

International Space Station Acoustics – A Status Report

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Abstract

It is important to control acoustic noise aboard the International Space Station (ISS) to provide a satisfactory environment for voice communications, crew productivity, 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 analysis 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 indicate 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 2003¹. Many new modules, and sleep stations have been added to the ISS since that time. In addition, noise mitigation efforts have reduced noise levels in some areas. As a result, the acoustic levels on the ISS have improved.

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¹Jerry R. Goodman, "International Space Station Acoustics," *NOISE-CON*, Conf (2003).

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International Space Station Acoustics – A Status Report

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It is important to control acoustical noise aboard the International Space Station (ISS) to provide a satisfactory environment for voice communications, crew productivity, 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 detect 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 2003. Many new modules, and sleep stations have been added to the ISS since that time. In addition, noise mitigation efforts have reduced noise levels in some areas. As a result, the acoustic levels on the ISS have improved.

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>OASPL</i>	=	when A-weighted, is also referred to as the “Sound Level” 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 as long as six months. And while the crew lives and work 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

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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 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 Subgroup in conjunction with the system teams which own the noise producing hardware, such as the Environmental Control and Life Support 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 Grosveldt et al.,³ Phillips and Tang,⁴ and by Goodman and Grosveldt⁵ on implementation of noise control for spaceflight vehicles in general.

The purpose of the current paper is to provide an updated status and documentation of the acoustic levels in the ISS since the first reporting of the levels in 2003 by Goodman.¹ Several new rooms, i.e. modules, have been added to the ISS, along with new sleep compartments. Also, noise remediation has been performed in the Russian Segment's Service Module. Finally, two examples of on-orbit noise problems and their resolutions will be discussed. These include intra-module ventilation fan (IMV) fan clogging, and a ventilation system back-pressure plate noise problem.

The sound pressure level(SPL) data provided in this paper were measured by the ISS on-orbit crew, using a Bruel and Kjaer 2260 Sound Level Meter (SLM). Crew-worn and fixed-location acoustic dosimeter measurements for the current time-frame are described by Limardo.⁶ The acoustic instrumentation, processes, and further discussion of acoustic monitoring aboard the ISS are described by Pilkinton.⁷

II. U. S. Segment Acoustic Levels

In 2003, the ISS U.S. Segment included the Node 1, Airlock, and U.S. Lab modules. Sound levels in Node 1 include an accepted exceedance to the NC-50 requirement in the 500 Hz octave band, and the SPL in this band fluctuates significantly over time, though average levels are fairly consistent. In order to present the most representative levels for Node 1, Figure 1 shows the acoustic levels from a spatial average over the four measurement locations in Node 1 and this spatial average is also averaged over time for measurements taken since 2002.

Airlock levels have remained consistently below the NC-50 continuous noise requirement, except at 500 Hz where levels meet NC-50, since 2003; however, depending on the amount of stowage in the Airlock's Crew Lock, levels inside that module can be significantly reduced, as shown in Fig. 1. Figure 1 shows acoustic levels in the U.S. Airlock and in Node 1.

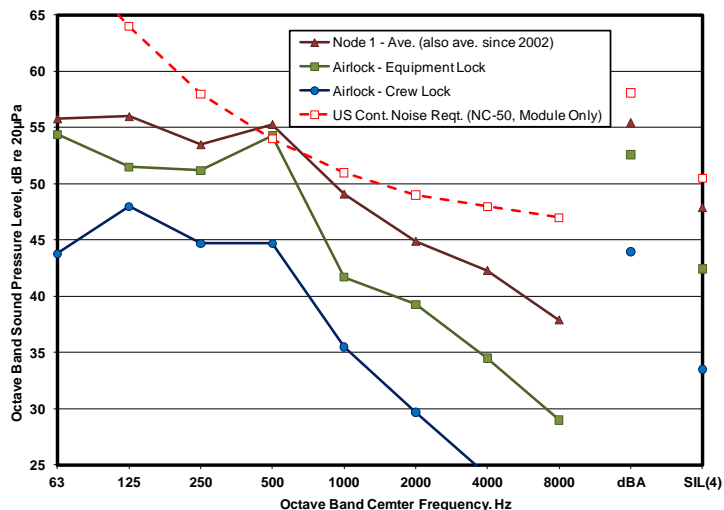


Figure 1. Node 1 and Airlock acoustic levels.

In the U.S. Lab, changes to the operational settings of the Pump Package Assemblies (PPAs) have reduced the sound levels. Figure 2 shows the SLM measurement locations in the U.S. Lab and also the locations of the PPAs. Each of the two PPAs includes a pump that provides cooling water for most of the hardware in the lab, one driving the moderate temperature loop (MTL) and one driving the low temperature loop (LTL). The PPAs are located in the aft-end of the lab, in Bay 6, and up until April 2003 were both operated simultaneously at approximate speeds of 14500 rpm (LTL) and 16000 rpm (MTL). However since 2003, the cross-over assembly that provides system redundancy has been utilized to allow one of the PPA pumps to drive both MTL and LTL loops as the nominal mode of operation. This was done primarily to preserve the life of one of the pumps, but also had the effect of significantly reducing the noise levels in the aft end of the lab, even though the single pump must run at a higher speed of approximately 18800 rpm. Figure 3 shows the SPLs at Rack Bay 6 with the PPAs running in dual-loop mode, and in the current operational setting of single-loop mode. In Figure 3, SPL reductions of 9-13 dB are seen in the 2 kHz octave frequency band.

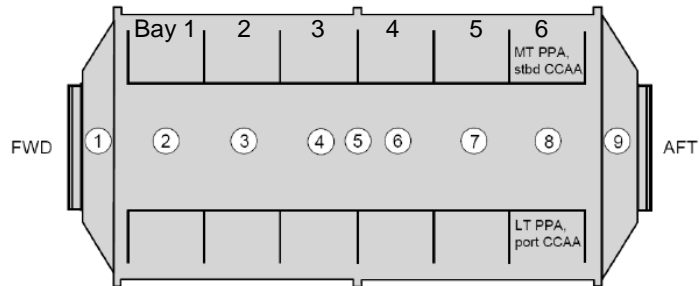


Figure 2. U.S. Lab measurement locations, including location 5 at the module’s longitudinal center. Locations are on the module centerline and 2-4 and 6-8 are also on the Bay centerlines as shown.

Figure 4 shows the sound level and NC level at Bay 5 as a function of time throughout the on-orbit life of the U. S. Lab. On the time axis the configuration and speeds of the PPAs are indicated. Note that the mean NC level decreases from NC-56 to NC-52 as the PPA is switched from dual to single-loop mode. However, there is a substantial fluctuation in the NC level, most likely caused by the tonal nature of the PPA noise, either being an unstable source, or by causing standing waves, coupled with the fact that the measurement location is only repeatable to approximately 0.3 meters. The measurements noted with “PPA tone” indicate where higher than usual PPA tones are present in the corresponding higher-resolution 1/3 octave band data (not shown here).

In 2008, three government furnished equipment (GFE) racks that are part of the Regenerative ECLS system (R-ECLSS) were temporarily added to the U. S. Lab. The R-ECLSS provides the additional capability needed to recycle carbon dioxide and urine into usable air and water. The three racks include the Water Reclamation System 1 (WRS1) and WRS2 racks along with the Oxygen Generation System (OGS) rack. These racks contain several pumps and fans, and also a urine centrifuge/separator that create significant noise. Continuous noise levels created by two of the racks, the WRS2 and OGS, significantly exceed their NC-40 acoustic requirement. And when they were added to the U. S. Lab they caused the noise levels in the forward end of the lab to increase. However, there were difficulties with operating the R-ECLSS⁸ so the impact of the increased noise levels in the lab was limited in time. Once the Node 3 module was added to ISS in 2010, the R-ECLSS racks were relocated to Node 3 and the U. S. Lab noise level returned to normal; however, this caused elevated noise levels within Node 3, as will be discussed later in this Section II.

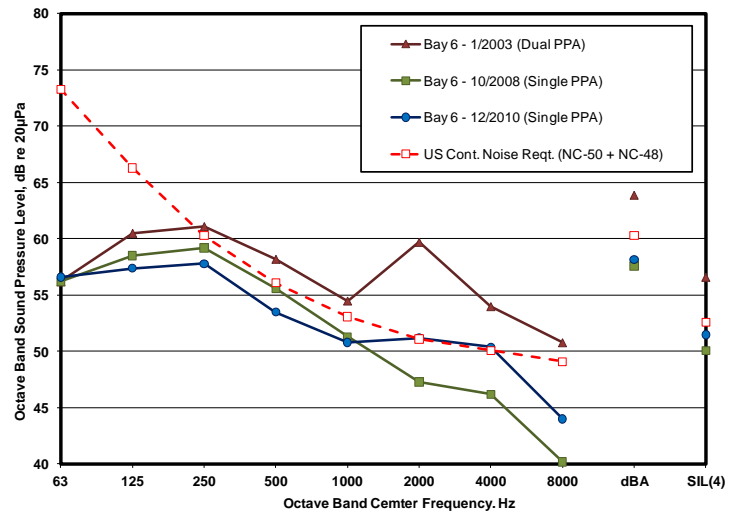


Figure 3. U.S. Lab acoustic levels reduced by changing from dual PPA to single PPA operations.

