

International Space Station Acoustics – A Status Report

Christopher S. Allen¹

NASA Johnson Space Center, Houston, Texas, 77058

It is important to control acoustic noise aboard the International Space Station (ISS) to provide a satisfactory environment for voice communications, crew productivity, alarm audibility, and restful sleep, and to minimize the risk for temporary and permanent hearing loss. Acoustic monitoring is an important part of the noise control process on ISS, providing critical data for trend analysis, noise exposure analysis, validation of acoustic analyses and predictions, and to provide strong evidence for ensuring crew health and safety, thus allowing Flight Certification. To this purpose, sound level meter (SLM) measurements and acoustic noise dosimetry are routinely performed. And since the primary noise sources on ISS include the environmental control and life support system (fans and airflow) and active thermal control system (pumps and water flow), acoustic monitoring will reveal changes in hardware noise emissions that may indicate system degradation or performance issues. This paper provides the current acoustic levels in the ISS modules and sleep stations and is an update to the status presented in 2011. Since this last status report, many payloads (science experiment hardware) have been added and a significant number of quiet ventilation fans have replaced noisier fans in the Russian Segment. Also, noise mitigation efforts are planned to reduce the noise levels of the T2 treadmill and levels in Node 3, in general. As a result, the acoustic levels on the ISS continue to improve.

Nomenclature

<i>dB</i>	=	decibel, unit of sound pressure level when referenced to 20 μ Pa
<i>dBA</i>	=	A-weighted decibel; also used in graphs to indicate A-weighted Overall Sound Pressure Level
<i>NC</i>	=	indicates use of the Noise Criterion family of curves
<i>OASPL</i>	=	Overall Sound Pressure Level denotes SPL including energy over the audible frequency range
<i>Sound Level</i>	=	OASPL when A-weighted, with units of dBA
<i>SIL(4)</i>	=	Speech Interference Level, arithmetic average of 500, 1000, 2000, and 4000 Hz Octave Band SPLs
<i>SPL</i>	=	Sound Pressure Level over a specified frequency range, e.g. octave band, 1/3 octave band

I. Introduction

THE International Space Station (ISS) is home, office, and laboratory for several astronauts and cosmonauts for time periods of six months, typically; however, starting in 2015 some crew-members, two at first, will stay aboard ISS for a full year. And while the crew lives and works aboard ISS, it is important that the acoustic environment allows adequate voice communications and alarm audibility, is conducive to concentration on tasks, provides for restful sleep, and reduces the risks for temporary and permanent hearing loss. However, in order to provide required life support (air and water) and thermal control for the crew and the many experiments, hundreds of noise sources, e.g. fans and pumps, along with corresponding air and water flows, are required and are present within the confined ISS environment in close proximity to the crew. These competing necessities create a challenging environmental acoustic problem to overcome and manage.

In order to control acoustic levels on ISS, the Acoustics System, i.e. all noise sources, controls, remediation, and monitoring, is managed by the JSC Acoustics Office along with other teams including the ISS Acoustics Working Group (AWG) and Multilateral Medical Operations Panel (MMOP) Acoustics Sub-working Group in conjunction with the system teams which own the noise producing hardware, such as the Environmental Control and Life Support

¹ Manager, JSC Acoustics Office, Chair, ISS Acoustics Working Group, Deputy, System Management and Integration Branch, 2101 NASA Rd. 1/SF22, and Senior Member, AIAA.

System (ECLSS) and the Active Thermal Control System (ATCS). The AWG is an advisory group comprised of NASA representatives from the Acoustics Office, Space Medicine, Crew Office, ISS Program Office, Safety, and others. The MMOP Acoustics Subgroup is comprised of the acoustics and audiology experts from the various international partners including American, Russian, European, Japanese, and Canadian members.

The methods and practices used to control the ISS acoustic environment include a strong set of requirements and verification requirements, with noise control implemented during the design and development of the hardware, combined with predictive analyses, testing, on-orbit acoustic monitoring, and if required, on-orbit mitigation of high noise problems. Goodman¹ describes in further detail some of the issues concerning control of noise on ISS, including the importance of having Program and Project Management support for controlling noise levels, which is critical.

Allen and Goodman² describe the process of ensuring safety of flight regarding acoustic levels on ISS, including the Certification of Flight Readiness (CoFR) process. Examples of hardware noise control are discussed by Grosveld et al.,³ Phillips and Tang,⁴ and by Goodman and Grosveld⁵ on implementation of noise control for spaceflight vehicles in general.

In 2011, Allen and Denham⁶ provided an update on the status of acoustic levels on ISS. At that time the reduction in sound levels in the US Lab, after the change in Pump Package Assembly (PPA) operations from dual- to single-pump operations, was documented. Also, acoustic levels in the, then recently added, European Columbus Operational Facility (COF), Japanese Experiment module (JPM), Japanese Logistics module (JLP), Node 2, and Node 3 modules were shown and discussed, as were the low acoustic levels in the new Crew Quarters. These additional living spaces allowed the ISS to move to 6-crew operations, and acoustic levels in the U.S. Segment met requirements in all modules except in Node 3. Levels in the Russian Segment were also shown, including sound level reductions in the Service Module (SM), where the crew spend much of their time. The noise controls used to affect these reductions in the SM were discussed in detail. Acoustic level reductions in the Mini-Research Module #1 (MRM1), due to quiet fan installations, were discussed, and levels in the remainder of the Russian Segment were presented. Finally, several on-orbit acoustic issues, and their resolution, were discussed. These included: 1) high flow noise from Node 2 backpressure plates, which were replaced on-orbit, and 2) high Inter-Module Ventilation fan (IMV) noise caused by dust which clogged and stalled the IMV fans.

The purpose of the current paper is to provide an updated status for 2015, covering up to ISS Increment 43. However, before discussing the acoustic levels, a change in the sound pressure level requirements for laboratory modules will be presented. Then, as with the 2011 update, acoustic levels in the U.S. Segment and the Russian Segment modules will be discussed. Levels in the U.S. Segment will be shown to still meet requirements, except for Node 3, while continued improvement in Russian Segment acoustic levels will be shown as the result of many quiet-design fan installations. Finally, on-orbit acoustic issues will be discussed, including high levels from the T2 treadmill, and a Waste and Hygiene Compartment (WHC) noise problem.

The sound pressure level (SPL) data provided in this paper were measured by the ISS on-orbit crew, using a Brüel and Kjær 2260 Sound Level Meter (SLM). Crew-worn and fixed-location acoustic dosimeter measurements for the current time-frame are described by Limardo.⁷ See also, papers by Limardo, and Allen regarding ISS crew's noise exposure and flight rules that govern when hearing protection use is needed aboard ISS.⁸ The acoustic instrumentation, processes, and further discussion of acoustic monitoring aboard the ISS are described by Pilkinton.⁹ Note that all SLM measurements are of Type 1 measurement accuracy.⁹

II. Acoustic Requirement Update

In April 2014, the ISS U.S. Segment continuous noise requirement for the complement of payloads, i.e. science experiment hardware, was changed. The old requirement, specified in SSP 57011, was the Noise Criterion curve, NC-48, and this limit applied to the combination of all continuous payload noise emissions, as predicted inside the module. The different laboratory modules all had different verification locations for this requirement, the U.S. Lab was verified at the module center, the JEM was verified at three separate

Octave Band Frequency, Hz; or Other Metric	NC~52	NC-52	NC-48 + NC-50
63	73	72.2	73.3
125	66	65.2	66.3
250	60	59.6	60.3
500	56	55.6	56.1
1000	53	53	53.1
2000	51	51	51.1
4000	50	50	50.1
8000	49	49	49.1
Sound Level, dBA	60	60	60.4
SIL(4), dB	52.5	52.5	52.6

Table 1. U.S. Segment acoustic requirements and related Noise Criterion Curves.

locations along the module centerline, and the COF used the average noise levels predicted throughout the module to verify this requirement. When evaluating whether or not exceedances to the NC-48 requirement were acceptable or not, the predicted payload noise levels were added to the lab vehicle’s acoustic levels, and this combination was compared to the combination of the NC-48 requirement and the vehicle’s NC-50 requirement. As a result, the final evaluation of a module’s composite vehicle plus payloads acoustic environment was compared to an ‘implicit’ requirement of NC-48 + NC-50. This combination is close to the NC-52 noise criterion curve. See Table 1.

The change that was implemented in SSP 57011 was to change the limit for the acoustic emissions of a module’s payload complement from NC-48 to a requirement of NC~52 for the combination of the payload complement and the vehicle acoustic levels. Since NC-48 + NC-50 is not exactly NC-52, NC~52 was adopted to be NC-48 + NC-50, where the decibel values are rounded to the nearest integer. These values are also listed in Table 1. The new NC~52 requirement is verified using the spatial average of predicted sound levels across the module, and is an actual requirement for the composite acoustic levels in the laboratory modules and not an implicit requirement made of two lower-level requirements. There were several advantages of this arrangement, including a reduction in exceedance paperwork, e.g. exceptions and waivers, and the ability of payloads to use available requirement allocation, where the vehicle sound level emissions were below the NC-50 allocation allotted to them.

In the following sections, the NC~52 curve will be used as the U. S. Segment requirement to which the on-orbit laboratory measurements are compared. In modules where there are no payloads, the NC-50 vehicle requirement applies. There is one exception, however, and this is with Node 3 where the actual NC-52 curve was specified in the Node 3 Prime Item Specification as the composite requirement including the vehicles and non-integrated GFE acoustic emissions.

Also shown in Table 1 are additional metrics corresponding to the NC curves. These metrics include the A-weighted Overall Sound Pressure Level, abbreviated ‘Sound Level,’ and the Speech Interference Level – Four Band Method, abbreviated SIL(4). The Sound Level is used to evaluate risk of hearing loss, as A-weighting is a frequency weighting to correct for the frequency response of humans to low-level noise and has been historically used to evaluate hearing loss risk. SIL(4) is a metric that represents difficulty in voice communications based on the background noise level in the frequency range where speech is located.¹⁰ As shown in Table 1, the Sound Level of the NC~52 curve is 60 dBA, and this is the same as the Sound Level requirement in the Russian Segment.

