National Aeronautics and Space Administration

Internal Acoustics of the ISS and other Spacecraft

Conference of the Australian Acoustical Society
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Outline

- 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

Background

- 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

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

*Hearing protection CANNOT be used to satisfy this limit

NASA-STD-3001 : Acoustic Limits for On-Orbit Phase*

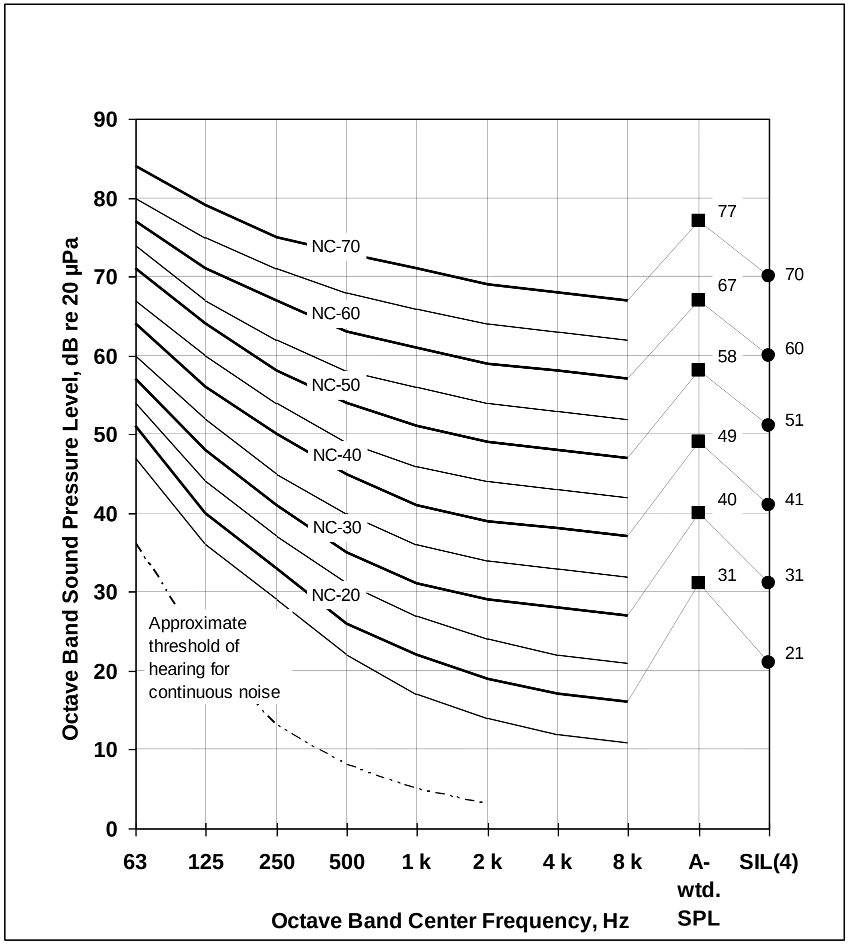
Mission Phase	Continuous Noise	Hazardous Noise	Intermittent Noise	Impulse Noise
On-Orbit	NC-50 Octave Band SPL limits. See Figure 8 and Table 7	< 85 dBA	Specified Sound Level (dBA) depending on duration, see Table 5	≤ 140 dB peak SPL
a. For Sleep on Missions > 30 days	NC-40 Octave Band SPL limits. See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

*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

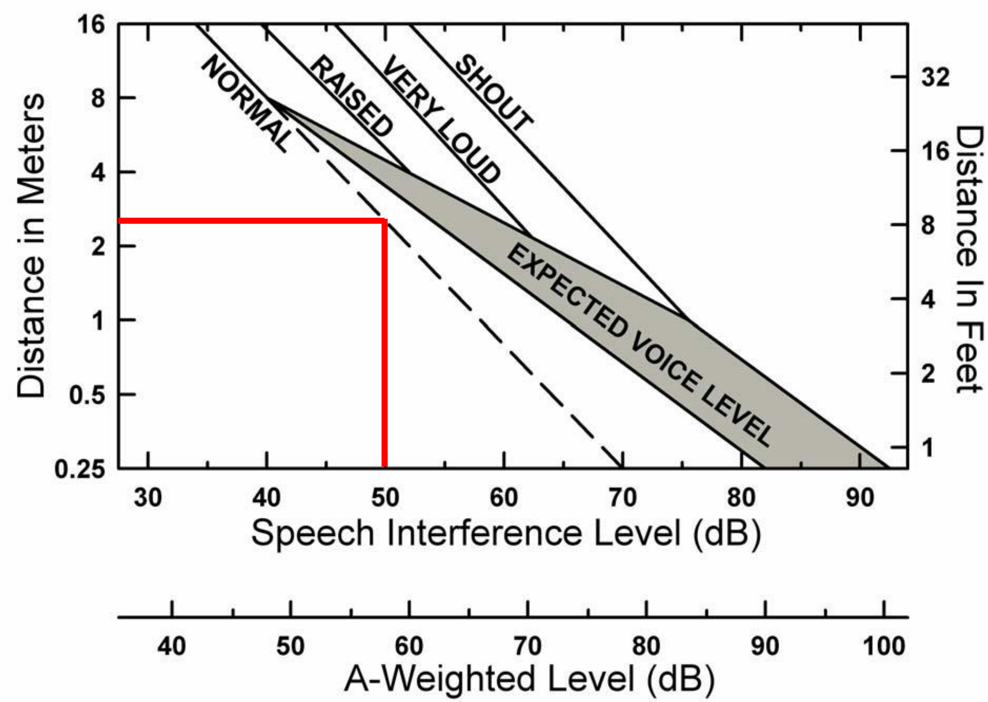
Relationship Between Metrics

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:

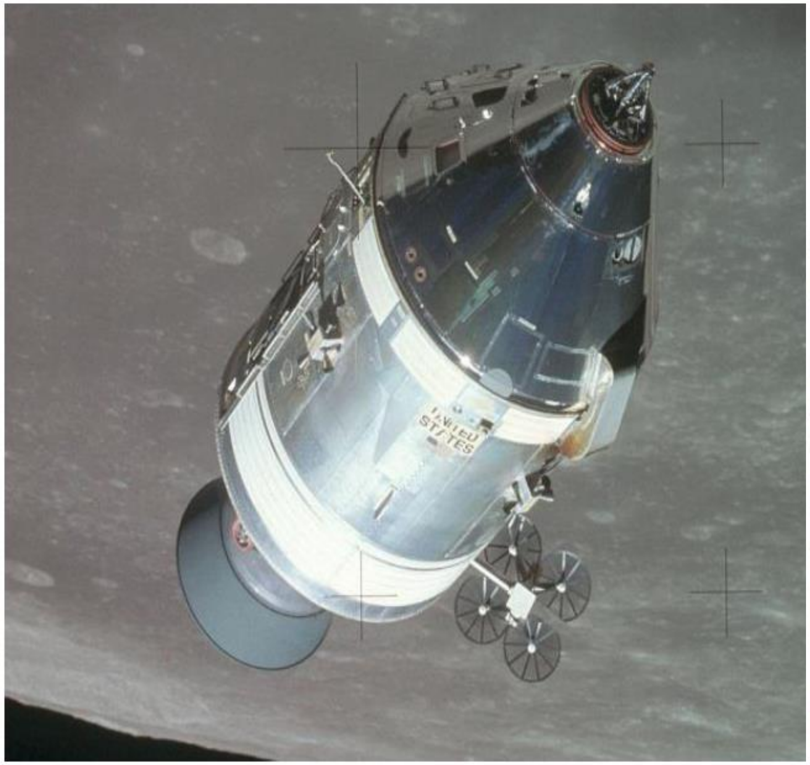
Goodman, Jerry R. and Grosveld, Ferdinand W. 2015.

Acoustics and Noise Control in Space Crew Compartments.

NASA/SP-2015-624, National Aeronautics and Space Administration,

Johnson Space Center, Houston, TX.

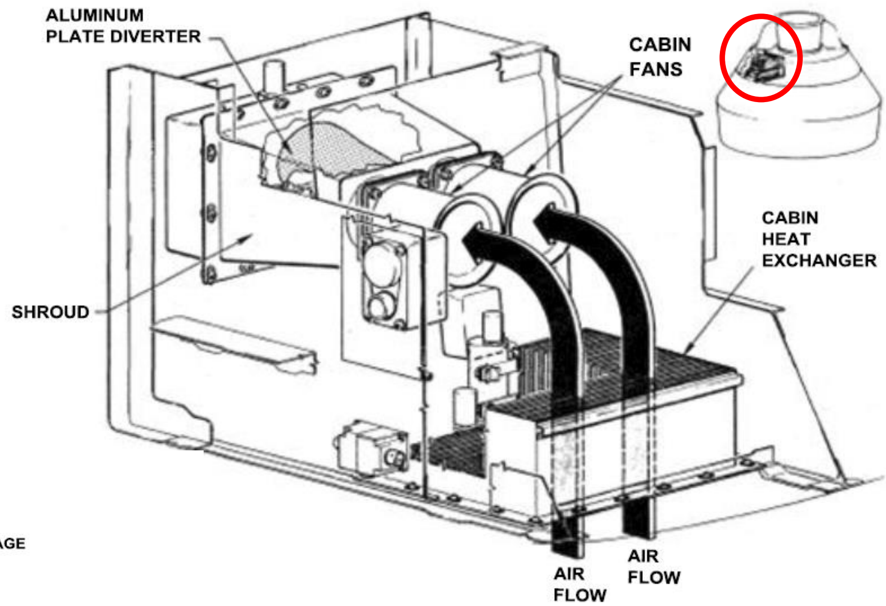
Apollo Command Module

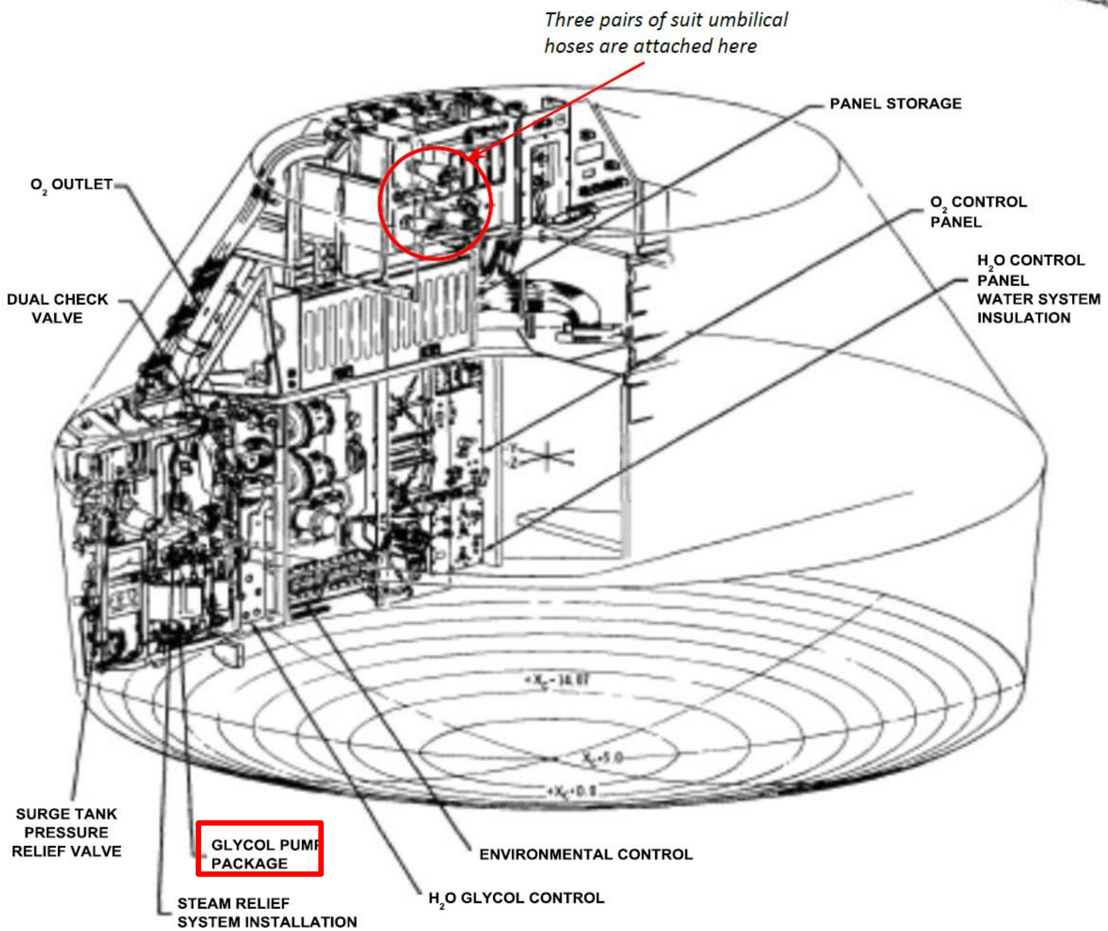


Speech Interference Level (SIL), was to be 55 dB or less, to allow for adequate communications between crew and ground or between the crew.

Apollo Noise Sources

Significant noise sources included the glycol cooling pumps, cabin fans, and suit loop fan/compressor

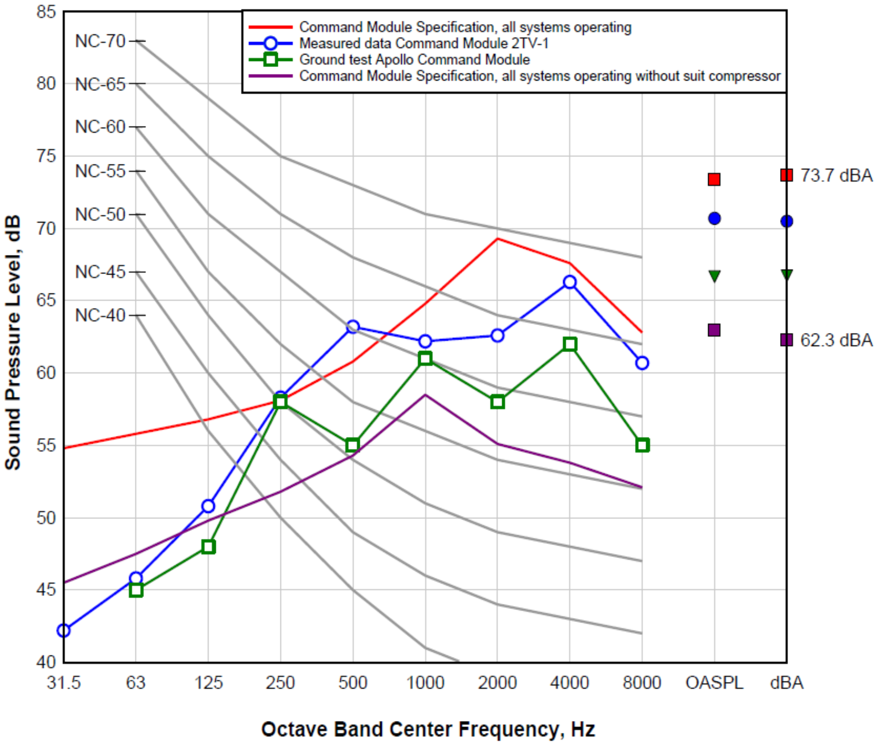


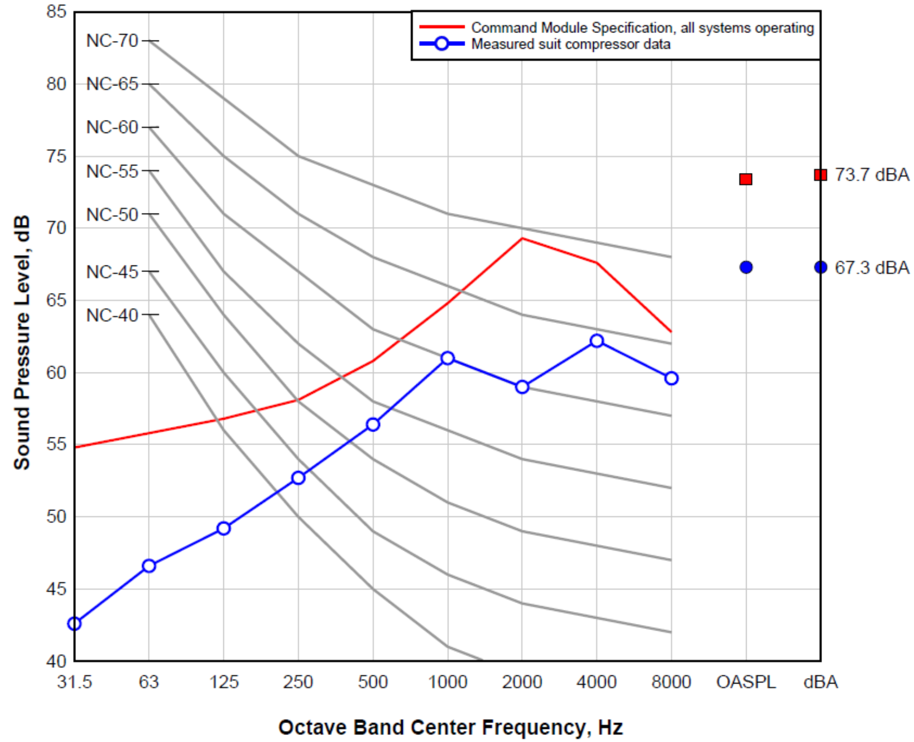


Prior to first crewed flight, because of crew inputs, noise reduction effort was made on glycol pumps. This was the first recorded noise mitigation effort in the Apollo program.

Apollo Acoustic Requirements and Performance

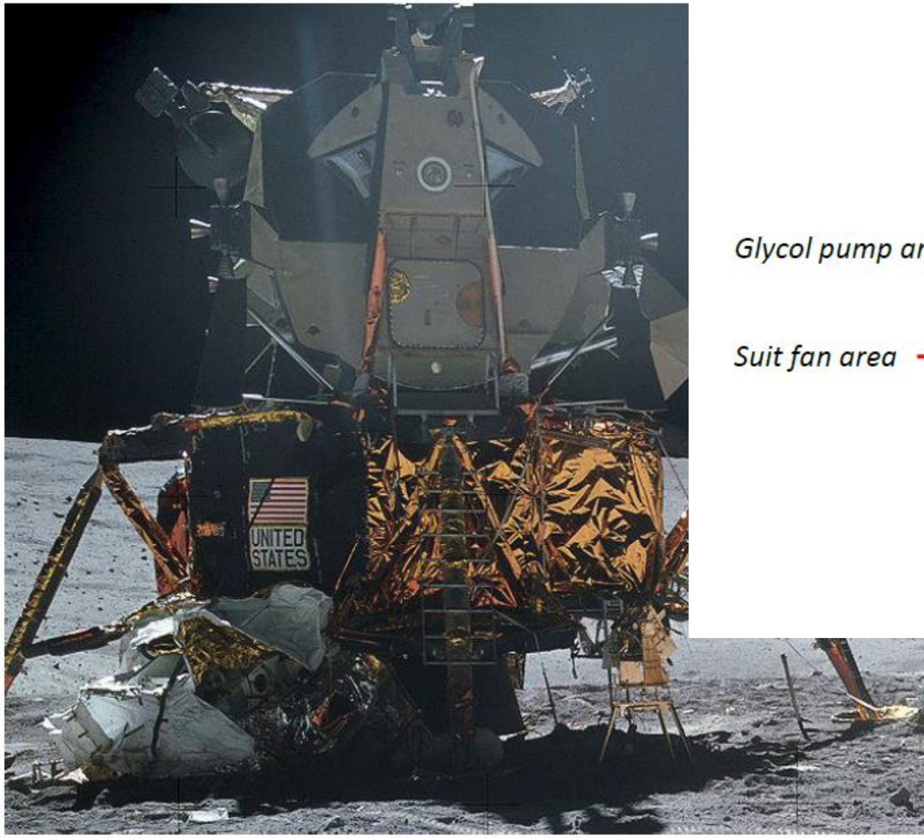
Speech Interference Level (SIL), was to be 55 dB or less, to allow for adequate communications between crew and ground or between the crew.

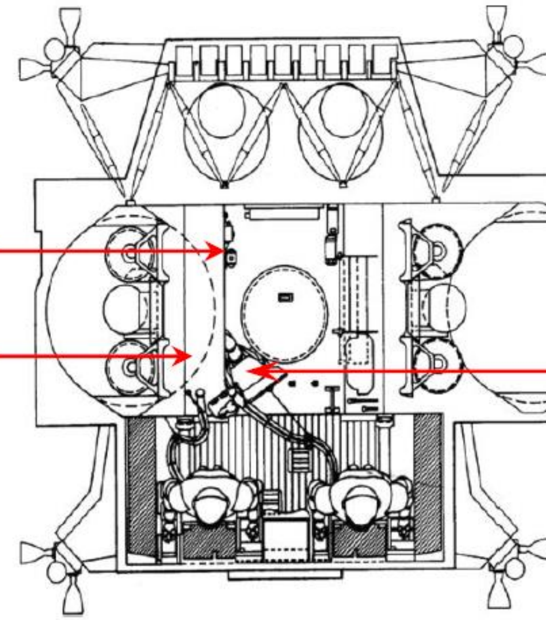


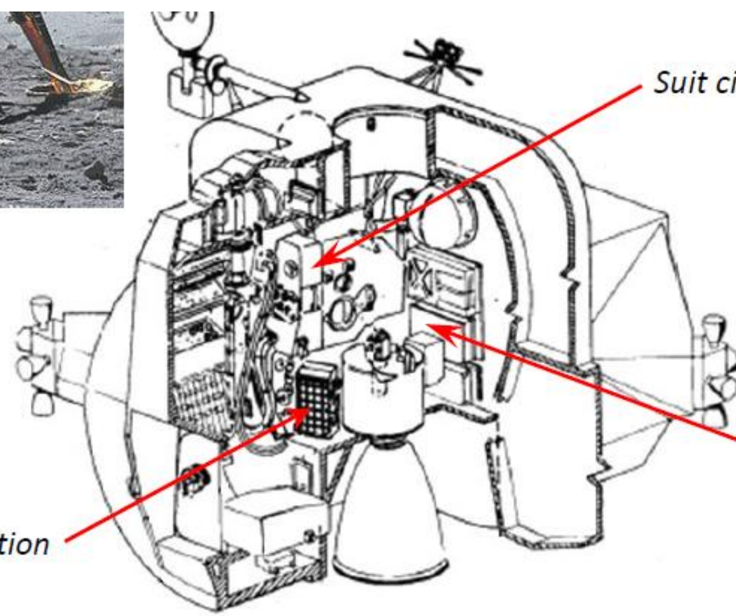


- Crew comments after first flight indicated that cabin fans were too noisy
- Determined during flight that cabin fans were not needed to run continuously
- Suit loop fan provided enough airflow

Apollo Lunar Module and Noise Sources

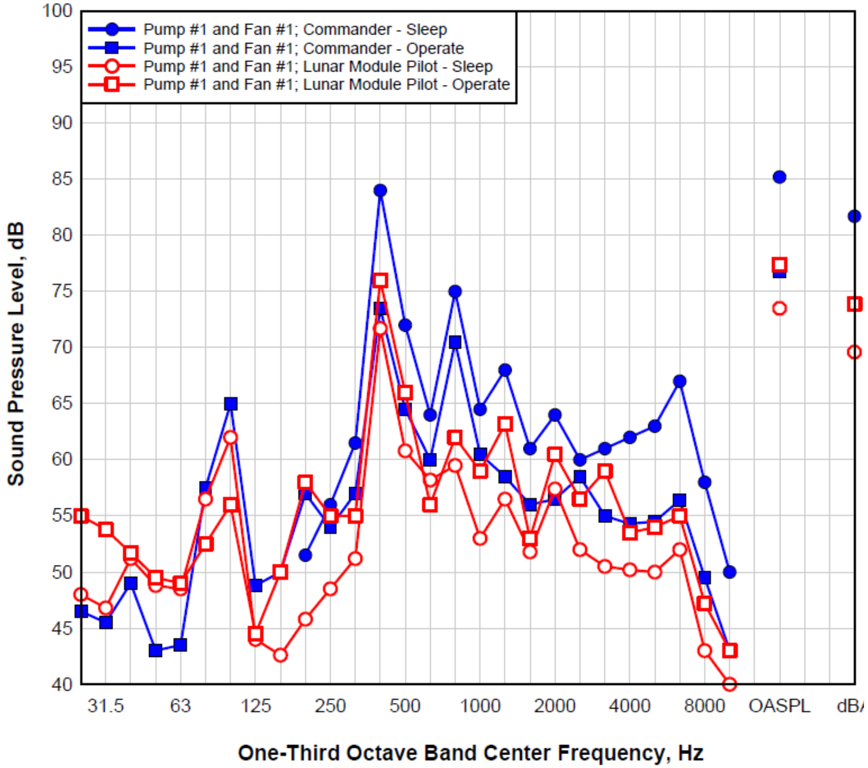


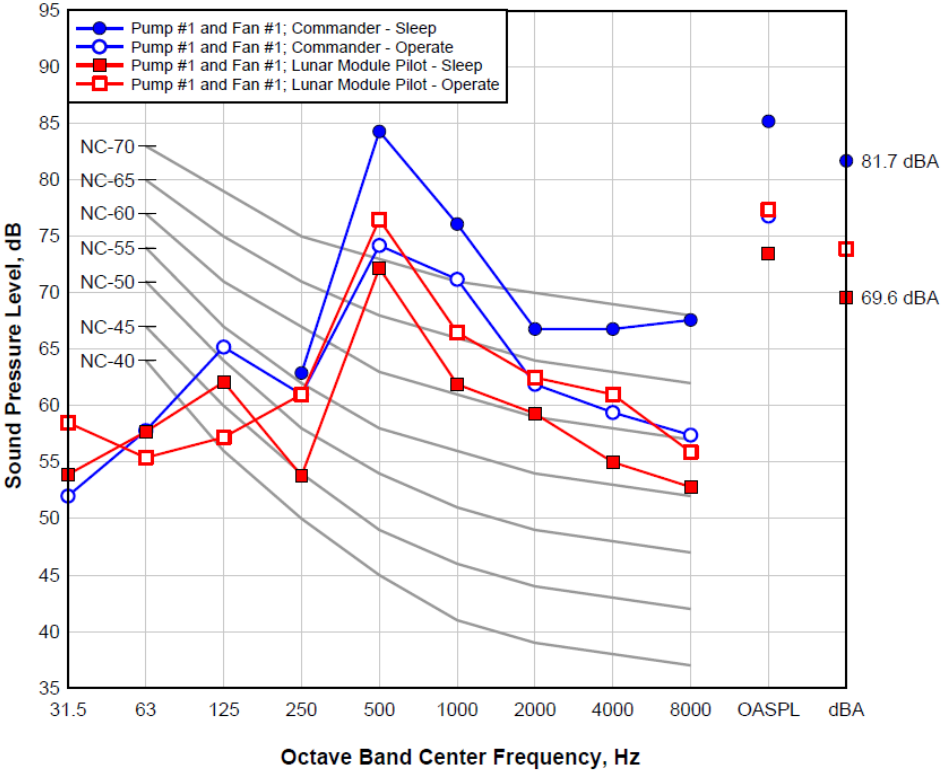




Early LM Acoustic Levels

Speech Interference Level (SIL), was to be 55 dB or less, to allow for adequate communications between crew and ground or between the crew.

