table 1. Crew-Worn Acoustic Dosimetry Data (Example).
L_{EQ} indicates the equivalent noise exposure level during the work and sleep-time periods. $L_{A,PK}$ indicates the highest instantaneous noise level measured during the measurement period, independently of the slow or fast response that the unit is set for and is averaged into the L_{EQ}.

Activity	Crewmember	S/N	Activation Time	$L_{A,PK}$ [dB]	L_{EQ} [dBA]	Rtime [h:min]	Location
Work-Time Period	A	1014	8:24 AM	119.6	69.9	13:22	ISS Modules
	B	1015	8:23 AM	122.9	70.1	13:21	ISS Modules
Sleep-Time Period	A	1014	9:47 PM	104.2	64.7	9:20	Sleep Station
	B	1015	9:45 PM	110.2	64.2	9:28	Sleep Station
Work-Time Period	C	1014	10:49 AM	128.0	69.4	13:26	ISS Modules
	D	1015	10:25 AM	125.1	67.8	13:47	ISS Modules
Sleep-Time Period	C	1014	12:16 AM	103.8	51.5	7:11	Sleep Station
	D	1015	12:13 AM	108.0	54.7	7:00	Sleep Station

SOURCE: Acoustic dosimeter data collected on January 2015.

An example graph of a crew-worn acoustic dosimeter logged data can be seen in Fig. 1. The graph has been divided into the work- and sleep-periods. The hazard level (85 dBA), the 16-hour L_{EQ} limit (72 dBA) – crew

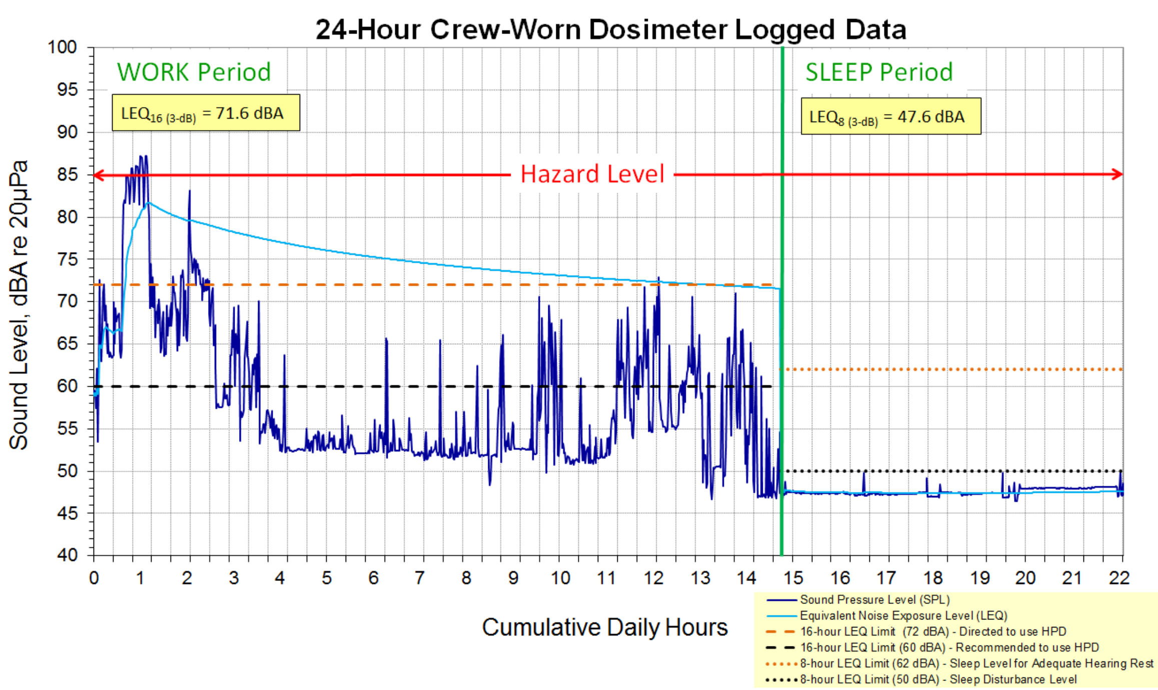

Figure 1. Crew-worn Acoustic Dosimeter Logged Data.
SOURCE: ISS Acoustic dosimeter data collected on August 2013, Increment 36.

directed to wear HPD, and the 60 dBA limit – crew recommended to wear HPD; have been identified in the graph. For this particular dataset, the equivalent noise exposure level (L_{EQ}) during the work-period was measured at 71.6 dBA. Based on the Noise Level Constraint ISS Flight Rule this crewmember was not required to don HPD during activities since the levels were not above the 16-hr L_{EQ} limit (72 dBA). However HPD was required since the L_{EQ} was above the hazard level for the first hour during the work-time period and also the flight surgeon can always recommend to don HPD whenever the levels go above 60 dBA based on the individual needs of the crewmember and the level and duration of the noise exposure. During the sleep-time period, the equivalent noise exposure level was 47.6 dBA, below the sleep disturbance level (50 dBA) and the sleep level for adequate hearing rest (62 dBA).

Crew-worn dosimetry data on ISS has been collected since Increment 1 (see Fig. 2). These data were based on all crewmembers who were a long-duration resident in ISS since November 2001. According to the World Health Organization (WHO),[12] for ground conditions, "Hearing loss is not expected to occur at L_{EQ}, 8-hr levels of 75 dBA or lower, even for prolonged occupational noise exposures." This L_{EQ}, 8-hr levels of 75 dBA corresponds to a L_{EQ16}, 16-hr levels of 72 dBA. In addition, WHO states, "It is expected that environmental and leisure-time noise with an L_{EQ24}, 24-hr of 70 dBA or lower will not cause hearing impairment in the large majority of people, even after a lifetime exposure." This L_{EQ24}, 24-hr level of 70 dBA corresponds to a L_{EQ16}, 16-hr "work" level of 72 dBA and with a L_{EQ8}, 8-hr "sleep" level of 62 dBA using the 3-dB exchange rate. Based on the trend of the data, many crewmembers' L_{EQ24} were above 70 dBA, which may require use of HPD according to the flight rule. Since Increment 21, more crewmembers' L_{EQ24} levels have been below 70 dBA. This decrease in noise exposure levels was mostly due to the result of general improvements in acoustic levels on ISS as described in Ref. 13. These improvements include noise mitigation in the Russian Segment (e.g., installation of quiet fans, mufflers, etc.), as well as the addition of new quieter modules (e.g. Columbus Module, Japanese Experiment Module etc.) and crew quarters. However, activities (e.g. crewmember running on treadmill) and conditions (e.g. clogged inter-module ventilation (IMV) fans) in ISS have elevated the noise levels during past increments. A recurring issue in the U.S.