III. U. S. Segment Acoustic Levels

Acoustic levels in the Node 1 and Airlock have consistently met requirements since 2003. The latest levels in these modules are shown in Fig. 1. The Airlock levels shown were measured on August 1, 2014 and are significantly below the NC-50 module requirement in both the Crew Lock and Equipment Lock.

The Node 1 levels were acquired on April 1, 2015. The spectrum that is shown in Fig. 1 is a spatial average of four separate measurements that were made at locations along the centerline of the module. Node 1 does not meet the NC-50 requirement in all frequency bands but does meet its specific vehicle requirement because an exception to the NC-50 requirement was approved in 1998 to allow the 500 Hz and 1000 Hz octave band SPLs to be up to 59 dB and 54 dB, respectively, based on ground-test measurements. Node 1 does meet these exception levels.

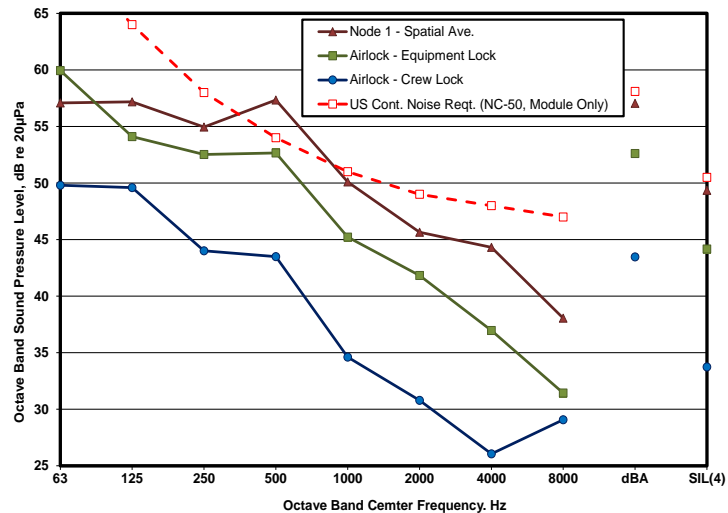


Figure 1. Node 1 and Airlock acoustic levels (2014, 2015).

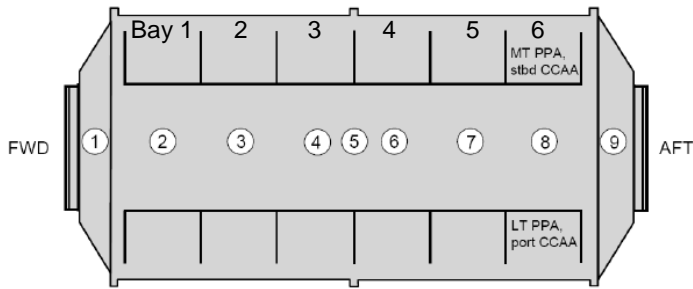


Figure 2. U.S. Lab measurement locations, including location 5 at the module’s longitudinal center. Locations are on the module centerline and 2-4 and 6-8 are also across from the Rack Bay centers, as shown.

spectra in some locations may have exceeded NC~52 in some octave frequency bands, but as an average the U.S. Lab’s acoustic environment has met the NC~52 requirement during this time.

Levels in the other U.S. Segment laboratories, the COF and JPM, remain well below requirements. Fig. 4 shows the COF and JPM spatial average spectral levels along with those of JEM Logistics module – Pressurized (JLP), Cupola, and the Permanent Multipurpose Module (PMM). Note that the COF and JPM averages are below the NC-50, vehicle only requirement, whereas they are required to meet the NC~52, vehicle plus payloads requirement. So, the acoustic environment in these modules remain consistently well below the continuous noise requirement. The COF acoustic levels shown in Fig. 4 were measured on April 1, and are a spatial average of 5 measurement locations. When compared to the corresponding levels in Ref. 6, the current data show increases from NC-41.1 to NC-49.9, from a SIL(4) of 38.7 dB to 45.7 dB, and a sound level increase from 45.7 dBA to 53.5 dBA. It is thought that this increase in acoustic levels has been caused by the addition of payloads, which is as-expected.

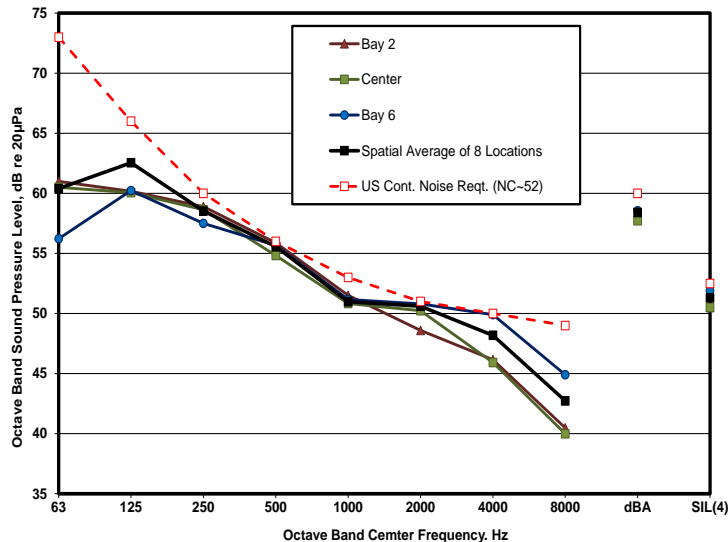


Figure 3. Current U.S. Lab acoustic levels (April 1, 2015).

much since 2010. The values of NC-47.8, SIL(4) of 44.5, and sound level of 51.7 dBA are within 1 dB of corresponding values reported in Ref. 6.

The Cupola is a small room, just large enough for a crew-member to enter up to the waist, and the room is surrounded by windows that look out onto the Earth below. The Cupola is mostly used for photography and video. Acoustic levels in this small module have increased approximately 3 dB since 2010, but still meet its NC-50 requirement at NC-49.2, with a SIL(4) of 45.6 dB, and a sound level of 54.9 dBA.

Acoustic levels in the U.S. Lab have remained consistent, for the most part, since the 2011 update. Fig. 2 shows the SLM measurement locations in the U.S. Lab, and Fig. 3 shows the current U.S. Lab acoustic levels at locations 3, 5, and 8, as well as the spatial average spectrum of the locations shown in Fig. 2 (location 5 was omitted since it is not evenly spaced with the others).

Since 2010, levels in the U.S. Lab have remained very consistent, ranging from NC-50.2 to NC-52.8, except during times when stalling IMV fans caused sound levels to increase.⁶

During nominal IMV operations, U.S. Lab average SIL(4) ranged from 50.1 dB to 52.5 dB, and sound levels ranged from 56.6 dBA to 59.1 dBA. During these periods,

The JPM levels shown in Fig. 4 were measured on May 28, 2014 and are a spatial average of three measurement locations spanning the module. When compared to the corresponding levels in Ref. 6, the current data show increases from NC-45.8 to NC-47.4, from a SIL(4) of 46.0 dB to 47.0 dB, and a sound level increase from 52.7 dBA to 53.8 dBA. This small increase in acoustic levels also may have been caused by the addition of payloads to this laboratory module.

The JLP and PMM are basically stowage closets and remain at low levels. The JLP levels have increased from NC-42.1 to NC-44.2, from a SIL(4) of 39.6 dB to 44.1 dB, and a sound level increase from 47.1 dBA to 51.1 dBA. But, these levels are still very low, well below the JLP’s NC-50 requirement. The PMM noise levels have not changed

Acoustic levels in Node 2 are shown in Fig. 5. Levels at all six measurement locations remain below its NC-50 requirement, and the spatial average metrics (of the four central measurement locations) are NC-49.4, SIL(4) of 46.1 dB, and sound level of 54.1 dBA. Levels in Node 2 have consistently met NC-50, and this is important because four of the crew's sleep stations, i.e. Crew Quarters, are located within Node 2. These CQs contain continuously operating fans and make noise in addition to the Node 2 module, but these levels are low enough that NC-50 is still not exceeded.

Levels in Node 2 do exceed requirements significantly when any of the several IMV fans in Node 2 (or adjacent modules) are stalled. See Ref. 6 for more details.

Most of the exercise in the U. S. Segment takes place in the Node 3 module. The Treadmill 2 (T2) and Advanced Resistive Exercise Device (ARED) are located in Node 3, but these are considered intermittent noise sources. Their acoustic emissions are not included in the SLM measurements of continuous noise. T2 noise measurements have been made, and results of these measurements will be discussed, below.

Another significant intermittent noise source in Node 3 is the Waste and Hygiene Compartment (WHC). Acoustic emissions of the WHC are also discussed, below. Both T2 and WHC have continuous noise sources (cooling fans), but these are fairly quiet and do not impact Node 3's continuous noise levels.

Node 3 also houses the Regenerative Environmental Control and Life Support System (R-ECLSS). These racks recycle the air and water from crewmember's carbon dioxide exhalation, urine, and waste water, and this system requires pumps, separators, and other rotating/noise producing hardware. As a result, meeting acoustic requirements in Node 3 is very challenging. Similar to Node 2, Node 3 was successful in meetings its "core module" continuous noise requirement of NC-50. Its integrated continuous noise requirement including core module plus R-ECLSS hardware was set at NC-52. This is the actual NC-52 curve, and not the approximate NC~52. See Table 1 for the NC-52 and NC~52 SPL values in each octave frequency band.

Acoustic levels in Node 3 are shown in Fig. 6. Levels at all six measurement locations exceed NC-52 with exceedances in the 250, 500, and 1000 Hz octave frequency bands and nearly reach the NC-60 curve. The spatial average metrics (of the four central measurement locations) are NC-58.6, SIL(4) of 51.7 dB, and sound level of 61.5 dBA. Because of the low noise levels in the 2000 and 4000 Hz octave bands, the SIL(4) value is close to the SIL(4) value of the NC~52 curve. This indicates that voice communications in Node 3 are in line with requirements.