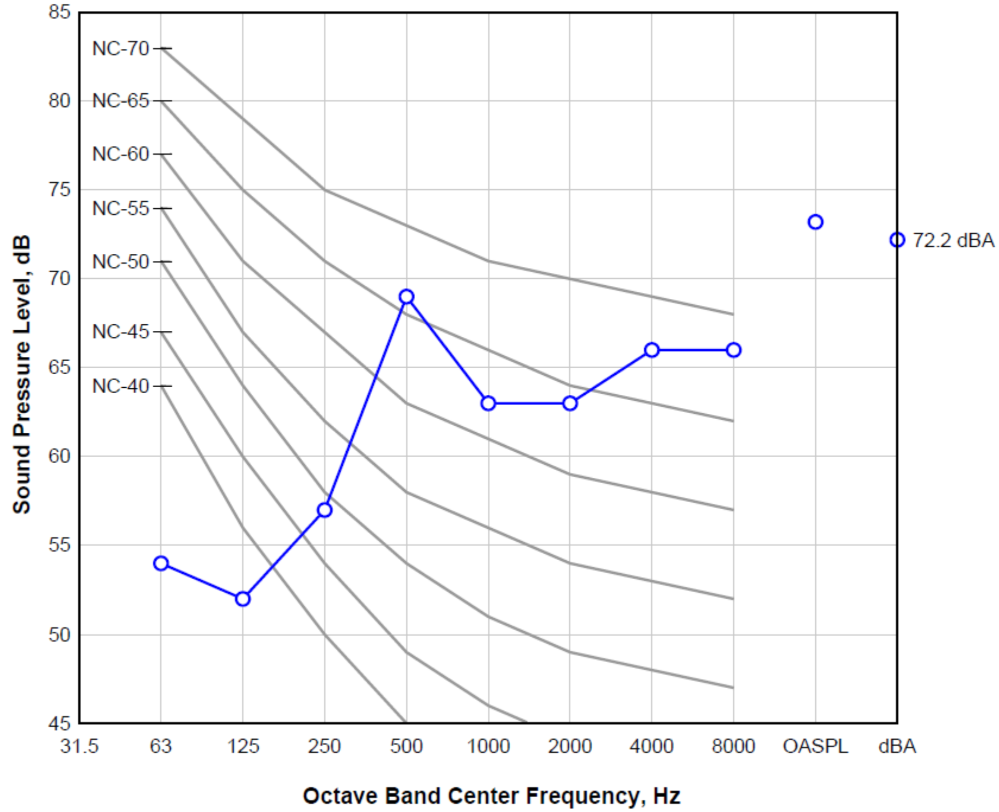


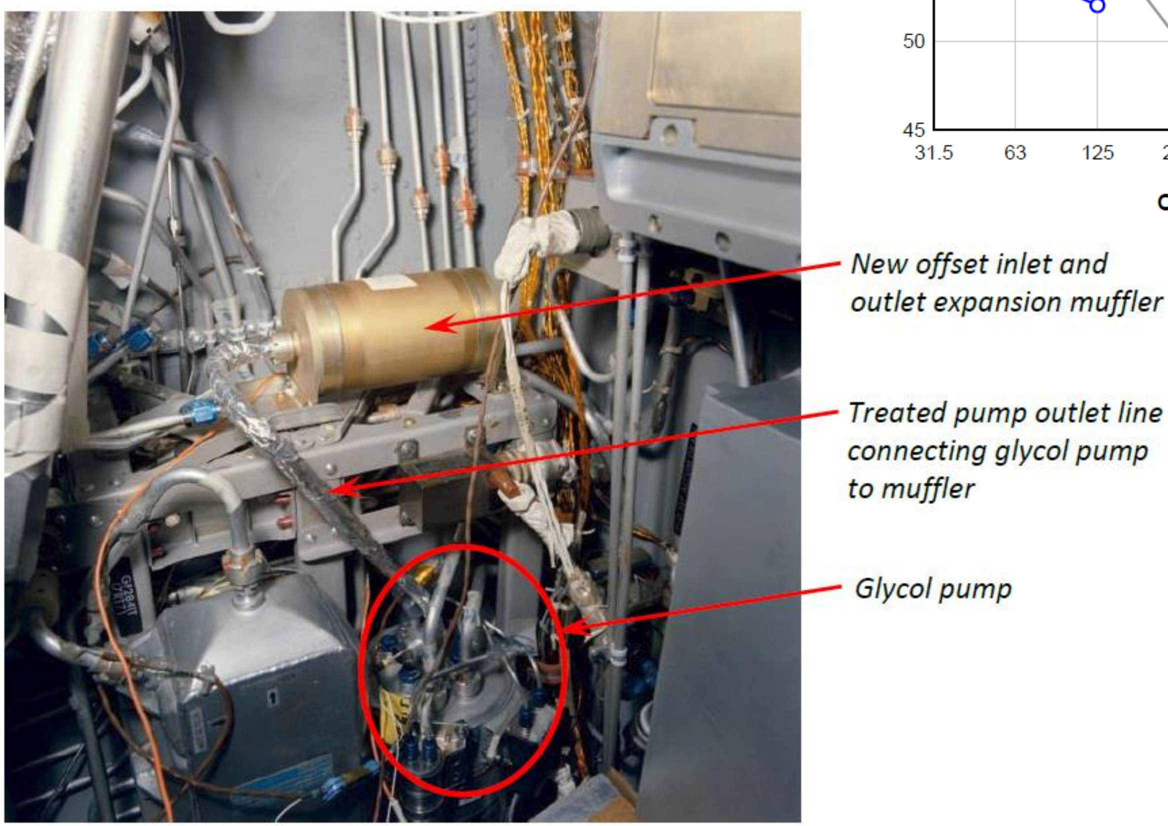


- Many crew complaints about noise, especially the glycol pump
- When space suits were worn, it was said that levels inside were high
- Hearing protection was generally used
- Most significant issue was with sleeping while on the Moon

LM Modifications

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.

Apollo Acoustic Summary

- 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:

Goodman, Jerry R. and Grosveld, Ferdinand W. 2015.

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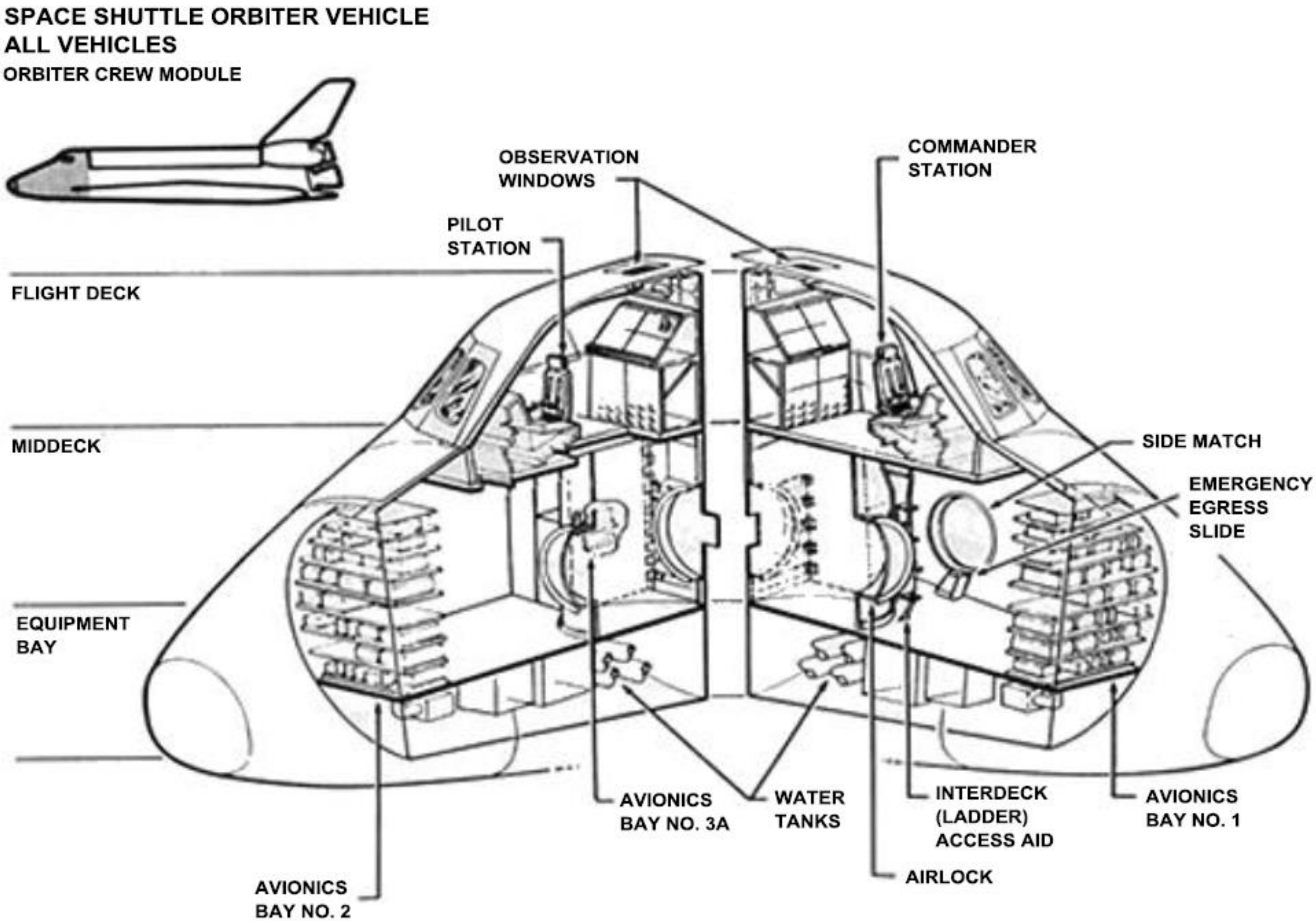
Space Shuttle Flight Deck and Mid-Deck

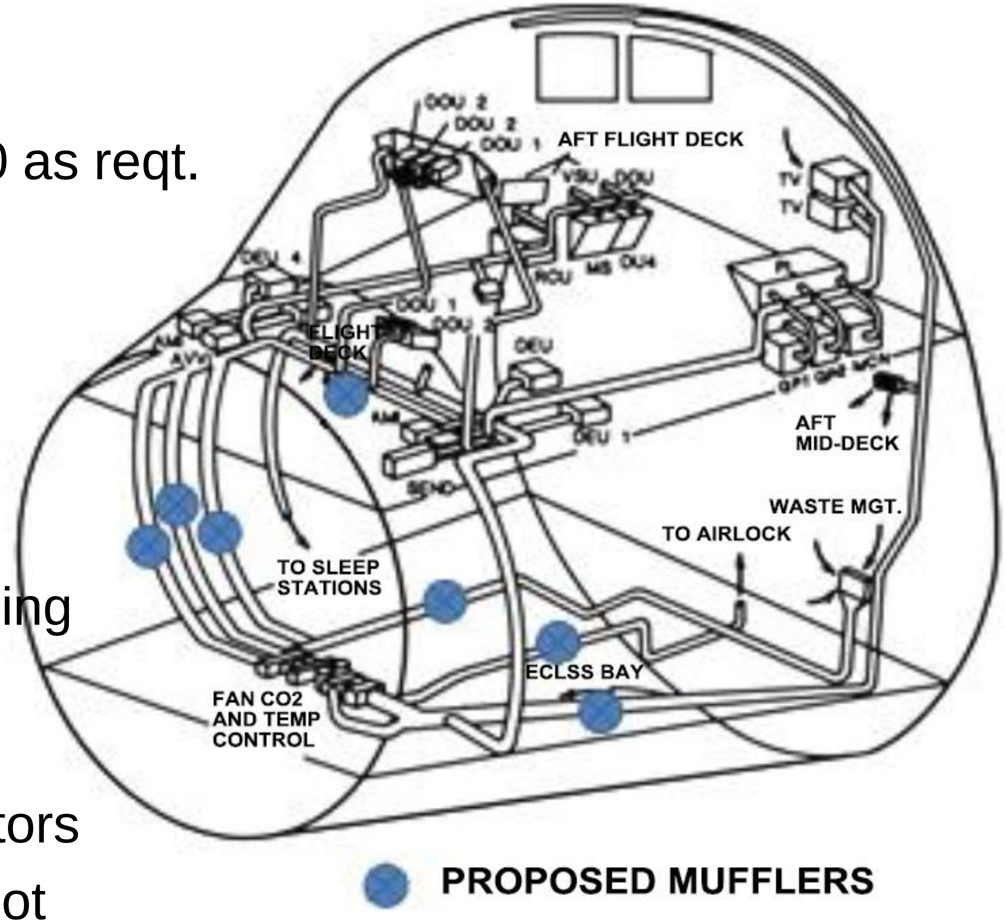


Space Shuttle Acoustic Noise Control Plan (ANCP)

- **SYSTEMS ENGINEERING APPROACH**
- **IDENTIFY ALL NOISE SOURCES**
  - PART NUMBER, SYSTEM, LOCATION
  - CONTINUOUS OR INTERMITTENT
  - RELATIVE SIGNIFICANCE (CONTRIBUTION 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

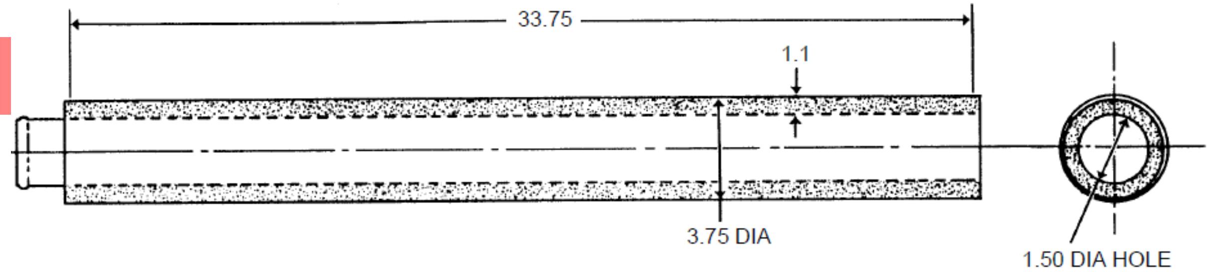
Implementation of ANCP

- 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

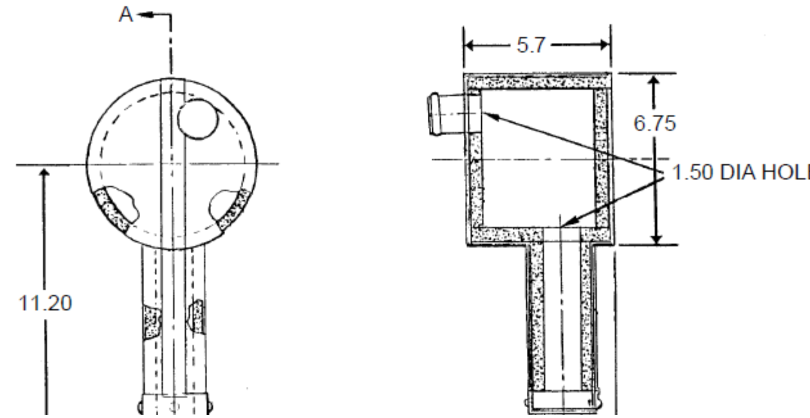
Noise Control

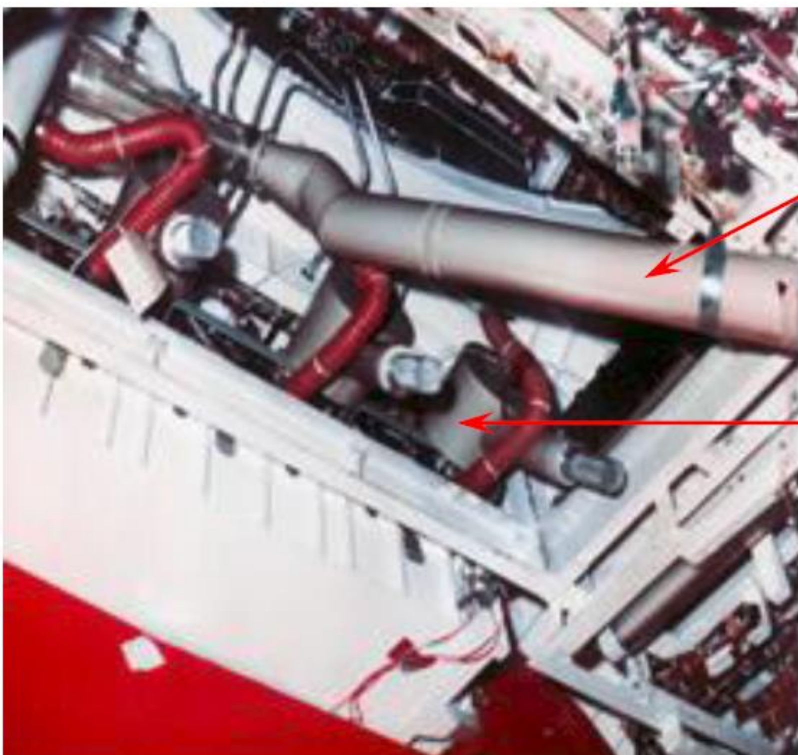


One example of Shuttle noise control is of Inertial Measurement Unit (IMU) mufflers added as Government Furnished Equipment.

EXHAUST MUFFLER
- DISSIPATIVE
- ALUMINUM TUBING
- FOAM LINING

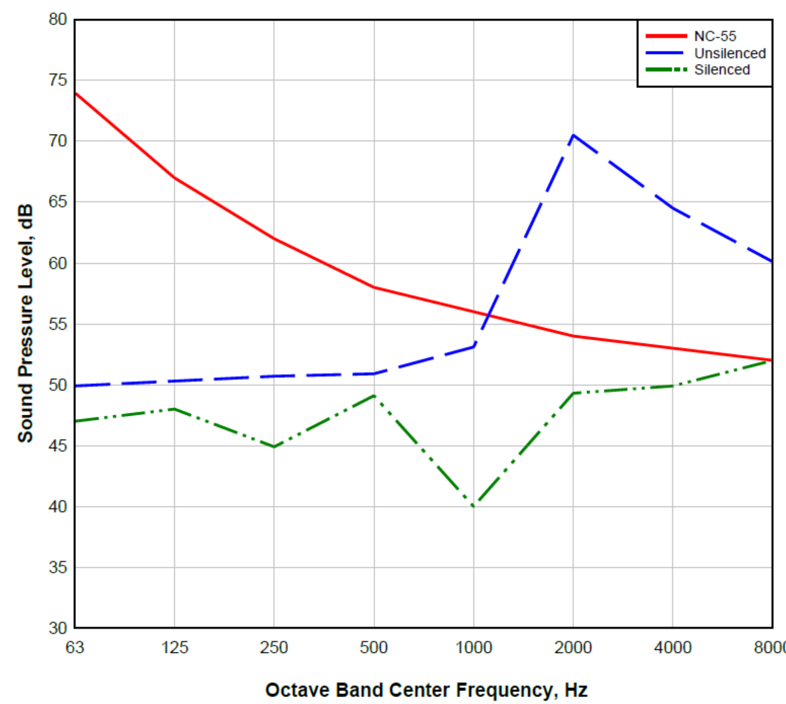
INLET MUFFLER
- REACTIVE
- ALUMINUM TUBING
- FOAM LINING



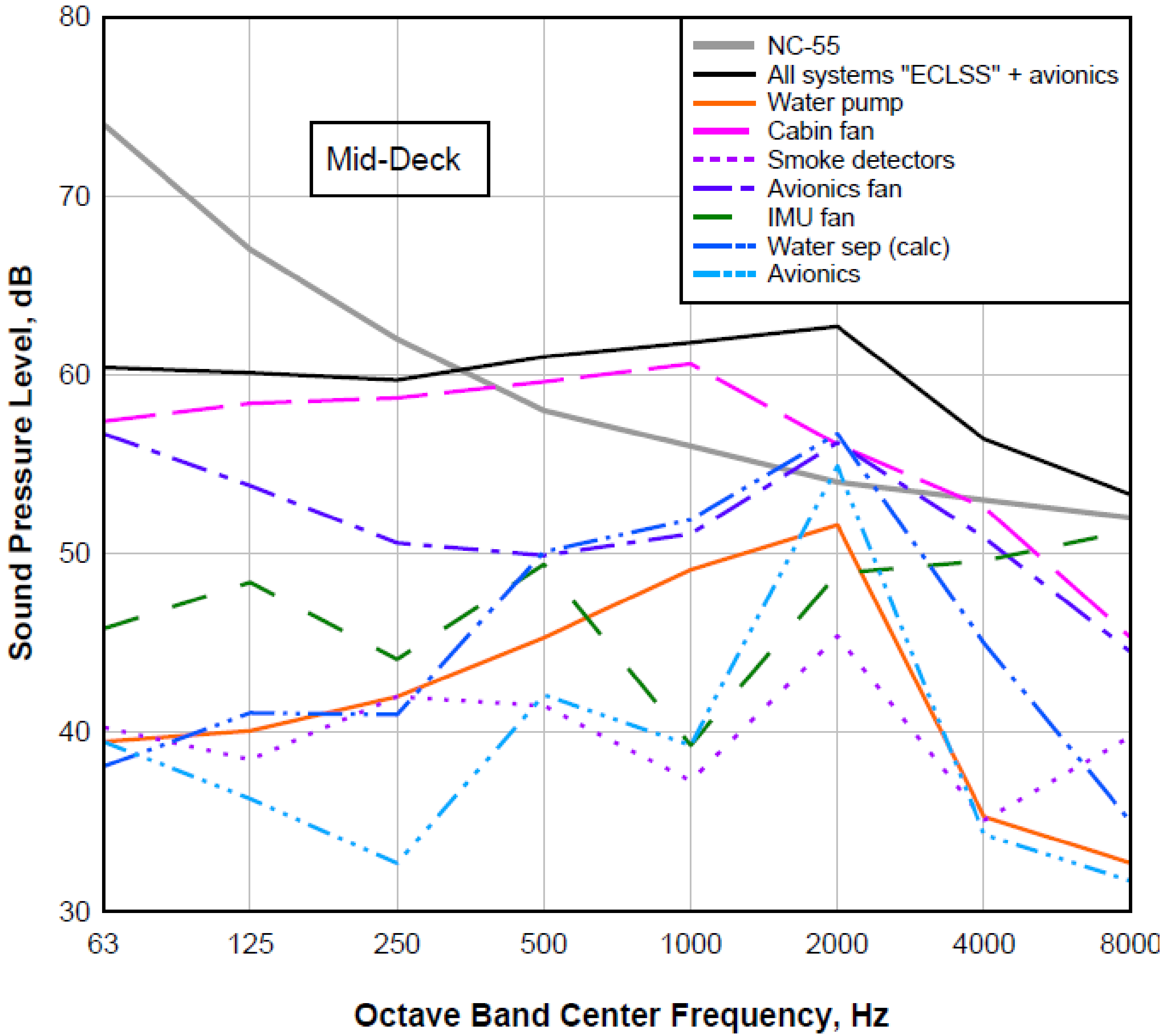


Outlet muffler

Inlet muffler (typical)