Current acoustic levels in the U. S. Lab are shown in Figure 5 at forward, center, and aft locations in the lab. Figure 5 also shows the average SPLs in the U.S. Lab. The U.S. Lab meets the U.S. continuous noise requirement

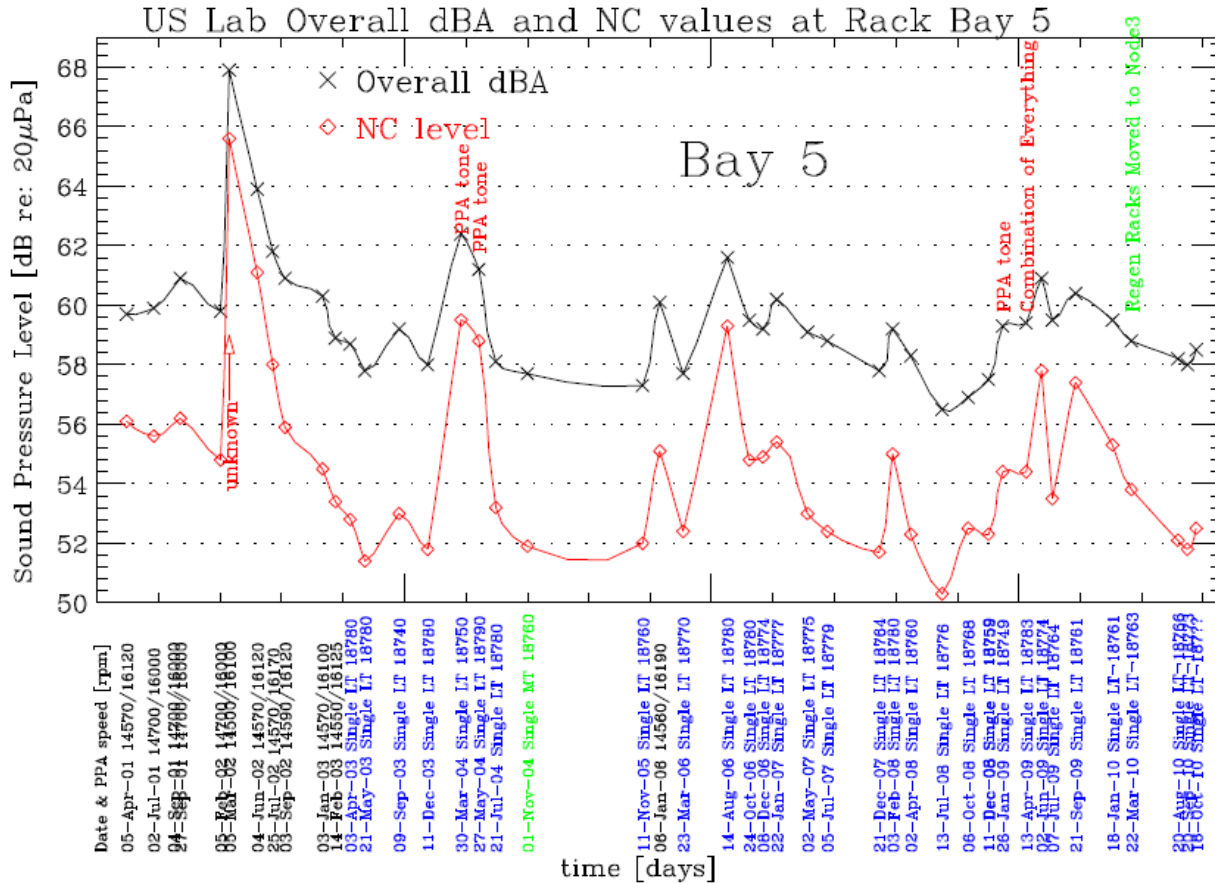


Figure 4. Sound Level and NC Level at Bay 5 as a function of time.

which includes the NC-50 allocation for modules and an NC-48 allocation for payloads. However, as can be seen in Fig. 4, the levels do fluctuate over time and may be over the requirement for a period of time. Several examples regarding on-orbit acoustic issue resolution are discussed in the paper.

Since 2003, several new modules have been added to the ISS U. S. Segment. Node 2 was added in October of 2007, the European Columbus Operational Facility (COF) module was added in February of 2008, the Japanese Pressurized Module (JPM) and Japanese Logistics Pressurized (JLP) module were added in the Spring of 2008, the Node 3 and Cupola modules were added in February 2010, and the Permanent Multipurpose Module (PMM) was added in February of 2011. The acoustic levels in each of these modules are discussed below.

The COF, JPM, JLP, PMM, and Cupola average acoustic levels are shown in Figure 6. These modules are all very quiet, below the NC-50 module continuous noise requirement. The JLP and PMM are used mainly for storage and do not have a significant number of noise sources. The Cupola is attached to Node 3, and is a small hexagonal room, just large enough to contain the upper part of a

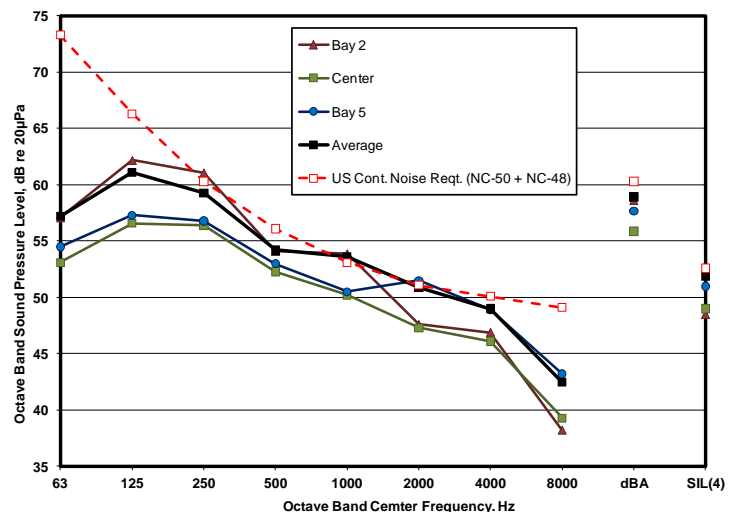


Figure 5. Current U.S. Lab acoustic levels.

crewmember, with windows on each of its seven sides. Once inside the crewmember can view the exterior of the ISS while manipulating the Canadian robot arm using the quiet Robotic Work Station.

The COF and JPM, in contrast to the JLP and PMM, are laboratory modules and have a significant number of noise sources. Substantial efforts to reduce the noise in COF and JPM were made to the benefit of the crew. With the addition of payloads (experiment hardware), the continuous noise requirement becomes NC-52 as described in Reference 2. However, as shown in Fig. 6, these laboratory modules are below the module-alone NC-50 requirement. There are currently payload operations in COF and JPM, but in the future more payload hardware is anticipated for these modules. It is expected that the noise levels in the COF and JPM will increase somewhat as more payloads are added to these modules, however noise levels should stay below the NC-52 requirement.

Node 2 contains the crew's sleeping quarters. As such, it is important for the noise levels to be low in Node 2. The current sound pressure levels in Node 2 are given in Figure 7, and these levels are below the NC-50 requirement. However, two significant on-orbit issues caused levels in Node 2 to be higher than expected, and well above the NC-50 requirement for a significant amount of time. The Node 2 on-orbit issues included a noisy air diffuser, and separately, noisy stalled inter-module ventilation (IMV) fans. In both cases, the situation was resolved. These two issues and their resolution will be discussed in more detail in Section IV.

Both nominal (thin lines) and current (thick lines) Node 3 sound pressure levels are shown in Figure 8. The nominal SPLs were measured shortly after Node 3 was docked to ISS, and in the first few months thereafter. However, after several months on-orbit Node 3 noise levels began increasing, and are currently at the higher levels shown in Figure 8. The increasing noise levels are thought to be caused by at least one stalled IMV fan, as was seen in Node 2. The reader is referred to Section IV for a detailed discussion of the phenomenon. Cleaning of the suspect Node 3 IMV fan was performed in April 2011 and SLM measurements to confirm the return to nominal sound levels is currently scheduled for June 2011.

The nominal Node 3 SPLs shown in Figure 8 are the acoustic levels of the Node 3 "core" systems, which include two PPAs (similar to those in the U. S. Lab), six IMV fans, and a common cabin air assembly (CCAA) fan and associated ducting system. Node 3 core is shown to meet its NC-50 continuous noise requirement. However, as with payload racks in laboratory modules, the specialized R-ECLSS GFE hardware, including the noisy WRS2 and OGS racks described above, were given an allocation such that the entire Node 3 module including this hardware is required to meet an NC-52 continuous noise requirement. On-orbit acoustic measurements of the entire system have not yet been made, as operational issues with the R-ECLSS hardware still exist. And, once these levels are measured, it will be determined whether or not additional noise controls will be required to quiet these racks. An estimate of the Node 3 SPLs, including the R-ECLSS racks is given in Figure 9, based on the core measurements made during ground tests along with the R-ECLSS

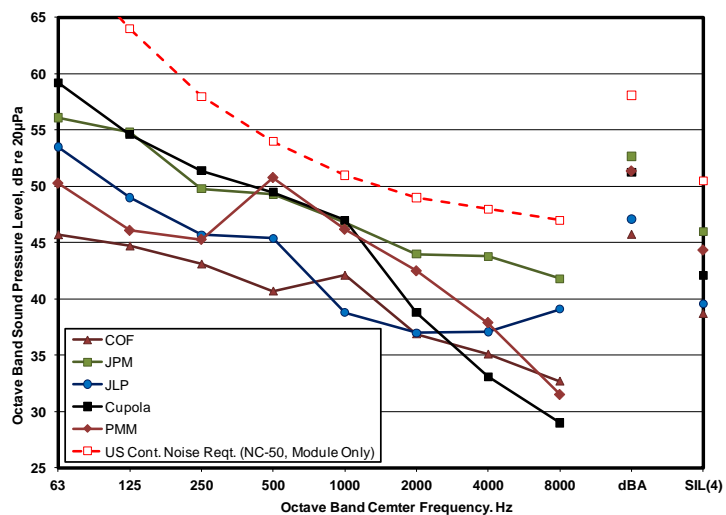


Figure 6. Average acoustic levels in COF, JPM, JLP, PMM and Cupola.