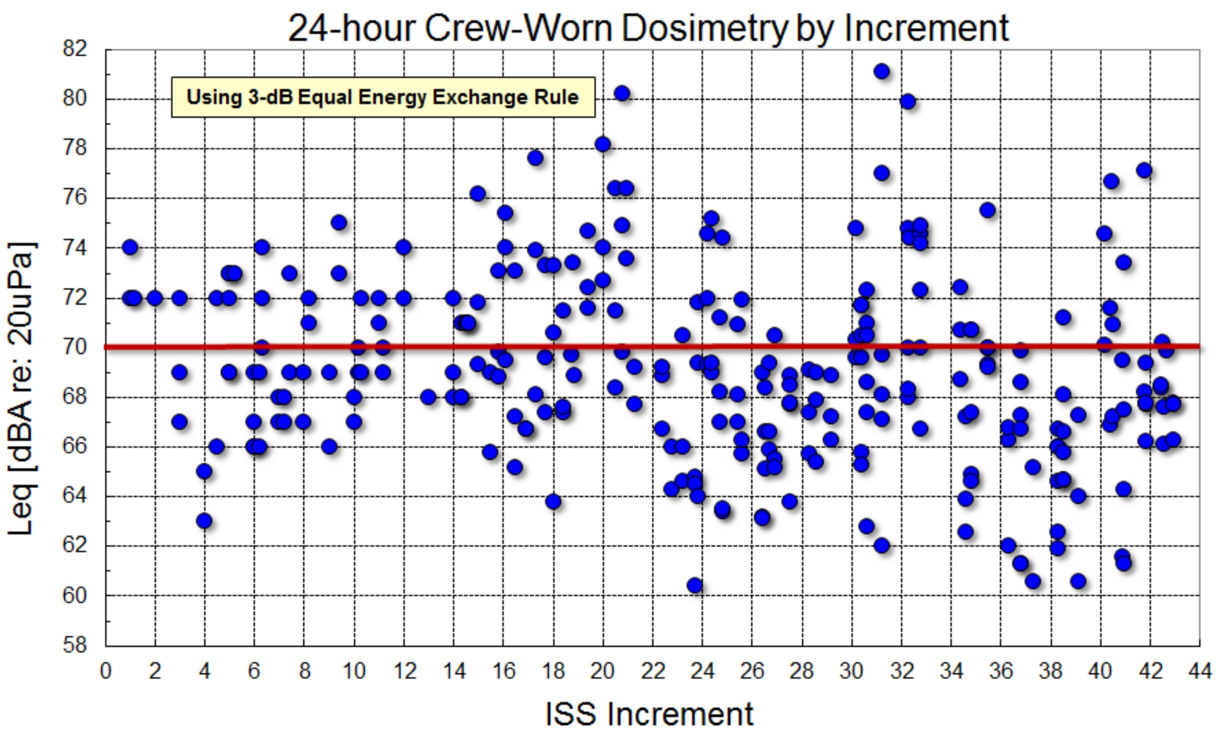

Figure 2. 24-Hour Crew-worn Dosimetry vs. ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2015 (Inc. 42).

segment, (especially in the Japanese Pressurized Module (JPM), Node 2, Node 3, and to a lesser extent in the U.S. Laboratory) is that stalled IMV fans, caused by dust clogging the fans, can be loud, approximately NC-60. These levels persist until the fans are cleaned. While stalled, the high noise levels increase the risks for degraded voice communications, and habitability. After the IMV fans were cleaned, noise levels returned back to nominal levels and theses were verified during the next acoustic measurement activities, as described in Ref. 2.

As previously reported, the noise exposure level for the work-time period was mostly dependent on where the crewmember spent most of their time and what activities or tasks they were performing.[1,2] A crewmember can either work in the Russian segment or in the U.S. segment (see Figs. 3 and 4 for a distribution of L_{EQ16} during work hours). The data showed that the crewmembers who worked most of their time in the Russian segment were initially exposed to higher noise levels than crewmembers who worked in the U.S. segment. However, their L_{EQ16} levels have been decreasing when compared to previous ISS increments.

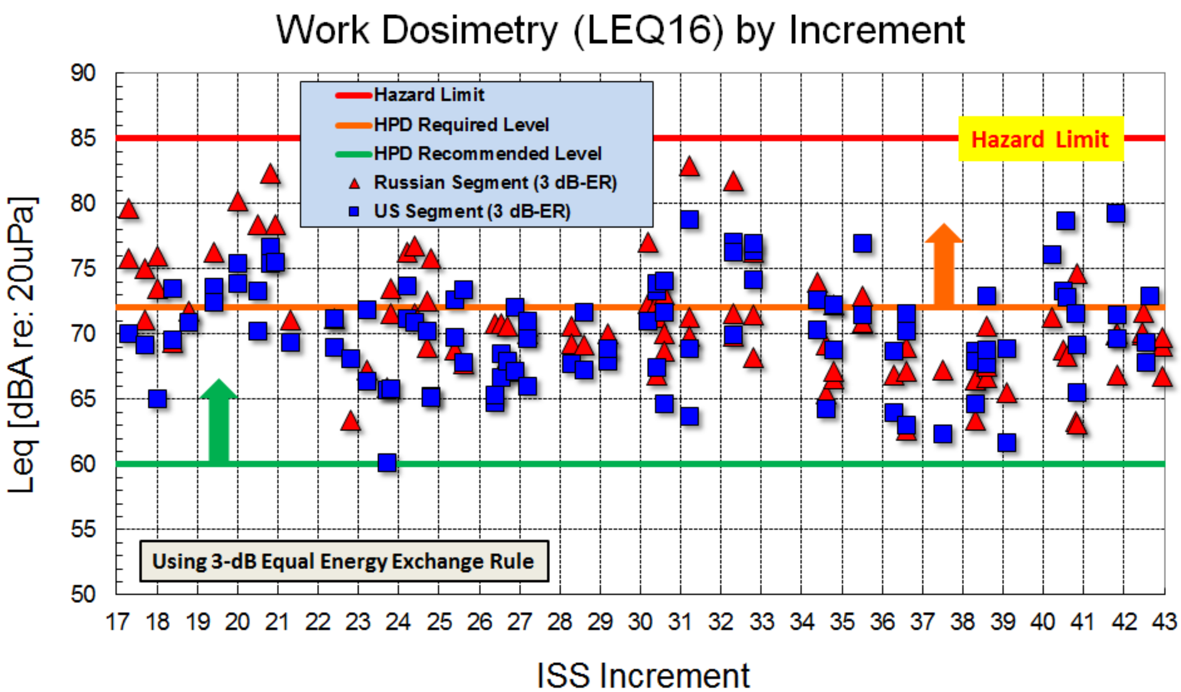

Figure 3. Distribution of L_{EQ16} during work hours by location.
SOURCE: Acoustic dosimeter data collected from July 2008 (Inc. 17) through March 2015 (Inc. 42).

