Internal Acoustics of the ISS and other Spacecraft

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Acoustics System Manager, ISS and MPCV Programs
• Background
• Apollo
  • Command Module (CM)
  • Lunar Module (LM)
• Space Shuttle Orbiter
  • Flight Deck
  • Mid-deck
• International Space Station (ISS)
  • U.S. Operating Segment (USOS)
  • Russian Operating Segment (ROS)
• Multipurpose Crew Vehicle (MPCV) / Orion
• Summary
• Acoustic environment inside spacecraft and space habitats must allow
  • Voice communications
  • Alarm audibility
  • Habitability (concentration on tasks)
  • Reduced risk for sleep disturbance
  • Reduced risk for hearing loss (TTS and PTS)
• Firm requirements needed
• Systems engineering approach (Acoustic Noise Control Plan)
  • Sub-allocate to sub-systems and components
  • Acoustic analysis or modeling
  • Perform early development testing
  • Develop and test noise controls
• Final verification of requirements by test
• Management support is critical
## NASA-STD-3001: Acoustic Limits for Launch, Entry, and Abort Phases

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>24-Hour Exposure</th>
<th>Ceiling</th>
<th>Impulse Noise</th>
<th>Infrasonic Noise 1-20 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch</td>
<td>Noise dose ≤ 100, equivalent to 8-hour 85 dBA TWA</td>
<td>≤ 105 dBA allows 10 dBA headroom for Personal Comm</td>
<td>≤ 140 dB peak SPL</td>
<td>&lt; 150 dB*</td>
</tr>
<tr>
<td>Entry</td>
<td>Noise dose ≤ 100, equivalent to 8-hour 85 dBA TWA</td>
<td>≤ 105 dBA allows 10 dBA headroom for Personal Comm</td>
<td>≤ 140 dB peak SPL</td>
<td>&lt; 150 dB*</td>
</tr>
<tr>
<td>Launch Abort</td>
<td>Noise dose ≤ 100, equivalent to 8-hour 85 dBA TWA</td>
<td>≤ 115 dBA</td>
<td>≤ 140 dB peak SPL</td>
<td>&lt; 150 dB*</td>
</tr>
<tr>
<td>Personal Communication</td>
<td>Noise dose ≤ 100, equivalent to 8-hour 85 dBA TWA</td>
<td>≤ 115 dBA</td>
<td>≤ 140 dB peak SPL</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>

*Hearing protection CANNOT be used to satisfy this limit*
### NASA-STD-3001: Acoustic Limits for On-Orbit Phase*

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Continuous Noise</th>
<th>Hazardous Noise</th>
<th>Intermittent Noise</th>
<th>Impulse Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-Orbit</td>
<td>NC-50 Octave Band SPL limits. See Figure 8 and Table 7</td>
<td>&lt; 85 dBA</td>
<td>Specified Sound Level (dBA) depending on duration, see Table 5</td>
<td>≤ 140 dB peak SPL</td>
</tr>
<tr>
<td>a. For Sleep on Missions &gt; 30 days</td>
<td>NC-40 Octave Band SPL limits. See Figure 8 and Table 7</td>
<td>&lt; 85 dBA</td>
<td>+ 10 dBA or less above background</td>
<td>+ 10 dB peak or less above background</td>
</tr>
<tr>
<td>b. For Sleep on Missions ≤ 30 days</td>
<td>NC-50 Octave Band SPL limits. See Figure 8 and Table 7</td>
<td>&lt; 85 dBA</td>
<td>+ 10 dBA or less above background</td>
<td>+ 10 dB peak or less above background</td>
</tr>
</tbody>
</table>

*Hearing protection CANNOT be used to satisfy these limits

- Additional requirements in Mission Operations Requirements Documents
  - Noise Exposure limits 70 dBA for 24-hour period (based on WHO)
  - Acoustic monitoring requirements
Relationship Between Metrics

Habitability (NC Curves) and Communication (SIL)

Distance for Just-reliable Communications

SIL = Ave. of 500Hz + 1 KHz + 2 KHz + 4 KHz dB readings
Apollo

Source:
Speech Interference Level (SIL), was to be 55 dB or less, to allow for adequate communications between crew and ground or between the crew.
Prior to first crewed flight, because of crew inputs, noise reduction effort was made on glycol pumps. This was the first recorded noise mitigation effort in the Apollo program.

Significant noise sources included the glycol cooling pumps, cabin fans, and suit loop fan/compressor.
Crew comments after first flight indicated that cabin fans were too noisy.

Determined during flight that cabin fans were not needed to run continuously.