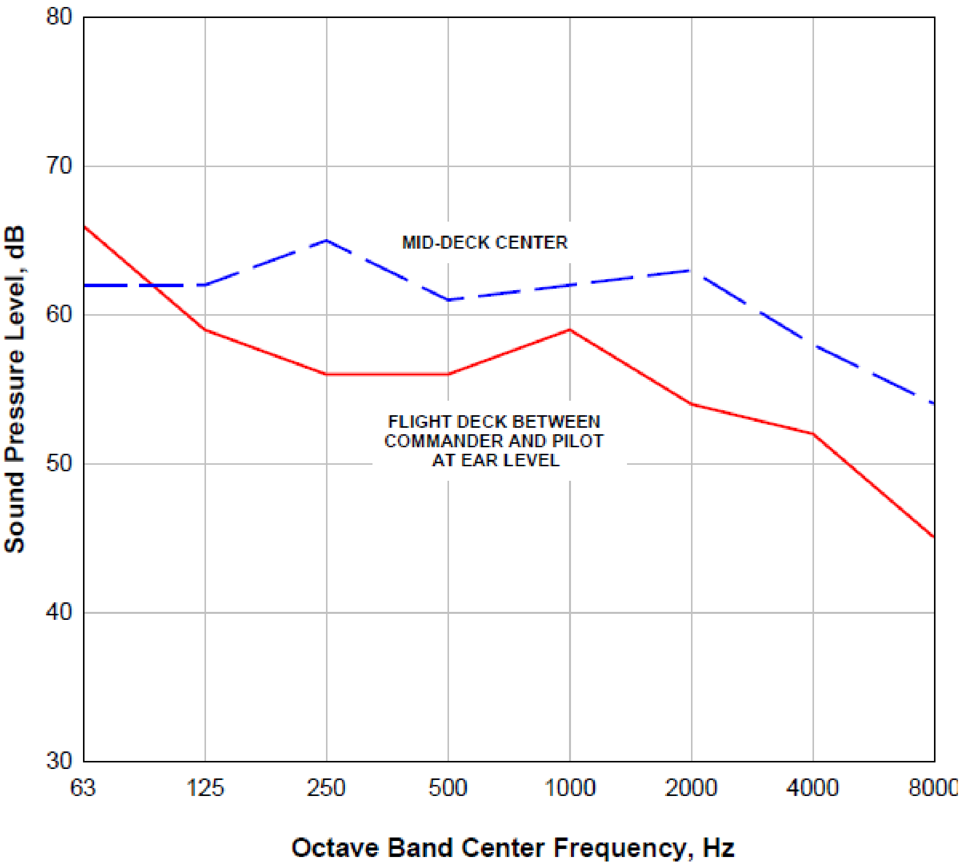
Shuttle Mid-Deck Noise Source Contributions



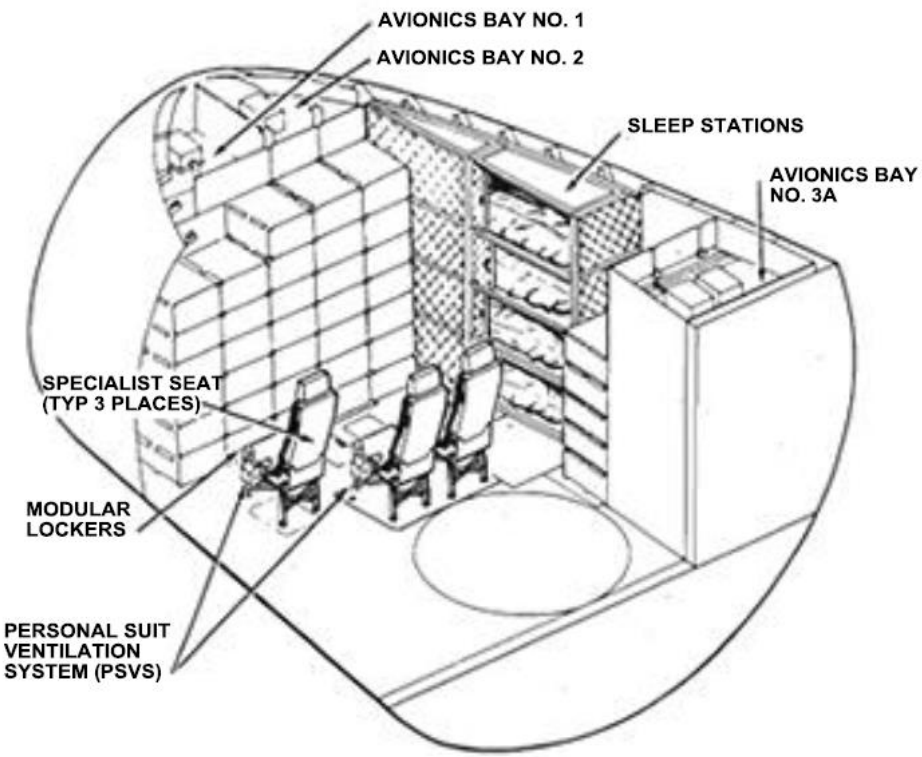
Orbiter Vehicle End Item (OVEI) Specificatoins

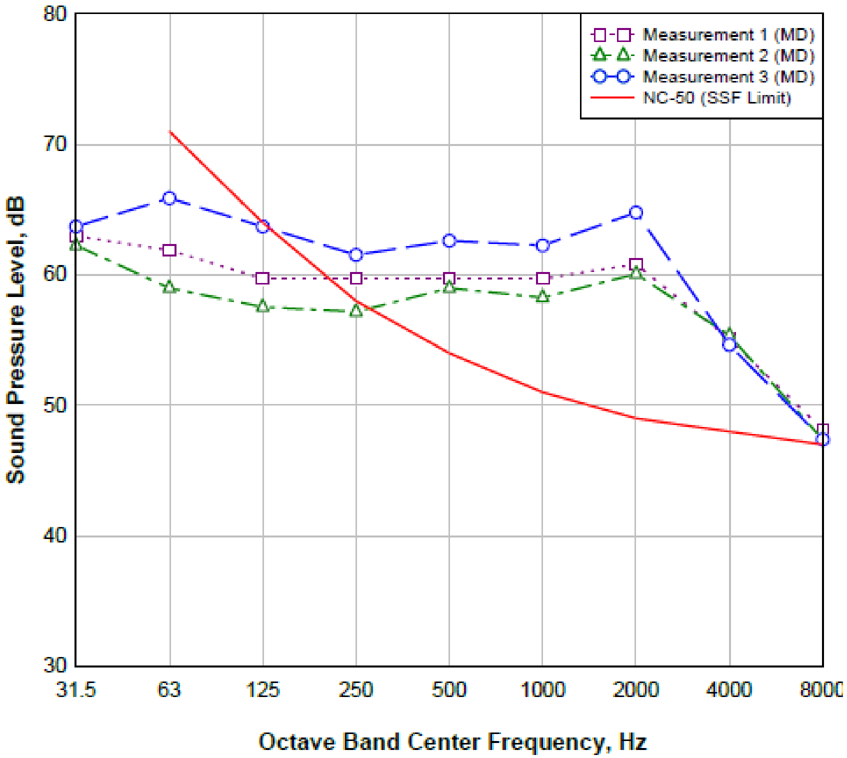
OVEI specifications, based on Orbital Flight Test configuration

	Octave Band Center Frequency [Hz]									
	63	125	250	500	1K	2K	4K	8K	O/A	dB A
Flight Deck	66	59	56	56	59	54	52	45	68	63
Mid-deck	62	62	65	61	62	63	58	54	71	68



Shuttle Mid-Deck Including Payloads STS-40





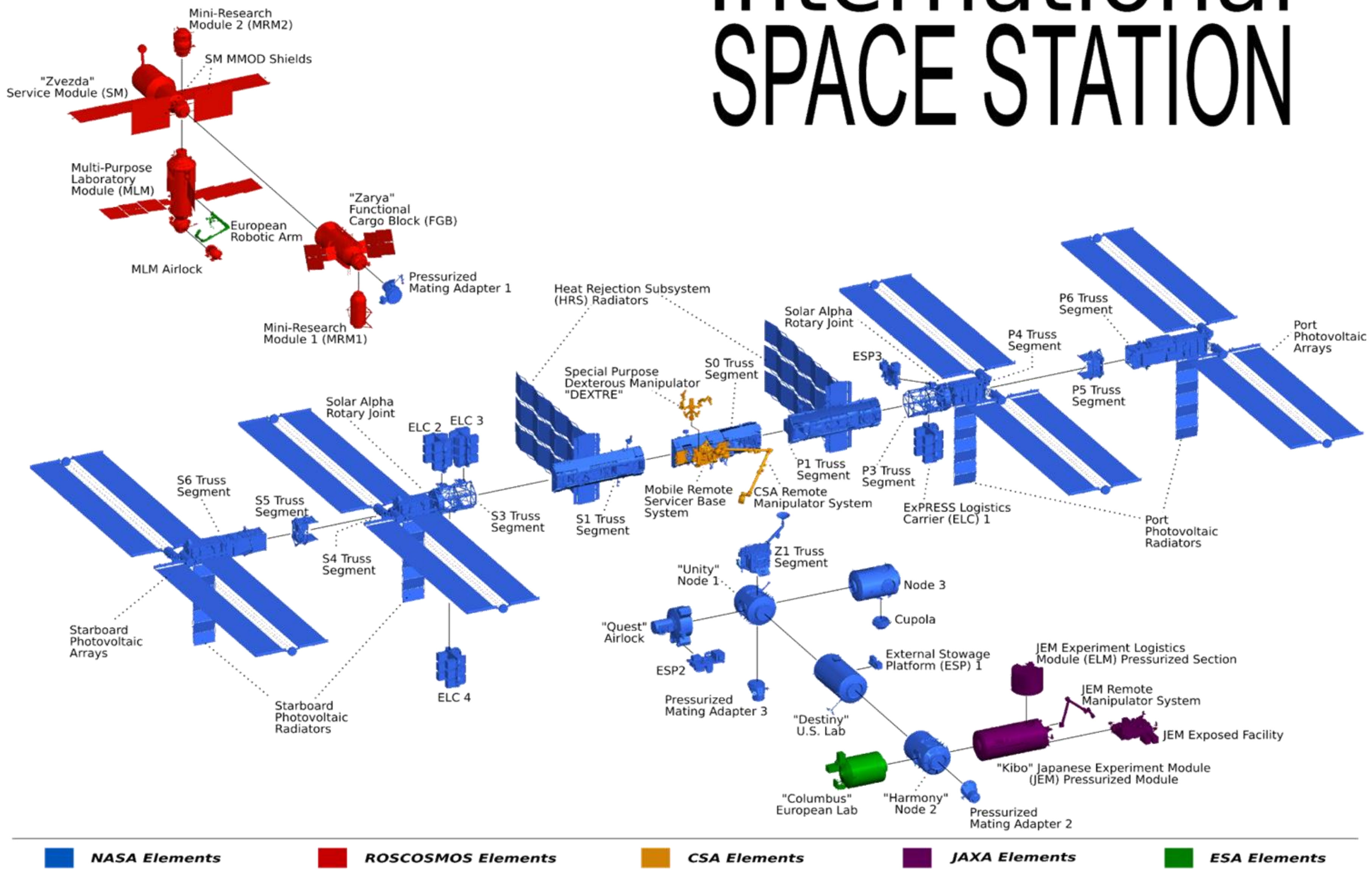
The communications capability within Spacelab had become obscured by the high ambient noise levels of the experiment hardware, and the crew had to move into the airlock to communicate with the ground (away from the experiments that they were operating). In Spacelab, the crew's callouts needed to be repeated. "Say again" was the phrase repeated over and over again, and the crew became very frustrated.

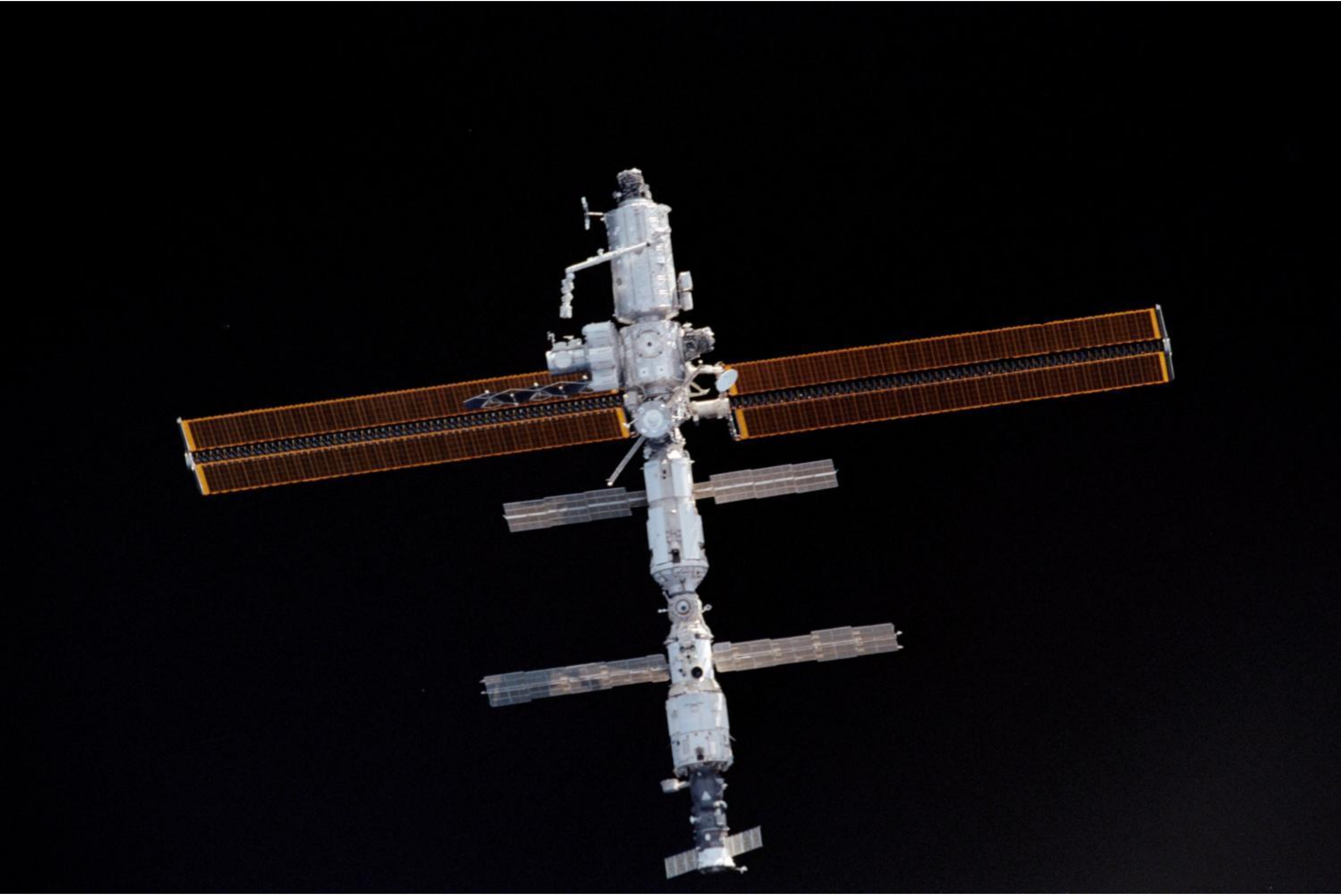
Shuttle Astronaut Summary – Flights 51-I, 61-B, 61-C