The noise produced by two R-ECLSS hardware racks, the Oxygen Generation System (OGS) rack and the second Water Reclamation System (WRS2) rack, cause the Node 3 noise exceedances. Specifically, the Urine Processing Assembly (UPA) in the WRS2 rack is the driving noise source. In an effort to quiet this source, the Mission Control

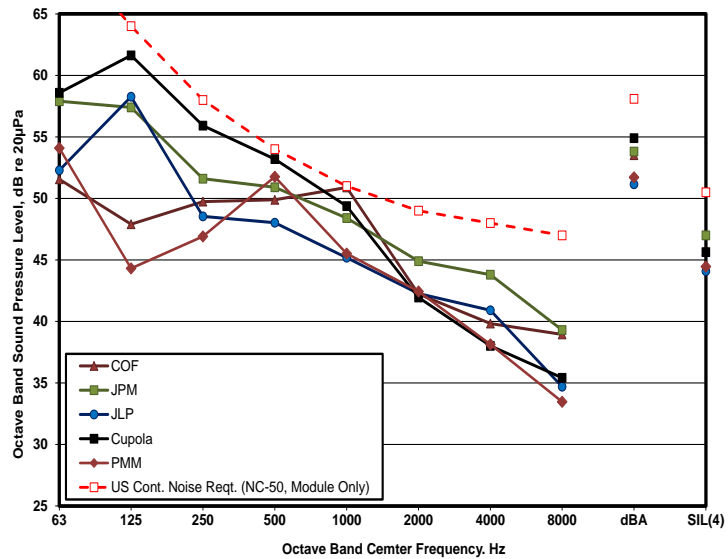


Figure 4. Current acoustic levels in COF, JPM, JLP, Cupola, and PMM (2014-2015).

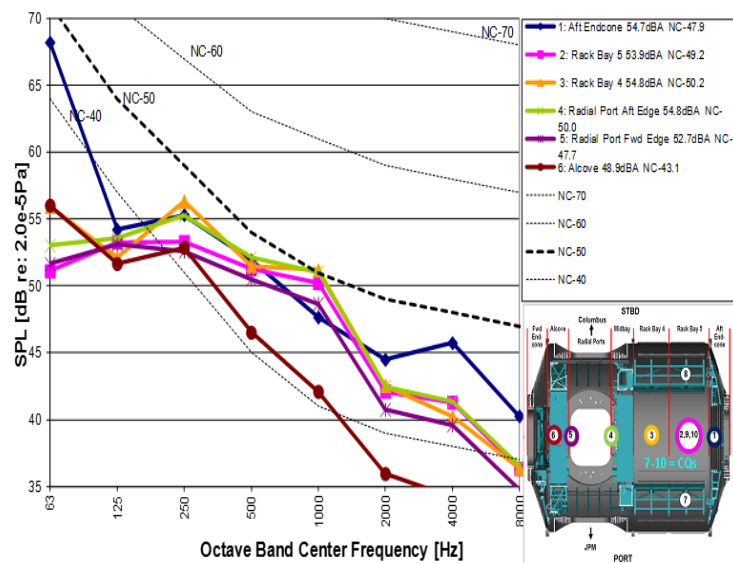


Figure 5. Current acoustic levels in Node 2 (April 1, 2015).

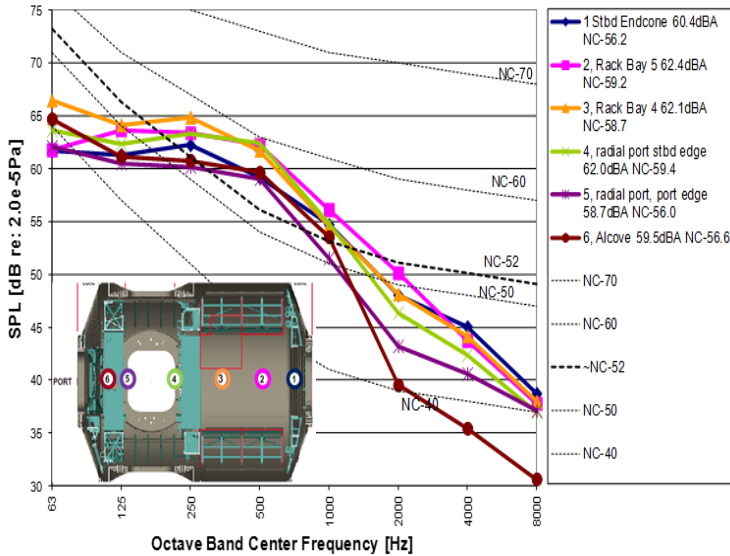


Figure 6. Current acoustic levels in Node 3 with Urine Processor Assembly off (April 1, 2015).

on high speed. At lower speeds this is also true (not shown). Sound levels of 50 dBA or below have been shown to be an acceptable level for restful sleep¹¹ and is the level required in the ISS Flight Rule B13-152, Noise Constraints Flight Rule for ISS sleep stations. A sound level of 62 dBA is considered in Flight Rule B13-152 that will provide adequate hearing rest from the day's noise exposure.⁷ The acoustic metrics inside the Starboard, Port, Overhead (Zenith), and Deck (Nadir) CQs are NC-49.7, NC-46.1, NC-46.7, and 43.7 and sound levels of 50.4 dBA, 50.1 dBA, 49.5 dBA, and 49.1 dBA, respectively. SIL(4) values are not relevant since CQs are only designed to house one crewmember.

Finally, Fig. 8 summarizes the latest spatial average acoustic levels in each of the U.S. Segment modules. Levels in Node 3 are shown both with and without the UPA in operation. However, these data were acquired on different days, and the difference between the levels with and without the UPA do not clearly show the impact of UPA operations.

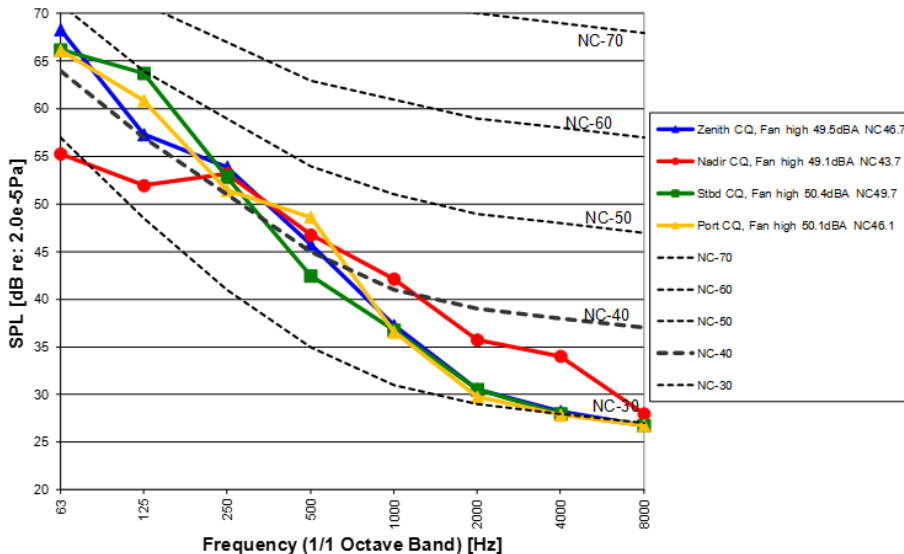


Figure 7. Current Crew Quarters acoustic levels (April 1, 2015).

Center in Houston (MCC-H) operates the UPA during the crew's sleep period, if possible. New sound blocking rack doors for WRS2 are being developed and will be delivered to ISS in 2015. If successful, new doors for the OGS rack may also be considered.

See Ref. 6 for more details on the Node 3 noise levels, including the levels of the core module without the R-ECLSS racks.

The acoustic levels inside the four Node 2 Crew Quarters (CQs) are shown in Fig. 7. These are the levels with the CQ fans on the high setting. The levels are generally lower at the two other fan speeds. The design requirement for interior of the CQs is NC-40, and levels at the lowest fan speed are below or close to this value (not shown). Fig. 7 shows that the sound levels of each CQ are at 50 dBA or below with their fans operating

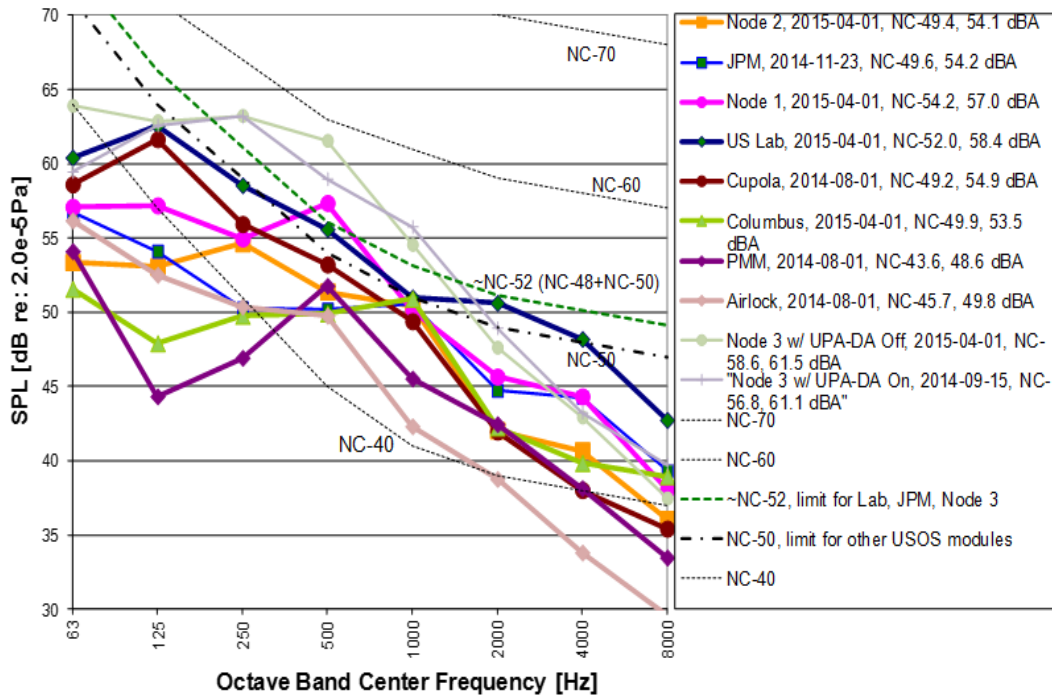


Figure 8. Summary of current average acoustic levels in U.S. Segment Modules (as of April 1, 2015).