Suit loop fan provided enough airflow.

Speech Interference Level (SIL), was to be 55 dB or less, to allow for adequate communications between crew and ground or between the crew.
• Many crew complaints about noise, especially the glycol pump  
• When space suits were worn, it was said that levels inside were high  
• Hearing protection was generally used  
• Most significant issue was with sleeping while on the Moon
To improve the sleeping environment for longer duration stays on the lunar surface, a significant effort was made to quiet the glycol pump, achieved 12 dBA reduction.

On Apollo 14 and subsequent lunar missions, the glycol pump noise, and the related issues with the sleep environment were reported as being much improved.
Even though there were acoustic specifications, the design approach did not include any method or checks to insure that these specifications would be met.

Management were initially reluctant to make design changes in order to address the high acoustic levels.

After mission impacts and crew comments convinced management to take action, only limited noise reductions were realized:
- LM glycol pump noise reductions were successful.
- Fortunate that operational work-arounds and the missions’ short durations resulted in a successful program:
  - Shutting off the CM cabin fans.
  - Use of hearing protection.

Following Apollo, a new design standard was implemented, including an NC-50 limit for continuous noise, and this standard impacted Space Shuttle and ISS acoustics efforts.
SPACE SHUTTLE ORBITER

Source:
Space Shuttle Flight Deck and Mid-Deck

SPACE SHUTTLE ORBITER VEHICLE
ALL VEHICLES
ORBITER CREW MODULE

FLIGHT DECK

MIDDECK

EQUIPMENT BAY

OBSERVATION WINDOWS

PILOT STATION

COMMANDER STATION

SIDE MATCH

EMERGENCY EGRESS SLIDE

INTERDECK (LADDER) ACCESS AID

AVIONICS BAY NO. 1

AVIONICS BAY NO. 2

AVIONICS BAY NO. 3A

WATER TANKS

AIRLOCK
Space Shuttle Acoustic Noise Control Plan (ANCP)

- SYSTEMS ENGINEERING APPROACH
- IDENTIFY ALL NOISE SOURCES
  - PART NUMBER, SYSTEM, LOCATION
  - CONTINUOUS OR INTERMITTENT
  - RELATIVE SIGNIFICANCE (CONTRIBUITION TO TOTAL CREW MODULE NOISE)
- DETERMINE SOURCE-TO-LISTENER NOISE PATHS
  - AIRBORNE
  - ENCLOSURE TRANSMISSION
  - STRUCTURE-BORNE
- ESTIMATE COMBINED SYSTEMS NOISE IN FLIGHT DECK AND MID-DECK
- ESTABLISH RELATIVE CONTRIBUTION OF EACH SOURCE TO TOTAL NOISE
- SPECIFY NOISE CRITERIA FOR EACH SOURCE (ALLOWABLE)
- DEFINE NOISE TEST REQUIREMENTS, COMPONENTS, SYSTEM, GENERAL & ADJACENT WORKING AREAS
- IDENTIFY COMPONENTS/SYSTEM ELEMENTS REQUIRING NOISE CONTROL MEASURES
  - PERFORM ANALYSES TO ESTABLISH DYNAMIC BEHAVIOR OF SUSPECT HARDWARE (FINITE ELEMENT METHODS) AS REQUIRED
  - DETERMINE SILENCING REQUIRED IN EACH OCTAVE BAND
  - EVALUATE AVAILABLE OPTIONS (SEE SILENCING OPTIONS)
  - ASSESS COST, WEIGHT, DOWN-TIME, WORK-AROUND
  - OPTIMIZE SILENCING MODIFICATIONS
- PERFORM NOISE TEST(S) TO VERIFY EFFECTIVENESS OF NOISE MITIGATION APPLICATIONS
  - COMPARE WITH ALLOWABLE NOISE REQUIREMENTS
  - NON-COMPLIANCE=REASSESSMENT/ADDITIONAL SILENCING
Implementation of ANCP

- NC-50 was implemented
- Contractor did not except NC-50 as reqt.
  - Thought to be too stringent
  - Not necessary
- NC-55 accepted as a GOAL

- Significant effort put into controlling noise
- Mostly targeted paths
- Significant use of vibration isolators
- Duct treatment considered but not implemented
- Quiet fan development project was started, but was cancelled due to cost
One example of Shuttle noise control is of Inertial Measurement Unit (IMU) mufflers added as Government Furnished Equipment.
Shuttle Mid-Deck Noise Source Contributions