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

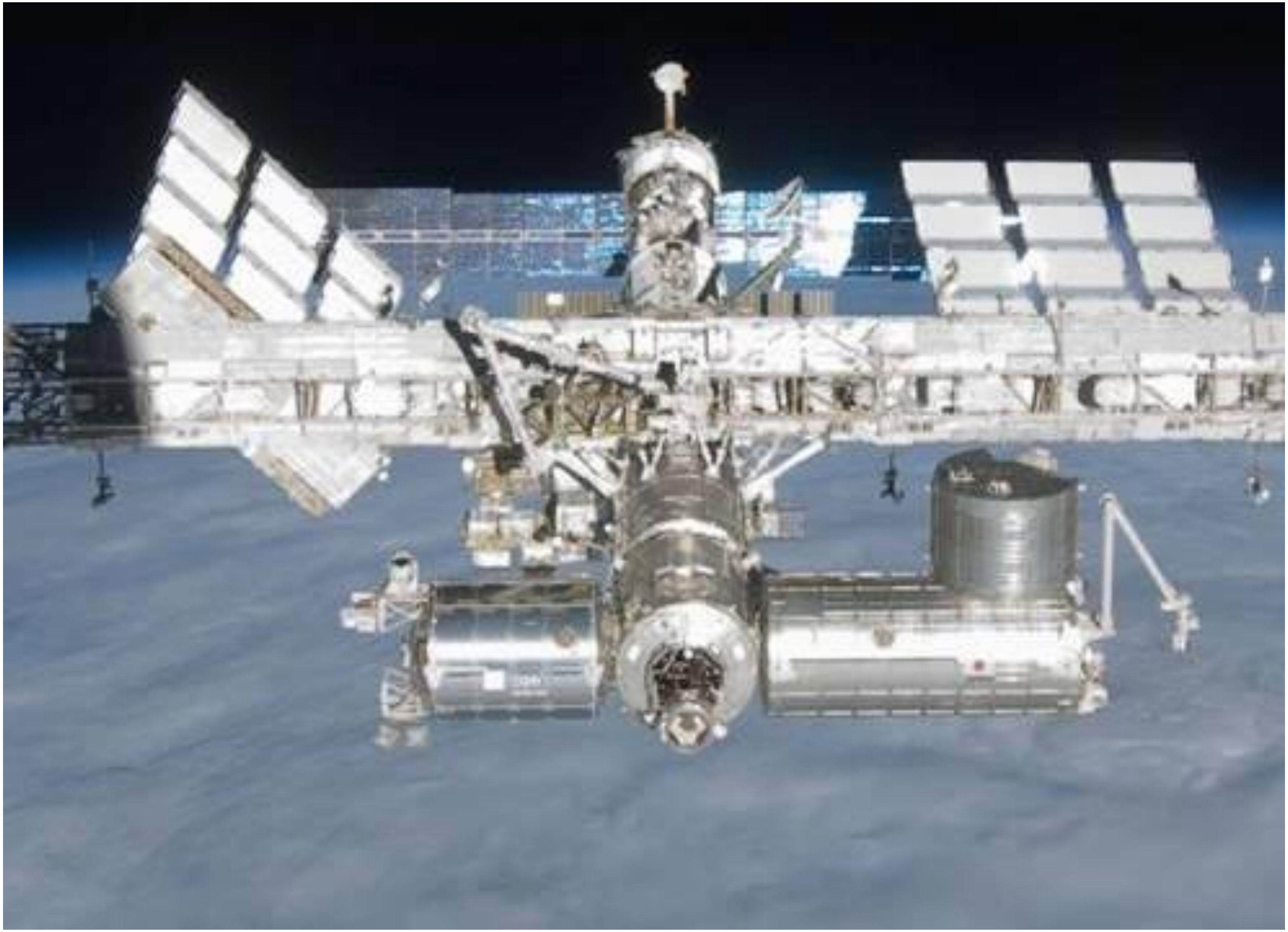
ISS

International SPACE STATION

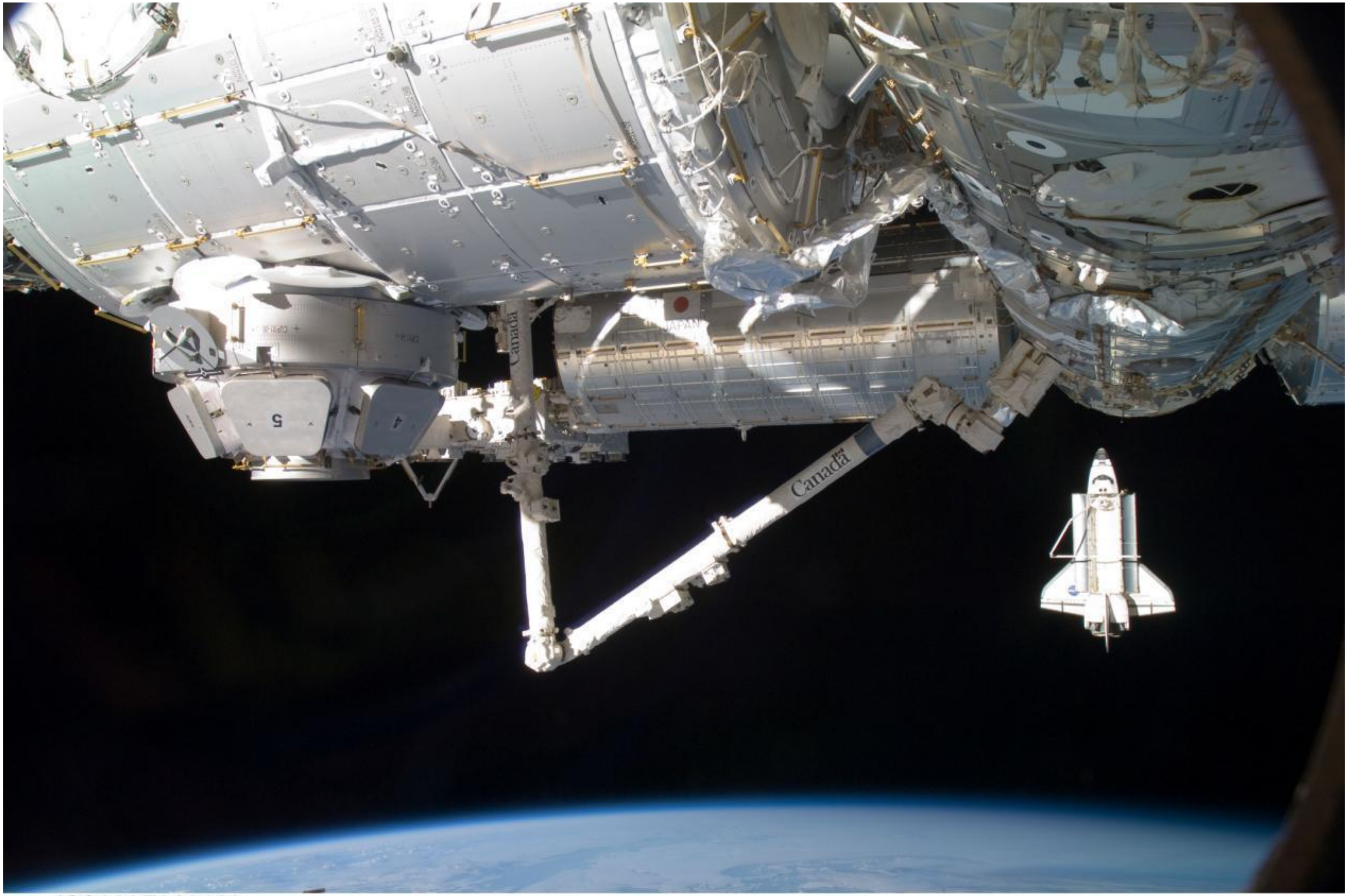




US Segment Acoustics – Assembly Complete

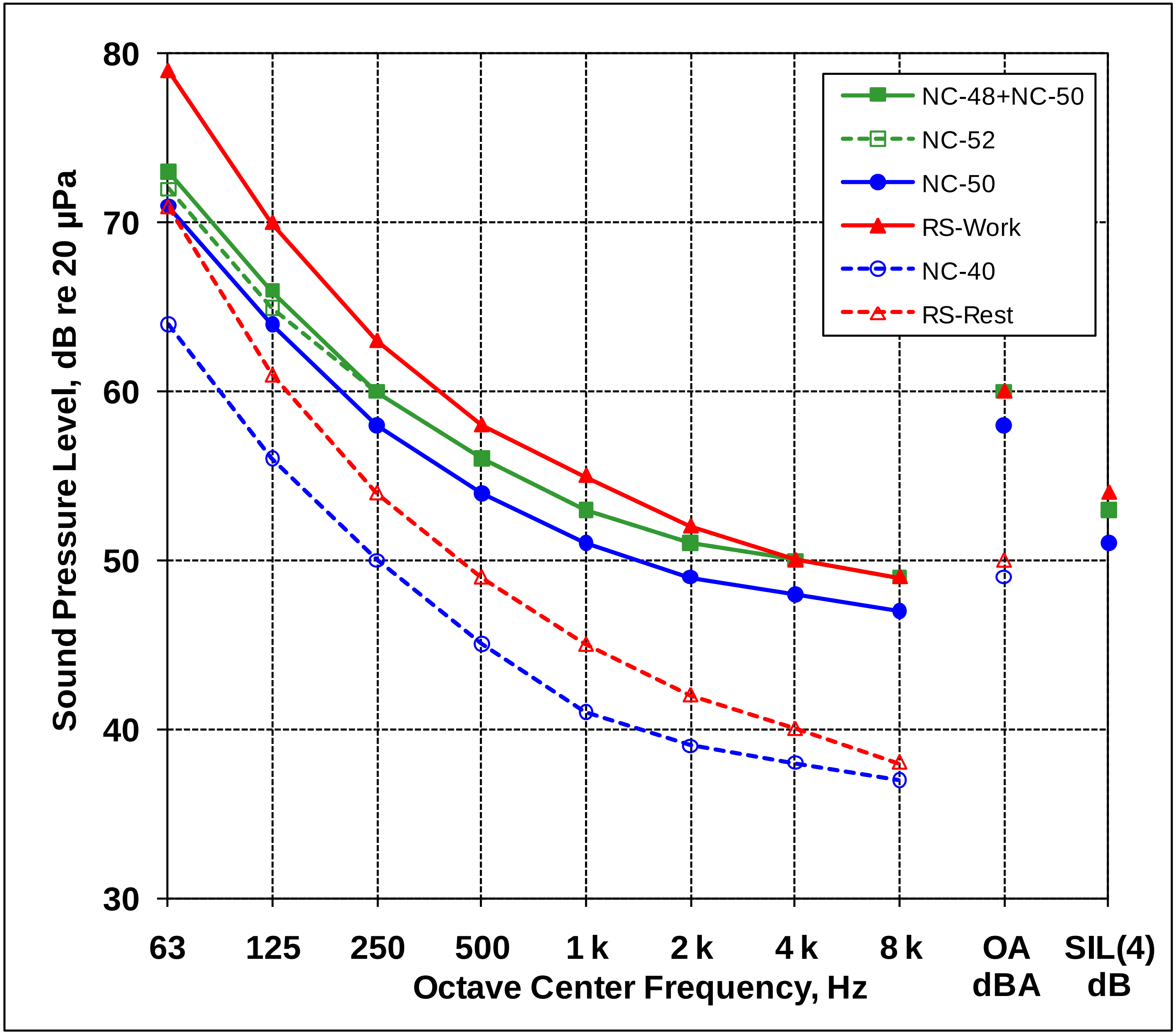


ISS US Segment – Node 3 and Cupola



ISS022E069162

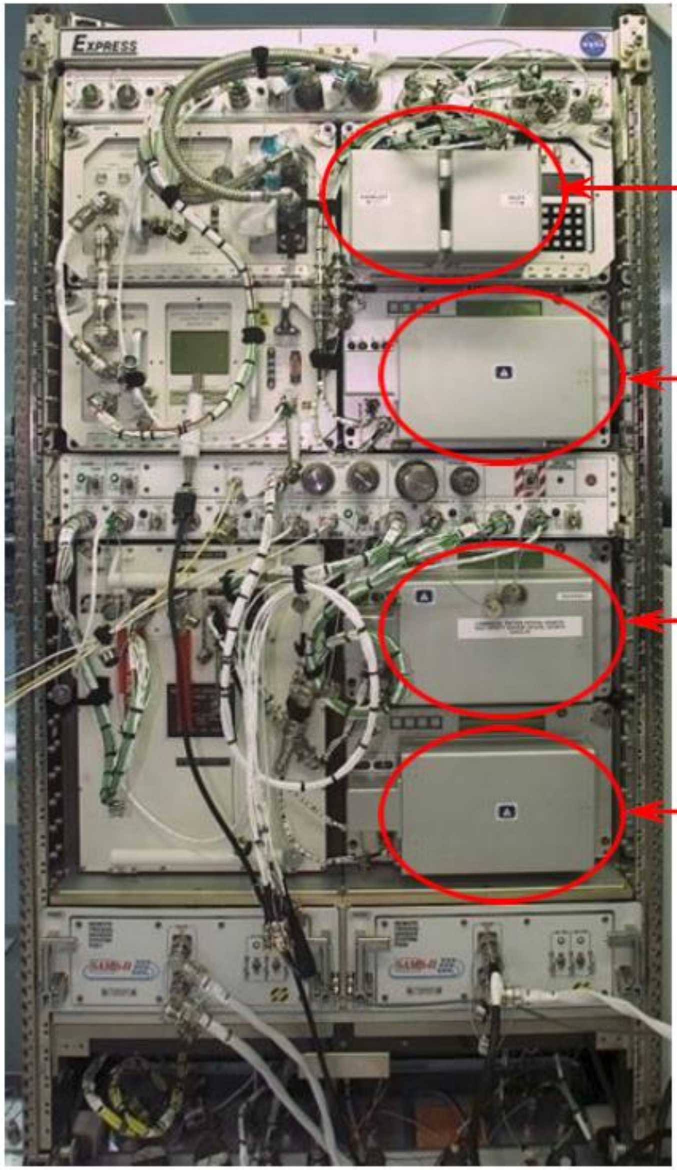
ISS Continuous Noise Requirements



On-Orbit Anomalies – T2

ISS023E053664

Add-on Mufflers for ExPRESS Rack Payloads



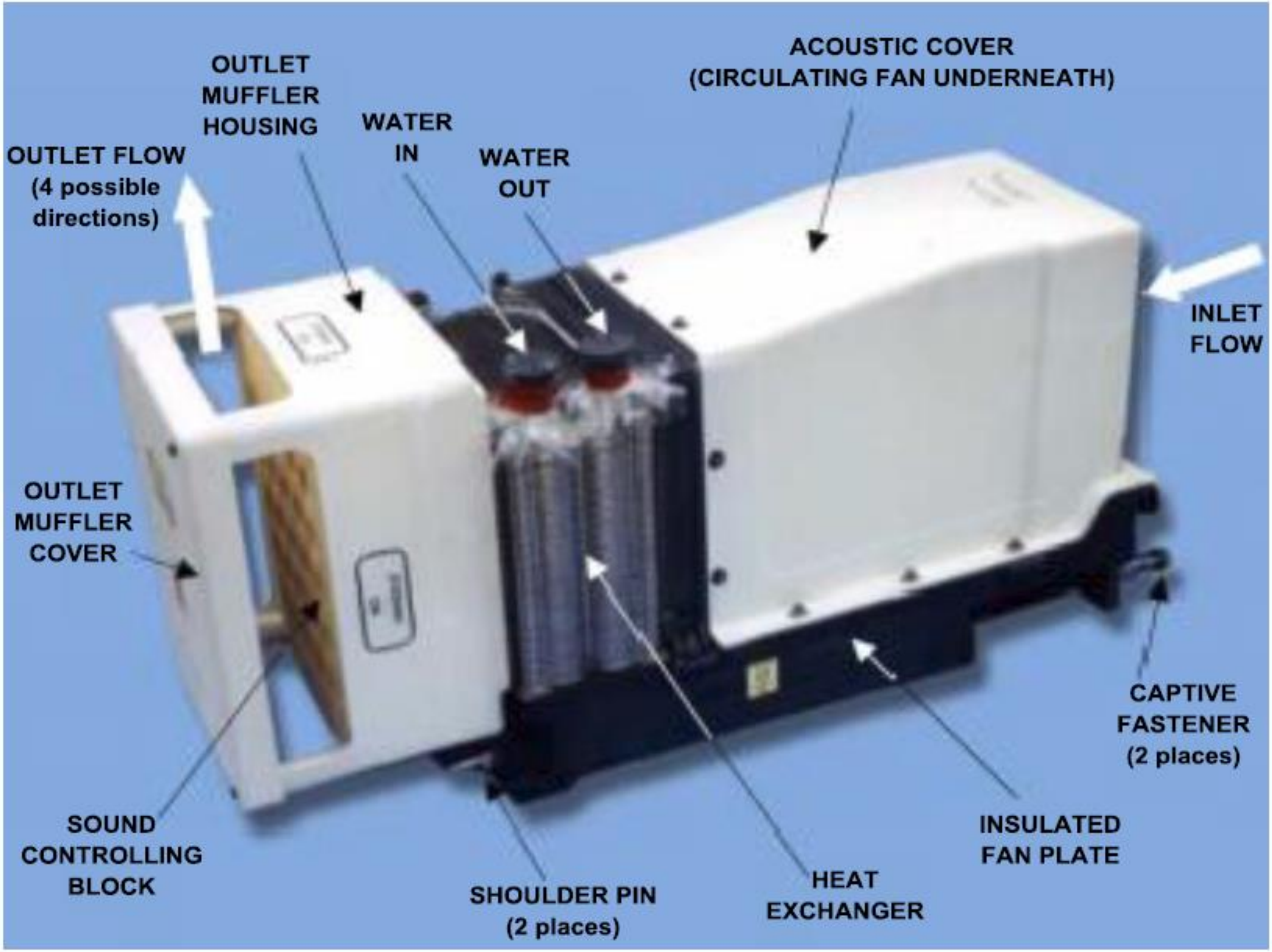
Commercial Generic Bioprocessing Apparatus

Protein Crystal Growth Single Thermal Enclosure System

Commercial Protein Crystal Growth

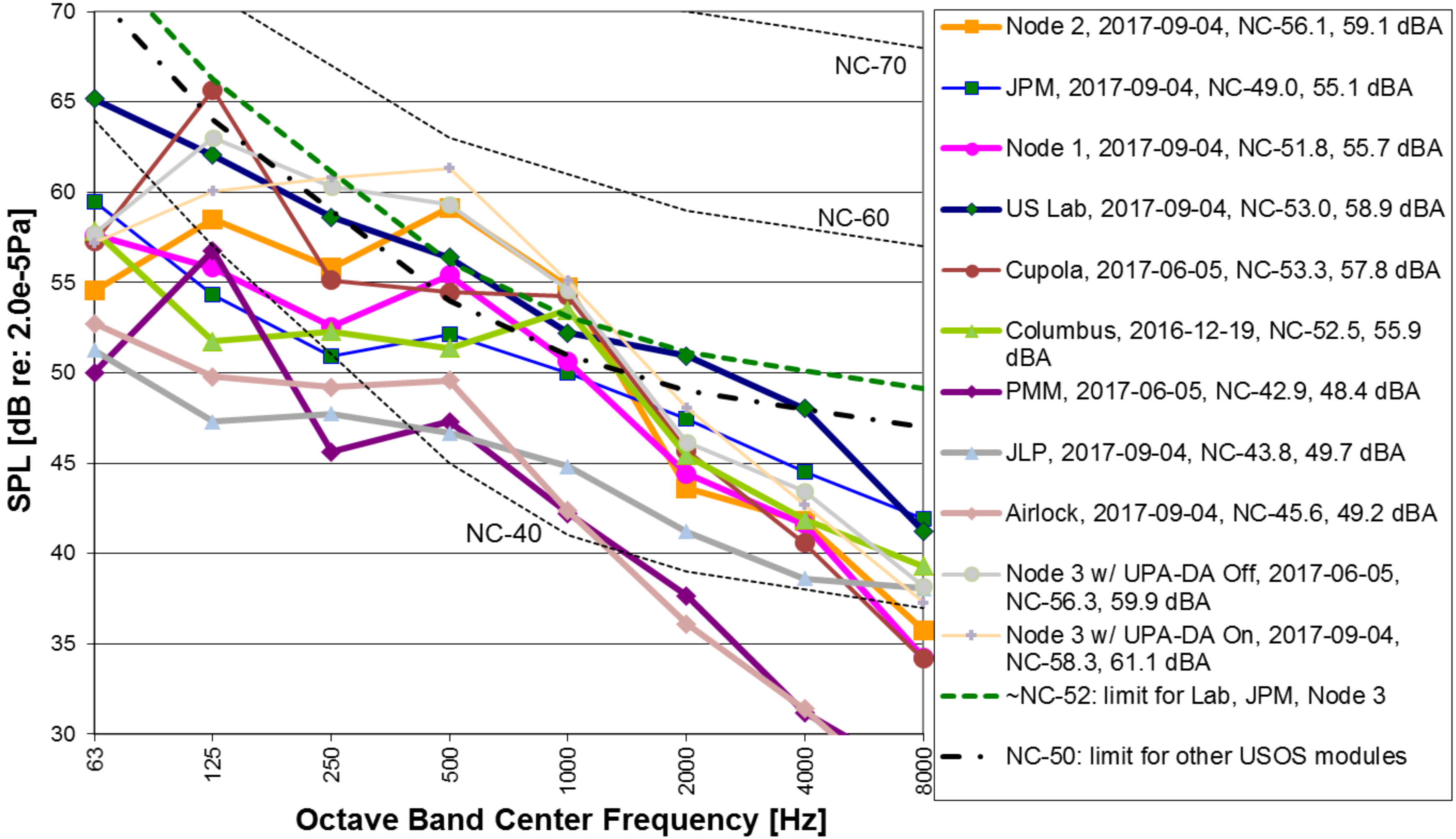
Space Acceleration Measurement System II

ExPRESS Racl AAA Fam Noise Controls



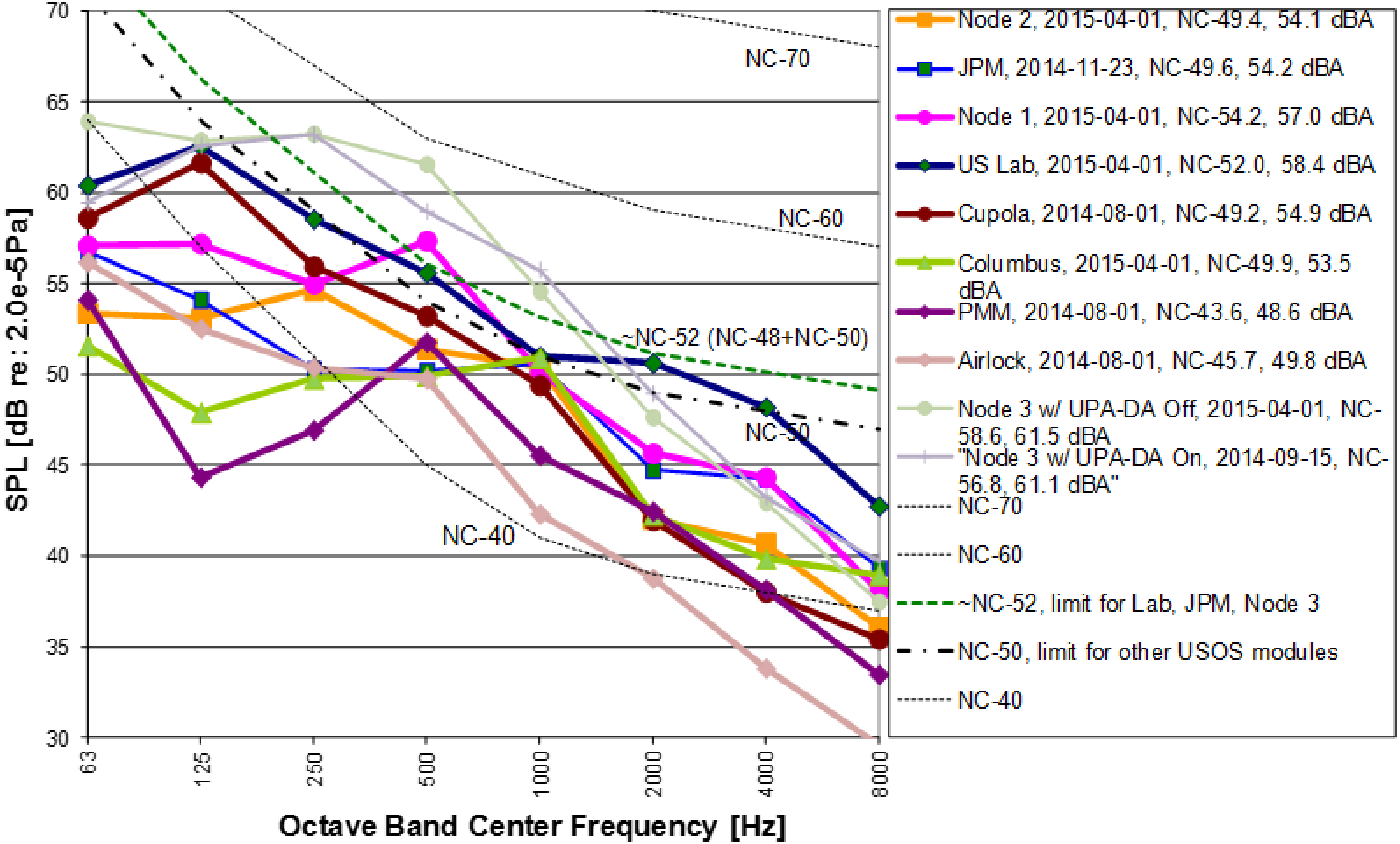
Average Acoustic Levels in U.S. Segment Modules

As of September 4, 2017



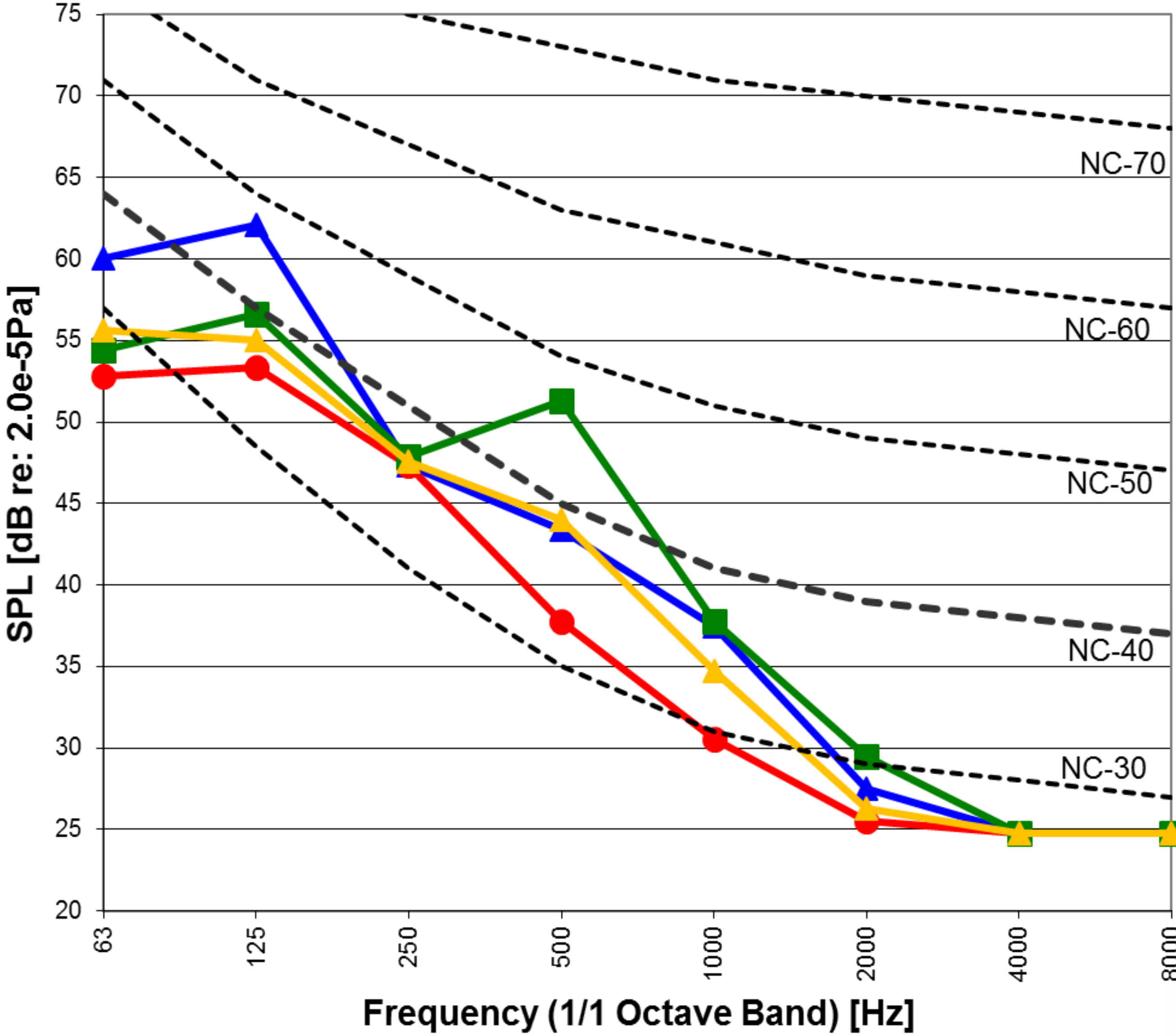
Average Acoustic Levels in U.S. Segment Modules