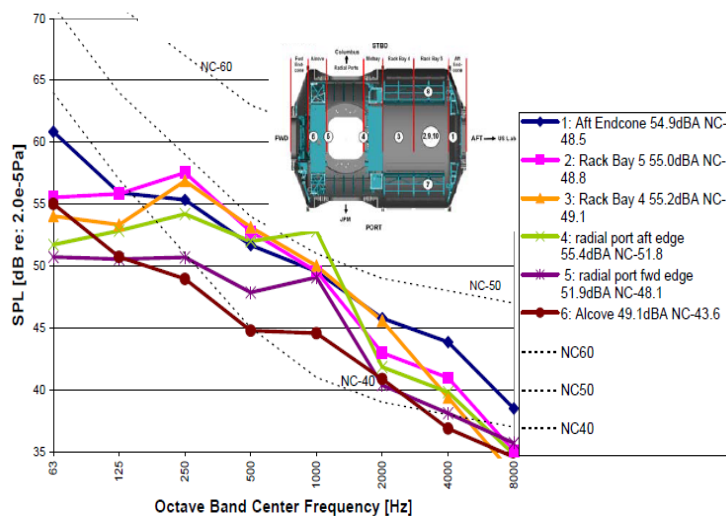


Figure 7. Acoustic levels in Node 2.

An estimate of the Node 3 SPLs, including the R-ECLSS racks is given in Figure 9, based on the core measurements made during ground tests along with the R-ECLSS

measurements performed either on the ground or in the case of the WRS2 and OGS racks, on-orbit while they were installed inside U. S. Lab. A ray tracing analysis was performed to estimate the Node 3 composite sound levels.

Node 3 also houses several significant intermittent noise sources such as exercise devices and the ISS's second toilet. The exercise devices include the Advanced Resistive Exercise Device (ARED), and the COLBERT second Treadmill (T2). The toilet rack is called the Waste and Hygiene Compartment (WHC), which includes a Russian-built toilet that is similar to the one in the Service Module. The maximum noise levels of the T2 and WHC measured on-orbit are 80 dBA and 72 dBA, respectively, at the expected crew-head locations. The sound levels of T2 and WHC are above the intermittent noise requirements (see Ref. 1, 2). However, these levels have been reviewed and have been determined to be safe by the ISS Safety Review Panel. Resulting safety Non-Compliance Reports (NCRs) have been approved for this hardware for the nominal operational scenarios. Impacts of the high noise levels include decreased voice communication effectiveness, which is of less concern during exercise, and degraded alarm audibility, especially while inside the WHC with the toilet running. The associated levels are not high enough to cause an increased risk for hearing loss. Because of the nature of ARED, basically a weight-lifting simulator, the noises created are spurious and impulsive or of very short duration. ARED impulse noise is well below the 140 dB requirement, and the remaining intermittent noise meets the intermittent noise requirement.

With elevated noise levels in Node 3 being caused by off-nominal IMV noise, elevated R-ECLSS noise levels, and the significant intermittent noise sources, Node 3 is an extremely challenging acoustic environment, and does not currently meet the continuous noise requirement. As such, continued monitoring and noise reduction efforts will be pursued in Node 3. Other than Node 3, the U. S. Segment modules currently meet their continuous noise requirements, with many of the modules being significantly below NC-50. The low acoustic levels in so many modules represent a significant improvement in the overall ISS acoustic environment since 2003. Acoustic levels in ISS are also a significant improvement over the Space Shuttle Orbiter

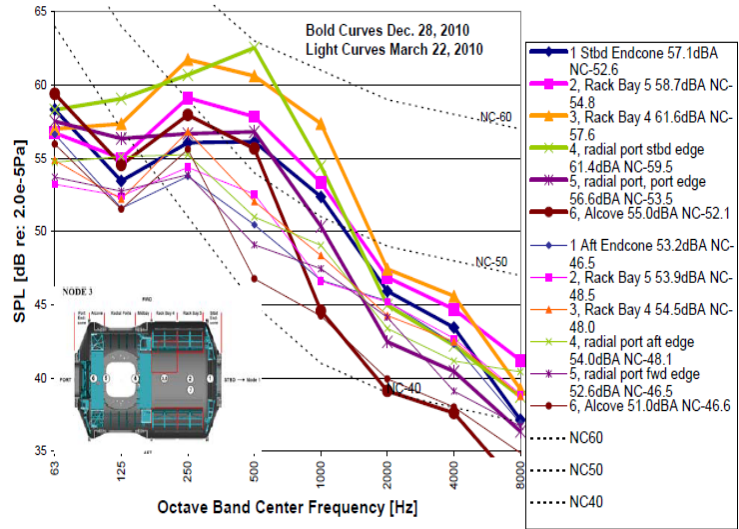


Figure 8. Acoustic levels in Node 3.

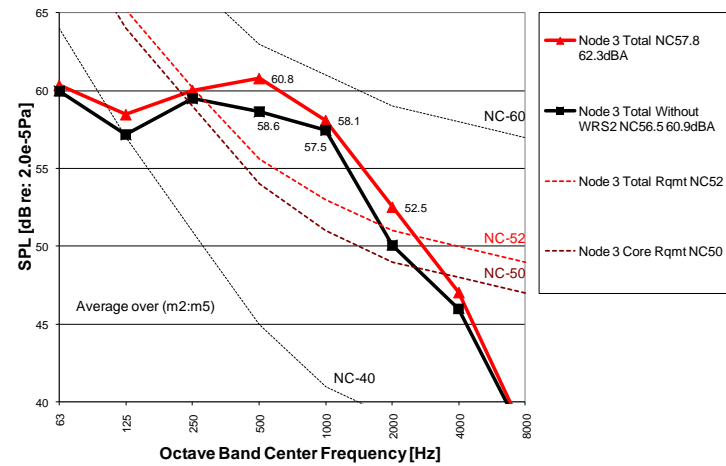


Figure 9. Predicted acoustic levels in Node 3 including R-ECLSS racks (WRS2 on and off).

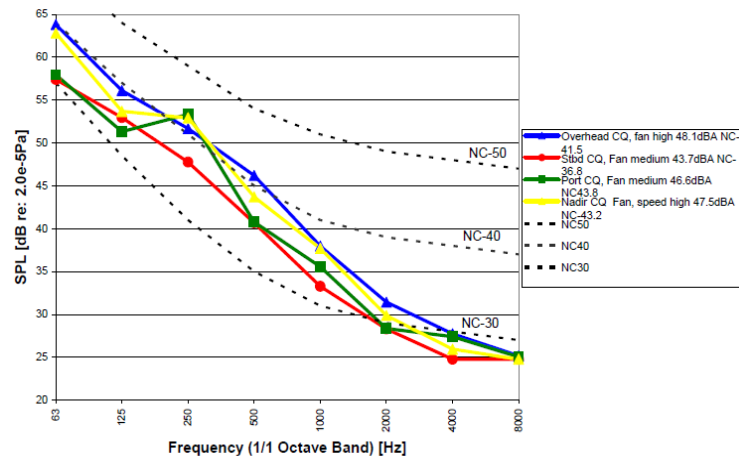


Figure 10. Acoustic levels in the ISS Crew Quarters.

interior environment of approximately NC-64 and 68dBA in the mid-deck and NC-58, 63.4 dBA in the Flight Deck.⁹ Skylab acoustic levels (three missions between May 1973 and 1974) were NC-55, 58 dBA averaged over the habitable volume and NC-43, 45 dBA in the sleep area.¹⁰

In addition to the new ISS modules, four new sleep stations, the ISS Crew Quarters (CQ) racks, have been added, and the Temporary early Sleep Station (TeSS) has been retired. The four CQ racks are located in Node 2. However, one of these was temporarily located in the JPM prior to installation into Node 2. Broyan et al.¹¹ describes the CQ racks, as well as the work performed to reduce the acoustic levels inside the CQs. Sound pressure levels measured inside each of the four CQs on-orbit are shown in Figure 10. As described in Reference 8, at all speeds the CQs are close to the NC-40 continuous noise requirement for sleep, and are lower than 50 dBA, which is adequate for hearing rest, and meets the World Health Organization’s recommendations for sound levels during sleep.¹²

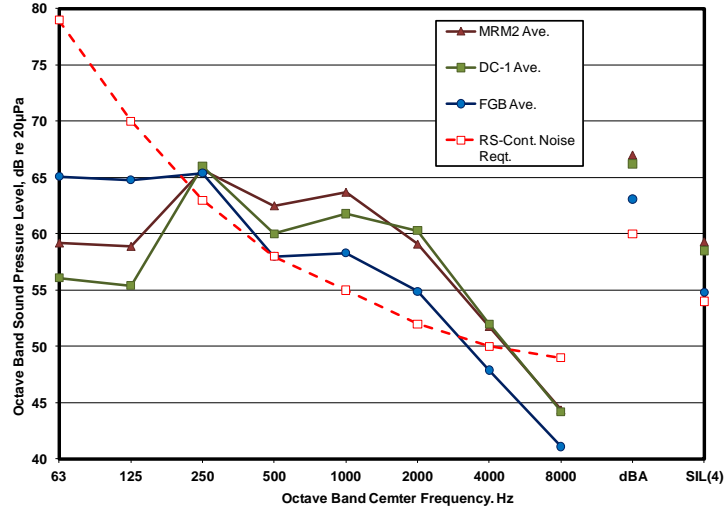


Figure 11. Average sound pressure levels inside the FGB, DC-1, and MRM2.

III. Russian Segment Acoustic Levels

In 2003, the ISS Russian Segment (RS) included the Functional Cargo Block (FGB), Service Module (SM), and the Docking Compartment (DC-1) modules. Since 2003, two new modules have been added to the Russian Segment. Mini Research Module 2 (MRM2) was added in November 2009, and the Mini Research Module 1 (MRM1) was added in May 2010.

Noise levels in the FGB have been decreasing with the continued addition of stowage in the aisle-way of the FGB. Also, three additional SLM measurement locations have been added in the FGB to better represent the habitable volume, as is done in the other modules. Figure 11 shows the current sound pressure levels of the FGB.

The DC-1 noise levels have been stable since 2003. And MRM2, a near-duplicate of the DC-1, has very similar acoustic levels. Figure 11 also gives the sound pressure levels in DC-1 and in MRM2. The levels in these modules are fairly high with sound levels of approximately 67 dBA. However, the crew is expected to spend limited time (less than 2 hours per day) inside these modules. Safety NCRs are in place in acceptance of these modules regarding acoustical noise for the intended operations.