IV. Russian Segment Acoustic Levels

In the 2011 ISS Acoustics status update, Ref. 6, the noise controls implemented as part of the Service Module (SM) remedial action plan (RAP) were discussed in detail. These noise controls were added to the air conditioning system (acronym CKB in Russian), carbon dioxide removal system (Vozdukh), and to the ventilation system. The CKB controls included a compressor acoustic wrap, hose lagging, fan acoustic cover, and a new/improved acoustic close-out panel on each of the two CKB units. Vozdukh noise controls included an acoustic form-fitted cover over the micro-compressor and additional acoustic blankets between the micro-compressor and close-out panel. Ventilation system controls included fan vibration isolators and casing wraps on many of the 40+ fans in the SM. Several of these fans were also equipped with inlet and/or outlet mufflers. Please refer to Ref. 6 for details, including photographs and discussion of their effectiveness.

In addition to these noise controls, status on the development of a new quiet-design fan to replace many of the SM and other Russian Segment fans was discussed, including the aerodynamic and acoustic performance of the new fan design, which were both vastly improved over the previous fan model. By 2011, only two of these fans had been installed in the Mini-Research Module #1, MRM1, and noise reductions of this installation were presented.⁶

In the following discussion, details of the subsequent quiet fan installations and their noise reducing effects will be discussed in detail. These installations, so far, have occurred in the SM, MRM1, MRM2, and Docking Compartment (DC1). Acoustic levels in the Functional Cargo Block (FCB) and SM crew cabins, called kayutas, will also be presented.

A. Quiet Fan Installations

The Service Module contains more than 40 fans as part of its ventilation system. These fans contribute significantly to the acoustic levels within the SM. The fans are placed throughout the SM, within airflow ducting, in spaces behind closeout panels (as there is airflow behind the panels in the equipment compartment), and also may be mounted freely in the working compartment.

In Fig. 9, the working compartment air exits the air conditioner through fans at the forward end of the SM and then flows towards the aft end of the SM. The air is conducted by fans into the return-air ducts as shown, and then back to

the air conditioner. Also in Fig. 9, the starboard kayuta (Russian sleep station) is shown. Note that a fan near the middle of the SM ventilates the kayuta by drawing air into a short duct and then exhausting the air into the kayuta ceiling where a large circular register distributes the air. The air then exits the kayuta through a grill in the lower portion of the kayuta door into the working compartment. A similar but mirrored arrangement is present with the port kayuta on the other side of the SM. With the four CQs in Node 2, these two kayutas make up the six ISS crew sleep stations.

Fig. 10 shows all of the SM fans, 19 of which have been replaced with quiet fans beginning in 2012. Seven were replaced in 2012, nine were replaced in 2013, and three were replaced in 2014. SM sound levels since Increment I are given in Fig. 11, and the dates where the quiet fan installations occurred are indicated in this figure. Also shown in Fig. 11 is the RAP contract goal of 63 dBA. And with the current quiet fan installations, it is seen that the sound levels in some locations are below 63 dBA, while the other locations in the main part of the cabin are close to 63 dBA.

The resulting acoustic levels measured in the SM are shown in Figs. 12 and 13 compared to the Russian Segment specification. Note that for the Russian Segment a sound level requirement of 60 dBA is also in force, with 63 dBA being the RAP goal. The spatial average acoustic metrics for the main cabin, i.e. spatial average of the centerline locations, 3, 4, 8, and 12, of the SM for the SLM survey taken November 23, 2014 are NC-58.1, SIL(4) of 56.2 dB, and sound level of 63.5 dBA. The lowest noise

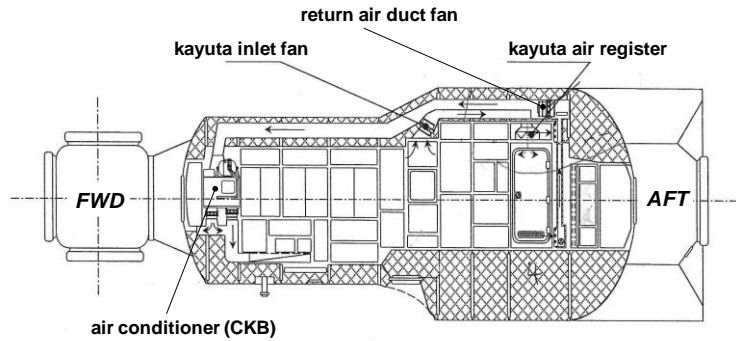


Figure 9. Geometry and airflow inside the Service Module.

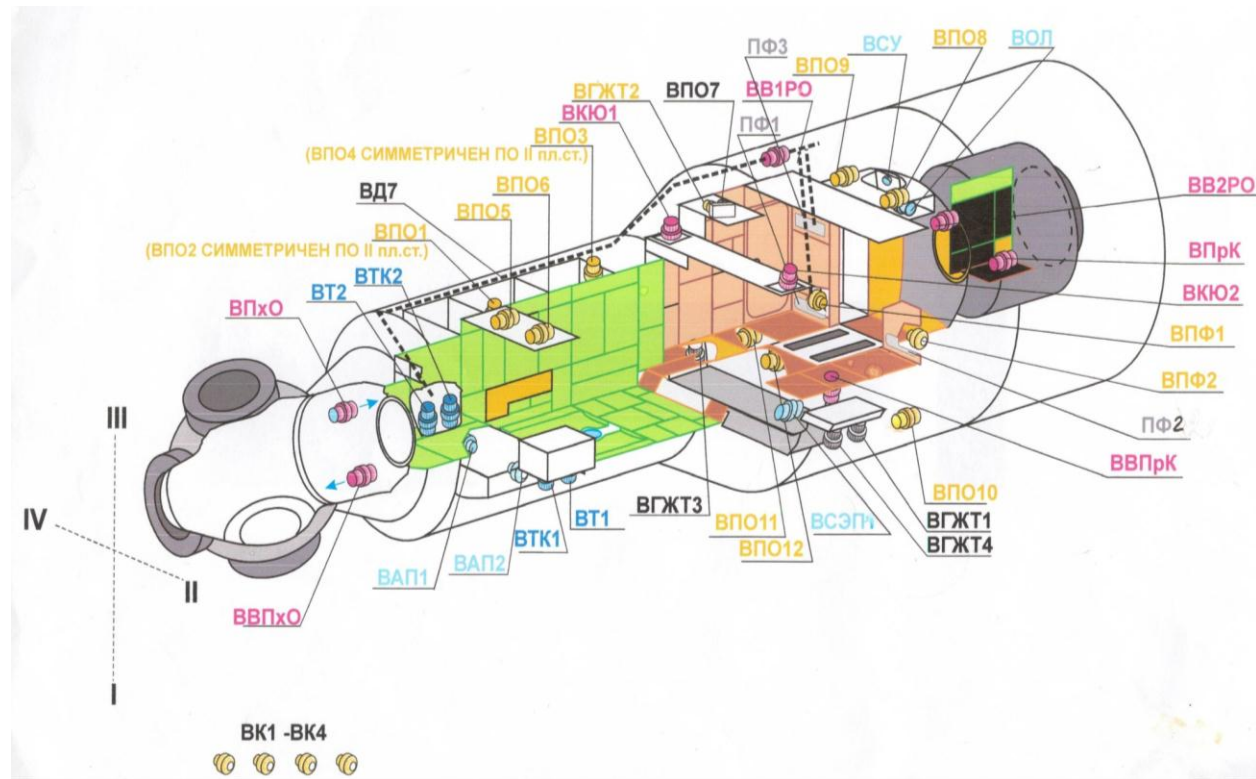


Figure 10. Service Module fans.

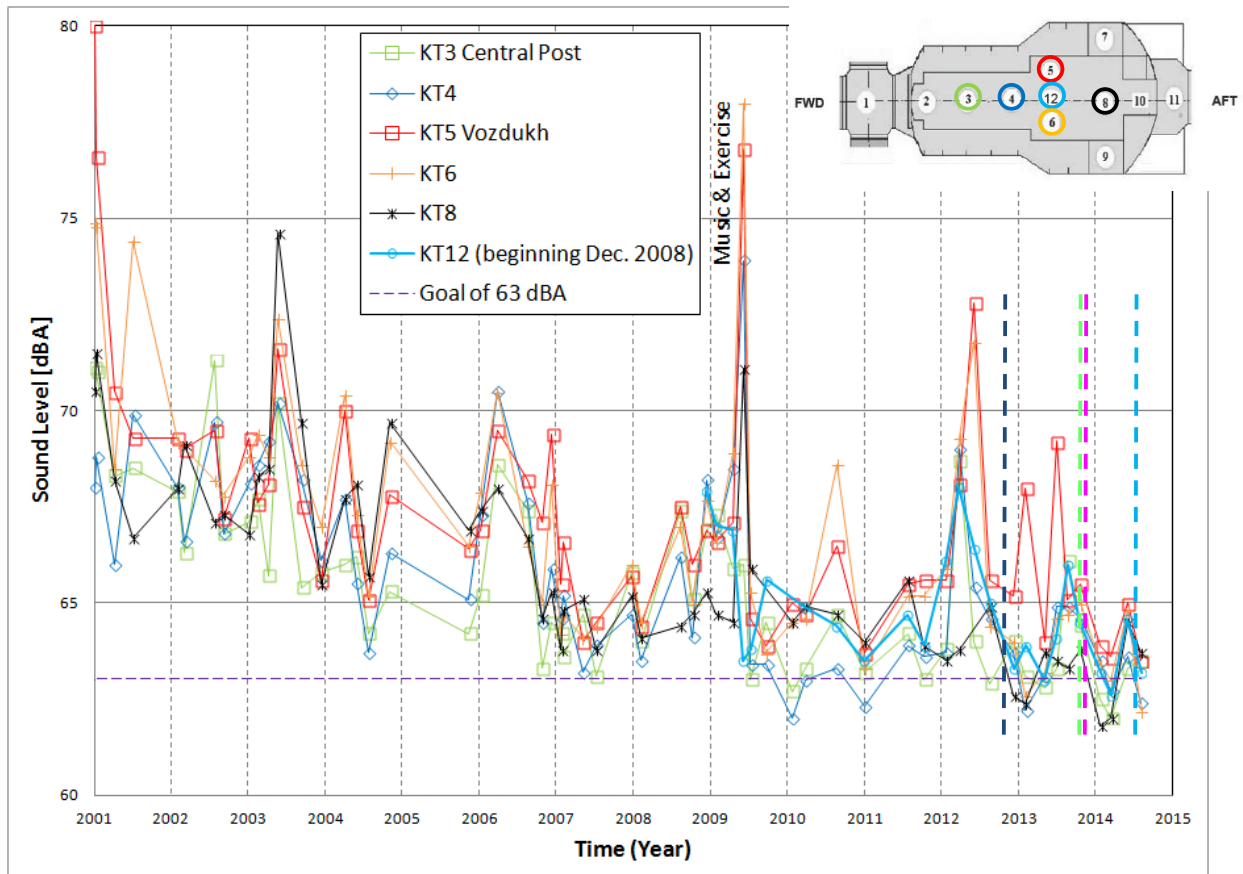


Figure 11. Sound levels as a function of time in the main portion of the Service Module.

levels in the SM were measured on September 15, 2014, and these main SM cabin levels are shown in Fig. 14. The spatial average metrics for this measurement are NC-56.2, SIL(4) of 54.3 dB, and sound level of 62.0 dBA.