As of April 1, 2015

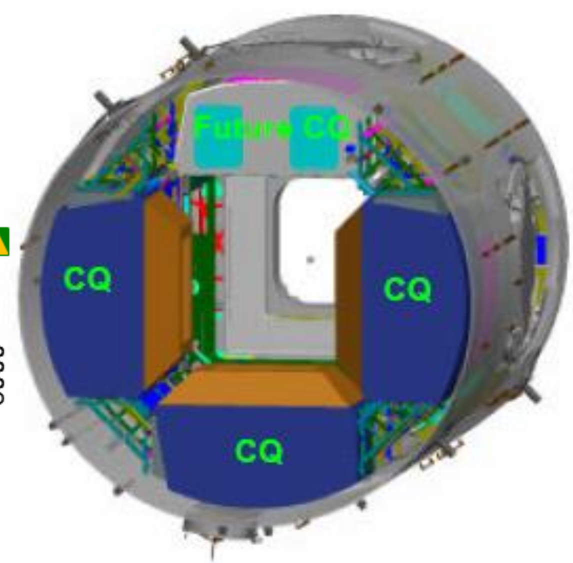


US Segment – Crew Quarters

As of September 4, 2017

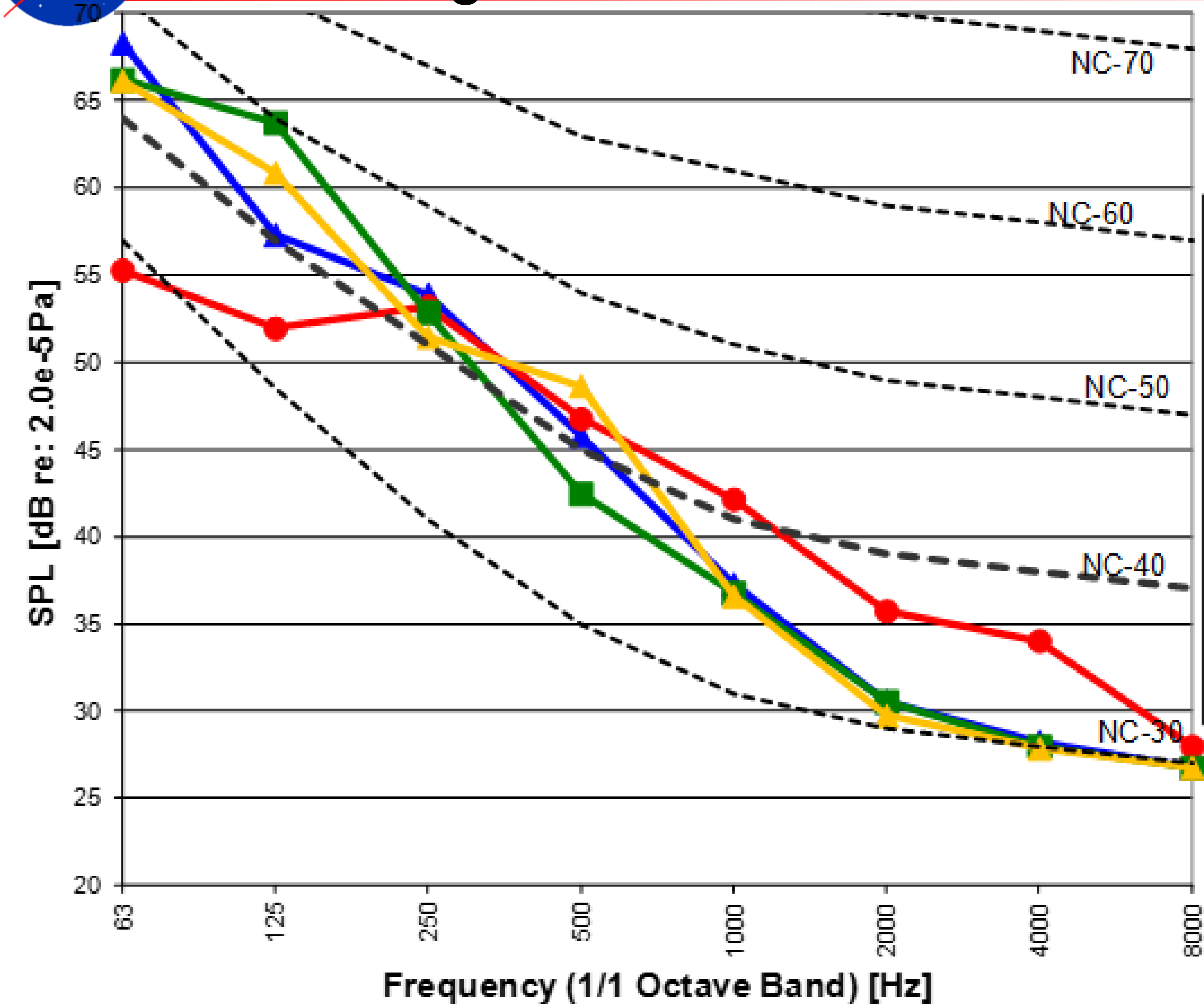


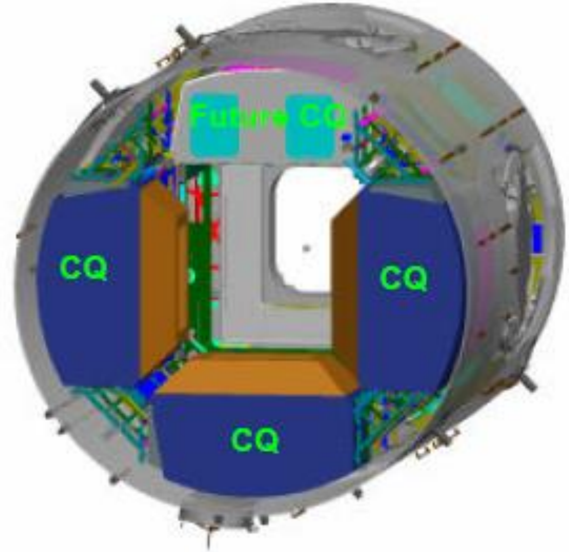
- CQs on High Speed
- Sound Levels <50 dBA



US Segment – Crew Quarters

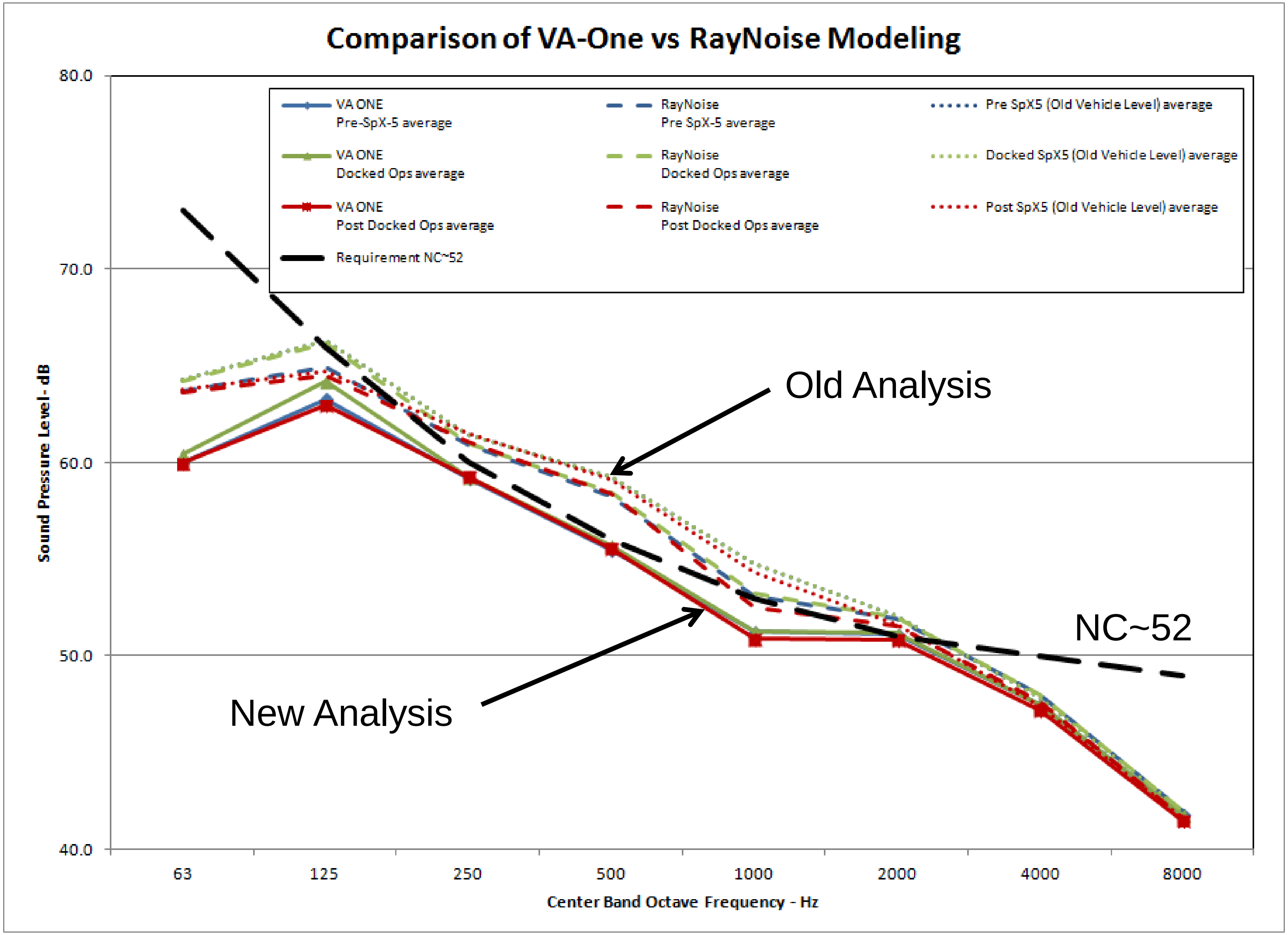
As of April 1, 2015



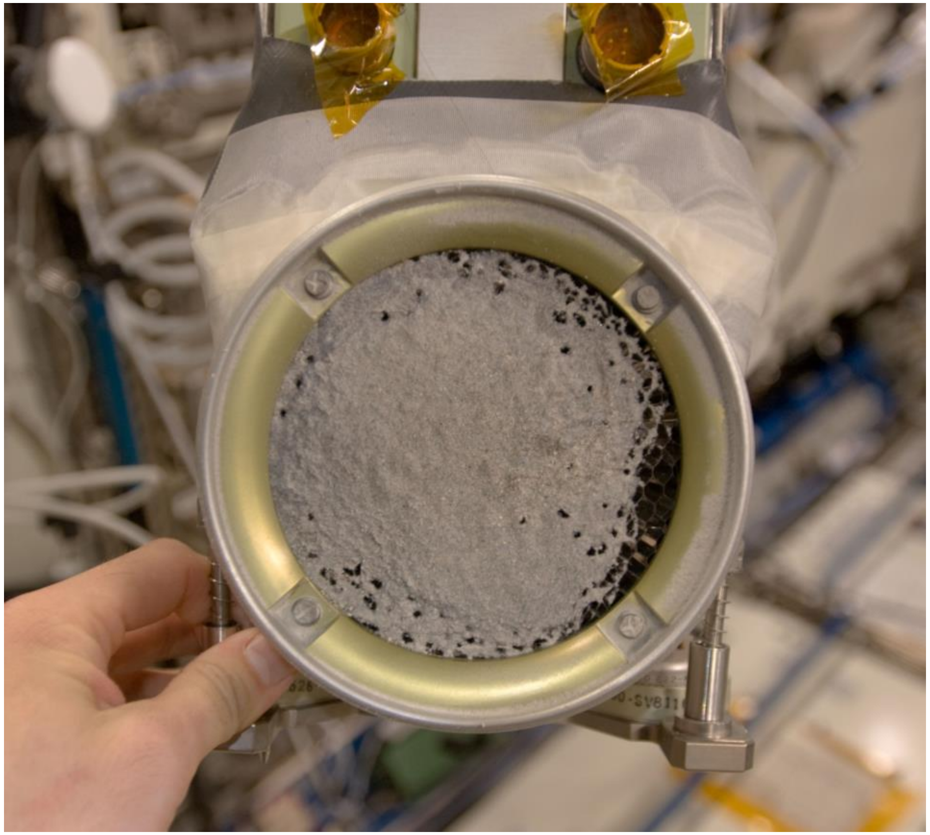


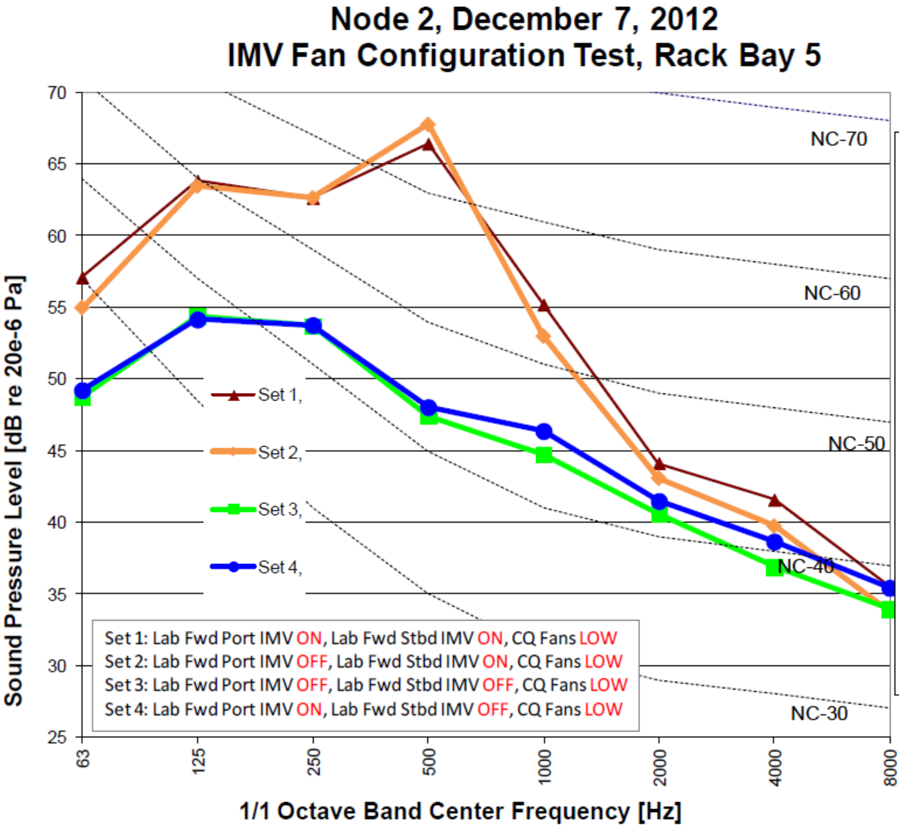
- CQs on High Speed
- Sound Levels ~50 dBA

Increment 41, ALL Eleven Facilities Operating



IMV Fan Clogging and Elevated Noise Levels

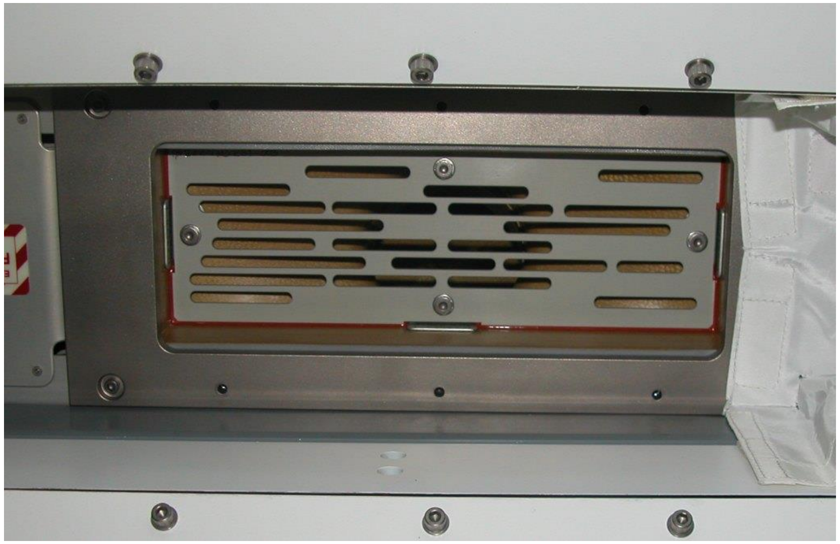




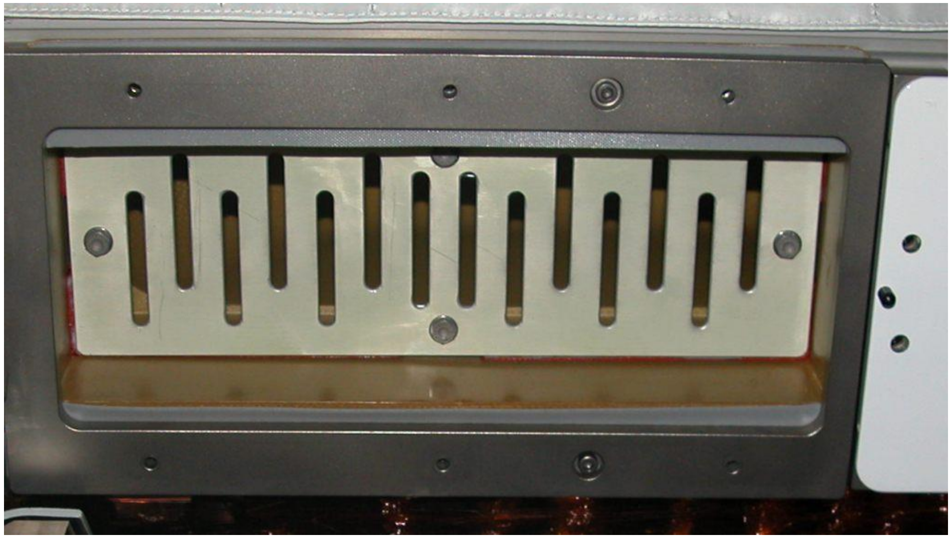
Old and New Node 2 Cabin Air Diffuser Plates Changed Out on October, 31, 2008.

Old NOD2OS3 (upstream), 11% Open area

Old NOD2OS5 (downstream), 10% open

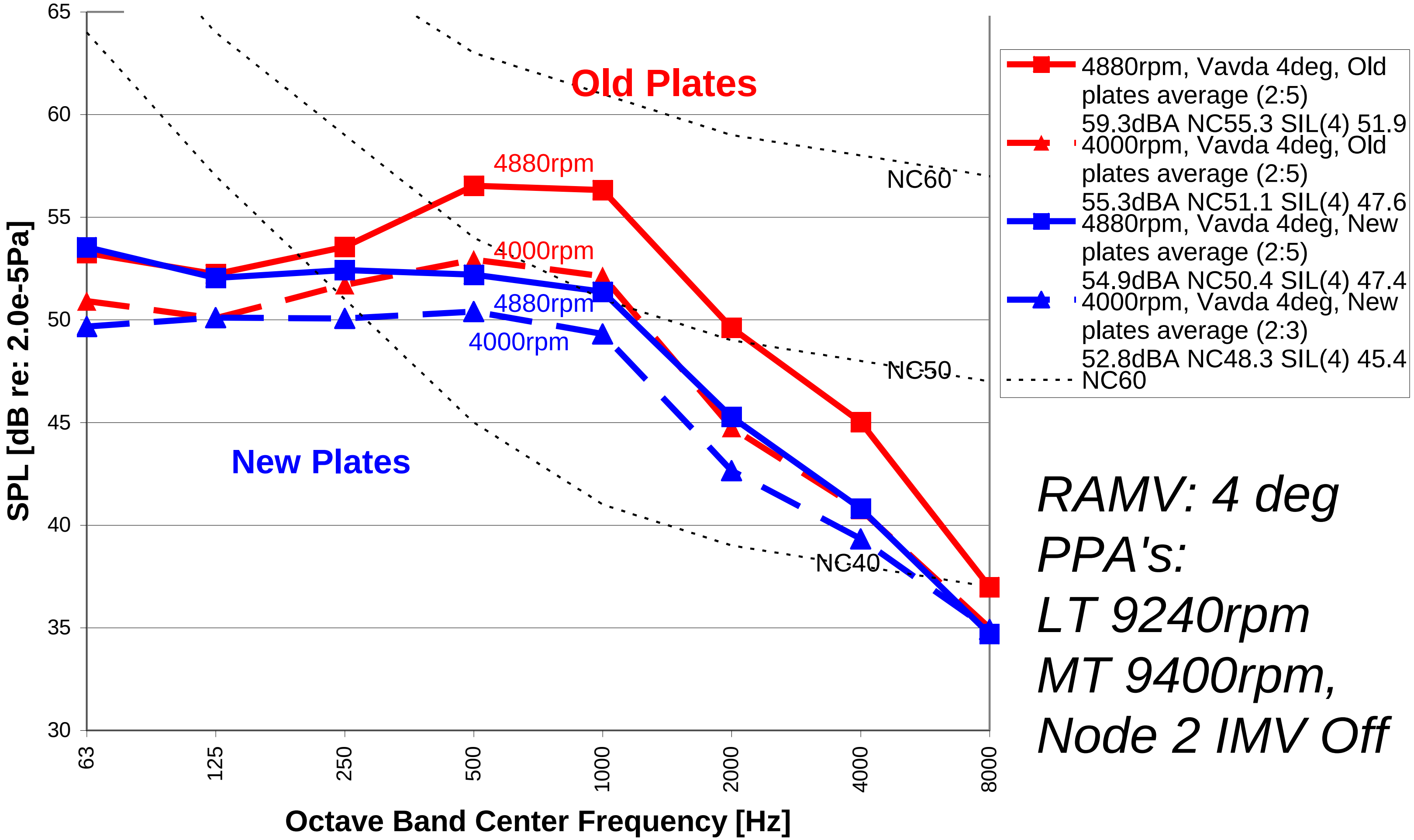


New NOD2OS3 (upstream), 22% open area



New NOD2OS5 (downstream), 18% open

Old and New Node 2 Cabin Air Diffuser Plate Acoustic Levels



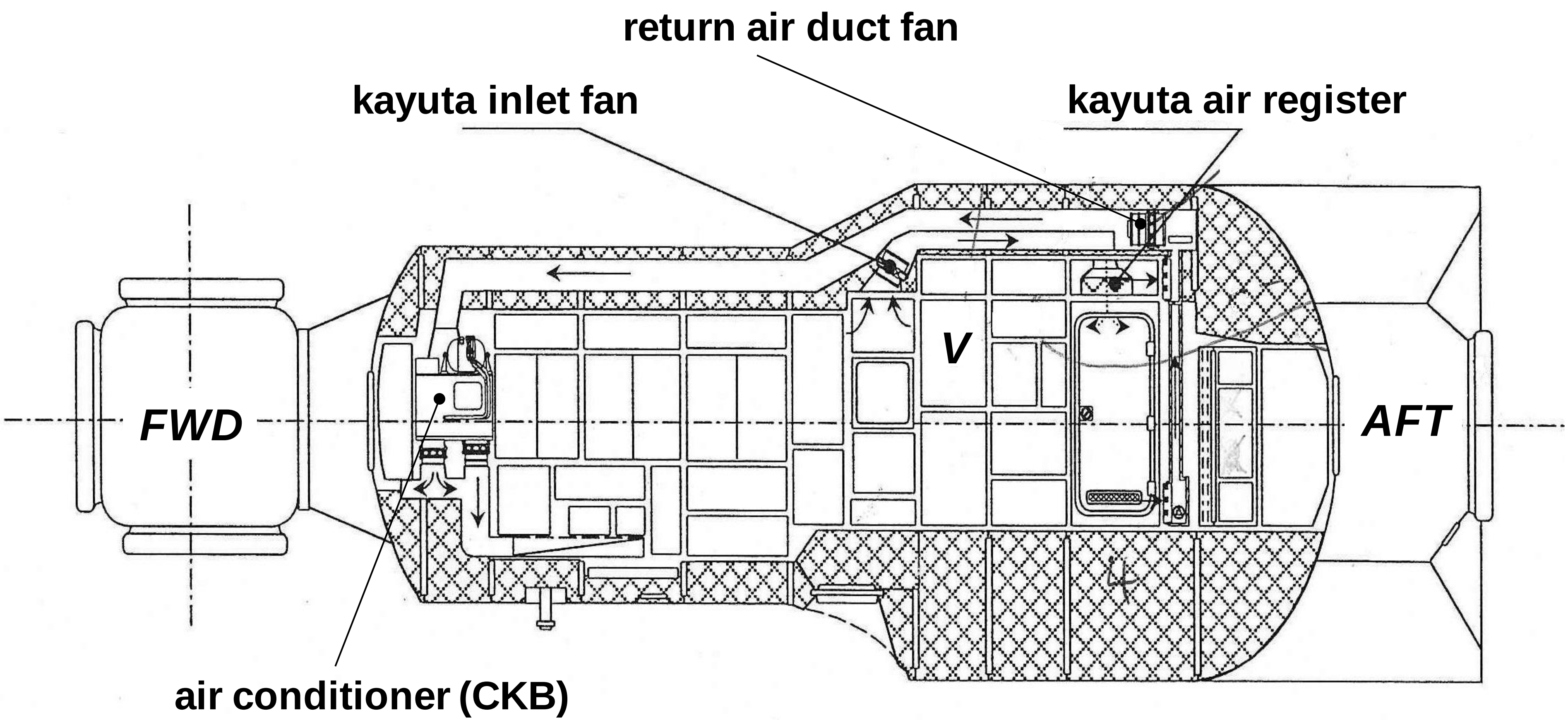
RAMV: 4 deg
PPA's:
LT 9240rpm
MT 9400rpm,
Node 2 IMV Off