Since 2003, there has been a significant amount of work performed to reduce the noise levels in the SM. Beginning in 2003, as a result of a contract between NASA and Rocket Space Corporation – Energia (RSC-E), U. S. and Russian acoustic specialists have worked together, along with the Russian Institute of Biomedical Problems (IBMP), in an effort to bring the SM sound levels down to 63 dBA. In order to achieve these reductions several noise producing systems were addressed; these include the ventilation, carbon dioxide removal, and air conditioning systems. And in addition to these early activities, a longer-term activity to develop a flight prototype quiet fan, as a replacement for one fan model fan that is often used, was undertaken. These efforts are described briefly below.

A. Ventilation System

The Service Module contains more than 40 fans, which contribute significantly to the acoustic levels within the SM. These 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 Figure 12, 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 by fans in the return air-duct, back to the air conditioner. Also in Fig. 12, the starboard kayuta (sleep station) is shown. Note that ventilation in the kayuta is obtained by a fan near the middle of the SM that draws air into a short duct, and exhausts the air into the kayuta ceiling where a large circular register distributes the air into the kayuta. 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.

The first priority for noise reduction in the SM was to reduce the noise levels in the kayutas. Prior to this activity, sound levels were in the range from 62 to 66 dBA, up to 16 dBA above the 50 dBA requirement for sleep¹. Much of the problem was as a result of the removal of the kayuta doors during Increment 1 (November 2000 to March 2001). These doors were replaced as part of this activity.

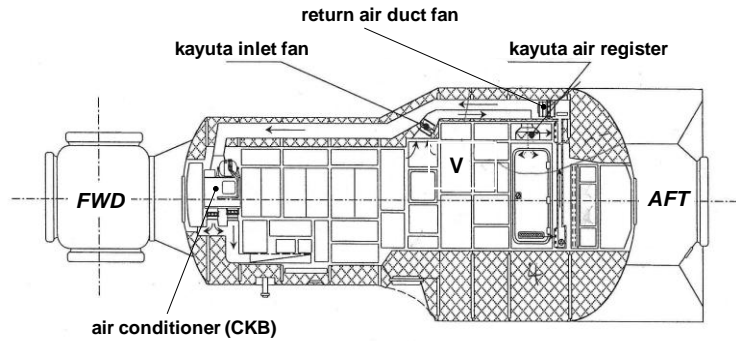


Figure 12. Geometry and airflow inside the Service Module.



Figure 13. Return air duct fan acoustic lining, including fan inlet (left) and outlet (right) treatments.

In addition to the door replacement, several additional noise treatments were applied. The major source of noise inside the kayuta was identified to be the fan directly above each kayuta in the main return air duct. Although, there was no direct airborne connection between this fan and the kayuta, it was determined that this fan was exciting the duct structure and the structure above the kayuta, causing the kayuta panels to vibrate and radiate noise. To reduce this noise, these fans (one above each kayuta) were re-mounted using specially designed vibration isolators (previously they were hard-mounted), and inlet and outlet sound absorptive linings were installed inside the duct just upstream and downstream of the fan (Fig. 13).

The second most important noise source in the kayutas was the kayuta inlet (supply) fan. To address this source, again vibration isolation was added, but in this case took the form of a soft duct extension, that also included some sound absorption (Fig. 14). A fan speed controller was also added to help reduce the fan speed (at the discretion of the crew) and corresponding sound levels. Finally, acoustic treatment (absorption and damping) was added to each of the kayuta registers (Fig. 14).



Figure 14. Kayuta inlet (supply) fan and register acoustic lining, including fan inlet treatment (louvers and vibration isolation) view from cabin (left), back-side view (middle) and register lining (right).

The resulting acoustic noise reductions are provided in Fig 15a, which shows the sound levels as function of time since the beginning of human habitation aboard the ISS (Increment 1). It can be clearly seen that noise levels were reduced when the door on the starboard kayuta was re-installed at the end of 2005, and again when the port kayuta door was re-installed in October 2006. The installation of the remainder of noise controls occurred during the first Quarter of 2007. The lowest level recorded in the kayutas was 51 dBA, compared to the 50 dBA requirement, an overall reduction of 14 dBA from Increment 1 levels. Typical noise levels measured in the kayuta are between 52 and 56 dBA, still a significant improvement over the previous levels. On occasion it is clear that the SLM measurement was made with a kayuta door fully or partially open, resulting in higher than normal levels. Figure 15b provides spectral comparisons of before versus after remediation in octave band SPLs for the port and starboard

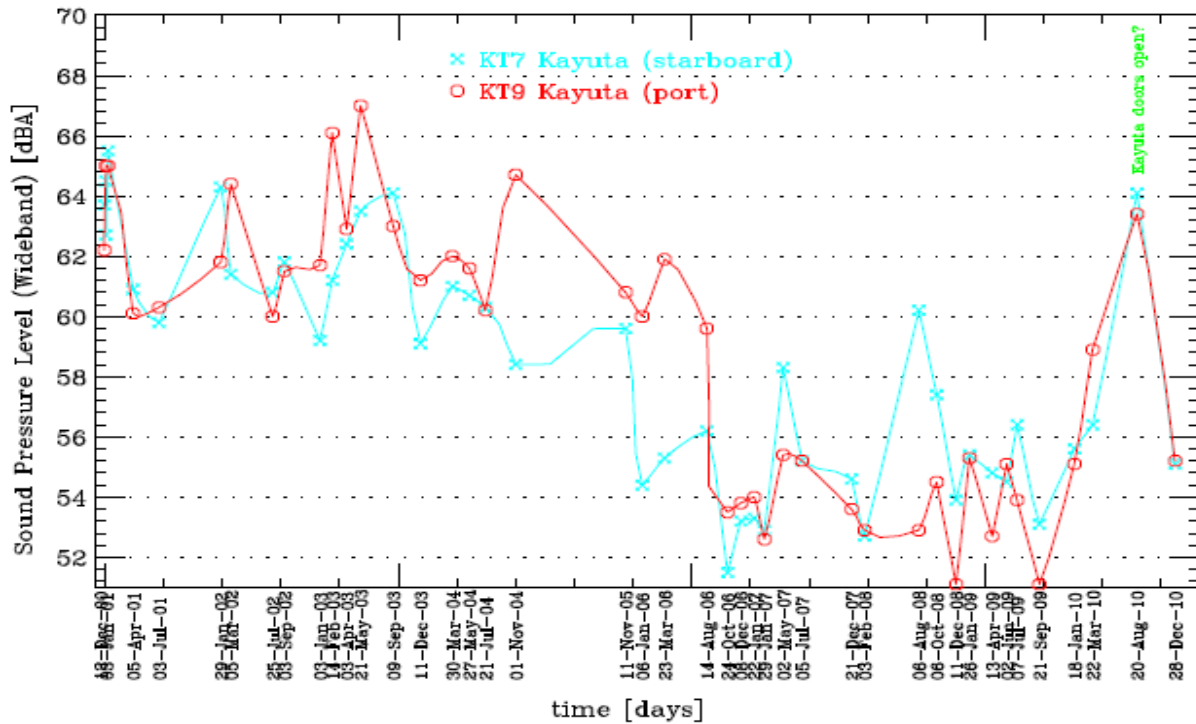


Figure 15a. Starboard and port kayuta sound levels as a function of time.

kayutas compared to the Russian requirement for sleep. Levels are close to meeting the sleep requirement except in the 250 Hz octave band where there is an exceedance of approximately 6 dB in both kayutas. In order to meet the spectral and 50 dBA Russian sleep requirements in the future, it is thought that the replacement of the fan in the return duct above each kayuta with one of the quiet fans, described in Section III, D, will be required.

To reduce noise levels in the working compartment (crew habitable volume), acoustic treatments were applied to many SM fans as space (volume) around the fans allowed. In all, twenty fans were mounted on vibration isolators, and ten were wrapped with acoustic casing covers; six inlet mufflers and four outlet mufflers were also placed on various fans. Figure 16 shows examples of casing covers, and mufflers installed on the SM fans.

It is difficult to show the isolated effects of these fan treatments, as the carbon dioxide removal system and air conditioner noise controls were installed within the same time-frame. The composite noise reduction results for levels in the SM working compartment from all of the acoustic treatments will be discussed below.

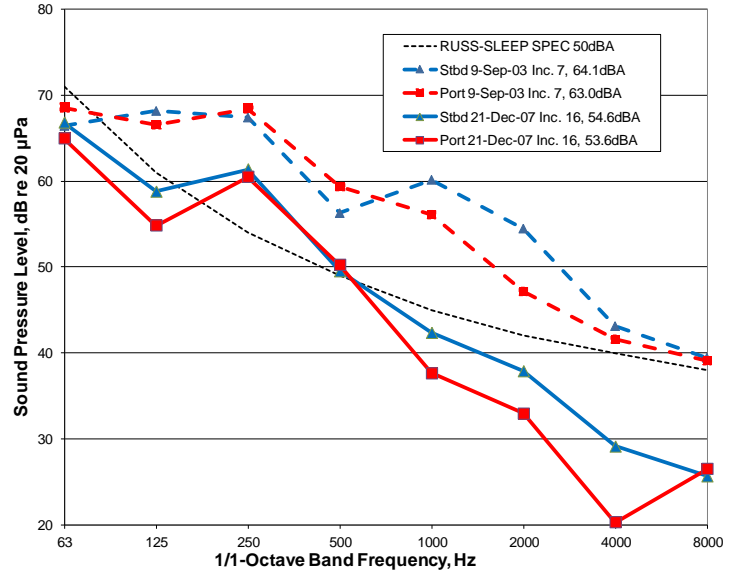


Figure 15b. Starboard and port kayuta sound pressure levels before and after door replacement and implementation of noise controls.