Noise levels in the kayutas have remained consistent since 2011. Fig. 15 shows the acoustic levels in each kayuta, taken on April 1, 2015, with sound levels in the starboard and port kayutas of 55.0 dBA and 53.1 dBA, respectively. These levels are typical; however, there is some evidence that the quiet fan installations are reducing levels in the kayutas, as well. The lowest levels ever measured inside the kayutas were measured on September 15, 2014, and are shown in Fig. 16. These levels are nearly in full compliance with the Russian Segment specifications with sound levels in the starboard and port kayutas of 50.8 dBA and 50.2 dBA, respectively. It is unclear what caused the kayuta levels measured on September 15, 2014 to be lower than other surveys. It may be that the sleep station doors were shut more tightly than usual, allowing the noise reducing effects of the quiet fans to become evident.

The Russian Segment sleep specification requires levels to be 50 dBA inside the kayutas, in agreement with the ISS Flight Rule B13-152. As discussed above, the SM kayuta sound levels are typically slightly above this level, but there have been no complaints of sleeplessness due to noise. It should also be noted that the typical kayuta levels are well below the 62 dBA required for hearing rest. Further discussion of kayuta and CQ noise levels as they relate to the ISS crew's noise exposure is presented by Limardo et. al.⁷

In Ref. 6, the high noise levels in the Mini-Research Module #1 (MRM1) were presented along with noise level reductions in MRM1 after the replacement of the two heat exchanger fans with quiet-design fans. Since then, an additional fan was replaced in 2012 and another in 2014. Four out of the MRM1's five fans have been replaced. Fig. 17 shows the noise level reductions achieved with the first two replacement fans as well as with four out of five MRM1 fans replaced. Significant noise reductions greater than 10 dB in frequency bands of 1000 Hz and above are seen in Fig. 17, along with overall sound level reductions of 11 dBA and 9 dBA at the two locations shown. Fig. 18 shows the resulting acoustic levels throughout the entire module. Note that the acoustic levels closer to the docked Soyuz (nadir end of MRM1), where there are no MRM1 fans, are higher than the levels throughout the rest of MRM1. This indicates that noise is coming into MRM1 from the Soyuz, which is known to have high noise levels. Sound Levels in the MRM1 are now low enough that they meet the MRM1's limited occupancy noise requirement of 63 dBA, and as a result the MRM1 acoustics Safety Non-compliance Report (NCR) has been retired.

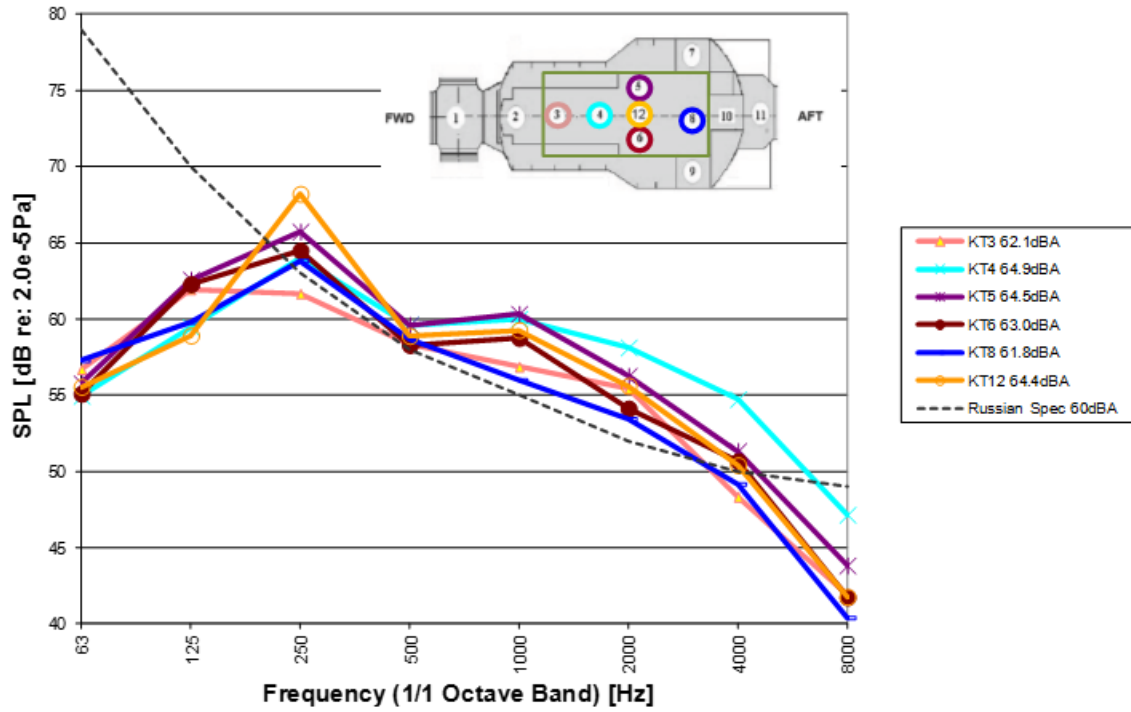


Figure 12. Octave Band Sound Pressure Levels in the main portion of the Service Module (November 23, 2014).

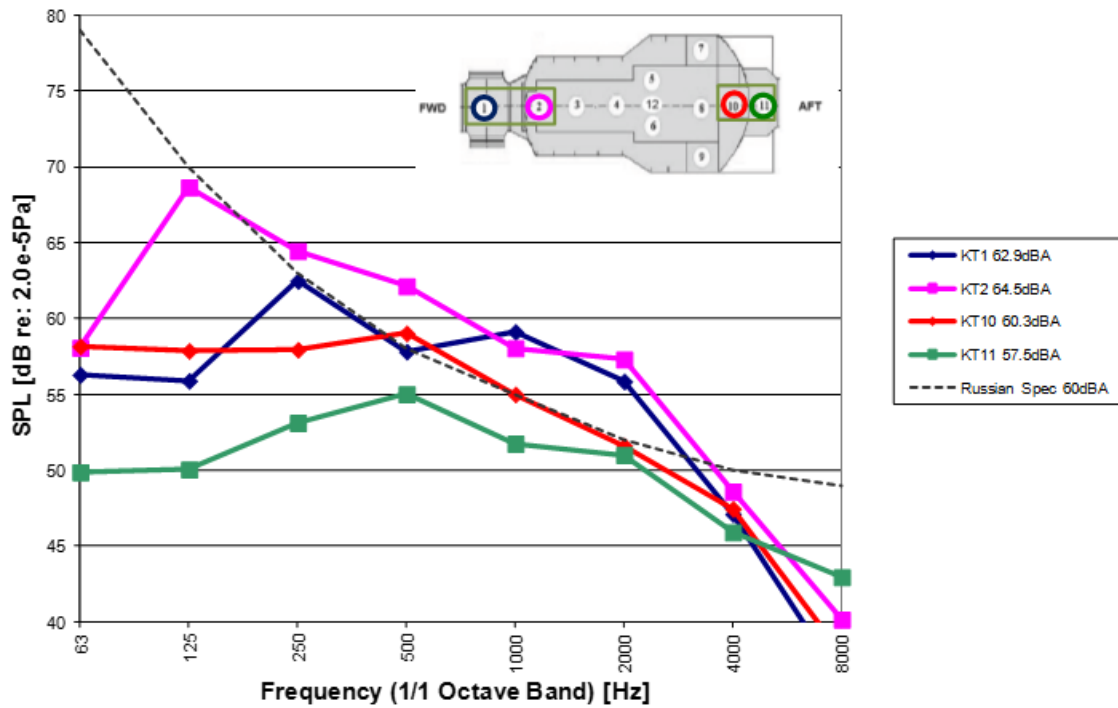


Figure 13. Octave Band Sound Pressure Levels at the ends of the Service Module (November 23, 2014).

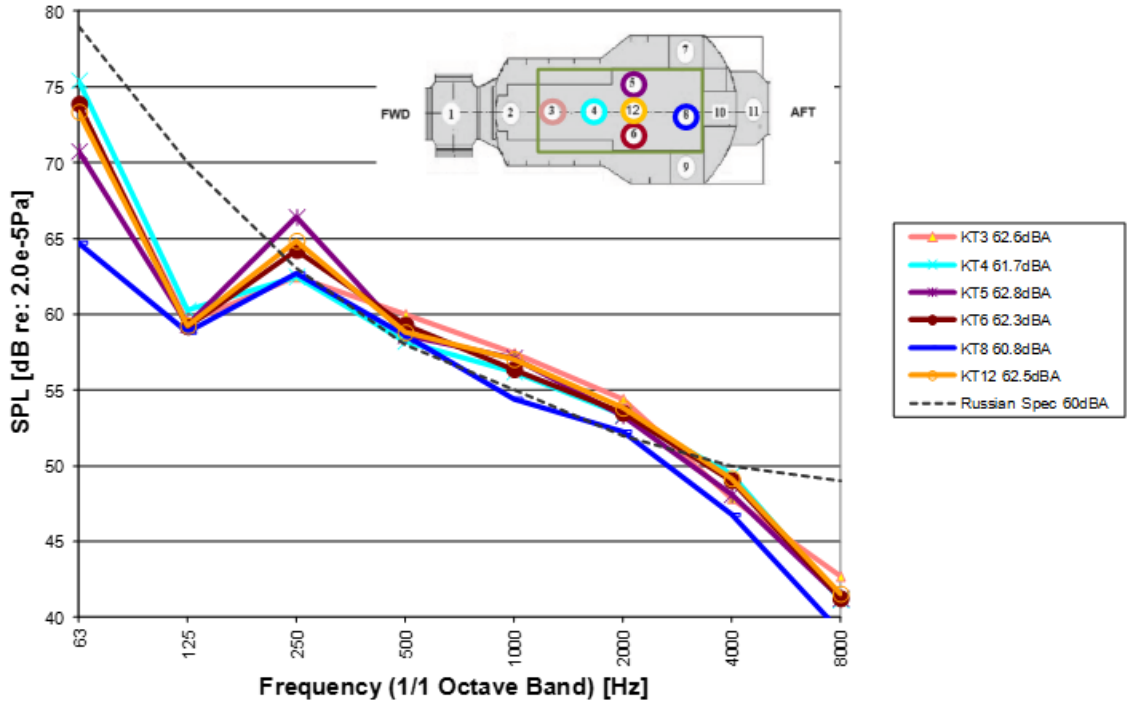


Figure 14. Octave Band Sound Pressure Levels in the main portion of the Service Module (September 15, 2014).