RSOS

Service Module Acoustic Remediation

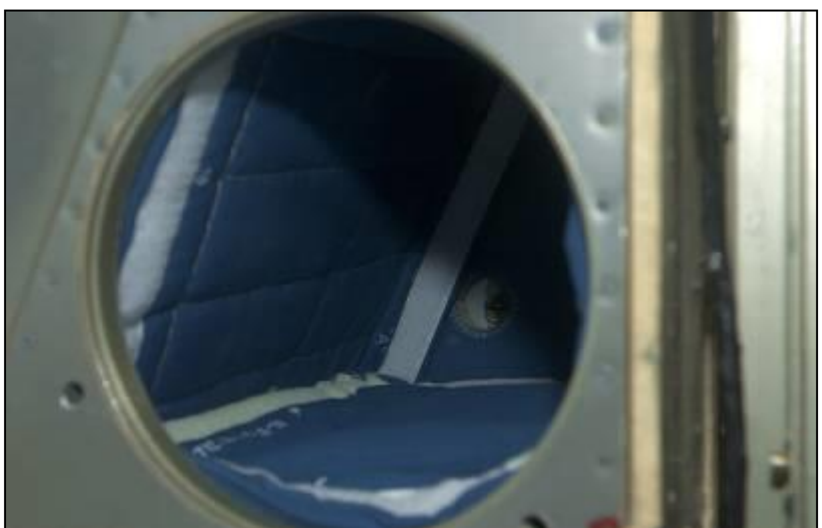
- Ventilation System
  - Kayutas
  - Main Cabin
- CKB (Air Conditioner) System
- Vozdukh (CO_2 Removal) System
- Quiet Fan Development

Russian Segment Acoustics – SM



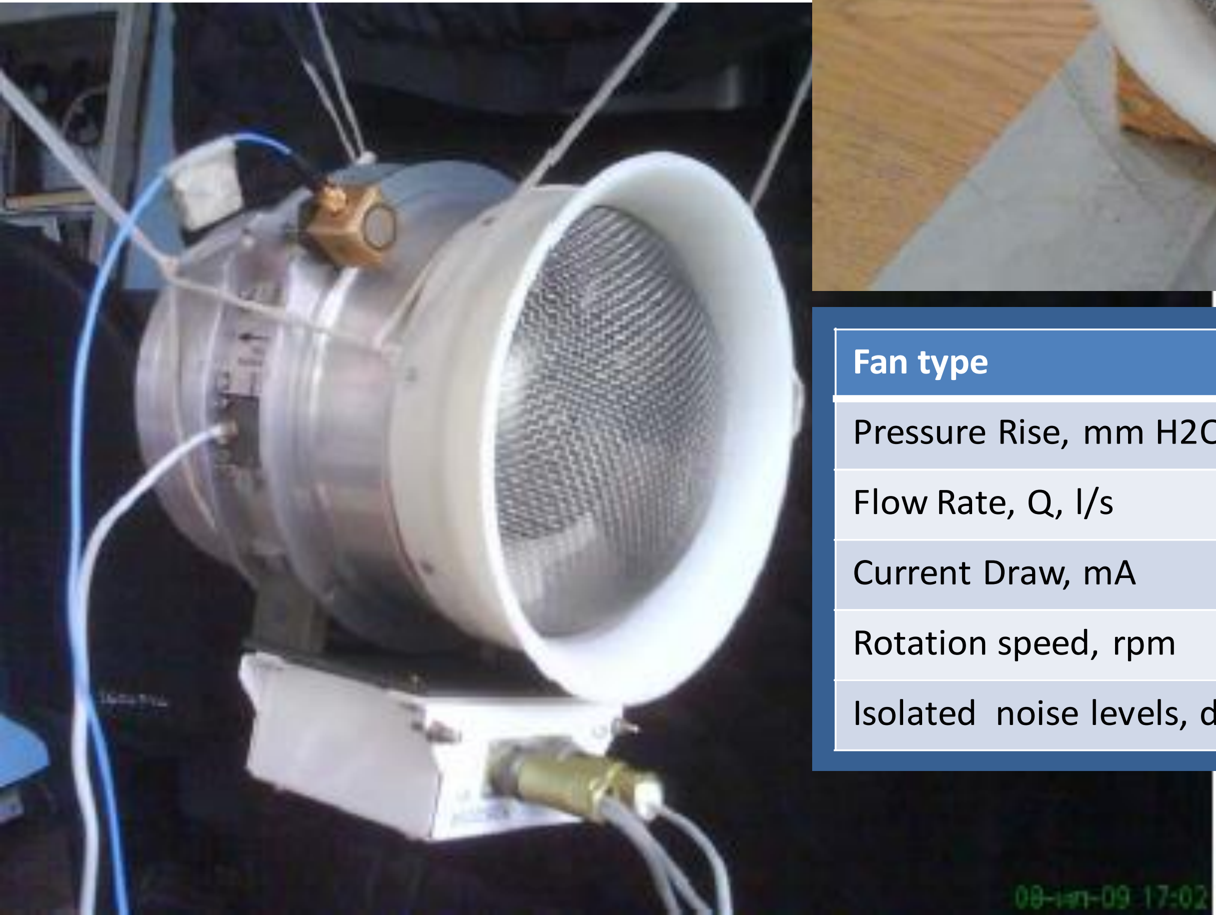
Kayuta Noise Controls

Kayuta Noise Controls



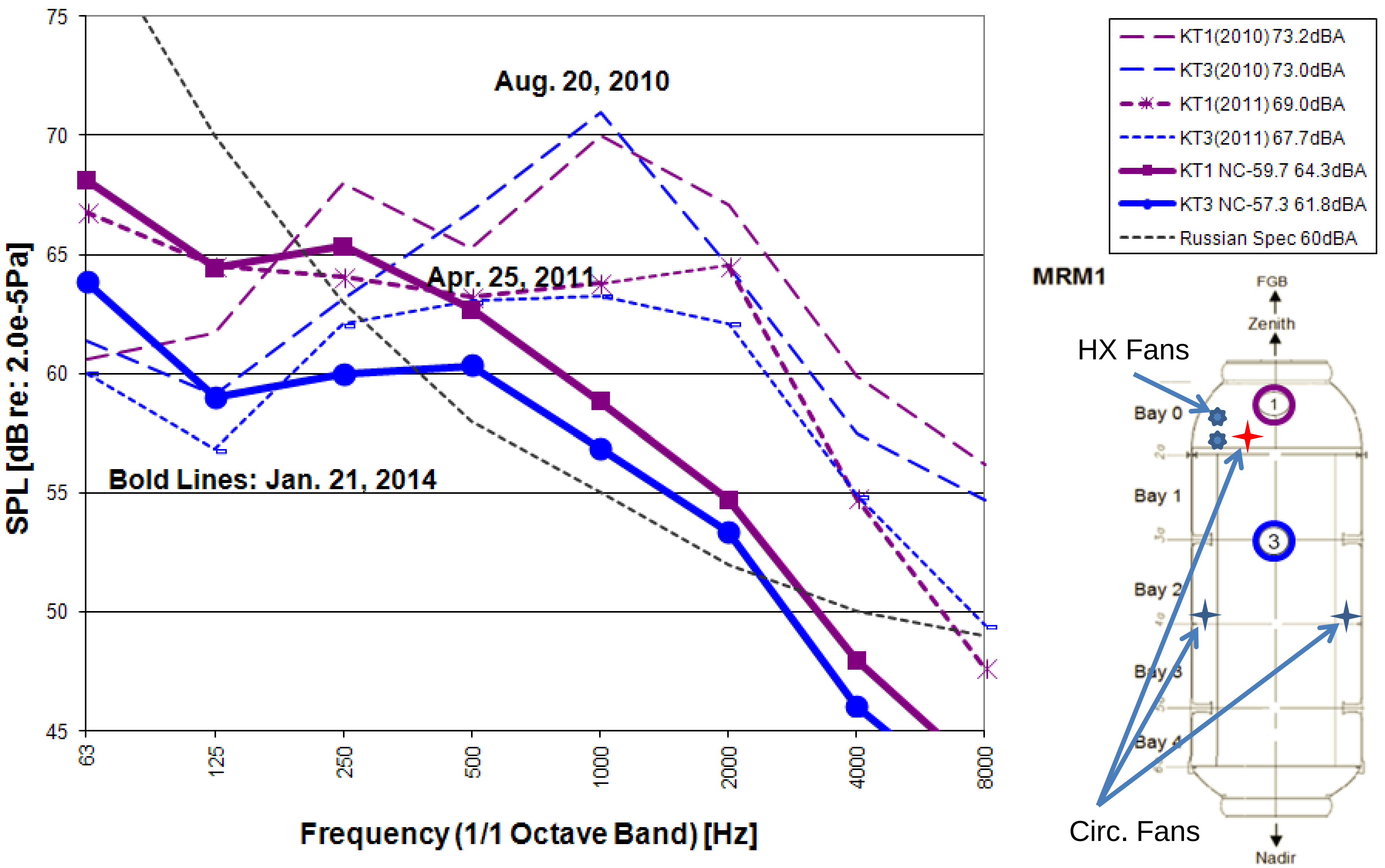
Kayuta Noise Controls

RSC-Energia Quiet Fan

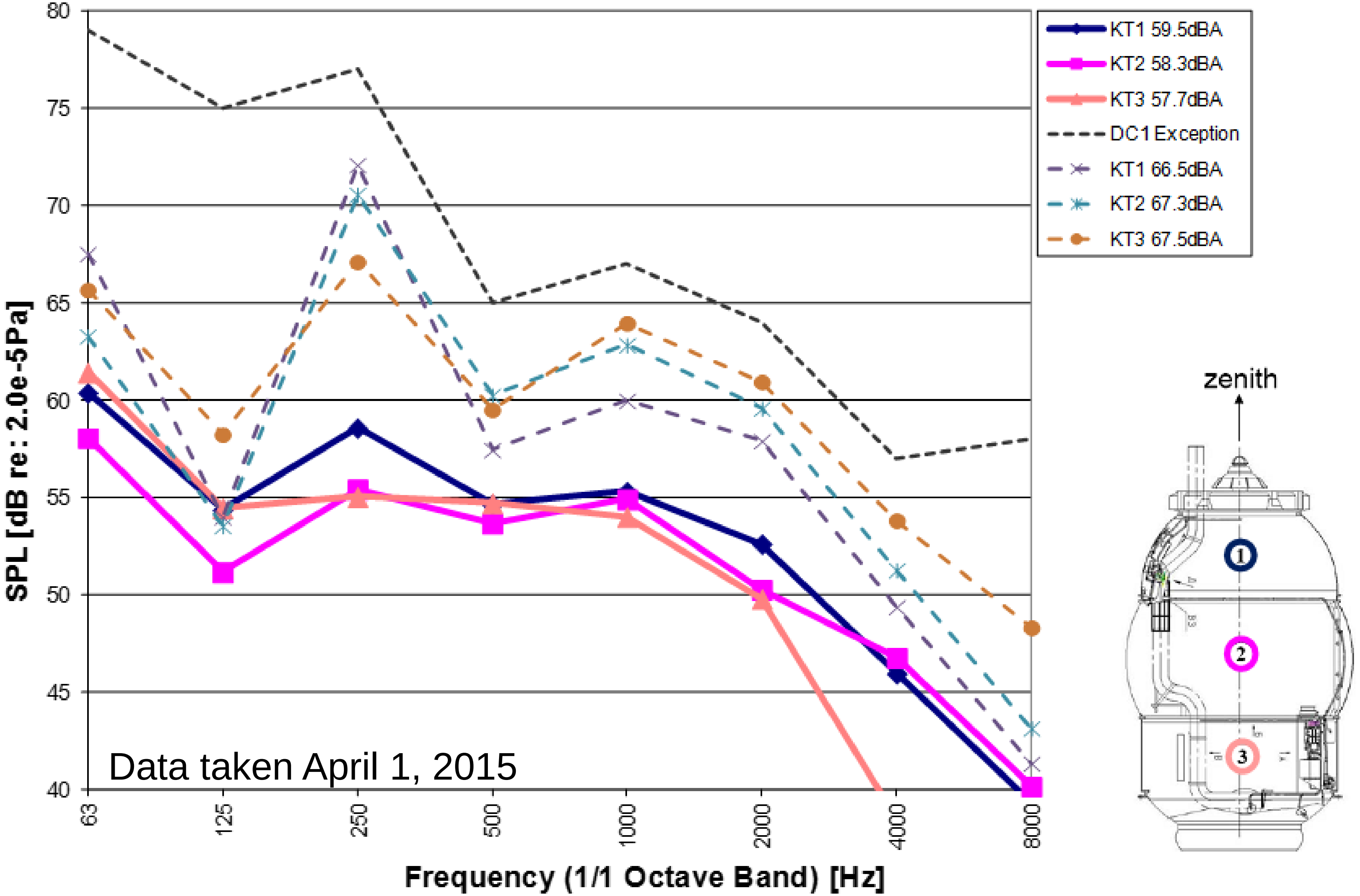


Fan type	Original Fan	Quiet Fan
Pressure Rise, mm H2O	4 (0.16 in H2O)	4 (0.16 in H2O)
Flow Rate, Q, l/s	47.0 (100 cfm)	83.4 (176 cfm)
Current Draw, mA	470	470
Rotation speed, rpm	3120	2010
Isolated noise levels, dBA	61-64	48

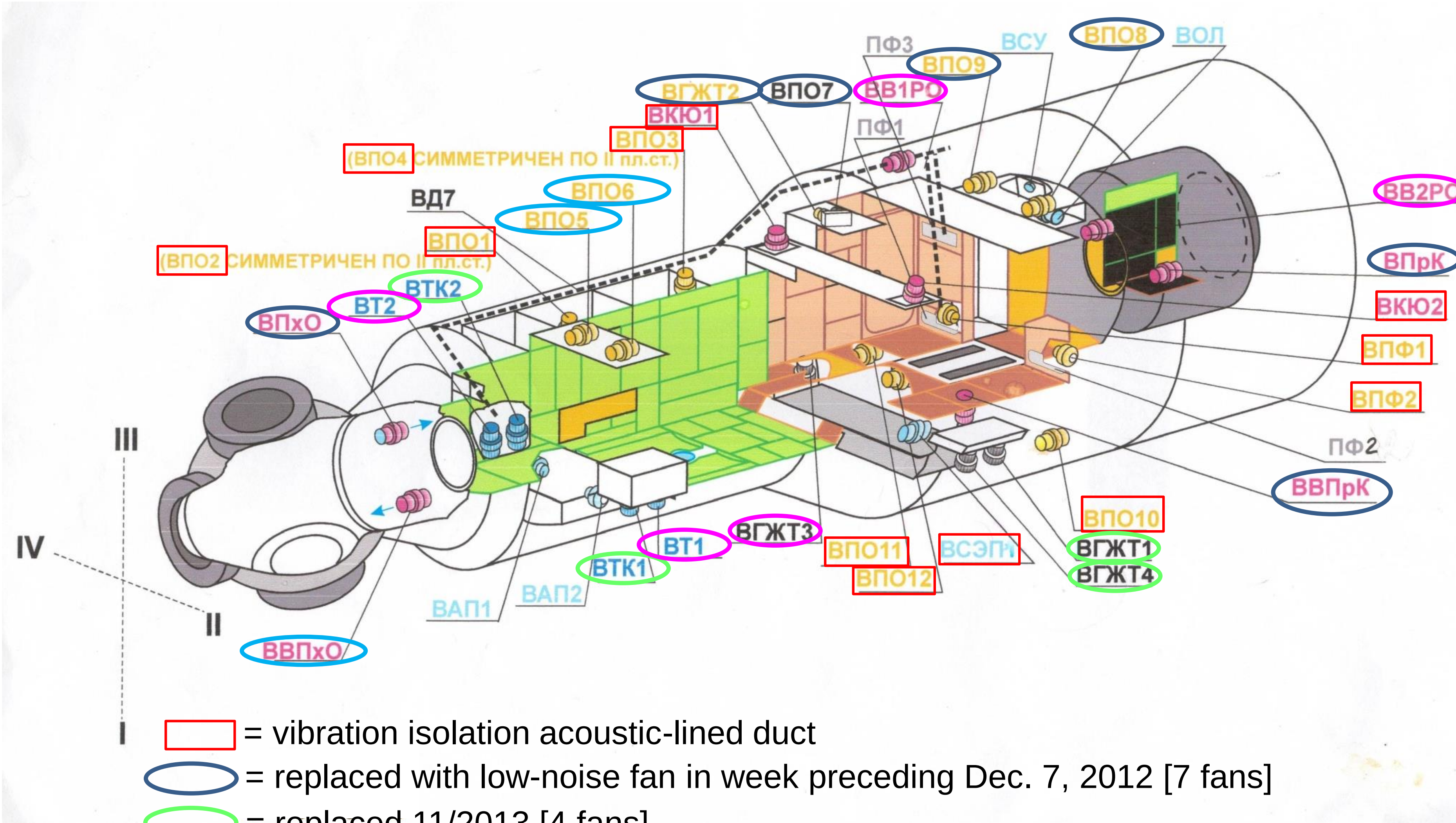
MRM1 Noise Reduction – Quiet Fan Installations



Russian Segment Acoustics – DC1



SM Fans



= vibration isolation acoustic-lined duct

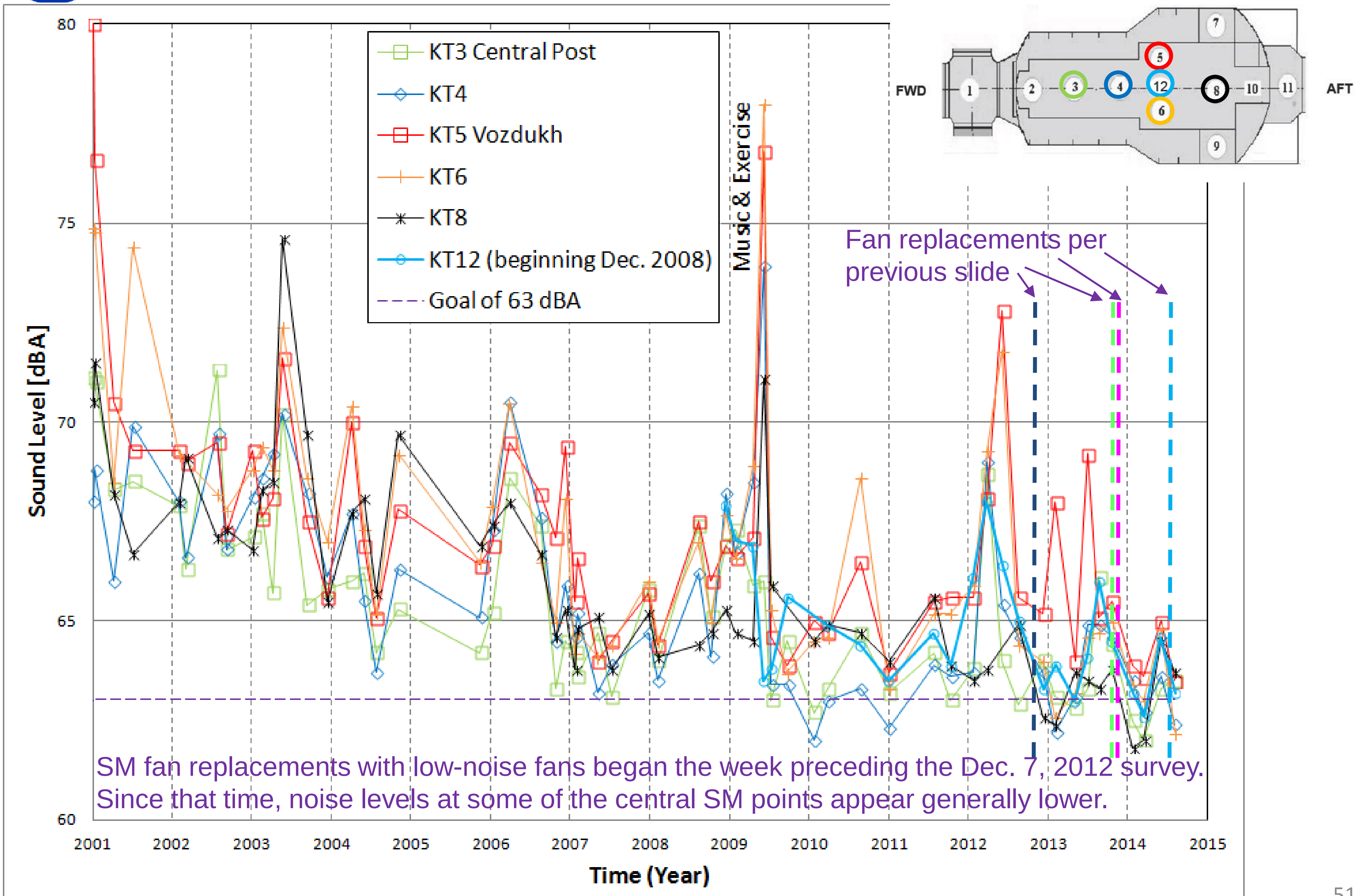
= replaced with low-noise fan in week preceding Dec. 7, 2012 [7 fans]

= replaced 11/2013 [4 fans]

= replaced 12/2013 [5 fans]

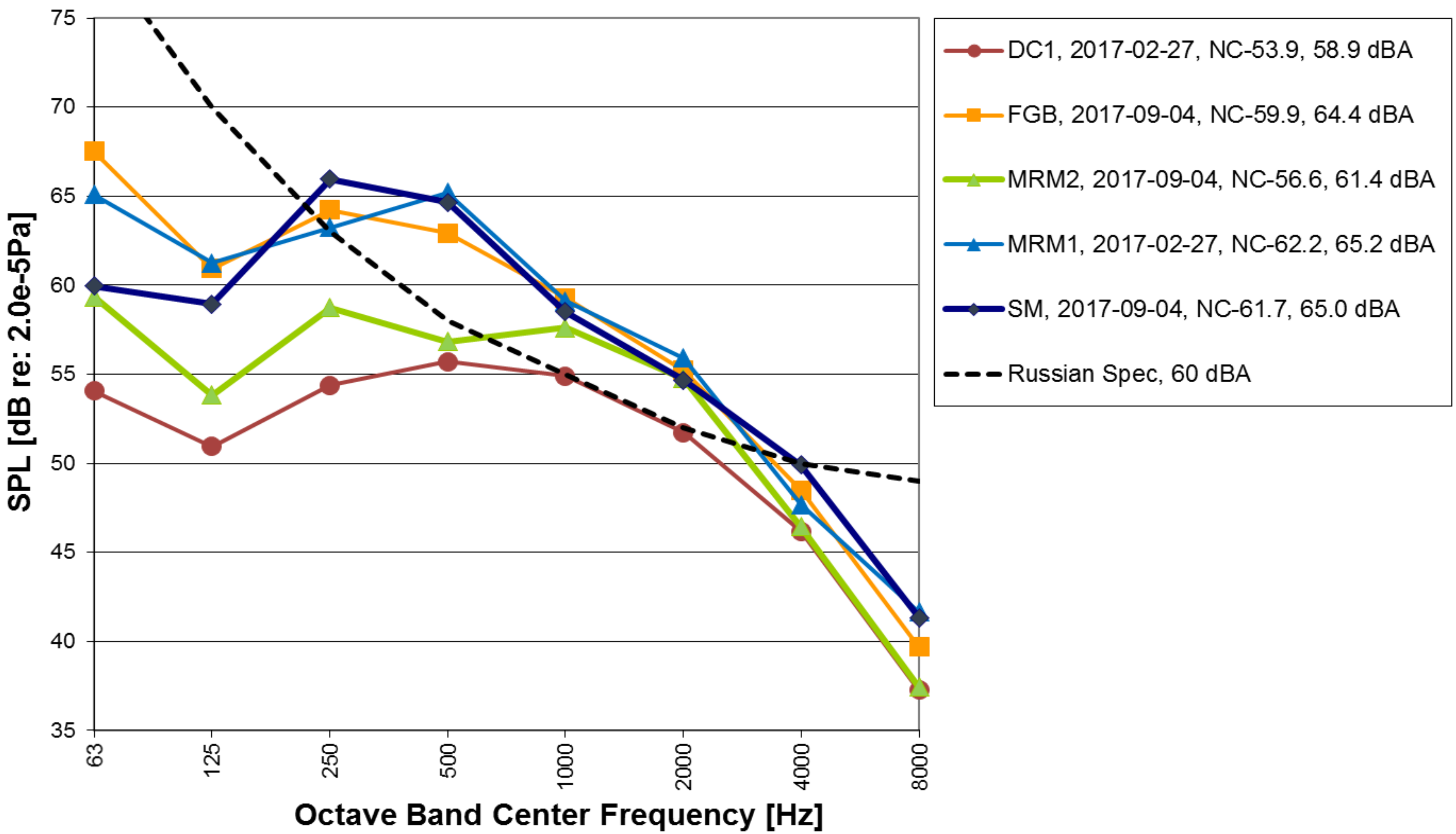
= replaced by 7/2014 [3 fans – but Nikimash not RSC-E fans]