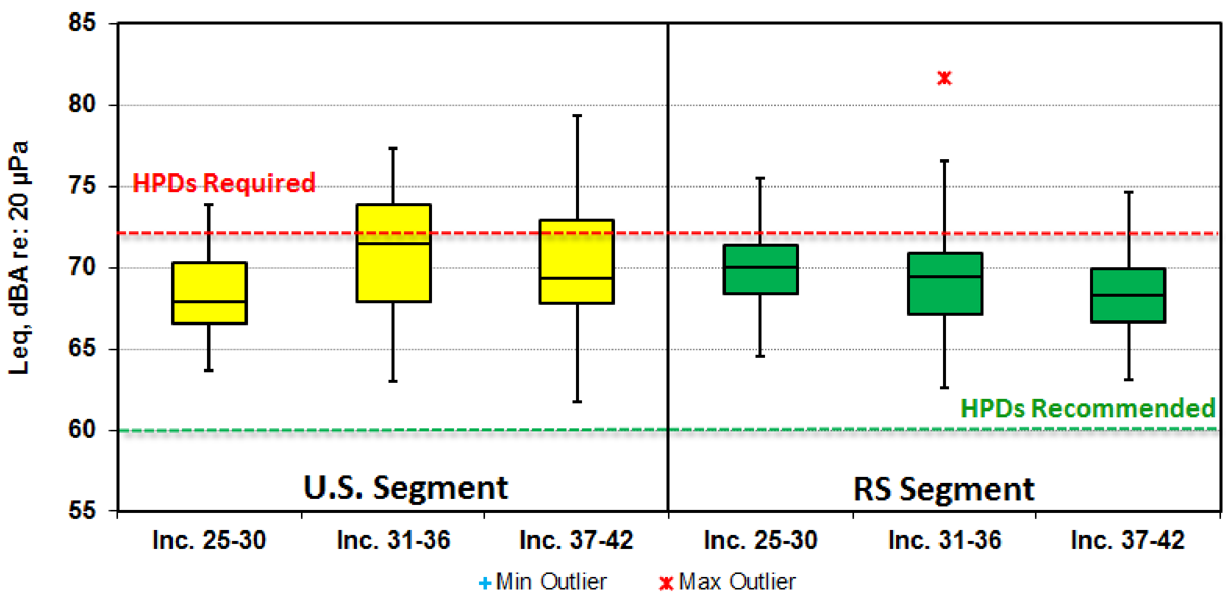

Figure 4. Time comparison of the distribution of L_{EQ16} during work hours in the US and RS segments.
SOURCE: Acoustic dosimeter data collected from October 2010 (Inc. 25) through March 2015 (Inc. 42).

For crewmembers who have spent most of their time working in the U.S. segments, levels have decreased from the previous reported levels (Inc. 31-36 vs. Inc. 37-42). Recently reported levels (Inc. 37-42) have a lower average but a wider data range. Use of hearing protection was recommended to crewmembers when working in the Russian Service Module, exercising on the treadmills (e.g. Node 3), and when exposed to higher noise levels during crew activities or tasks. The crew sleep stations were designed to provide a personal, private area for a crewmember to rest, sleep, and work and for personal activities.[1] Currently there are a total of six permanent sleep stations: two Russian sleep stations (Port and Starboard kayutas) located in the Russian segment in the Service Module and the other four sleep stations (crew quarters) are located in the U.S. segment in Node 2. The ISS crew quarter (CQ) provided a quiet area for recovery (reduced acoustic stimulus to the ears) from daytime noise exposure levels. Noise levels in the Russian sleep stations (kayutas) have previously been a concern, but levels have decreased on the average by approximately 10 dBA since levels first measured in November 2001.[1] For this reporting period (Inc. 37-42), L_{EQ8} have been measured above 62 dBA during Increments 38, 40, 41 and 42 and as low as 50 dBA during Increment 38. See Fig. 5. When compared to the previously reported levels (Inc. 25-30 and Inc. 31-36), the sleep-time period noise levels (L_{EQ8}) during the ISS increments 37-42 have continued to decrease on average in the kayutas but data shows a wider range (see Fig. 6).