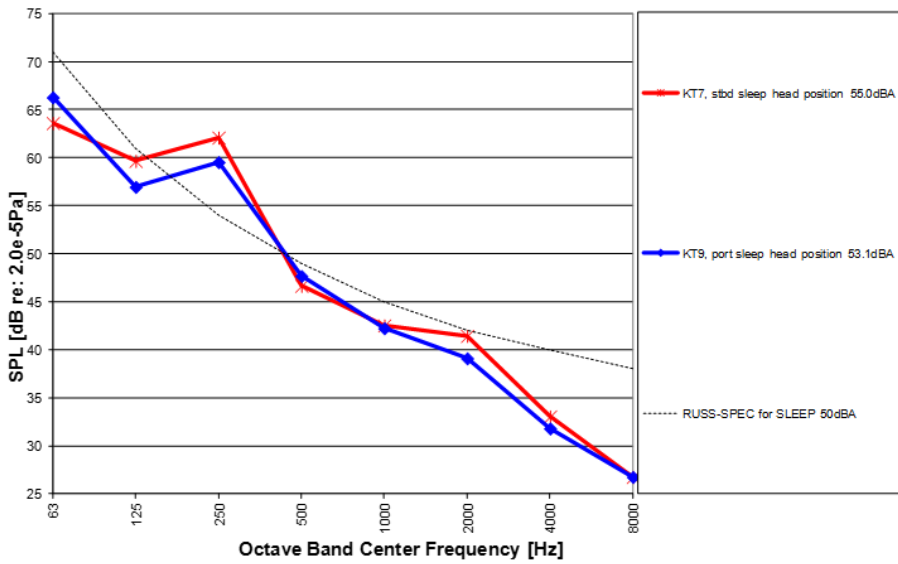


Figure 15. Starboard and port kayuta sound pressure levels. (April 1, 2015)

Recently, quiet fan replacements were installed in the Docking Compartment (DC1) module. All three of the DC1 Fans were replaced with quiet fans in March 2015. A comparison of acoustic levels before and after these replacements is shown in Fig. 19. Significant reductions, some greater than 10 dB, are seen in most of the octave band SPLs as well as reductions of 7-10 dBA. Fig. 20 shows that the average SPLs and sound levels in DC1 now meet the Russian continuous noise specification, including the 60 dBA sound level requirement. As a result of the quiet fan installations, DC1 has gone from being one of the loudest Russian Segment module to the quietest module.

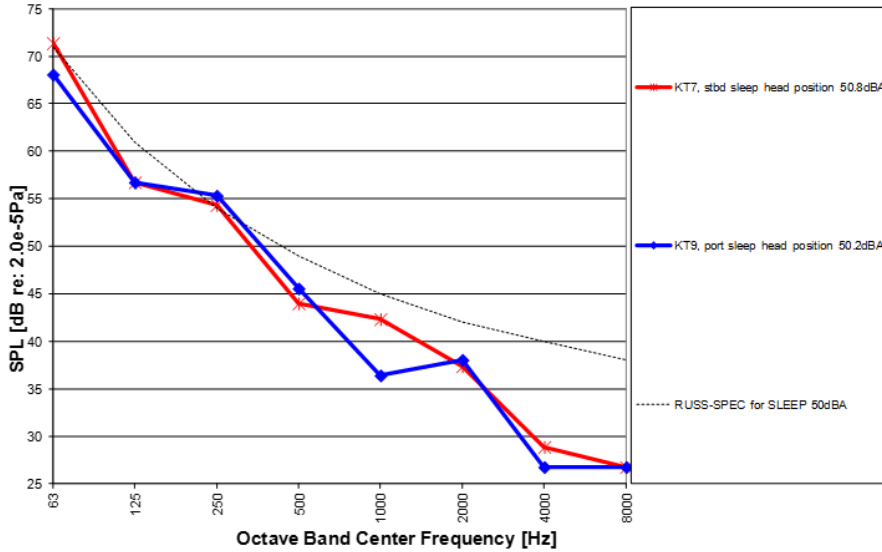


Figure 16. Starboard and port kayuta sound pressure levels. (September 15, 2014)

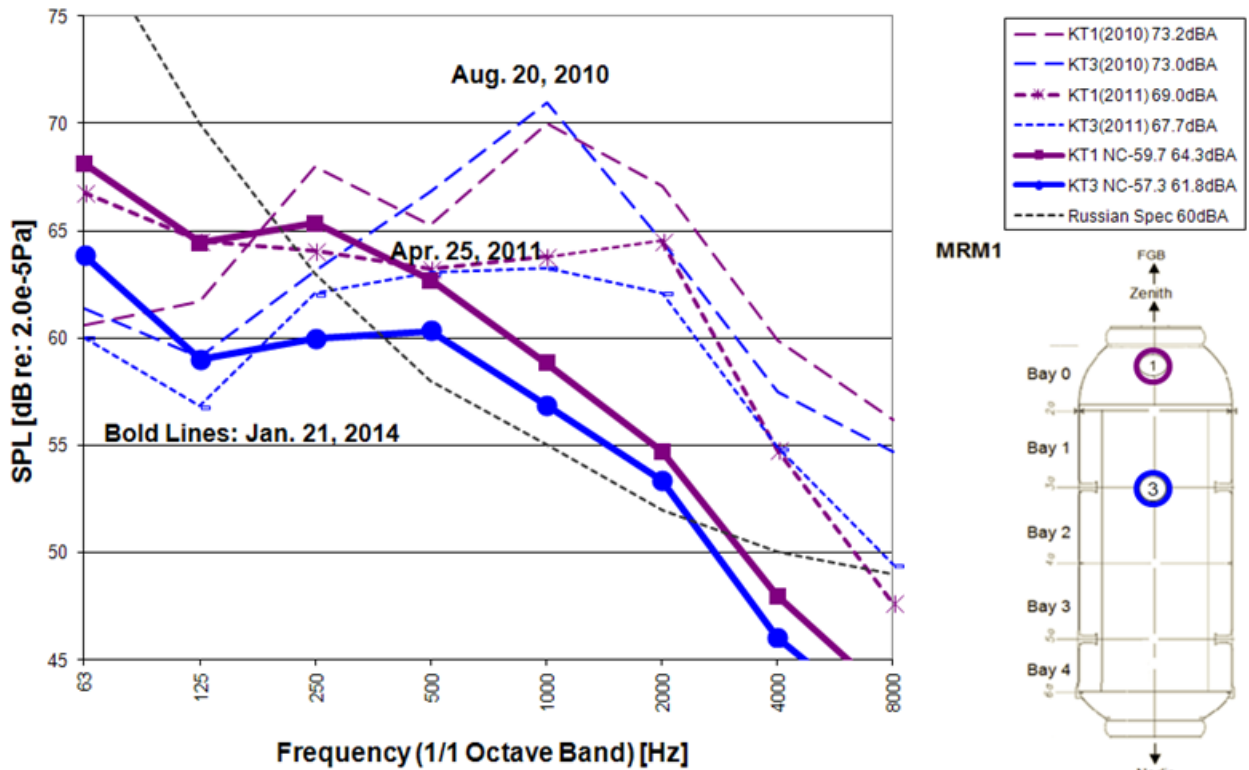


Figure 17. Acoustic level reductions in MRM1 since replacement of 4 old-style fans with quiet fans.

Finally, in the MRM2 and FGB modules, no fans have been replaced with quiet fans at this time. However, quiet fan installations are planned to happen in both modules in the near future.

Fig. 20 gives the current spatial average acoustic levels inside all of the Russian Segment modules including the MRM2 and FGB. The SM spatial average in Fig. 20 is taken from the centerline locations, 3, 4, 8, and 12.

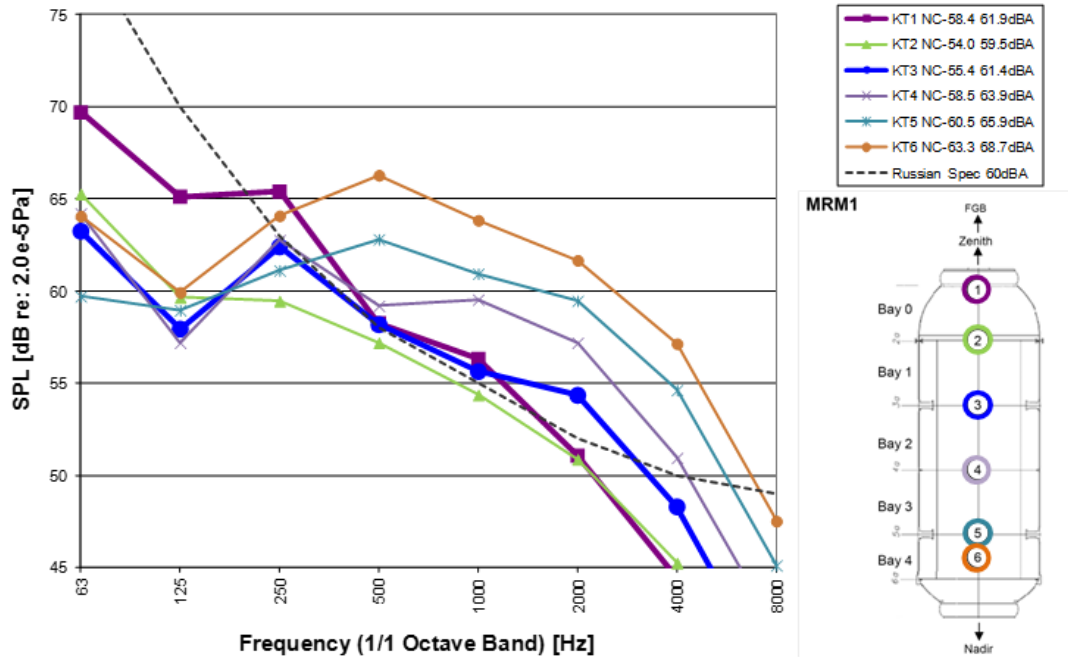


Figure 18. Acoustic levels in MRM1 since replacement of 4 old-style fans with quiet fans. (September 15, 2014).