SM Central Control Points vs time



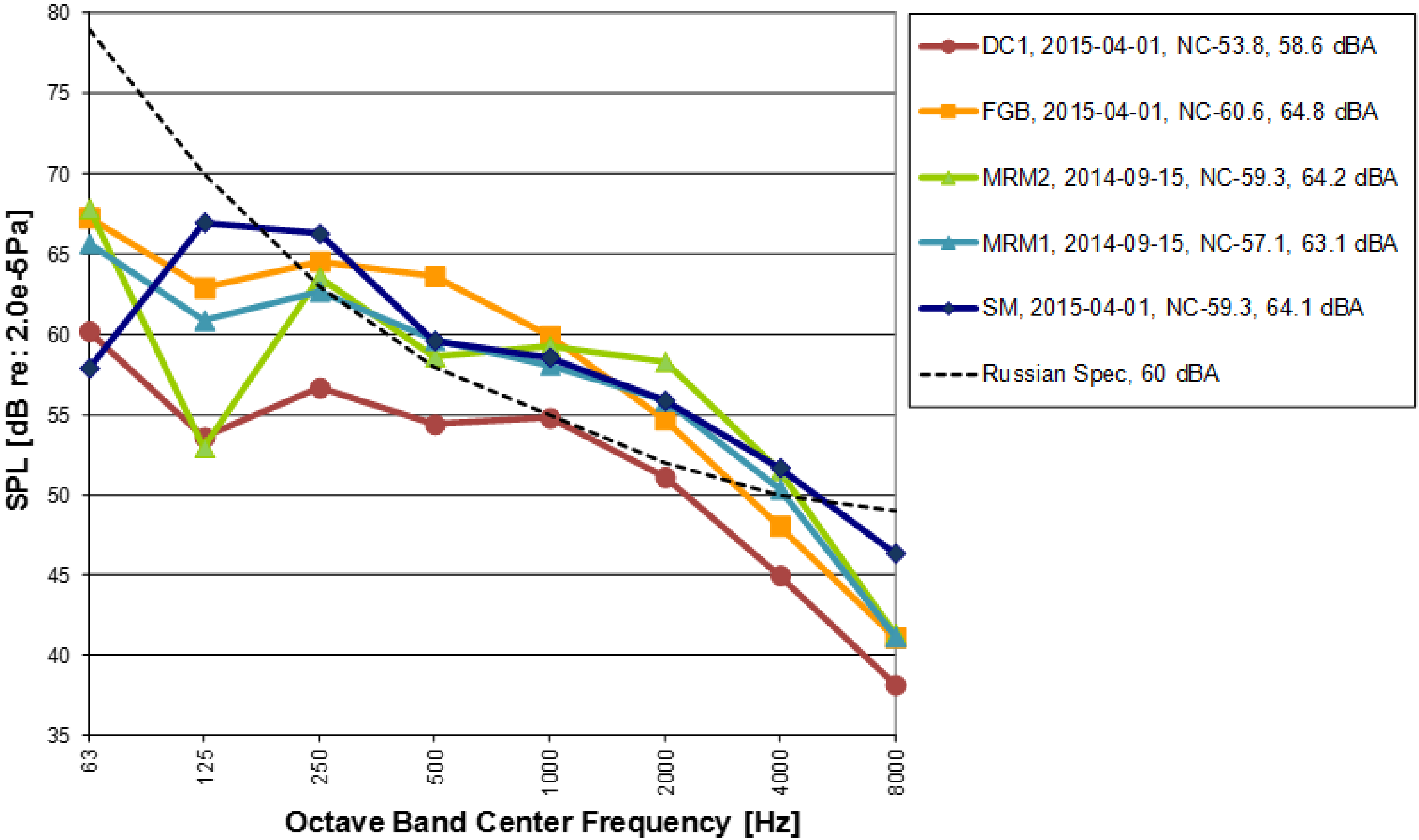
Average Acoustic Levels in Russian Segment Modules

As of September 4, 2017



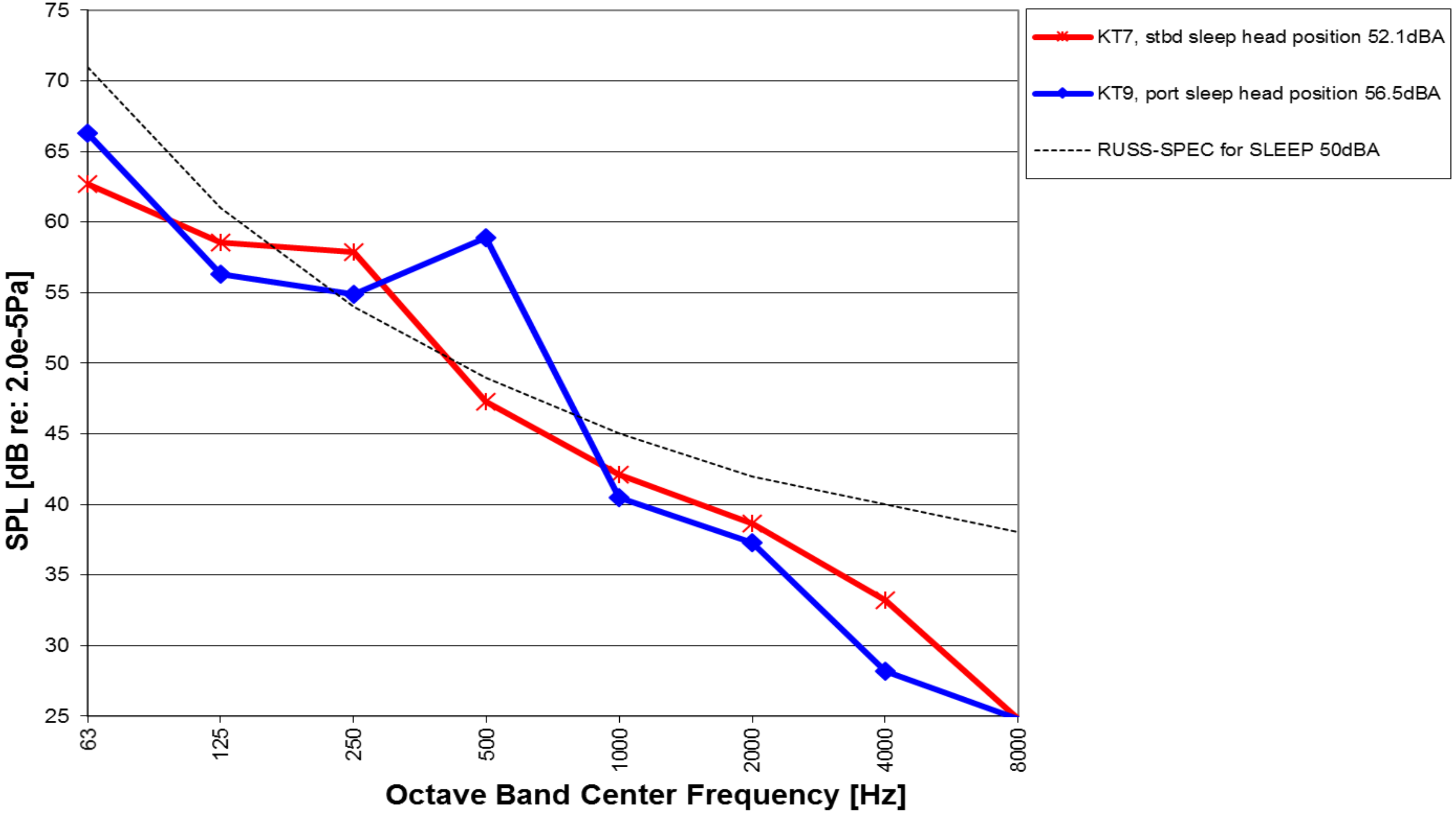
Average Acoustic Levels in Russian Segment Modules

As of April 1, 2015



SM Sleep Station Noise Levels

As of September 4, 2017



MPCV / Orion

Source:

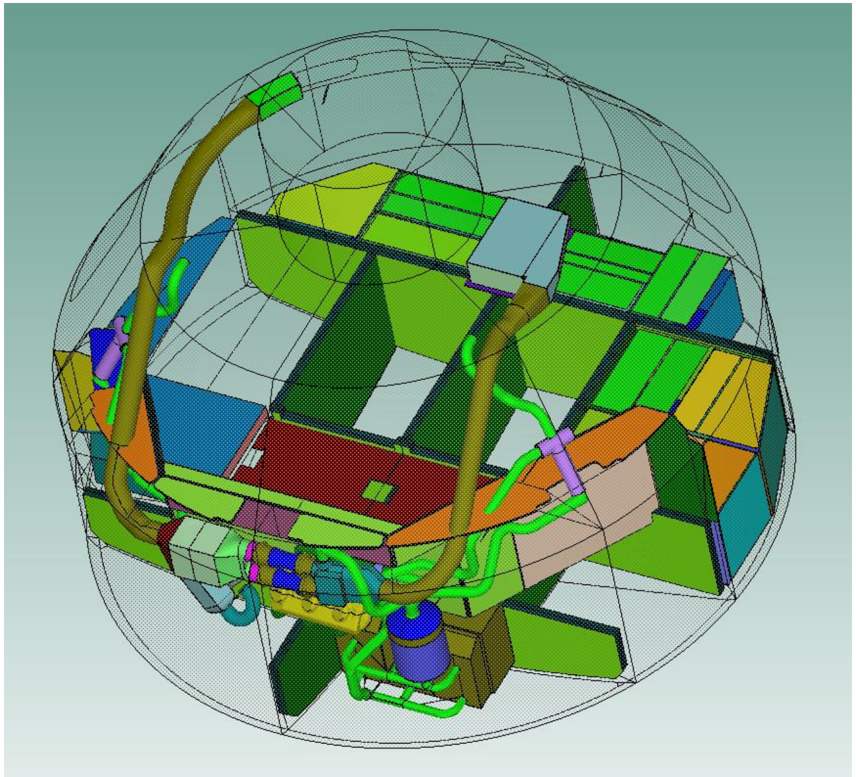
Chu, S. Reynold, Dandaroy, I., and Allen, C. S. 2016. ‘Innovative Approach of Developing Spacecraft Interior Acoustic Requirement Allocation’, In Proceedings of New England Noise Con-2016, Providence, RI.