- NC-55
- All systems "ECLSS" + avionics
- Water pump
- Cabin fan
- Smoke detectors
- Avionics fan
- IMU fan
- Water sep (calc)
- Avionics

Sound Pressure Level, dB vs Octave Band Center Frequency, Hz
OVEI specifications, based on Orbital Flight Test configuration

<table>
<thead>
<tr>
<th>Octave Band Center Frequency [Hz]</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1K</th>
<th>2K</th>
<th>4K</th>
<th>8K</th>
<th>O/ A</th>
<th>dB A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Deck</td>
<td>66</td>
<td>59</td>
<td>56</td>
<td>56</td>
<td>59</td>
<td>54</td>
<td>45</td>
<td>68</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Mid-deck</td>
<td>62</td>
<td>62</td>
<td>65</td>
<td>61</td>
<td>62</td>
<td>63</td>
<td>58</td>
<td>71</td>
<td>68</td>
<td></td>
</tr>
</tbody>
</table>
The communications capability within Spacelab had become obscured by the high ambient noise levels of the experiment hardware, and the crew had to move into the airlock to communicate with the ground (away from the experiments that they were operating). In Spacelab, the crew’s callouts needed to be repeated. “Say again” was the phrase repeated over and over again, and the crew became very frustrated.
Shuttle Astronaut Summary – Flights 51-I, 61-B, 61-C

<table>
<thead>
<tr>
<th>Question</th>
<th>Yes</th>
<th>No</th>
<th>No Response</th>
<th>Major Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hearing protection used</td>
<td>6</td>
<td>21</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Sleep disturbed</td>
<td>18</td>
<td>9</td>
<td>6</td>
<td>Need better isolation</td>
</tr>
<tr>
<td>Speech interference</td>
<td>16</td>
<td>11</td>
<td>6</td>
<td>Must shout between decks</td>
</tr>
<tr>
<td>Annoyed</td>
<td>13</td>
<td>10</td>
<td>10</td>
<td>Intermittent noise bothersome</td>
</tr>
<tr>
<td>Interference with concentration</td>
<td>5</td>
<td>16</td>
<td>12</td>
<td>More quiet desirable</td>
</tr>
<tr>
<td>Interference with relaxation</td>
<td>14</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Notice vibration</td>
<td>17</td>
<td>10</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Notice noise more late in flight</td>
<td>7</td>
<td>26</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Notice noise more when tired</td>
<td>4</td>
<td>21</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Block out unpleasant noise</td>
<td>17</td>
<td>10</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Greater sensitivity in space</td>
<td>1</td>
<td>25</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Prefer lower background noise</td>
<td>20</td>
<td>7</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Lower Space Station noise</td>
<td>25</td>
<td>2</td>
<td>6</td>
<td>Strong agreement on this</td>
</tr>
</tbody>
</table>
International SPACE STATION
Add-on Mufflers for ExPRESS Rack Payloads

- Commercial Generic Bioprocessing Apparatus
- Protein Crystal Growth Single Thermal Enclosure System
- Commercial Protein Crystal Growth
- Space Acceleration Measurement System II
Average Acoustic Levels in U.S. Segment Modules

As of September 4, 2017
Average Acoustic Levels in U.S. Segment Modules

As of April 1, 2015

Graph showing SPL (Sound Pressure Level) in dB re: 2.0e-5Pa versus Octave Band Center Frequency in Hz for various segments and nodes with their respective NC values and noise levels.
US Segment – Crew Quarters

As of September 4, 2017

Zenith, 48.3 dBA
Nadir, 42.6 dBA
Stbd, 49.7 dBA
Port, 45.2 dBA

- CQs on High Speed
- Sound Levels <50 dBA
US Segment – Crew Quarters

As of April 1, 2015

Zenith, 49.5 dBA
Nadir, 49.1 dBA
Stbd, 50.4 dBA
Port, 50.1 dBA

- CQs on High Speed
- Sound Levels ~50 dBA
IMV Fan Clogging and Elevated Noise Levels

Node 2, December 7, 2012
IMV Fan Configuration Test, Rack Bay 5

Sound Pressure Level [dB re 20\textmu Pa]

1/1 Octave Band Center Frequency [Hz]
Old and New Node 2 Cabin Air Diffuser Plates
Changed Out on October, 31, 2008.