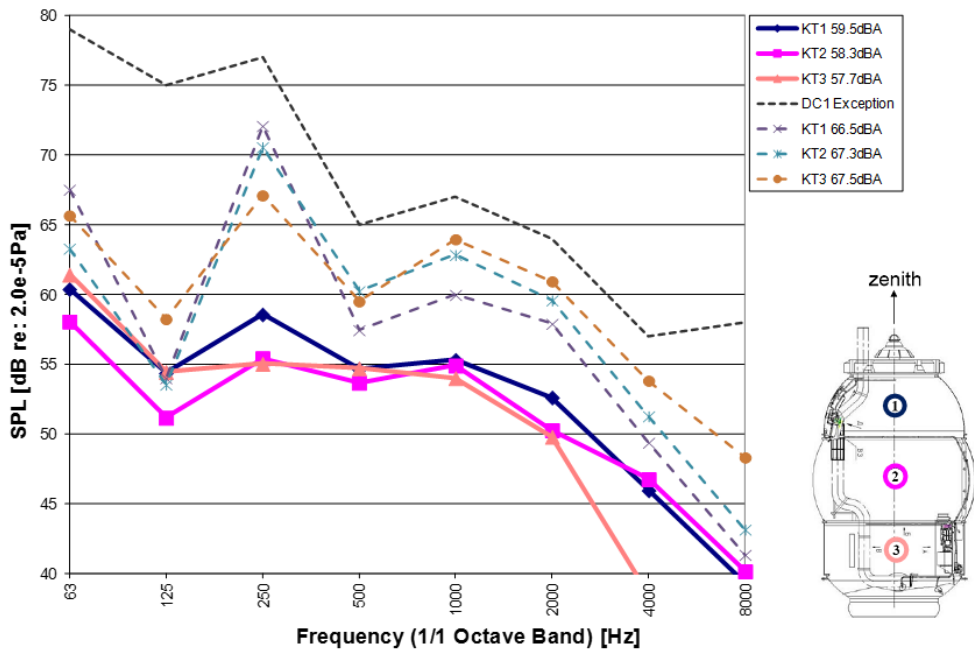


Figure 19. Acoustic Levels in DC1 before and after replacement of 3 old-style fans with quiet fans, compared with requirement exception levels. (April 1, 2015).

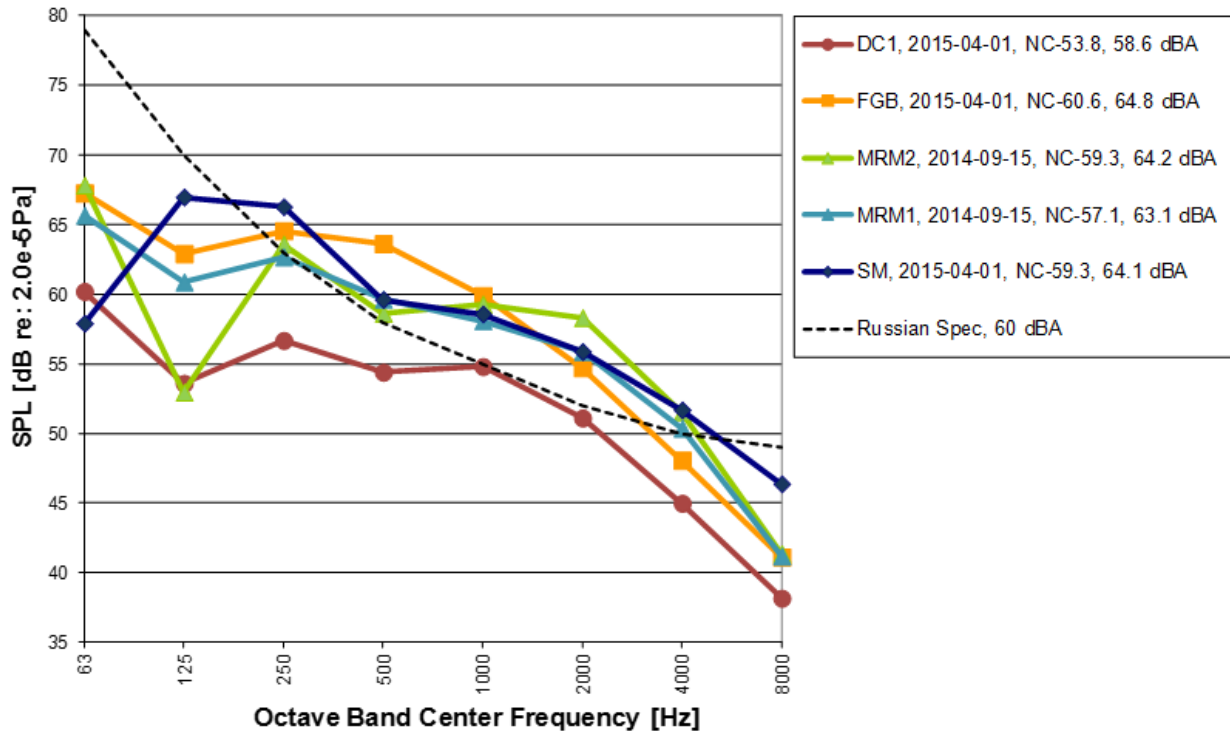


Figure 20. Summary of current average acoustic levels in Russian Segment Modules (as of April 1, 2015).

V. On-Orbit Acoustic Issue Resolution

Even though extensive efforts are made to resolve significant acoustic issues while flight hardware is still on the ground, issues resulting in high acoustic levels do occasionally happen on-orbit. These issues are worked and resolved through Mission Control. The solutions come in the form of hardware fixes (replacement or maintenance), noise controls, or as a last resort, hearing protection use in accordance with Flight Rule B13-152. This section will discuss two recent on-orbit issues, including: 1) on-orbit Waste and Hygiene Compartment (WHC) hazardous noise levels and resolution, and 2) Treadmill 2 (T2) hazardous noise levels and proposed resolution.

In March 2014, the crew reported that noise levels inside the Waste and Hygiene Compartment (WHC) were high. Review of crew-worn and static (fixed location) Acoustic Dosimeter data indicated that levels exceeded the 85 dBA Hazard Limit. As a result, the crew were asked to wear hearing protection devices (HPDs) as specified by Flight Rule B13-152.¹² A SLM measurement was performed as well as audio recordings using a video camera. The SLM data are shown in Fig. 21, where sound levels are shown to be 87 dBA, 20 dBA higher than nominal. The spectral shape is also clearly too high and abnormal, with a peak of 85 dB in the 1250 Hz 1/3 octave frequency band. Analysis performed on the audio recordings indicated gear-wear in the pump-separator unit was causing this noise. The pump-separator orbital replacement units (ORUs) are typically replaced approximately every 6 months. But, because of the high-levels of noise, this ORU was replaced sooner than usual. And once the pump-separator was replaced, the noise levels returned to nominal. Nominal WHC noise levels, with approximate sound levels of 67 dBA are also shown in Fig. 21, along with a measurement inside the WHC with the pump-separator turned off (54 dBA). Further discussion and analysis of the Acoustic Dosimeter data concerning this WHC noise issue is presented by Limardo et. al.⁷

As with the WHC, the crew reported a high-noise issue with the ISS Treadmill 2 (T2). Acoustic levels from T2 were originally measured on the ground during T2's certification testing which took place in an anechoic chamber located at Johnson Space Center. Predictions including ISS module reverberation were also performed and indicated that while T2 did not meet its original noise requirement its noise level would meet flight rule levels and would not require mandatory hearing protection use. T2 was originally installed in Node 2, and SLM measurements were made

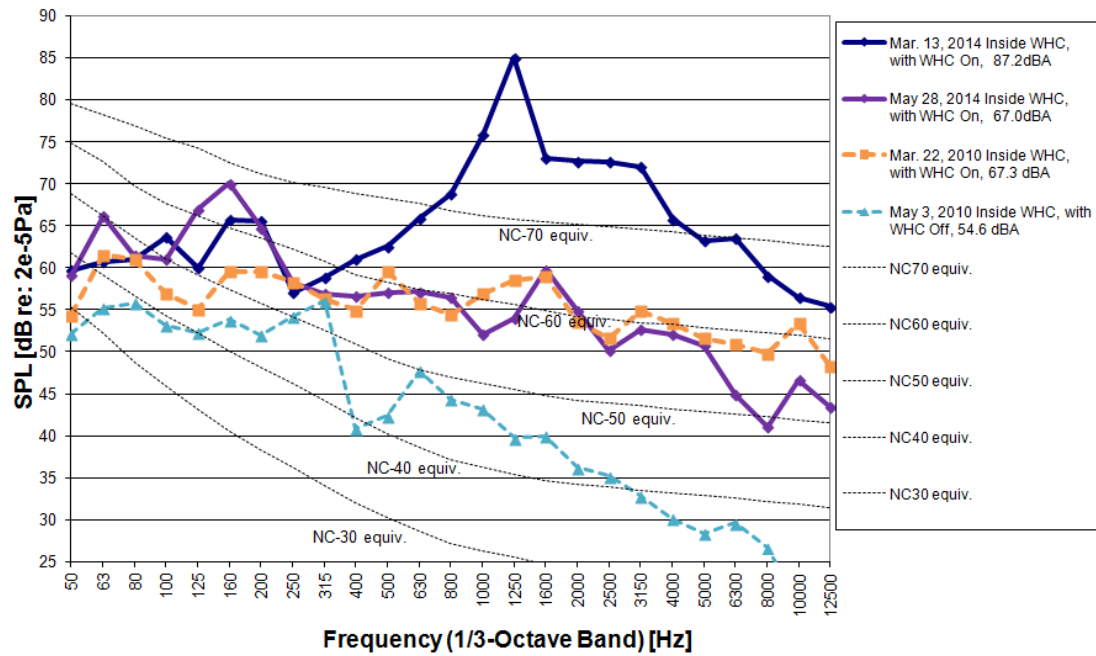


Figure 21. Acoustic Levels the WHC, before, during, and after resolution of loud pump-separator.