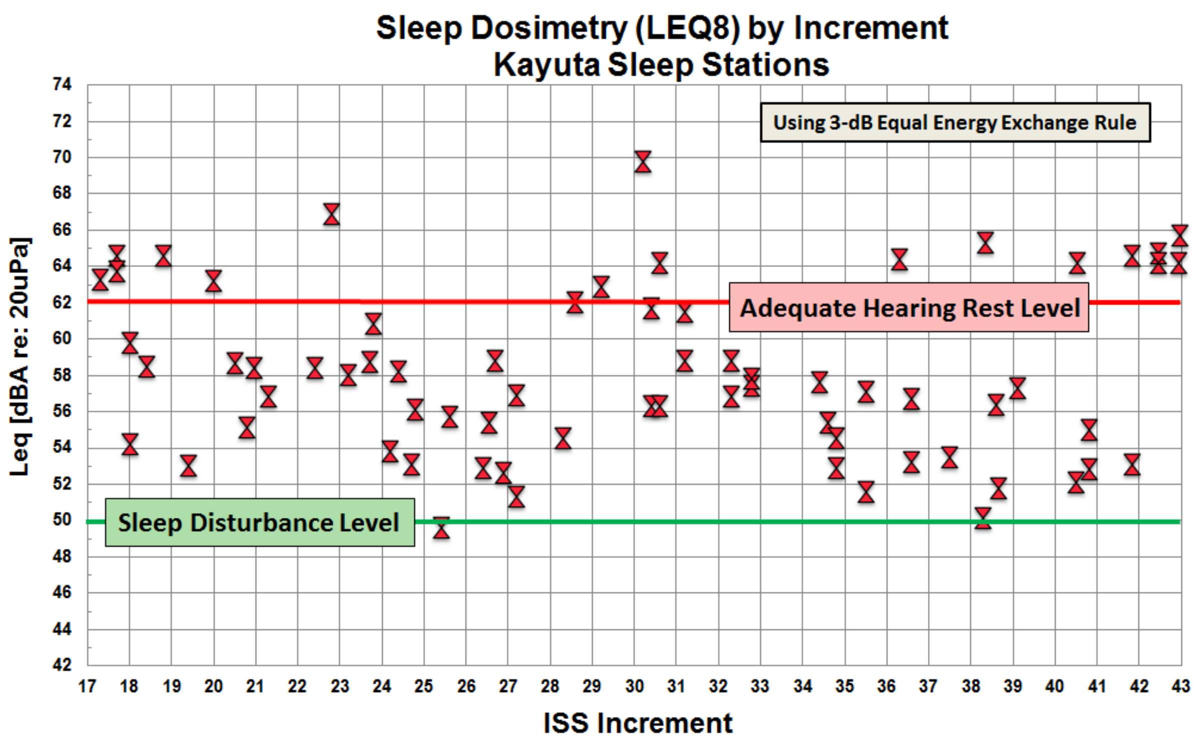

Figure 5. Sleep Dosimetry vs. ISS Increments (Russian Segment).
SOURCE: Acoustic dosimeter data collected from October 2010 (Inc. 17) through March 2015 (Inc. 42).

The ISS crew's sleep-time noise exposure levels for CQs located in the U.S. segment are shown in Fig. 7. The four permanent U.S. CQs (Port, Starboard, Deck and Overhead) became available to ISS crewmembers starting in Increment 18. Overall, sleep-time noise levels in the permanent U.S. CQs have remained below the adequate hearing rest level (62 dBA). The measurements in the U.S. CQs have been measured as low as 44 dBA (increment 27) to as high as 59 dBA (increment 31). When compared to the previously reported levels,[1,2] the current sleep-time period noise levels during the ISS increments 37-42 have remained statistically the same but lower than the sleep-time period noise levels in the Russian segment (see Fig. 6). However, the U.S. and Russian sleep stations are adequately quiet, when doors are closed, to provide auditory rest and do not increase the risk for hearing loss. The exceedances of the sleep requirements (U.S.: 49 dBA (L_{EQ8}) and Russian: 50 dBA (L_{EQ8})) are considered, however, potentially disruptive to restful sleep. The WHO recommends a night noise exposure (L_{night}) value of 40 dBA or lower to be the target of the night noise guideline to protect the public.[14] However, WHO also recommends an L_{night} value of 55 dBA or lower as an interim target when the 40 dBA level cannot be initially met. Crew debriefs have indicated that crew sleep had not been affected by ISS sleep station noise levels. Different types and sizes of HPDs are always available to crewmembers on ISS, if needed.

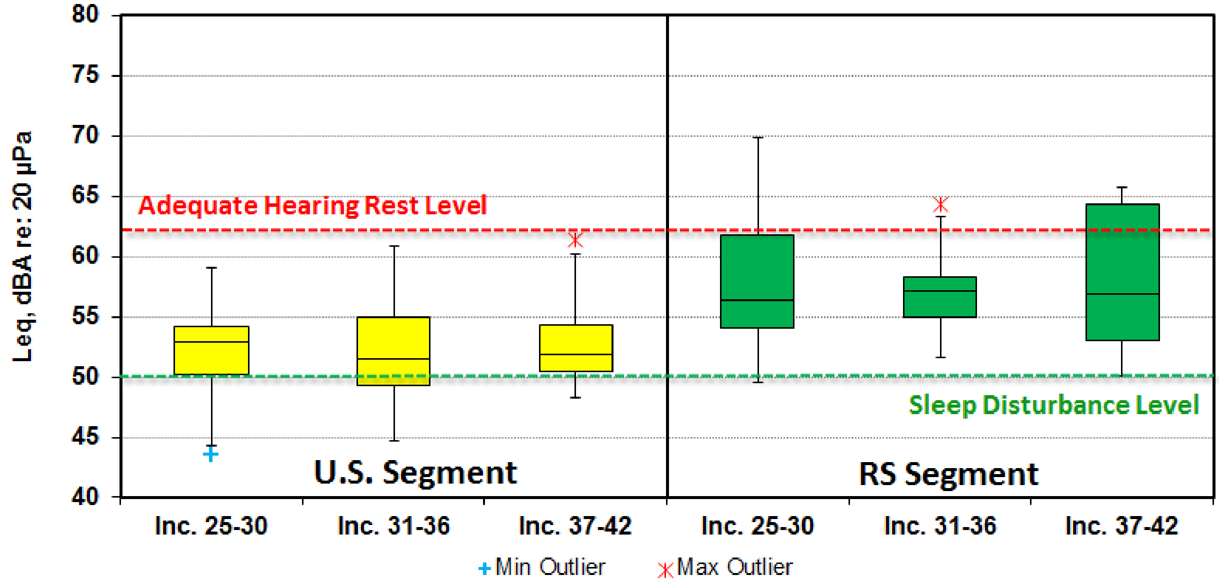

Figure 6. Time comparison of the distribution of L_{EQ8} during sleep time hours in the U.S. and RS segments.
SOURCE: Acoustic dosimeter data collected from October 2010 (Inc. 25) through March 2015 (Inc. 42).