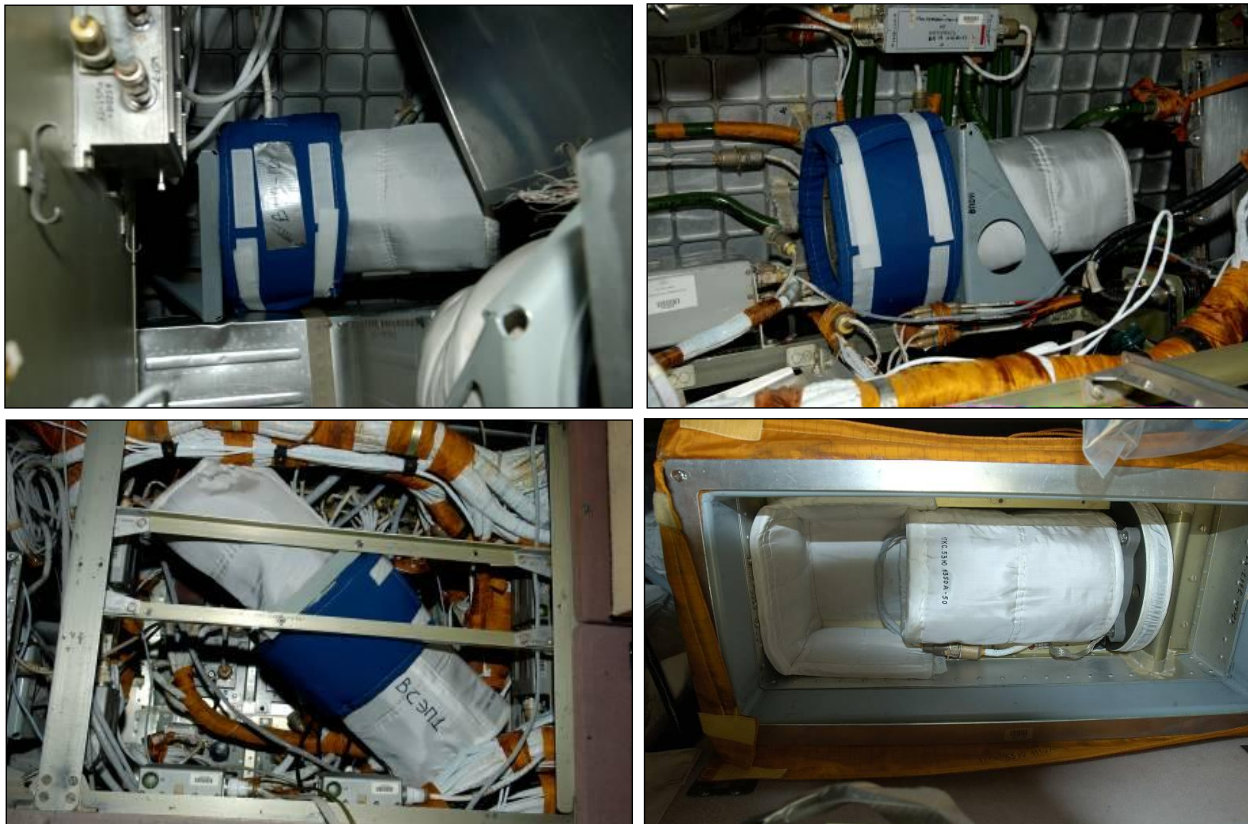


Figure 16. Examples of Service Module fan acoustic treatments.

B. Carbon Dioxide Removal System (Vozdukh)

The Service Module's carbon dioxide removal system or "Vozdukh" is a significant source of both continuous and intermittent noise. The intermittent noise produced very high acoustic levels on the order of 75 dBA. So, this was addressed early on in Increment 1 when the crew built an acoustic cover of their own design and fabrication. This cover was subsequently replaced with a ground built/designer cover. The location of the Vozdukh is shown with a "V" in Figure 12.

The Vozdukh's continuous noise was not addressed until the noise reduction campaign that began in 2003. The continuous noise is produced by a micro-compressor that is always running. In order to address this noise source, a form-fitted soft acoustic cover was installed, and then additional acoustic blankets were placed between the micro-compressor and the closeout panel (which is adjacent to the working compartment).

Figure 17 shows the resulting noise reduction, first after applying the cover, and then after applying the supplemental mats. These data were measured without the closeout panel in order to obtain a better signal-to-noise ratio on the source noise reduction. A sound level reduction of 9 dBA, and significant noise reductions of at least 10 dB in the 1/3 octave band sound pressure levels above 800 Hz are observed. It is also seen in Fig. 17 that the closeout panel provides a small amount of additional noise reduction, approximately 2 dBA.

Since the measurements were made very close to the closeout panel in Fig. 17, the noise reductions realized in the working compartment are smaller than that shown for the isolated Vozdukh. Again, the composite noise reductions in the SM from all noise treatments will be discussed below. Note that in Fig. 17, initial Vozdukh microprocessor SLM measurements were made with nearby SM fans off and on. Thus, it can be seen that the tonal peaks at 315 Hz, and the majority of the acoustic energy below 160 Hz is generated by fans, and not the Vozdukh micro-compressor.

C. Air Conditioning System (CKB)

The most significant noise source in the forward end of the SM is the air conditioner or "CKB" (in Cyrillic characters, and is pronounced "ess-ka-ve"). The CKB noise sources include a compressor, fluid lines, a centrifugal fan, and two other fans (included as part of the ventilation system discussed above) on each of the two units. The location of the starboard CKB is shown in Fig. 12, and the port CKB is in a similar location, across the aisle-way.

Noise controls for the CKB included a cover for each unit's compressor, and wrapping of the fluid lines (Fig. 18). In addition, a cover for the centrifugal fan (not shown), and a new acoustic closeout panel (to replace a thinner split-panel cover) for each air conditioner unit (Fig. 18) were developed and installed.

The noise reductions obtained with the new CKB acoustic closeout panel is presented in Fig. 19, which show sound level reductions of 5 dBA and indicate a 1/3 octave band sound pressure level reduction of at least 5 dB at frequencies above 800 Hz.

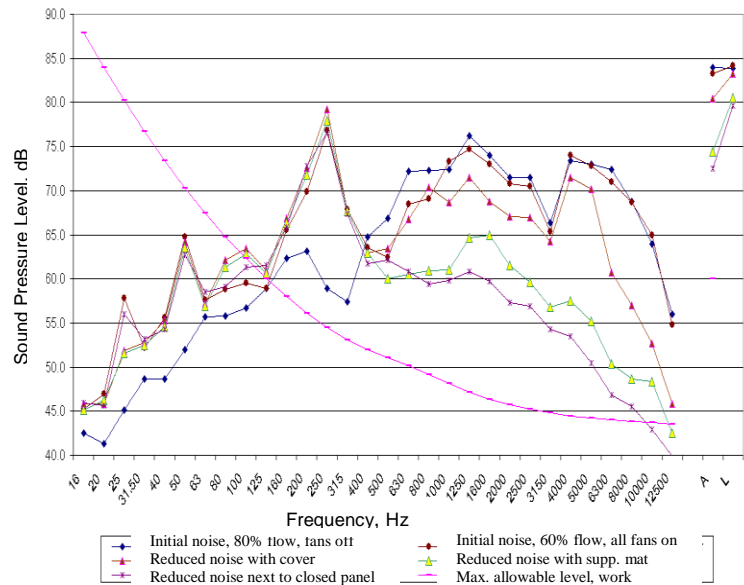


Figure 17. Acoustic levels before and after the installation of a cover and then sound absorbing mats on the Vozdukh microprocessor (measured with the closeout panel removed).



Figure 18. Air conditioner (CKB) acoustic treatments including compressor and fluid line wrappings (left), and the new single-piece acoustic close-out panel (right).

D. Flight Prototype Quiet Fan

In addition to the above short-term noise mitigations, a longer term activity to develop a spaceflight qualified quiet fan prototype was undertaken. It was decided to replace one type of fan that is used in 12 locations in the SM, and is also used in other Russian modules. The goals for this fan were to meet the performance characteristics of the previous fan (80 l/s, 4 mm H₂O pressure rise), but with a resulting uninstalled sound level of 50 dBA or less, measured at a distance of 1 meter.

In order to accomplish the above goals both a quieter motor, and a quieter aerodynamic design were developed for the new fan. The original SM fans were based on designs of the MIR space station fans, and included a fairly high rpm, with cambered flat-plate blades cross-sections with no twist. In order to meet the performance and acoustic requirements, an approach was adopted to reduce the speed of the fan, but increase the blade-loading in order to maintain the flow-rate of the fan. Computational fluid dynamics methods were used to design rotor and stator cascades with aerodynamically optimized blades including variable thickness and twist, and these

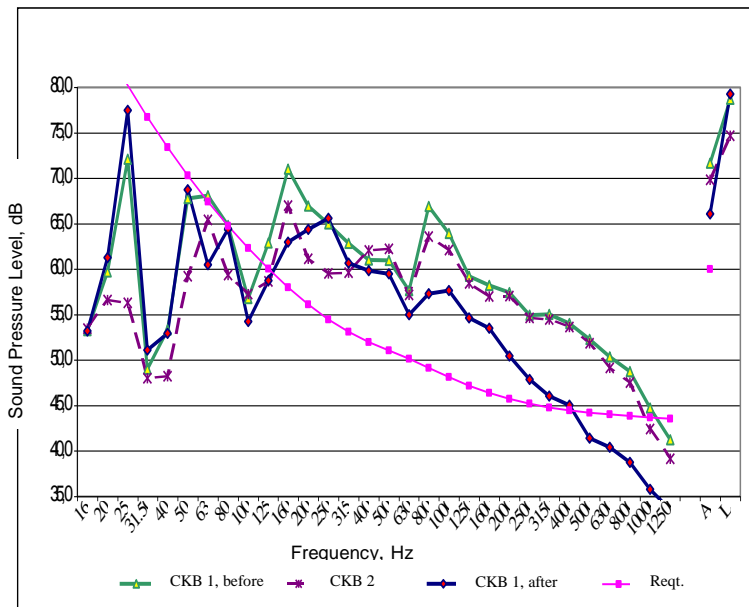


Figure 19. Acoustic levels before and after the installation of a new closeout panel on the CKB1 air conditioner compared to the Russian Segment allowable SPLs. Unmodified CKB2 levels also shown.