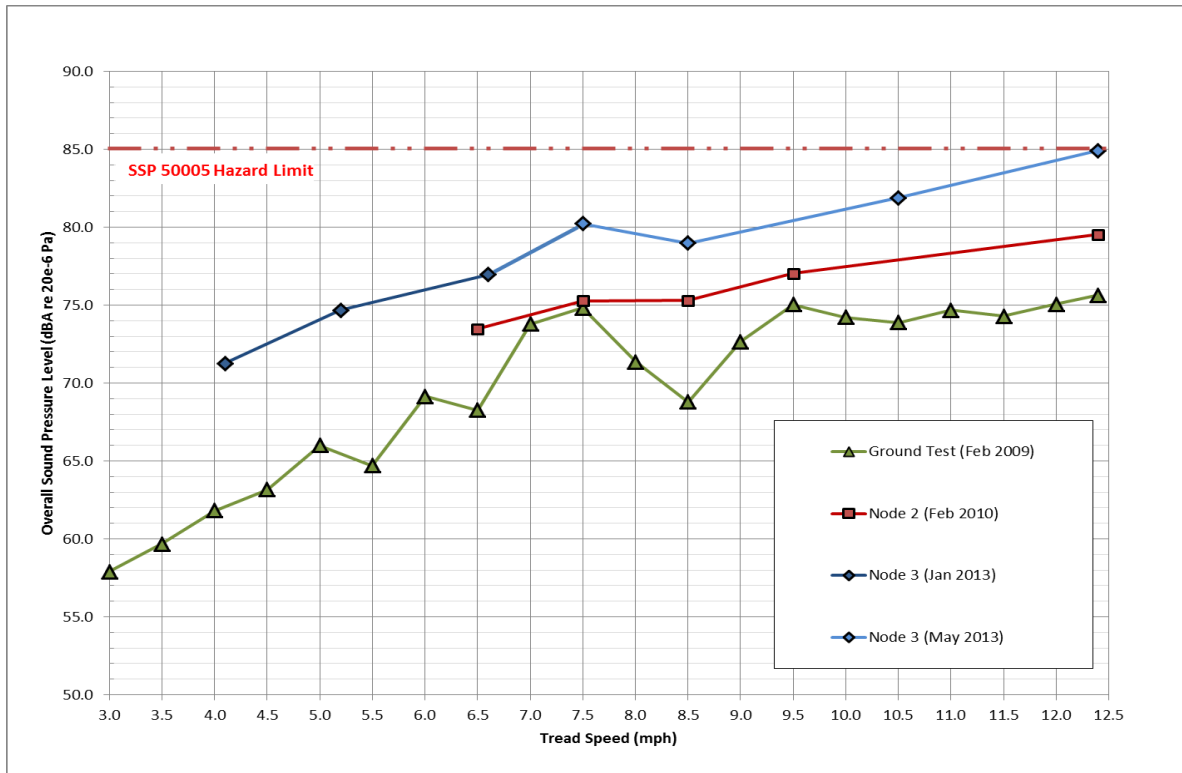


Figure 22. T2 sound levels at runner's ear as a function of tread speed, compared to ISS Hazard Level.

of it operating at this location. Results from the original anechoic chamber testing and Node 2 SLM measurements are shown in Fig. 22, and the Node 2 results agreed with the predicted noise levels.

After the Regenerative ECLSS racks were installed in Node 3, the T2 was moved from Node 2 to Node 3. Since Node 2 and Node 3 are very similar in geometry and construction, as was the location of the T2 within the nodes, it was thought that T2 noise levels within Node 3 would be similar to the levels with T2 in Node 2. However, after the crew reported that T2 levels in Node 3 seemed high, another SLM survey of Node 3 was performed with T2 operating. Fig. 22 also shows results of this survey, performed in two parts in January 2014 and May 2014. From this figure it is clear that T2 sound levels in Node 3 are significantly higher, ~ 5 dBA, than the levels measured in Node 2. And, as the treadmill's speed increases up to 12 mph, the sound levels reach the Hazard Level. As a result, when T2 operates at speeds above 10 mph, which is easier to sustain in microgravity, the crew are asked to wear HPDs.

The cause of the T2's higher noise levels when installed inside Node 3 instead of in Node 2 is thought to be a result of acoustic reflections. The WHC "Kabin", the privacy partition that sticks out into the aisle way, provides a reflection surface that is adjacent to and very close to the T2 tread belt, which is T2's dominant noise source. In addition, when in Node 2, the T2 was surrounded on three sides by CQs. The large CQ interior cavities and external acoustic treatment, though very thin, may have absorbed some of T2's noise emissions when in Node 2.

Based on the theory of increased reflections and reverberation in Node 3, sound absorbing blankets are being developed and will be applied on the WHC and one other rack surface near the T2 to absorb this noise. It is out of the scope of this paper to describe in detail the design of the acoustic blankets, however this is to be reported on in the future. The blankets are currently under construction and are scheduled to be delivered to ISS and installed by early 2016.

VI. Conclusion

Since 2011, acoustic levels in the ISS U.S. Segment have remained consistent, with all modules meeting their respective requirements, except Node 3. Node 3 exceedances are caused by the Regenerative ECLSS racks, of which the WRS2 rack is hoped to be quieted with new rack-doors in 2016. Stalled IMV fan noise did impact the U.S. Lab, Node 2, Node 3, JPM, and COF for periods of time, but these noise increases were temporary and were recovered to nominal levels after the stalled fans were identified and cleaned. The NC~52 composite requirement for modules with payloads was made explicit instead of applying two separate requirements, one for the vehicle and one for the payload complement. ISS CQ levels also remain consistent with interior sound levels of 50 dBA or less.

In the Russian Segment, since 2011, improvements in noise levels were seen as a result of the installation of more than 25 quiet-design fans. Sound levels in the DC1 were reduced by 9 dBA, and its acoustic levels now meet the Russian Segment specification for continuous noise during work hours. Sound levels in the MRM1 were reduced by 10 dBA from its initial levels, and its acoustic levels now meet its Russian Segment specification for reduced crew occupancy. The MRM1 Safety NCR was retired as a result. Sound levels in the SM were reduced by a more modest amount, ~1-2 dBA, because of the large number of original fans remaining. However, the lowest average levels ever documented in the SM were measured to be 62 dBA, with typical noise levels reduced down to ~63 dBA, which is the Remedial Action Plan goal. The noise levels in the kayutas were also measured at their lowest levels, near 50 dBA with octave band SPLs essentially meeting the Russian Segment specification for sleep. The levels in the kayutas varied, however, possibly because of kayuta door positioning.

Two on-orbit acoustic issues were discussed. High noise levels produced by the WHC were first mitigated through hearing protection use, and later remediated with the replacement of the pump-separator. High noise levels produced by the T2 treadmill continue to be an issue. The crew wears hearing protection when using T2. Acoustic blankets are currently being developed mitigate these levels, and are hoped to be installed in 2016.

Acknowledgments

The author would like to thank Steve Morris of Boeing Environments for his help with the planning, analysis, and plotting of the SLM data. Thanks also go to Holly Smith-Dalenberg, Andrew Boone, and Kenny Rafanan of the Bioastronautics Contract for their help with SLM measurements planning, execution, and support in Mission Control. Finally, these measurements would not have been possible without the support from Ariel Macatangay, Brian Balu, and the Bioastronautics Contract hardware engineering team, who arranged for calibration, manifesting, and shipment of the acoustic measurement hardware for delivery to ISS.

References

- ¹Goodman, J. R., “International Space Station Acoustics,” *Proceedings of NOISE-CON 2003*. Washington, DC: US Institute of Noise Control Engineering, 2003.
- ²Allen, C. S., and Goodman, J. R., “Preparing for Flight – The Process of Assessing the ISS Acoustic Environment,” *Proceedings of NOISE-CON 2003*. Washington, DC: US Institute of Noise Control Engineering, 2003.
- ³Grosveld, F.W., Goodman, J.R. and Pilkinton, G.D. “International Space Station acoustic noise control - Case studies,” *Proceedings of NOISE-CON 2003*. Washington, DC: US Institute of Noise Control Engineering, 2003.
- ⁴Phillips, E., and Tang, P., “ISS Human Research Facility (HRF) Acoustics,” *Proceedings of NOISE-CON 2003*. Washington, DC: US Institute of Noise Control Engineering, 2003.
- ⁵Goodman, J.R., and Grosveld, F.W. “Acoustics in habitable space vehicles and enclosures,” *Proceedings of the Third IAASS Conference*, Rome, Italy, 21-23 October 2008.
- ⁶Allen, C. S., and Denham, S. A., “International Space Station Acoustics – A Status Report,” *Proceedings of International Conference on Environmental Systems 2011*. American Institute of Aeronautics and Astronautics, AIAA 2011-5128, 2011.
- ⁷Limardo, J., Allen, C. S., and Danielson, R. W., “Status: Crewmember Noise Exposures on the International Space Station,” *Proceedings of International Conference on Environmental Systems 2015*, ICES 2015-239, 2015.
- ⁸Limardo, J., 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.
- ⁹Pilkinton, G.D. “ISS Acoustics Mission Support,” *Proceedings of NOISE-CON 2003*. Washington, DC: US Institute of Noise Control Engineering, 2003.
- ¹⁰ANSI S12.65-2006, American National Standard for Rating Noise with Respect to Speech Interference, 2006.
- ¹¹Kim, R., and van den Berg, M., “Summary of night noise guidelines for Europe,” *Noise and Health*, 12:47, 2010, pp. 61-63.
- ¹²NSTS-1282, “ISS Generic Operational Flight Rules,” Vol. B, B13-152, “Noise Level Constraints.”