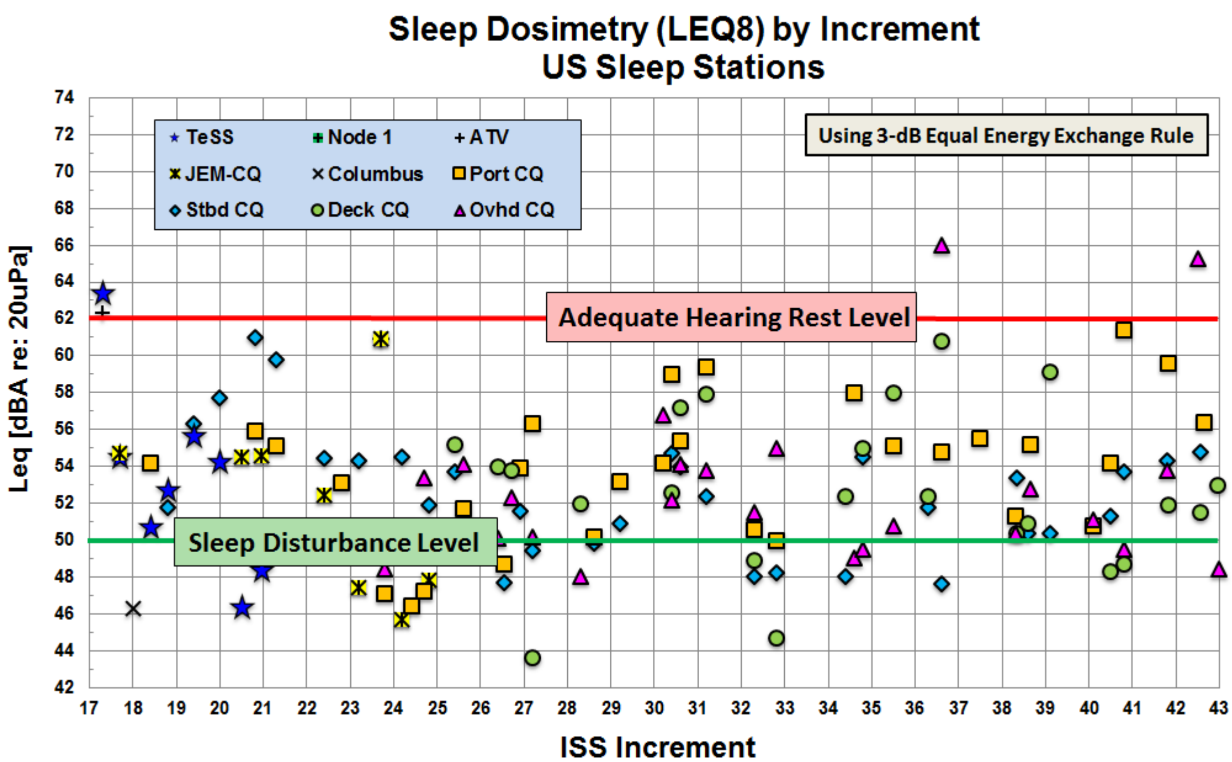

Figure 7. Sleep Dosimetry vs. ISS Increments (U.S. Segment).
SOURCE: Acoustic dosimeter data collected from July 2008 (Inc. 17) through March 2015 (Inc. 42).

During this reporting period (Inc. 37-42), the data show that the equivalent noise exposure levels in the kayutas, in the Russian segment, were higher than the CQ noise levels located in the U.S. segment (Node 2). Figure 8 shows the distribution of L_{EQ} levels during sleep hours. The levels indicated that the overhead CQ was the quietest sleep station in the U.S. segment and the starboard kayuta was the quietest in the Russian segment. But the kayutas had levels above the adequate rest hearing level (62 dBA) whereas the U.S. sleep stations were all below 62 dBA. This difference could be due to sleep station's design features and also whether or not the crew sleep station's door was kept opened or closed during this sleep-time period, i.e., crew preferences. Overall, the crew sleep stations provided a quiet area for recovery (reduced acoustic stimulus to the ears) from daytime noise exposure levels.

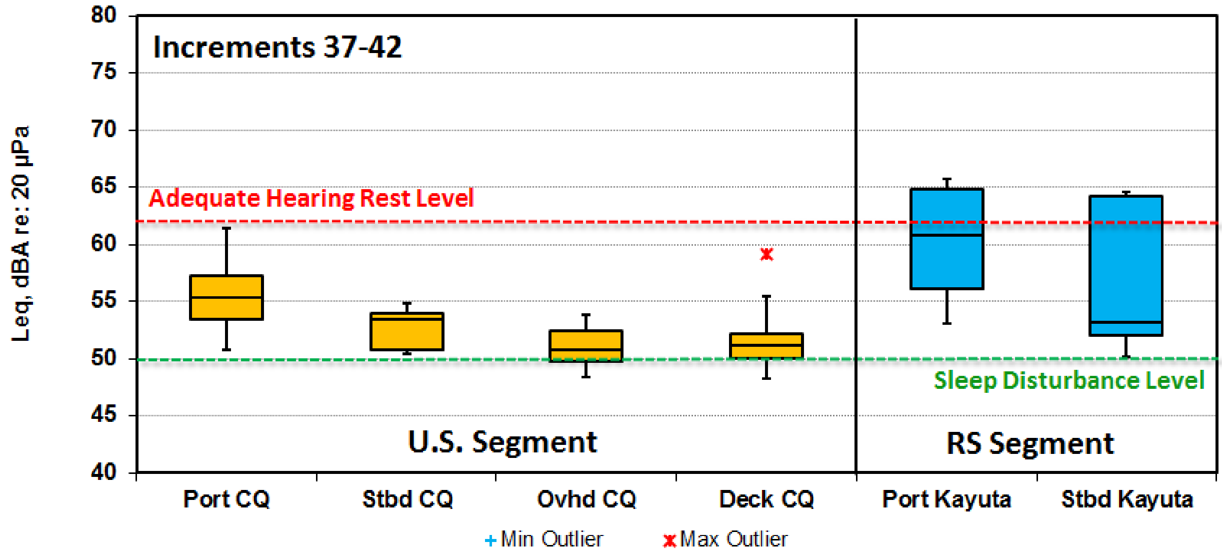

Figure 8. Distribution of L_{EQ8} during sleep hours by location.
SOURCE: Acoustic dosimeter data collected from April 2013 (Inc. 37) through March 2015 (Inc. 42).

After reviewing the trend of the average work-time period noise exposure level data (combining U.S. and Russian crewmember's data), it was concluded that levels have remained consistently stable and below the 16-hour L_{EQ} limit (72 dBA), with the exceptions of a few increments (e.g. 17, 19, 20, 31, 32 and 41) where levels were above the HPD required limit. (See Fig. 9). The average noise exposure levels for the sleep-time period continue to remain below the adequate hearing rest level (62 dBA). See Fig. 10. This data includes all six sleep stations.