Fan type	Original Fan	Quiet Fan
Pressure Rise, mm H ₂ O	4	4
Flow Rate, Q, l/s	47.0	83.4
Current Draw, mA	470	470
Rotation speed, rpm	3120	2010
Isolated noise levels, dBA	61-64	48

Table 1. Comparison of original fan and replacement quiet fan performance and sound levels (measured 1m distance, normal to the fan).

fan that has the same housing size, but operates at a higher pressure rise. This higher pressure-rise fan is used in several important noisy locations, including above the kayutas inside the return duct (kayutas primary noise source), and are also the main noise source in the MMR1, discussed in subsection F. Work is currently underway to replace all SM and MRM1 fans of both pressure rise types described above with quiet fans, which are currently being manufactured.

E. Service Module Working Compartment Composite Noise Reductions

All of the above Service Module noise controls were applied on-orbit after development and testing on the ground by RSC-E. The SM “Complex Stand,” a very high fidelity mockup, was used to test the effectiveness and fit of the modification hardware. The JSC Acoustics Office reviewed the testing results, and provided some acoustic materials for the earliest noise controls. These were later replaced with Russian acoustic materials. The

cascades were fabricated using a numerically controlled machining process.

The resulting performance and acoustic comparison between the original and new quiet fans is shown in Table 1. The quiet fan met the 50 dBA sound level requirement, with an uninstalled noise reduction of 15 dBA. These reductions are based on ground test data.

Even with the reduced noise levels, the flow performance of the quiet fan was significantly better than the original fan, as shown in Table 1. And because of the increased performance, it was decided to use the quiet fan to replace an additional model

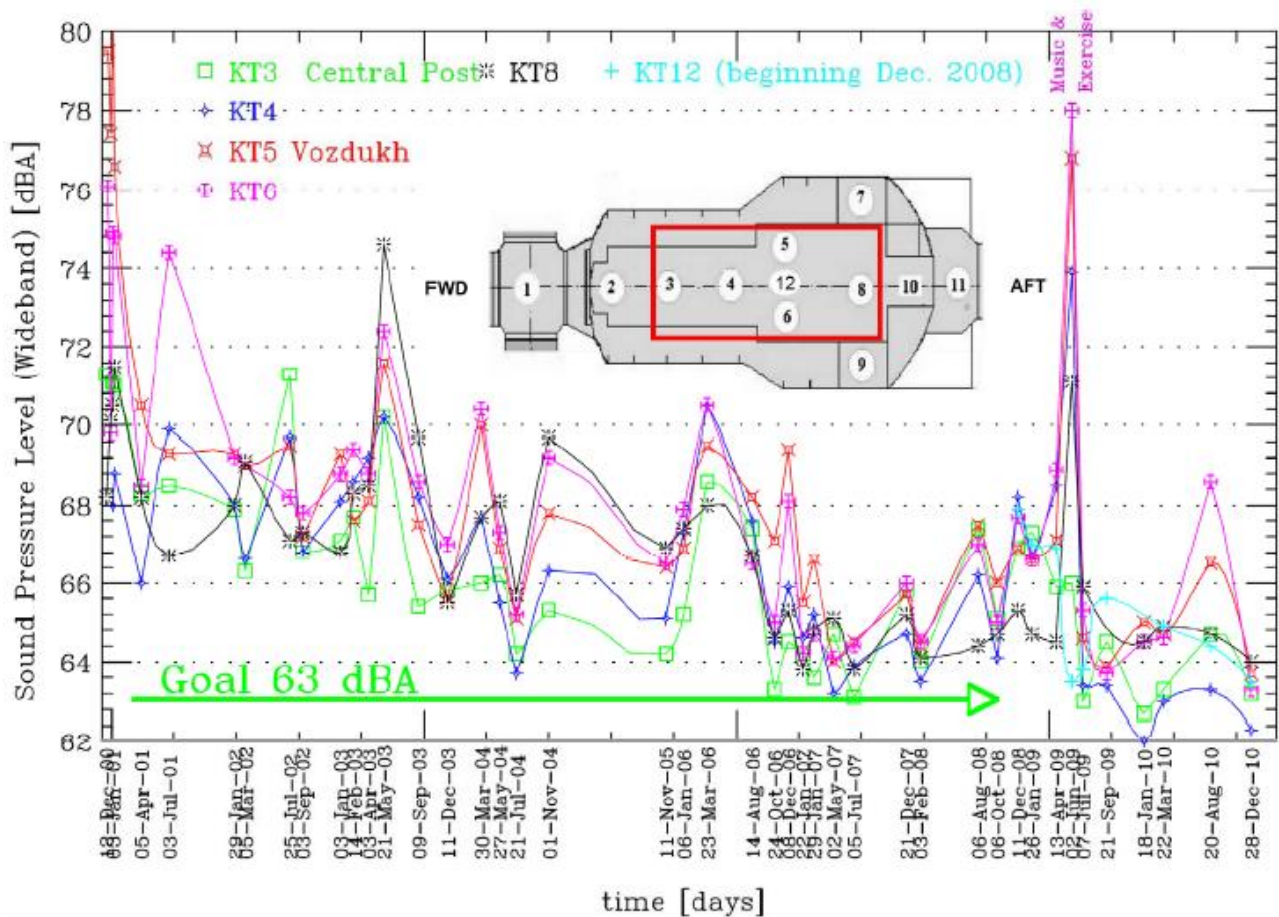


Figure 20. Sound levels as a function of time in the main portion of the Service Module.

effectiveness of the treatments was measured on-orbit.

Sound level reductions in the main cabin, including all acoustic treatments except for the quiet fans, which have not yet been installed in the SM, are shown in Fig. 20. Since 2003, noise reductions of 3-5 dBA in the main part of the cabin are shown. Levels are approximately 63-65 dBA, compared to a Russian Segment continuous noise requirement of 60 dBA, and a contract goal of 63 dBA. After the noise controls were completely implemented in early 2007, the variation (spread) in sound levels across the cabin was also reduced.

Current octave band sound pressure levels, measured in the main portion of the SM working compartment are shown in Fig. 21. Levels at both ends of the SM are shown in Fig. 22. These levels are as high as 68 dBA near the CKB at control point 2, and are as low as 60 dBA in the aft end of the SM. A plan view of the SM is shown inset in Figures 20-22, showing the SM control points (labeled KT in Russian on plots 21 and 22).

Figure 20 shows how the noise levels in the main portion of the SM working compartment have varied over time. The sound levels are shown to decrease by 3-5 dBA. After the noise controls were completely implemented in early 2007, the variation (spread) in noise levels across the cabin was also reduced.

These noise reductions are seen as a significant improvement for the crew. And, along with the significant noise reductions shown inside the crew's sleep quarters (kayutas) as discussed in subsection A, the SM noise remediation efforts have been very successful. It is hoped that with the installation of quiet fans in the SM, the noise level will be reduced further to at least the 63 dBA goal, and possibly to the 60 dBA sound level requirement.

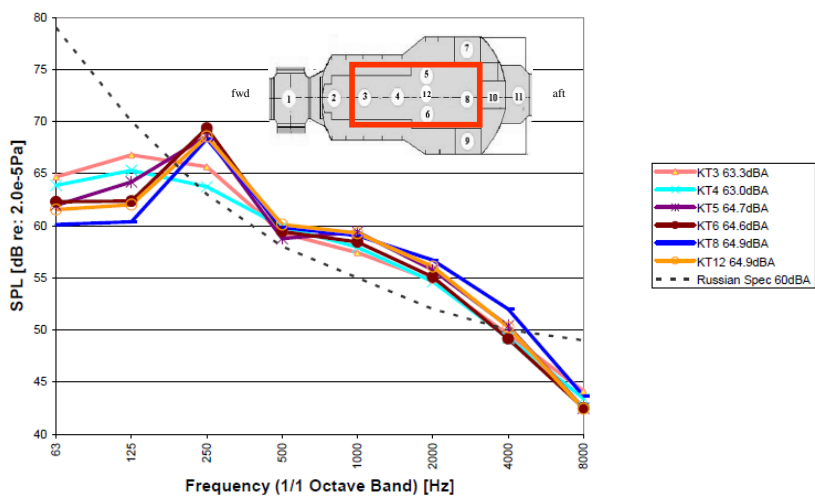


Figure 21. Octave Band Sound Pressure Levels in the main portion of the Service Module (data taken March 22, 2010).

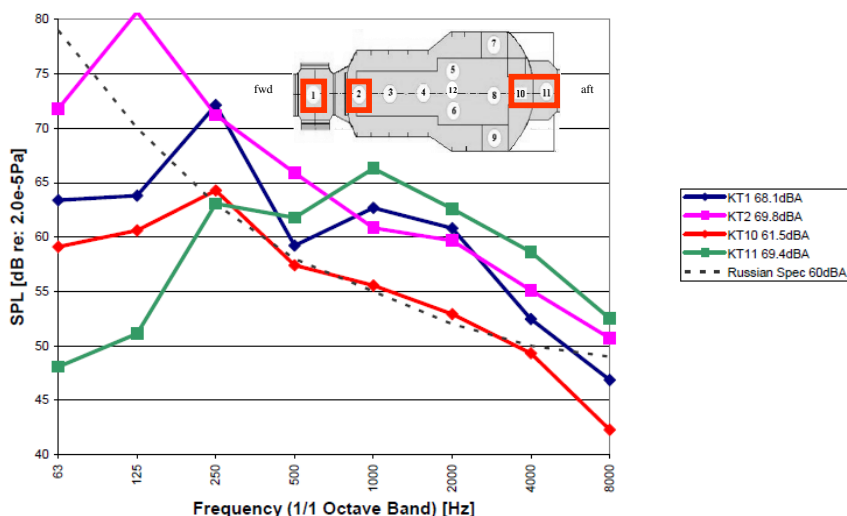


Figure 22. Octave Band Sound Pressure Levels at the ends of the Service Module (data taken March 22, 2010).