Old NOD2OS3 (upstream), 11% Open area
Old NOD2OS5 (downstream), 10% open

New NOD2OS3 (upstream), 22% open area
New NOD2OS5 (downstream), 18% open
Old and New Node 2 Cabin Air Diffuser Plate Acoustic Levels

Node 2, Compare New vs Old Plates for CCAA 4880 and 4000rpm (Measured Data on 31Oct08)

- **Old Plates**: 4880rpm, Vavda 4deg, Old plates average (2:5)
  - 59.3dBA NC55.3 SIL(4) 51.9
- **New Plates**: 4880rpm, Vavda 4deg, New plates average (2:5)
  - 54.9dBA NC50.4 SIL(4) 47.4
- **Old Plates**: 4000rpm, Vavda 4deg, Old plates average (2:5)
  - 55.3dBA NC51.1 SIL(4) 47.6
- **New Plates**: 4000rpm, Vavda 4deg, New plates average (2:3)
  - 52.8dBA NC48.3 SIL(4) 45.4

**RAMV**: 4 deg

**PPA's**:
- LT 9240rpm
- MT 9400rpm, Node 2 IMV Off
RSOS
• Ventilation System
  • Kayutas
  • Main Cabin
• CKB (Air Conditioner) System
• Vozdukh (CO2 Removal) System
• Quiet Fan Development
Russian Segment Acoustics – SM

- Kayuta inlet fan
- Return air duct fan
- Kayuta air register
- Air conditioner (CKB)

FWD

AFT
Kayuta Noise Controls
Kayuta Noise Controls
## RSC-Energia Quiet Fan

<table>
<thead>
<tr>
<th>Fan type</th>
<th>Original Fan</th>
<th>Quiet Fan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Rise, mm H2O</td>
<td>4 (0.16 in H2O)</td>
<td>4 (0.16 in H2O)</td>
</tr>
<tr>
<td>Flow Rate, Q, l/s</td>
<td>47.0 (100 cfm)</td>
<td>83.4 (176 cfm)</td>
</tr>
<tr>
<td>Current Draw, mA</td>
<td>470</td>
<td>470</td>
</tr>
<tr>
<td>Rotation speed, rpm</td>
<td>3120</td>
<td>2010</td>
</tr>
<tr>
<td>Isolated noise levels, dBA</td>
<td>61-64</td>
<td>48</td>
</tr>
</tbody>
</table>
MRM1 Noise Reduction – Quiet Fan Installations

Aug. 20, 2010

Aug. 20, 2010

Bold Lines: Jan. 21, 2014

Frequency (1/1 Octave Band) [Hz]

SPL [dB re: 2.0e-5Pa]

65 70 75

60 65 70

60 65 70

55 60 65

50 55 60

45 50 55

30 50

250 500 1000 2000 4000 8000

HX Fans

Circ. Fans

KT1(2010) 73.2dBA
KT3(2010) 73.0dBA
KT1(2011) 69.0dBA
KT3(2011) 67.7dBA
KT1 NC-59.7 64.3dBA
KT3 NC-57.3 61.8dBA
Russian Spec 60dBA

1

FGB

2

Zenith

3

Nadir
Russian Segment Acoustics – DC1

Data taken April 1, 2015
SM Fans

= vibration isolation acoustic-lined duct

= replaced with low-noise fan in week preceding Dec. 7, 2012 [7 fans]

= replaced 11/2013 [4 fans]

= replaced 12/2013 [5 fans]

= replaced by 7/2014 [3 fans – but Nikimash not RSC-E fans]
SM fan replacements with low-noise fans began the week preceding the Dec. 7, 2012 survey. Since that time, noise levels at some of the central SM points appear generally lower.
Average Acoustic Levels in Russian Segment Modules

As of September 4, 2017

[SPL vs. Octave Band Center Frequency graph with data points for different modules and dates, including DC1, FGB, MRM2, MRM1, SM, and Russian Spec]
Average Acoustic Levels in Russian Segment Modules

As of April 1, 2015
SM Sleep Station Noise Levels
 As of September 4, 2017

![Graph showing SM Sleep Station Noise Levels](image)
MPCV / Orion

Source:

Orion Cabin System Models

- Noise sources include Cabin Fans, Suit Loop Fans, and Cooling Pumps
- Modeling performed with and without System Level Noise Controls
- Determined ideal source sound power levels using Power Injection Method

SEA Model, for > 1,600 Hz

Hybrid SEA-FE Model, for ≤ 1,600 Hz
ARS Fan 1 Source-to-Receiver Gains

Gains for Power Input at ARS Fans 1 to Total Energy of Habitable Volume, with NCT

ARS Fans 1&2 Allocated Source Power

Allocated Source Power for ARS Fans 1 & 2, with NCT
Suit Loop Fan Exhaust Sound Power Measurement Setup
Models of ARS Fan Source Sound Power Characterization