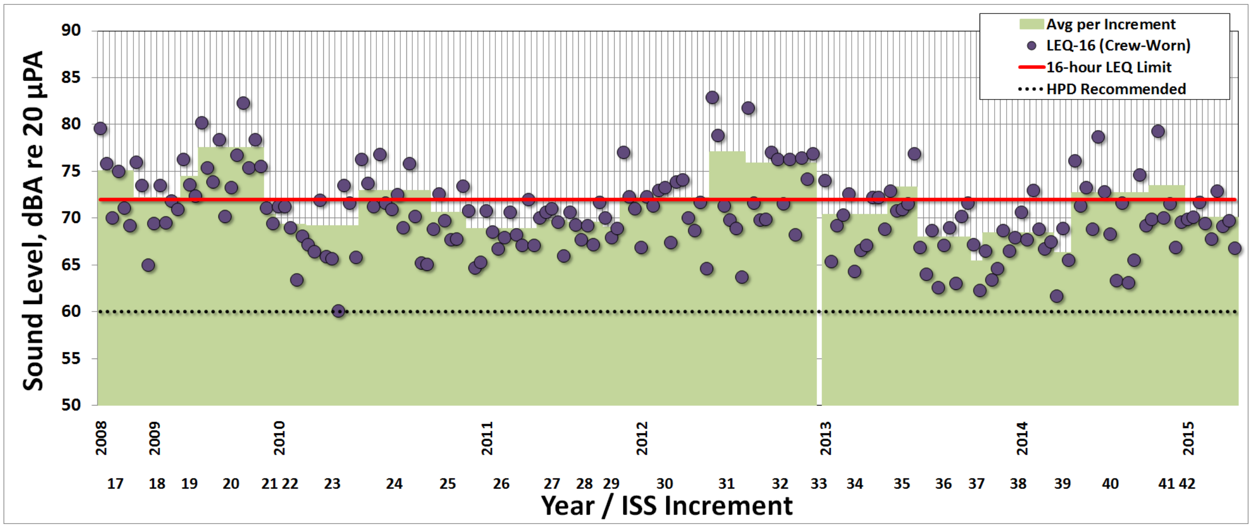

Figure 9. Distribution of L_{EQ16} during work-period hours.
SOURCE: Acoustic dosimeter data collected from July 2008 (Inc. 17) through March 2015 (Inc. 42).

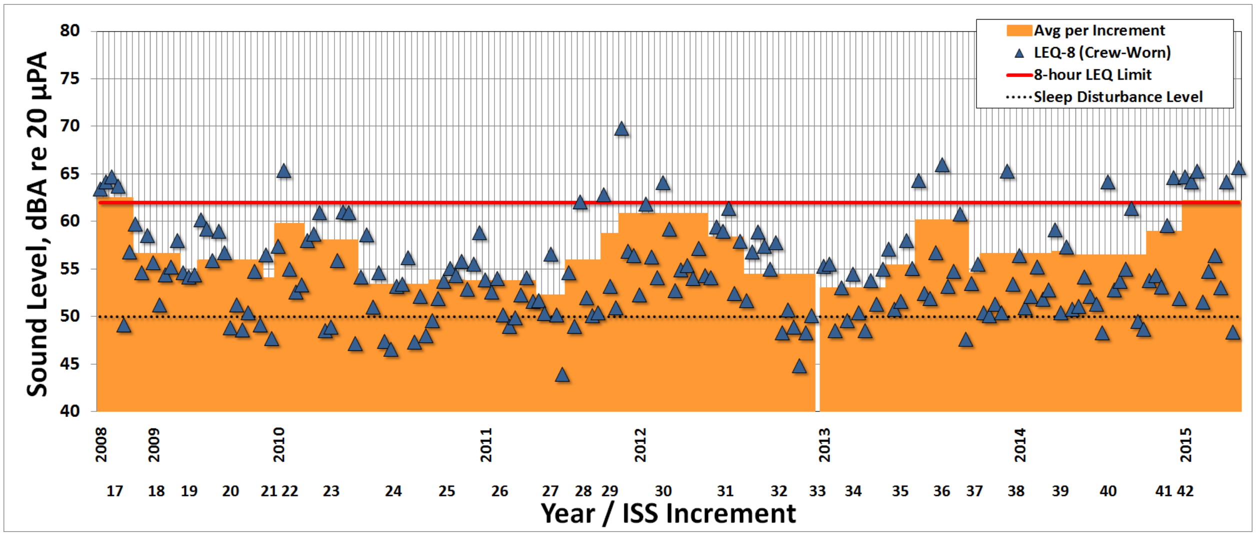

Figure 10. Distribution of L_{EQ8} during sleep-period hours.
SOURCE: Acoustic dosimeter data collected from July 2008 (Inc. 17) through March 2015 (Inc. 42).

B. Static location measurement

After completing the 24-hour crew-worn measurements, the dosimeters were then deployed at predetermined locations for 24-hours for area monitoring. The acoustic dosimeters 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 effect crew noise exposure. These locations are defined in a "static-deploy plan" by the JSC Acoustics Office and provided to the crew before the activity. Measurements have been recorded in various locations in the U.S. and Russian segments. The data logging feature on the dosimeters are a great tool for assessing and evaluating continuous or intermittent sources of noise in the environment by providing time-stamped acoustic data. However, during nominal and/or off nominal noise surveys, the ISS crewmembers have the option to take noise measurements with the sound level meter and/or acoustic dosimeter. If the measured noise level during a crew activity or task exceeds 60 dBA, then it will be included in the NHI and applicable hearing protection requirements will be documented for future crew task or activities. Recently, the crewmembers have indicated that levels inside the waste hygiene compartment (WHC) were higher than normal after conducting a maintenance activity. Levels were then recorded for 24 hours with an acoustic dosimeter. See Figures 11 and 12. The acoustic dosimeter data indicated that levels were indeed louder and even occasionally above the hazard level (85 dBA). At that point the WHC was included in the NHI and the crewmembers were required to wear HPDs when using the WHC per the ISS noise constraints flight rule. Following that incident, an updated NHI was provided to the ISS crewmembers and their crew surgeons. After reviewing the newly collected data with personnel from engineering, safety, medical and mission support, it was concluded that the pump inside the WHC was

Figure 11. Interior view of the WHC on ISS.
SOURCE: NASA

the source for the high noise levels. The pump was then replaced and the levels returned back to nominal levels. At that point, the WHC was then removed from the NHI (See Fig 13).