F. Mini Research Module 1 Noise Reductions

The Mini Research Module 1 (MRM1) is the latest module added to the Russian Segment, added in 2010. Ground and on-orbit acoustic tests indicate that the MRM1 originally produced fairly high sound levels of 73-74 dBA. This is compared to the Russian Segment requirement of 63 dBA for a module with an expected crew stay of up to 3 hours per day. The quiet fan was intended to be used in MRM1, but these fans were not available prior to MRM1 launch, so the original fans had to be used. However, in 2011, two quiet fans were delivered to the ISS to replace the two loudest fans in the MRM1, the heat exchanger fans, located near control points (KT) 1 and 2 in Fig. 23. These are of the higher pressure-rise type, where the use of the quiet fan is made possible by the efficient performance of the quiet fan. These replacement fans were installed in April 2011 and reduced the levels in the zenith end of the MRM1 by 5 dBA, from 73 dBA down to 68 dBA. The original MRM1 acoustic levels are shown in Figure 23, and the acoustic levels before and after the installation of the two quiet fans are shown in Fig. 24. It is anticipated that levels will be further reduced to the requirement of 63 dBA once the remaining 3 MRM1 fans (the

lower pressure-rise type) are replaced with quiet fans. These three additional fans are currently being fabricated and are scheduled to be available for flight by the spring of 2012.

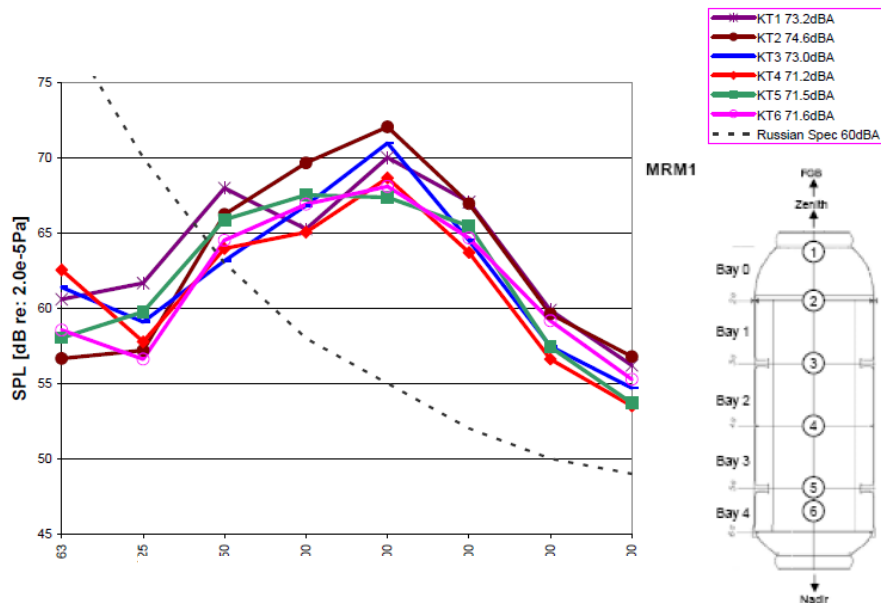


Figure 23. Acoustic Levels in MRM1 (data taken August 20, 2010).

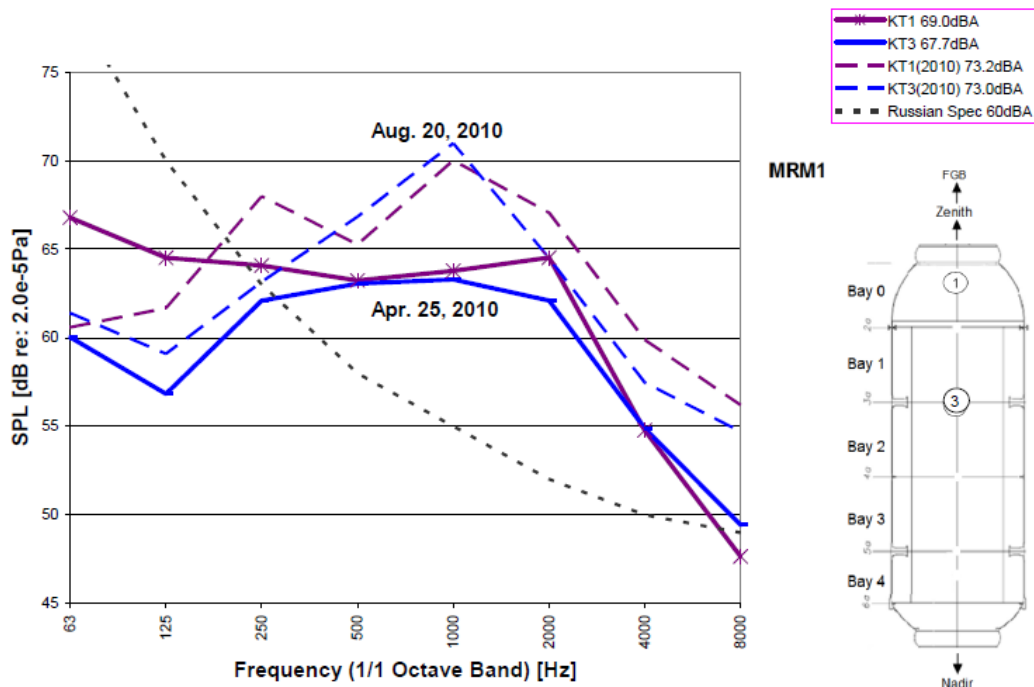


Figure 24. Acoustic Levels in MRM1 before and after replacement of heat exchanger fans with quiet fans.

IV. On-Orbit Acoustic Issue Resolution

Much work goes into controlling the acoustic levels in ISS modules, both by the hardware developers and the NASA monitors. These efforts include requirements development, Acoustic Noise Control Plan (ANCP) development, design for low noise, component noise testing, and acoustic modeling and prediction. And at the end of the hardware development cycle, remedial actions may still be needed when ground measurements show exceedances during verification testing. But even after these efforts and seemingly full-proof processes, there are still instances where unexpected acoustic issues arise on orbit. In this section, two such occurrences that affected the overall module noise levels will be discussed, including before and after acoustic levels, and the methods of resolution.

A. Node 2 Ventilation System Backpressure Plate Noise

During testing of Node 3, it was discovered that one of the orifice plates that balanced the airflow between registers of the Temperature and Humidity Control (THC) system ductwork was causing too-high noise levels, up to 10 dB above the NC-50 continuous noise requirement in the 1 kHz frequency band. Additionally, the sound pressure levels produced by this orifice plate or ‘backpressure plate’ were influenced by the position of the Remotely Actuated Manual Valve (RAMV), which directed a portion of the THC airflow into an adjacent module via an Inter-Module Ventilation (IMV) duct. When the valve was opened, and more airflow was conducted into the IMV duct, the quieter the backpressure plate became. However, the range of motion of this valve was limited, and the lowest noise levels produced were still above NC-50 by a significant amount. New backpressure plates were designed and installed, with increased open area to reduce the noise levels down to the NC-50 requirement.

Before the reason for the increased Node 3 noise levels was found, there was confusion as to why the Node 3 levels were high, but the Node 2 levels met requirements, even though the design of Node 2 and Node 3 were nearly identical. But when Node 2 arrived on orbit, and after being attached to ISS, the levels inside were measured to be well in excess of NC-50. In fact, the octave band sound pressure levels matched the original Node 3 levels when the Common Cabin Air Assembly (CCAA) speeds were the same.



Old NOD2OS3 (upstream), 11% Open area



Old NOD2OS5 (downstream), 10% open



New NOD2OS3 (upstream), 22% open area



New NOD2OS5 (downstream), 18% open

Figure 25. Old (top) and new (bottom) Node 2 THC backpressure plates.

The answer was found in the review of the Node 2 ground acoustic verification test records, where after the test it was discovered and documented that the position sensor for the RAMV was not reading correctly. In addition, the software limitations that limited the RAMV position during Node 3 testing were not yet implemented on Node 2. The result was that the RAMV had been inadvertently open during the Node 2 acoustic verification test, causing Node 2 acoustic levels to be lower than when in nominal configuration thus passing acoustic verification.

The final resolution was to perform an on-orbit replacement of the backpressure plates with a set similar in design to those that were used to fix the Node 3 noise problem. This corrective action was managed by Thales-Alenia Space International (TASI), the Node 2/3 hardware developer. Figure 25 shows the old and new backpressure plates, and Fig. 26 shows the on-orbit measured acoustic levels before and after the plates were installed in Node 2. Node 2 currently meets the NC-50 requirement.