**SEA Model, for > 1,600 Hz**
- Muffler connection to ducts and acoustic wrap on fan casing modeled with a SIF connection and high radiation loss factor of 50%
- Measurement side duct termination to anechoic chamber modeled using MAJ

**FE Model, for ≤ 1,600 Hz**
- Duct termination on measurement side is modeled as SIF connection (*radiation into a hemispherical infinite space*)
- Duct connection to muffler has been modeled as *pc* termination (*dissipation into an infinite duct*)
- ARS fan casing is very stiff and hence not modeled
Sound Power Level Allocations and Component Level Noise Control Requirements

ARS Fans 1&2

Allocated (Composite SEA & Hybrid) and Nominal Source Power for ARS Fan 1 & 2

Cabin Fan

Allocated (Composite SEA & Hybrid) and Nominal Source Power for Cabin Fan

Frequency (Hz, 1/3-Oct Center)
NASA has developed a strong system of Standards and Program Requirements, including verification requirements to control acoustical noise inside spacecraft and space habitats.

NASA employs system engineering principals to control the noise levels inside spacecraft and space habitats.

It is important to be diligent with oversight and insight, including participation in design reviews, to make sure programs and projects are including acoustics concerns in the design and development process.

It is important to perform system-level acoustic verifications by test in actual flight vehicle/habitat.

It is important to have management support, including NASA Program, NASA Institutional, Prime Contractor, and Sub-contractor management support.
BACKUP
List of Acronyms

- ARS: Air Revitalization System
- CM: Crew Module
- CPP1: Coolant Pump Package 1
- ECLSS: Environmental Control and Life Support System
- EFT-1: Exploration Flight Test 1
- HSIR: Human-Systems Integration Requirements
- MPCV: Multi-Purpose Crew Vehicle
- NCT: Noise Control Treatment
- PWL: Sound Power Level
- SPL: Sound Pressure Level
Science capabilities
Laboratories from five space agencies planned: U.S. Lab *Destiny* operating since Feb. 2001, ESA Lab *Columbus* operating since Feb. 2008, JAXA Lab *Kibo* will be fully operational after STS-127 in April 2009, Russian MLM will launch in 2010.

Orbital inclination/path
51.6 degrees, covering 90% of the world’s population

Altitude
Approximately 370 km (200 nautical miles) above the Earth

Speed
28,000 kph (17,500 mph), orbiting the Earth 16 times a day

Current Dimensions *(as of May 31, 2008)*
Length: 74 m (243 ft)\(^1,2\)
Width: 94 m (308 ft)
Weight: 276,808 kg (610,256 lbs)\(^2,3\)
Volume: 737 cubic meters (26,052 cubic feet)\(^2,3\)

Notes:
(1) Tip of Solar Array to SM Aft
(2) No visiting vehicles in measurement—Progress, ATV, HTV
(3) Includes one docked Soyuz up to 17A
Acoustic Monitoring Equipment

Sound Level Meter (SLM)

Acoustic Dosimeter (AD)

Acoustic Monitor (replaces SLM & AD)
US Segment Acoustics – US Lab

Data taken April 1, 2015
US Segment Acoustics – Node 1 and A/L

Data taken 2014, 2015
US Segment Acoustics – IP Modules and Cupola

Data taken 2014, 2015
2014 Noise Levels in RS Modules including DC1, MRM1, and MRM2

SPL [dB re: 2.0e-5Pa]

Octave Band Center Frequency [Hz]

- DC1, 2013-06-27, NC-62.9, 67.7 dBA
- FGB, 2013-06-24, NC-62.4, 64.7 dBA
- MRM2, 2013-10-16, NC-61.6, 66.6 dBA
- MRM1, 2014-01-21, NC-57.9, 63.7 dBA
- SM, 2014-03-13, NC-56.5, 62.3 dBA
- Russian Spec, 60 dBA
Ventilation System Noise Controls
Air Conditioning System (CKB) Noise Controls
Upon crew initiative, additional soundproofing device installed

Adapter, shock absorber, and soft soundproof cover installed
JEM Ops Status – July, 2012

- Comparison of the noise level and the air flow still shows good correspondence.

Exceedance of acoustic criteria and air flow degradation below limit correspond to each other.
• SPLs were measured from several distances from CPP1 inside EFT-1 at KSC.
• Source sound power was derived using the Eyring equation assuming hemispherical radiation.

\[ L_p(r) = L_w + 10 \log_{10} \left( \frac{Q}{4\pi r^2} + \frac{4}{R} \right) \]
Cabin SPL due to Allocated Noise Source Powers