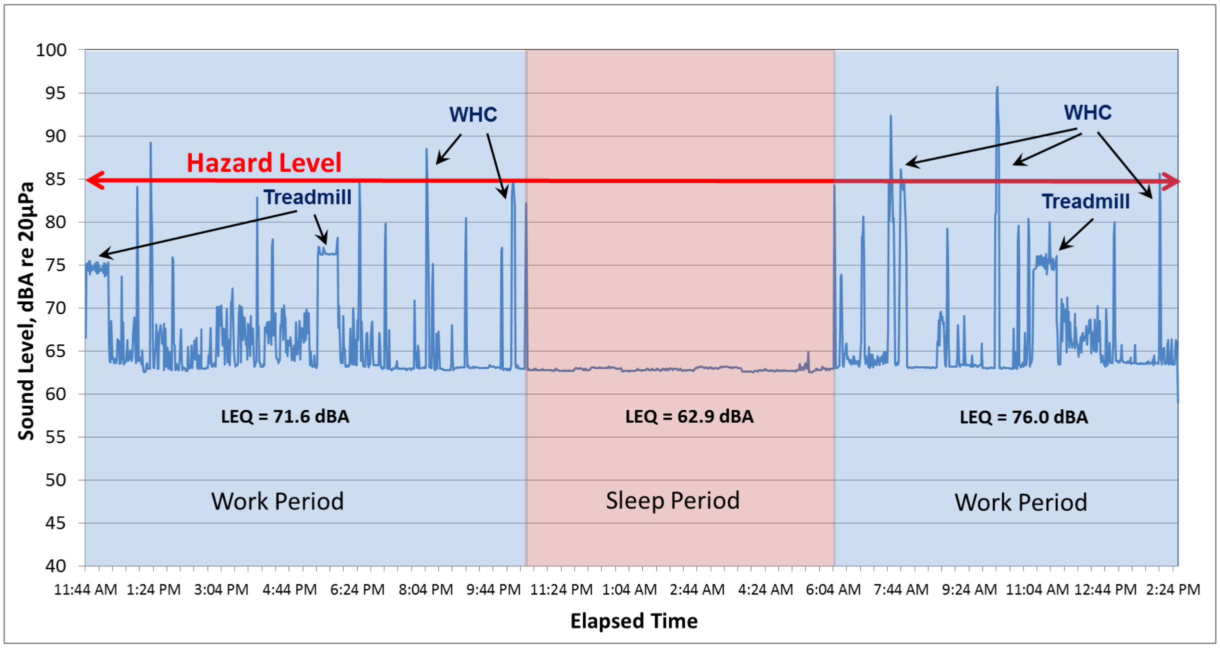

Figure 12. Acoustic Dosimeter Static Measurement – Inside WHC, Before Pump Replacement.
SOURCE: Acoustic dosimeter data collected on February 2014 (Inc. 39).

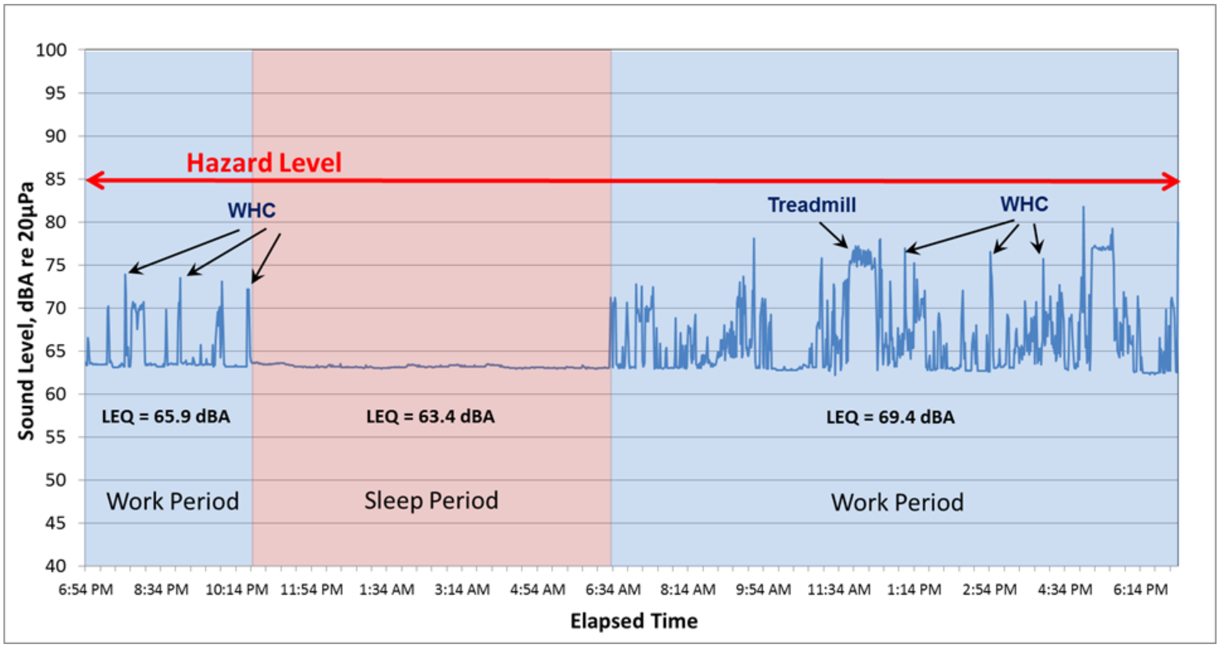

Figure 13. Acoustic Dosimeter Static Measurement – Inside WHC, After Pump Replacement.
SOURCE: Acoustic dosimeter data collected on April 2014 (Inc. 40).

III. Discussion

This paper describes the ISS noise exposure monitoring program as well as an assessment of acoustic dosimeter data collected since April 2013 to date. Acoustic data has been collected onboard ISS since it was first inhabited by three crewmembers on November 2001 (Increment 1). The data also provided trending information with regards to the work and sleep acoustic environments experienced by the crewmembers on ISS. The average noise exposure level in the ISS work environment during this reporting period (Inc. 37-42) has fluctuated from 62 to 74 dBA. The sleep environment average noise exposure level has also fluctuated from 54 to 62 dBA during this reporting period. Overall, there has been an improvement in the acoustical environment on ISS, with the exception of an environmental condition caused by off-nominal hardware condition (e.g. pump failure in the WHC). After maintenance was performed on the equipment, levels returned back to nominal levels. 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 data suggest an improvement in the ISS acoustic environment. Although hearing loss has been documented in long-duration spaceflights,[15-19] a recent epidemiological examination for mission-associated hearing threshold shifts (using a standard criteria of a 10 dB average shift or more of hearing thresholds in the high frequencies of 2000, 3000 and 4000 Hz since preflight audiometric tests) has revealed an incidence of such shifts in less than 5% of ISS crewmembers.[20] Lessons learned with regards to successful noise control techniques, acoustic requirements and flight rules from past space programs (e.g. Space Shuttle, Apollo, etc.) have shown to be very beneficial in helping reduce the environmental noise levels and at the same time reduce the crew noise exposure level on ISS.