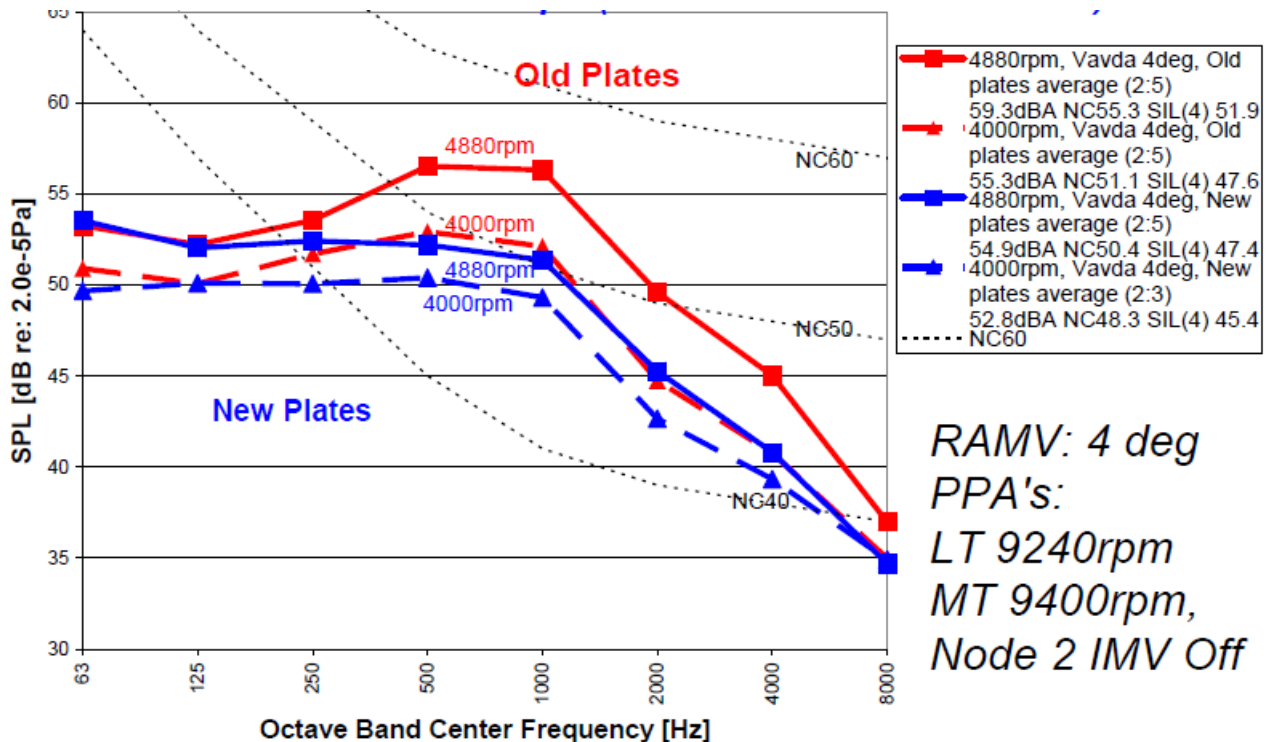


Figure 26. On-orbit acoustic Levels in Node 2, before (solid lines) and after (dashed lines) replacement of the THC backpressure plates for two cabin fan (AAA) speeds.

B. IMV Fan Clogging

In January 2009, sound pressure levels inside Node 2 began to increase above the NC-50 requirement. The octave band sound pressure levels were shown to match the spectral shape of the acoustic signature produced by a stalled Inter-Module Ventilation (IMV) fan, measured during ground tests. This phenomenon also occurred in Node 1 in 2001 (Increment 2), and the issue was resolved by cleaning the lint buildup from the IMV fan's flow straightener and upstream muffler. To perform this task, however, it is required to disconnect the ductwork from the IMV fan, a significant crew-time expenditure.

In 2010, the problem happened again, but because of crew-time priority issues the SPLs in Node 2 kept increasing as more lint built-up in the IMV fan inlet. After an acoustic trouble shooting session, where the SPLs were measured at repeated locations, and different IMV fans were turned on and off to identify which IMV fan was clogged, it became clear that at least three IMV fans were clogged, causing the fans to stall and produce high noise levels. Also, SPLs in the usually quiet JPM increased to a level of NC-67, and levels in the forward end of the U. S. Lab also increase 2-3 dB. In addition to acoustics issues, the stalled fans also led to improper mixing of air between modules, thus increasing the risk for carbon dioxide pockets and reduced oxygen content in localized areas.

After discussions with the Mission Management Team (MMT), a significant effort was made by the crew to clean several IMV fans, including those creating high noise levels in the U.S. Lab, Node 2, and JPM. Figure 27 shows photographs of the clogged JPM IMV fan before and after the cleaning and also shows a photograph of the

dust removed from the fan.¹³ As a result of the cleanings, noise levels returned to normal in the Node 2, U. S. Lab, and JPM. Figure 28 shows the relationship between the IMV fan's measured flow rate and the acoustic levels measured in the JPM.¹³

Just prior to the IMV fan cleanings in Node 2 and JPM, Node 3 began showing indications of stalling fan noise, and this noise has been increasing over time. IMV flow velocity measurements confirmed that one of the Node 3 IMV fans had low flow, and fixed-location (static) acoustic dosimetry measurements made while each fan was turned off and on gave extra confirmation of which of the Node 3 fans was stalling. The Node 3 forward starboard fan was cleaned and revealed a golf-ball-size dust ball on the fan's flow straightener. It is suspected that the sound levels in Node 3 have returned to normal, but this has not yet been confirmed.

The problem of dust buildup on ISS and resulting hardware anomalies is an on-going issue¹⁴ but is too broad of a topic to discuss in detail here. Related issues include loss of smoke-detection, false low-flow alarms in the CQs, and overheating problems, in addition to the air-mixing issues discussed earlier.

To prevent the IMV fan clogging from occurring so frequently in the future, new easy-to-reach filter screens have been proposed and may be installed in the inlet ducting of several of the IVM fans. These screens would be in addition to the already-in-place inlet screens of relatively high porosity. The mesh size of the new screens must be small enough to catch the lint, but large enough to as to avoid adding too much flow resistance to the fan.



Figure 27. Clogged JPM IMV fan, before (upper left) and after (upper right) cleaning, dust removed is also shown (lower).

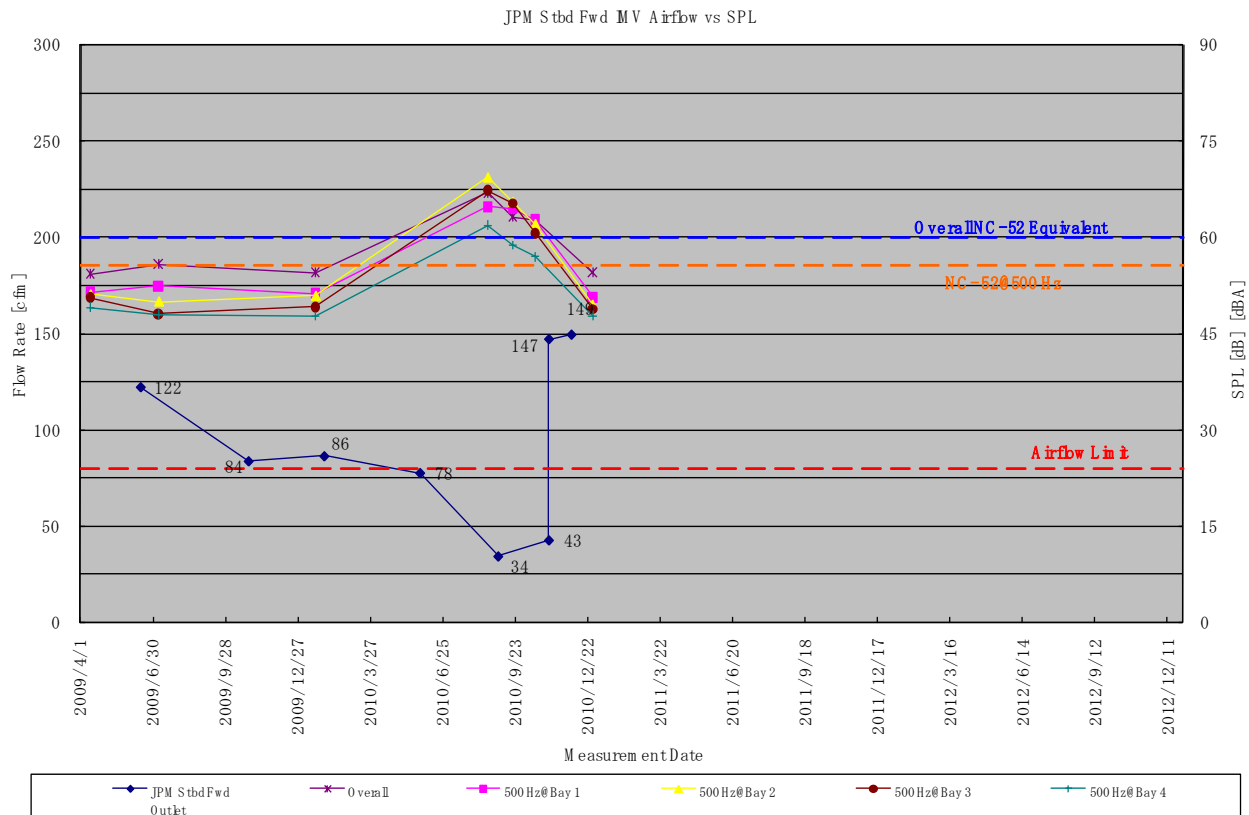


Figure 28. Relationship between IMV flow rate (cfm) and acoustic levels. Acoustic levels shown include A-weighted overall SPL in dBA (Overall), and 500 Hz octave band SPLs in dB, for various axial locations throughout the JPM. Dashed lines indicate the lower flow rate limit where IMV fan stall occurs, and also the corresponding module acoustic limits.

V. Conclusion

Since 2003, for a variety of reasons, noise levels aboard the International Space Station have improved significantly. In the U. S. Segment, many new modules have been added, and all of these meet the NC-50 continuous noise requirement. However, Node 3 noise levels are currently higher than the continuous noise requirement because of suspected IMV fan stalling noise. Currently, all U.S. Segment noise levels meet either NC-50 or NC-52 continuous noise requirements, except for Node 3.

In the Russian Segment, significant efforts have been made to reduce the noise levels in the Service Module, where the crew spends a significant amount of time every day. Noise levels in the newly added MRM1 are high, but work to reduce these levels is underway. The crew spends only up to three hours per day on an infrequent basis inside MRM1.

With the reductions in noise levels in the kayutas of the Russian Segment, and the addition of the four new Crew Quarters in the U. S. Segment, acoustic levels in all of the sleep stations provide an adequately quiet place to allow the crewmember's ears to recover from daily noise exposure. CQ levels are less than 50 dBA, and kayuta levels are 51-56 dBA.

There are still some acoustic challenges, however. In the U. S. Segment R-ECLS noise levels may need to be remediated, depending on the results of upcoming noise measurements. In the Russian Segment, further noise level

reductions are needed in the MRM1. Payload and GFE hardware noise issues were mentioned only briefly, above, but there are significant efforts underway to make sure these hardware items do not affect composite module noise levels. Finally, on-orbit acoustic issues continue to occur but can be mitigated with appropriate attention.

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The authors would like to dedicate this paper to the memory of Pietro Marucchi who led the way to the acoustical success of the Columbus, Node 2, and Node 3 modules.

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