IV. Conclusions

The crewmembers on ISS have several modules in which they can spend time during the day. Accurately tracking their activities, tasks, and noise exposure in these modules is a significant task. The current acoustic dosimeters used onboard ISS have the capability for measuring and logging data. However, correlating crew activities to the measured data can be a difficult task unless a crewmember's timeline is well defined with time stamps corresponding to completed activities. Currently, a correlation between the measured data and crew timeline is still lacking.

As part of the revised Noise Level Constraint ISS Flight Rule, data was collected during the acoustic dosimetry sessions with the basis for the identification and mapping of high-noise areas and activities on ISS that can contribute significantly to the noise exposure experienced by the ISS crewmember. This data was then compiled into the Noise Exposure Estimation Tool (NEET) where noise exposure was calculated and the need for HPDs was determined and documented in the NHI. The NEET and NHI were developed and are being maintained by the JSC Acoustics Office. The NHI was based on the data collected with the acoustic dosimeter, using the 3-dB equal energy ER. The NHI was provided to the crewmembers during every ISS increment and updated when any activity or task exceeded the noise hazard level (e.g. WHC issue). See Ref. 2 for a detail description of the elements used in the NHI. Hearing protection devices were required when the 16-hour L_{EQ} was 72 dBA or greater but only during activities where high noise exposure levels were present. Likewise, HPDs were recommended to the crew when the L_{EQ16} was 60 dBA or greater. Also HPDs were always required when the L_{EQ} was at or above the noise hazard limit.

During this reporting period, ISS Inc. 37-42 (April 2013 – March 2015), data have shown that levels are dependent on the acoustic environment and the activities and tasks being performed by the crewmember. Static dosimetry has also proven to be an aid for identifying hardware anomalies. As we learn how to better correlate the crew timeline, tasks, activities, and anomalies with the measured acoustic dosimetry data, our ability to protect the crewmembers onboard ISS will be greatly enhanced.

Acknowledgments

The authors would like to thank the ISS Biomedical Engineers for helping with the crew procedures, training, and anomaly resolutions and serving as the liaison to the ISS crew; the hardware engineers for keeping the acoustic dosimeters certified and ready for flight; and the International Partners for their collaboration with the noise exposure monitoring program.

The authors would also like to dedicate this paper to the memory of Rimma Bogatova who was an outspoken advocate for crew health, in particular for the hearing conservation of the cosmonauts in the Russian space program. Her enthusiasm and camaraderie will be greatly missed in the ISS Acoustics and Audiology community.

References

[1]Limardo, J. G., and Allen, C. S., “Analysis of Noise Exposure Measurements Acquired Onboard the International Space Station,” *Proceedings of International Conference on Environmental Systems 2011*. American Institute of Aeronautics and Astronautics, AIAA 2011-5137, 2011.

[2]Limardo, J. G., Allen, C. S., and Danielson, R. W., “Assessment of Crewmember Noise Exposures on the International Space Station,” *Proceedings of International Conference on Environmental Systems 2013*. American Institute of Aeronautics and Astronautics, AIAA 2013-3516, 2013.

[3]SSP 50260, “International Space Station Medical Operations Requirements Document (MORD),” February 2006.

[4]JSC 28913, “Medical Requirements Integration Document (MRID),” Rev A, March 2005.

[5]SSP 50260-1, “ISS Generic Groundrules, Requirements and Constraints (GGR&C), Part 1: Strategic and Tactical Planning,” Rev E, January 2011.

[6]SSP 50260-2, “ISS Generic Groundrules, Requirements and Constraints (GGR&C), Part 2: Execute Planning,” Rev C, February 2011.

[7]SSP 54025_54026-ANX 4, “Increment Definition and Requirements Document (IDRD) for Increments 25 and 26, Annex 4: Medical Operations and Environmental Monitoring,” May 2010.

[8]NSTS-1282, “ISS Generic Operational Flight Rules,” Vol. B, B13-152, “Noise Level Constraints.”

[9]Goodman, J. R., “International Space Station Acoustics,” *NOISE-CON 2003 Conference*, Cleveland, OH, 2003.

[10]NIOSH, “Preventing Occupational Hearing Loss – A Practical Guide,” No. 96-110, June 1996.

[11]Department of Defense Instruction, “DoD Hearing Conservation Program,” No. 6055.12, March 5, 2004.

[12]Berglund, B; Lindvall T, and Schwela D, “Guidelines for Community Noise,” World Health Organization, (Geneva, 1999).

[13]Allen, C. S., “International Space Station Acoustics – A Status Report,” *Proceedings of International Conference on Environmental Systems 2015*. American Institute of Aeronautics and Astronautics, AIAA 2015-286, 2015.

[14]Kim, R., and van den Berg, M., “Summary of night noise guidelines for Europe,” Noise and Health, 12:47, 2010, pp. 61-63.

[15]Buckey, J. C., Muskie, F. E., Klein-Schoder, R., Clark, J., Hart, S., and Havelka, J., “Hearing Loss in Space,” Aviation, Space, and Environmental Medicine, Vol. 72, No. 12, December 2001, pp. 1121-1124.

[16]Clark, J. B., and Allen, C. S., “Acoustic Issues,” Principles of Clinical Medicine for Space Flight, 1st ed., Springer, 2008, Chap. 24.

[17]Hodge, D. C., and Garinther, G. R., “Noise and Blast,” Bioastronautics Data Book, 2nd ed., NASA SP-3006, 1973, Chap. 15.

[18]Roller, C. A., and Clark, J. B., “Short-duration space flight and hearing loss,” Otolaryngology – Head and Neck Surgery, July 2003, pp. 98-106.

[19]Koros, A. S., Adam, S. C., Wheelwright, C. D., “Noise Levels and their Effects on Shuttle Crewmembers’ Performance: Operational Concerns,” N94-11538, 1994.

[20]Danielson, RW, Garcia J, and Murray M, “Analysis of Hearing Threshold Shifts among Astronauts on Long-Duration Missions”, poster at NASA Human Research Investigator’s Workshop, Galveston TX, January 2014.