500 LBS
500 LBS

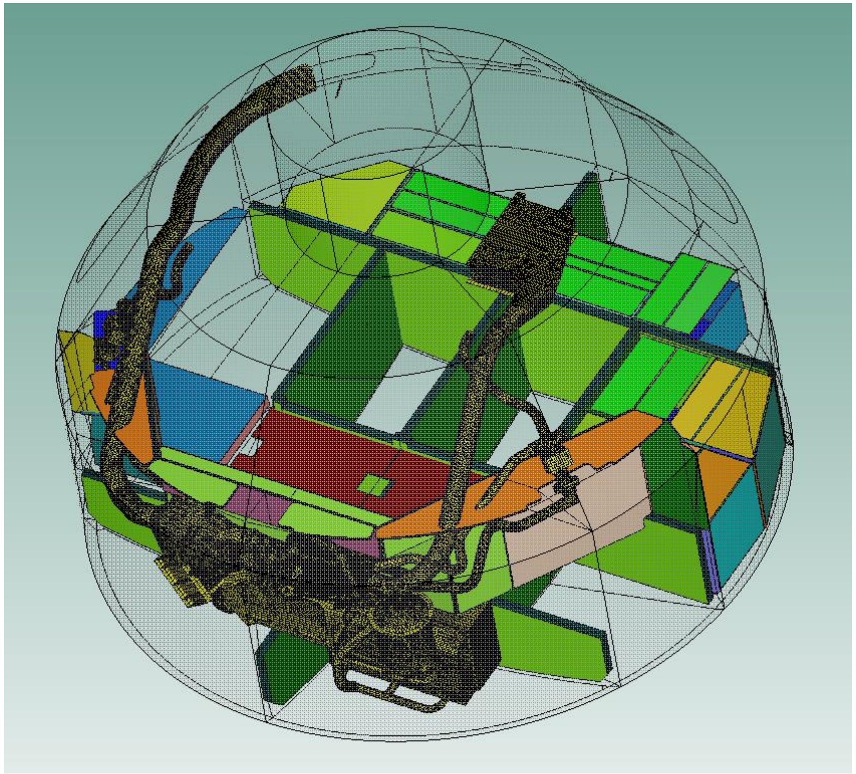
Orion Cabin System Models

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

SEA Model, for > 1,600 Hz

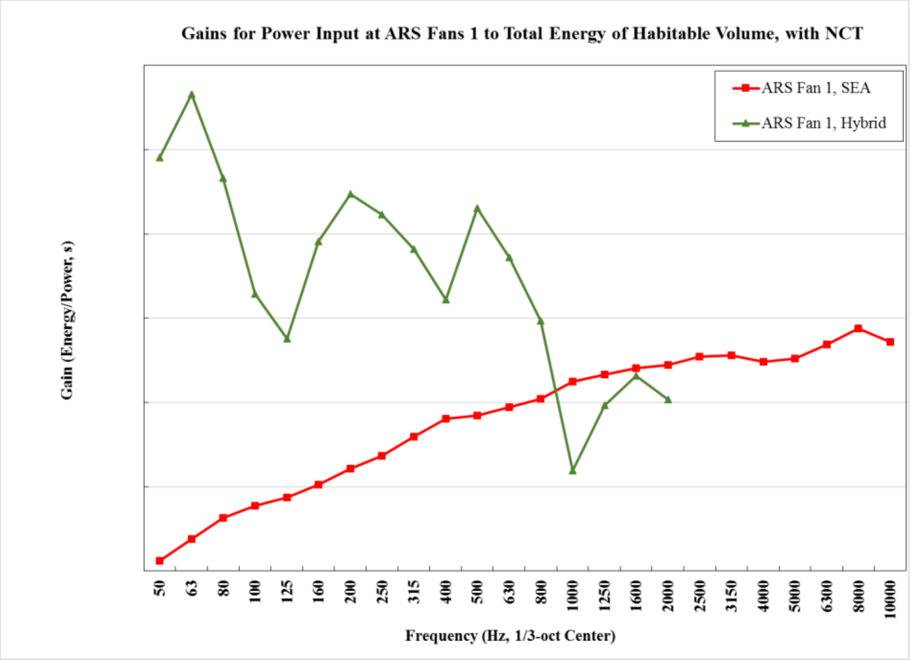


Hybrid SEA-FE Model, for ≤ 1,600 Hz

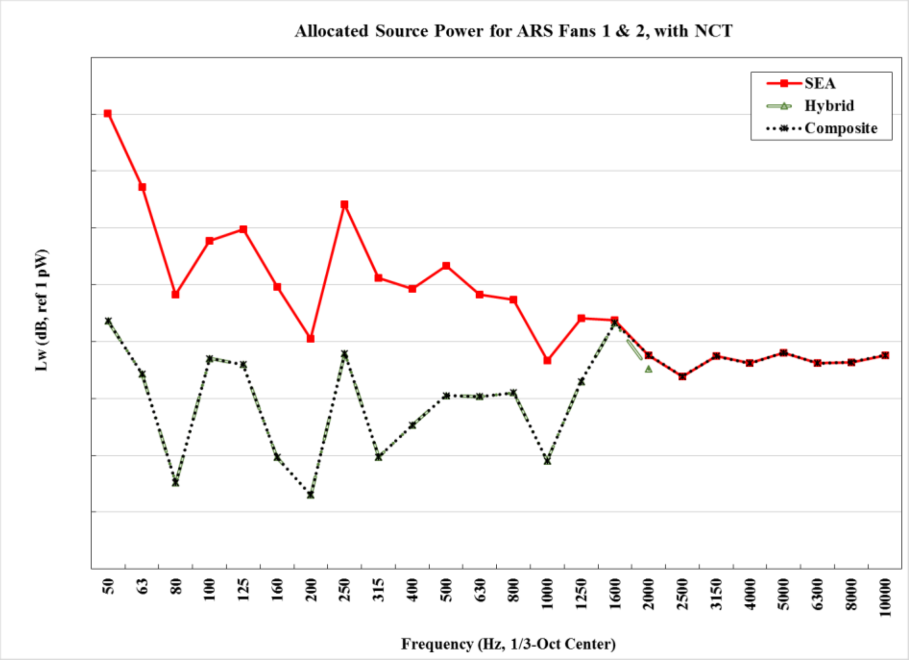


SEA vs. Hybrid SEA-FE

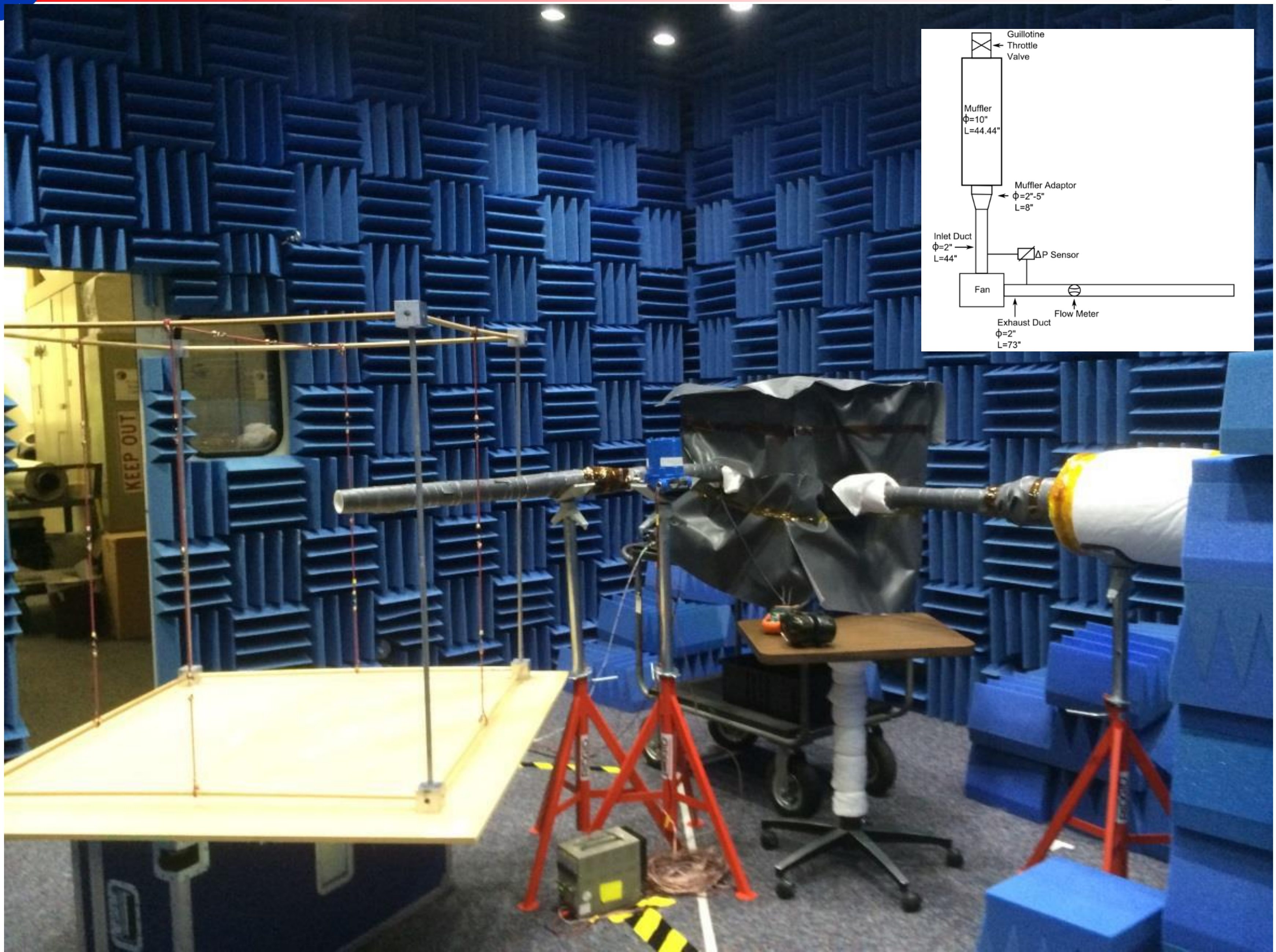
ARS Fan 1 Source-to-Receiver Gains



ARS Fans 1&2 Allocated Source Power

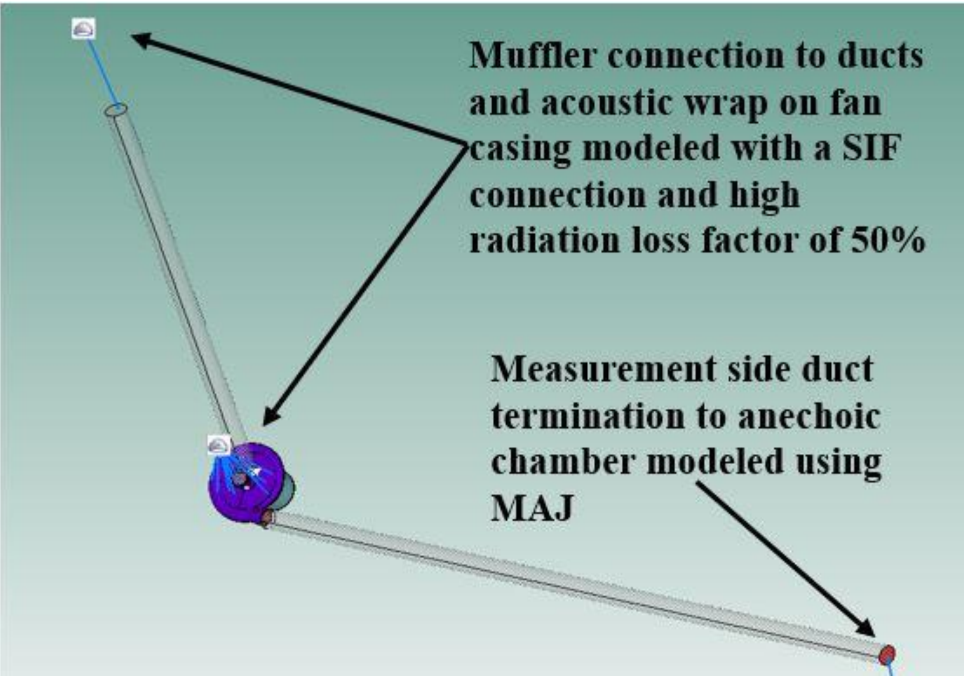


Suit Loop Fan Exhaust Sound Power Measurement Setup

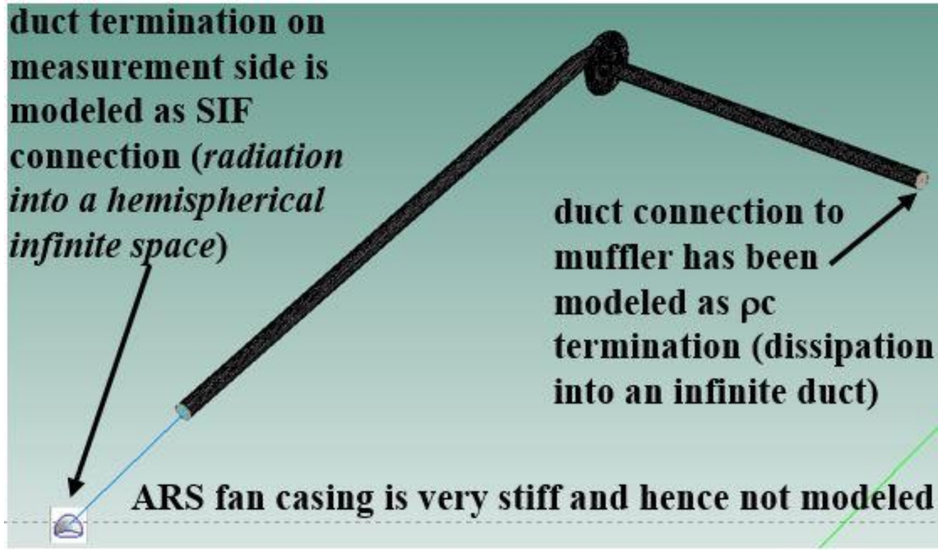


Models of ARS Fan Source Sound Power Characterization

SEA Model, for > 1,600 Hz

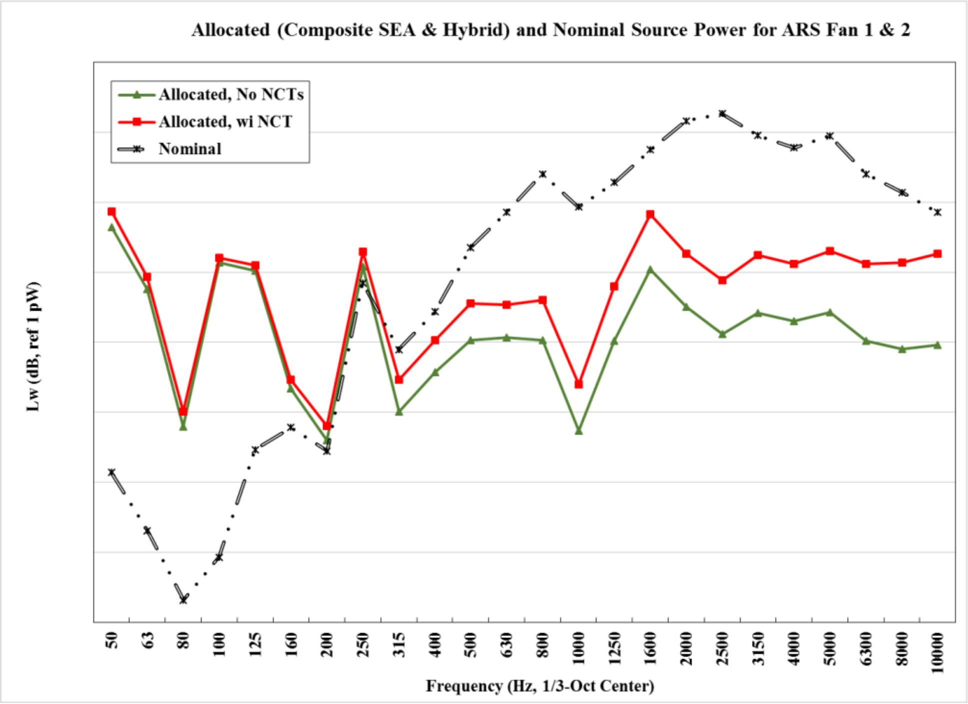


FE Model, for ≤ 1,600 Hz

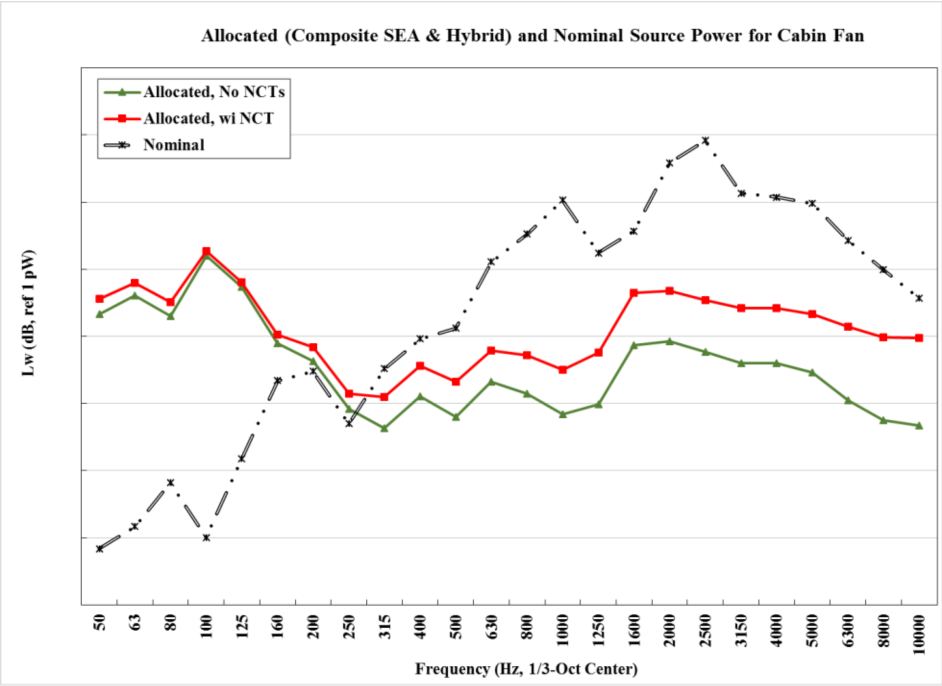


Sound Power Level Allocations and Component Level Noise Control Requirements

ARS Fans 1&2

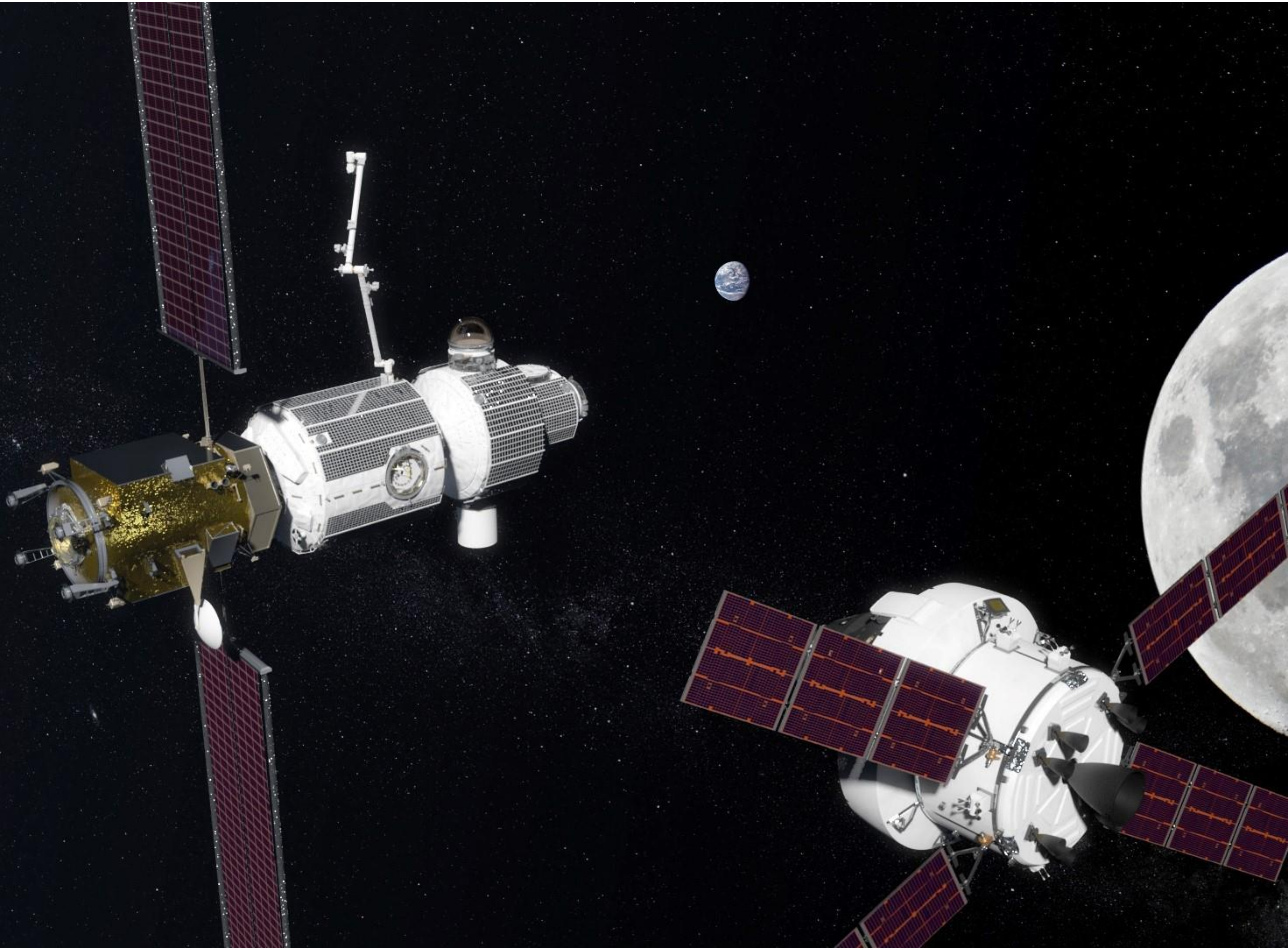


Cabin Fan



Summary

- 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

ISS Specifications

Assembly Complete Dimensions

Length: 74 m (243 ft)[1,2]
Width: 108.5 m (356 ft)
Weight: 366,591 kg (808,195 lbs)[2]
Volume: 930 cubic meters (32,857 cubic feet)[2]

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

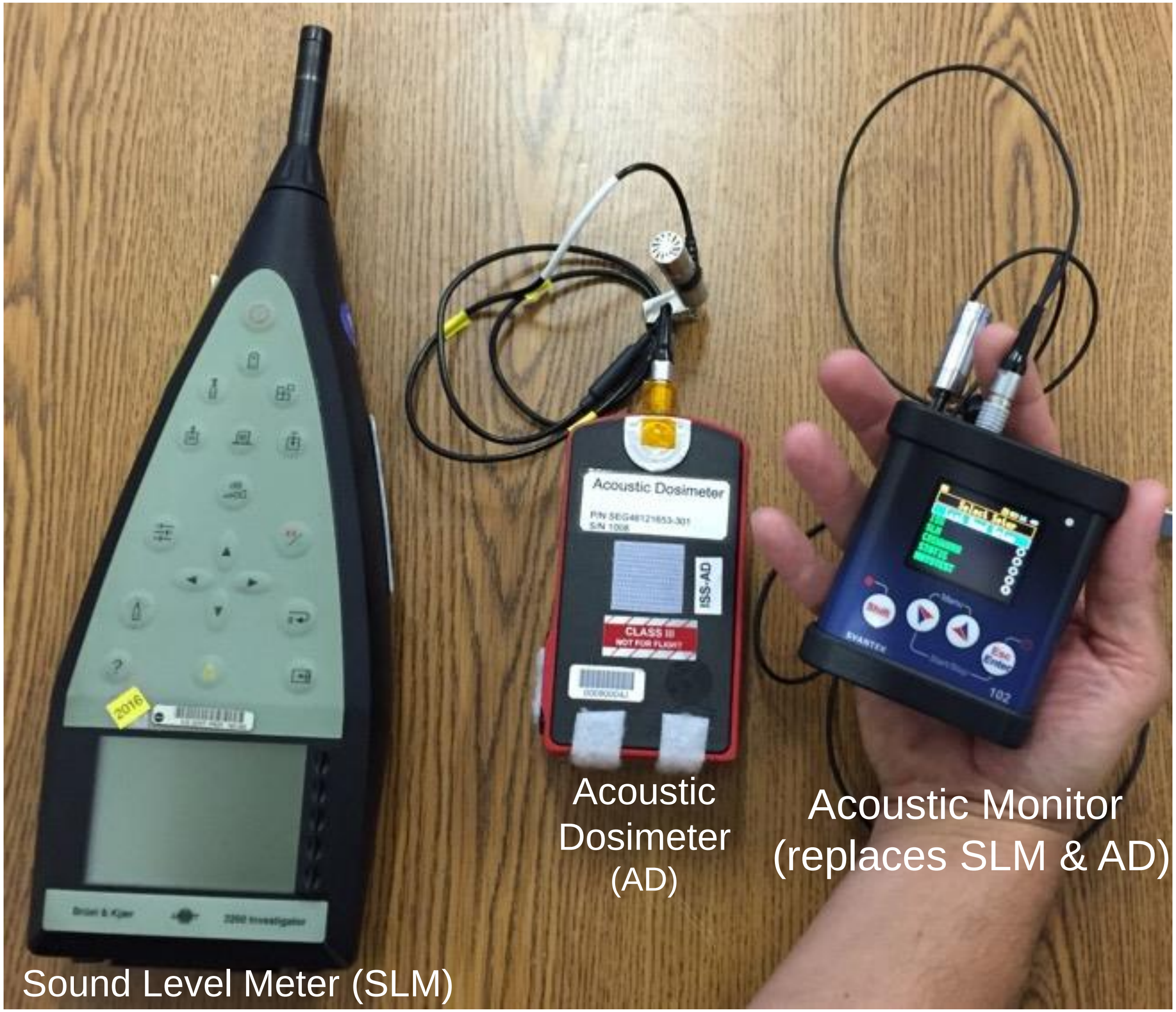
28,000 kph (17,500 mph), orbiting the Earth 16 times a day

Current Dimensions *(as of May 31, 2008)*

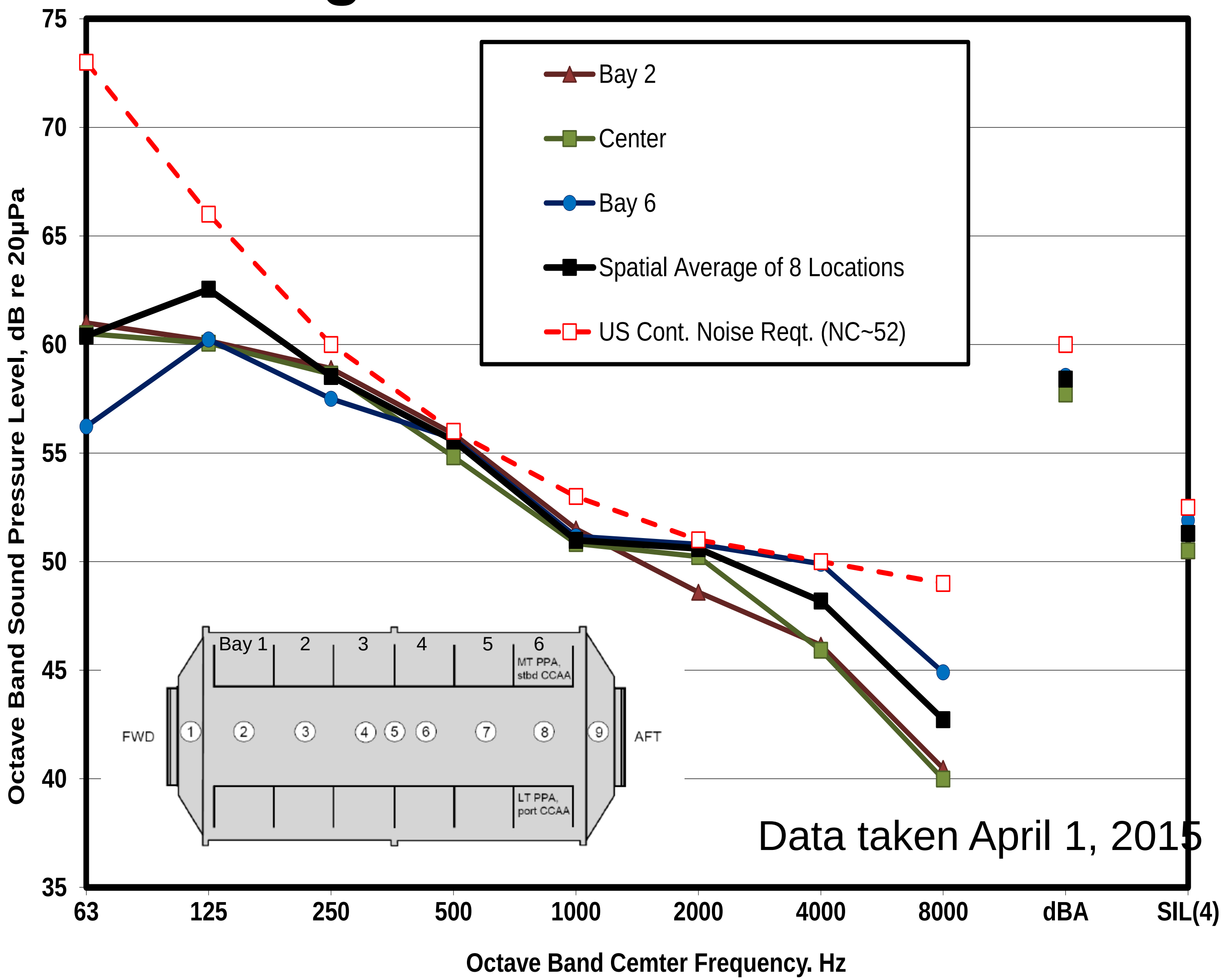
Length: 74 m (243)[1,2]
Width: 94 m (308 ft)
Weight: 276,808 kg (610,256 lbs)[2, 3]
Volume: 737 cubic meters (26,052 cubic feet)[2, 3]

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

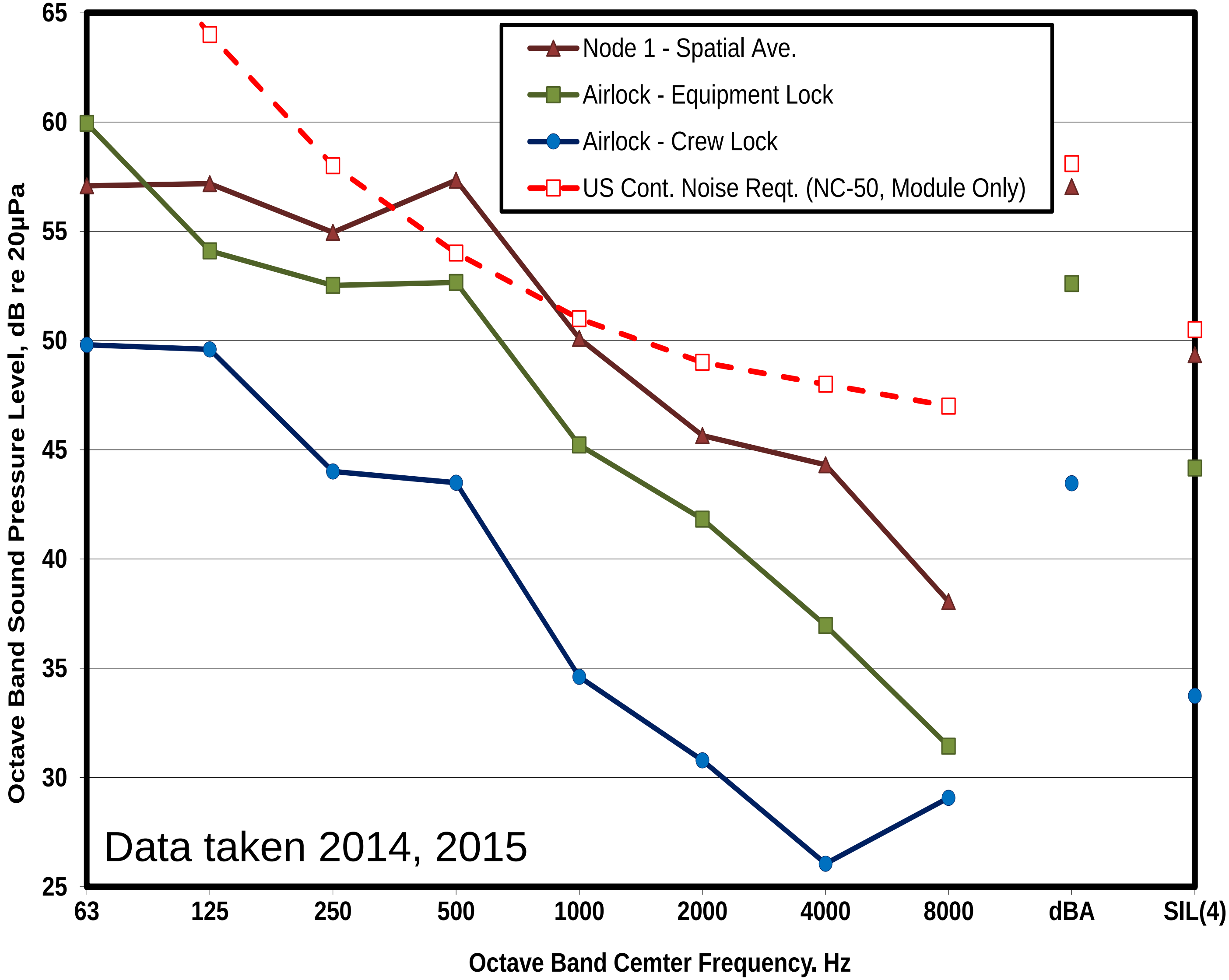
Acoustic Monitoring Equipment



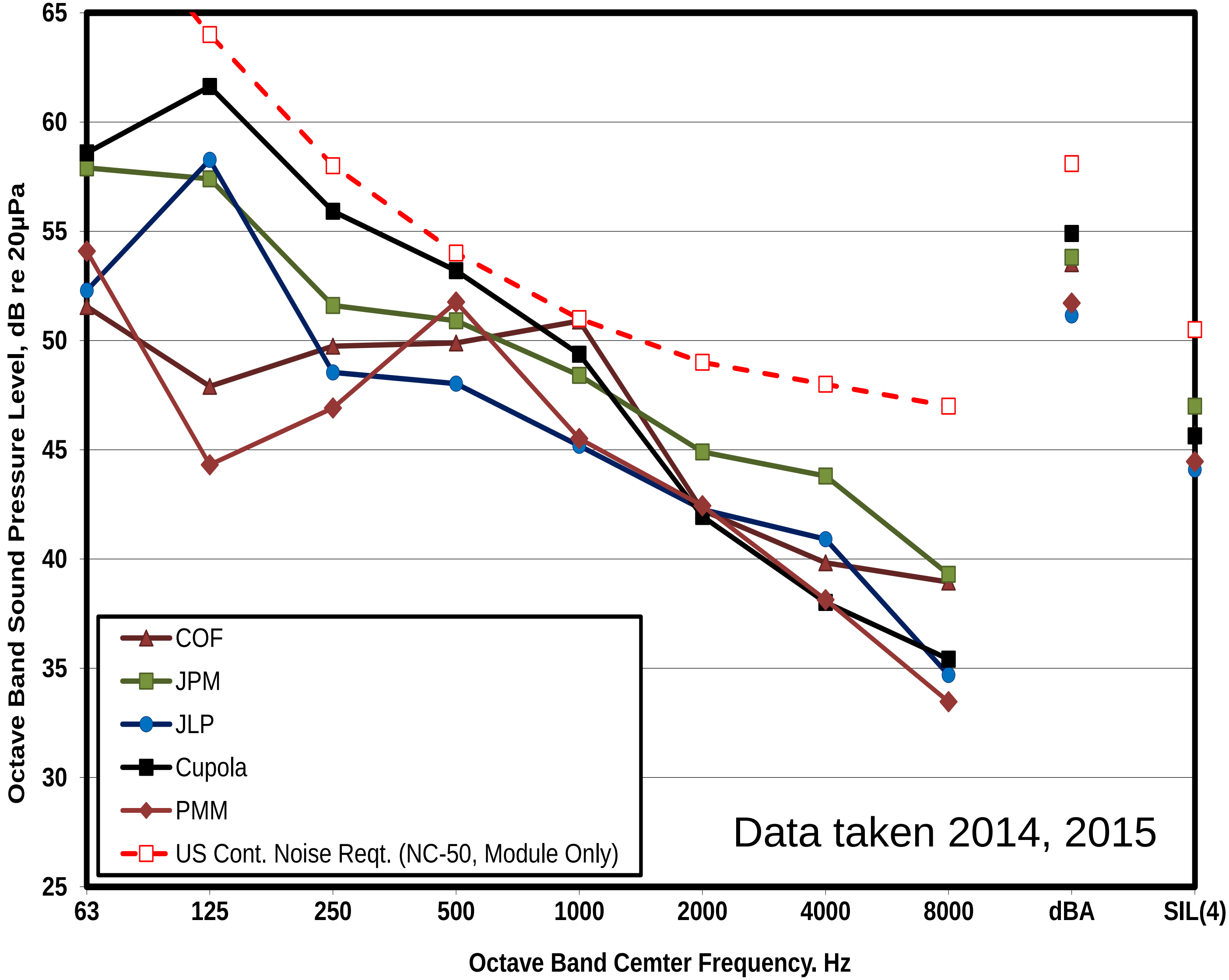
US Segment Acoustics – US Lab



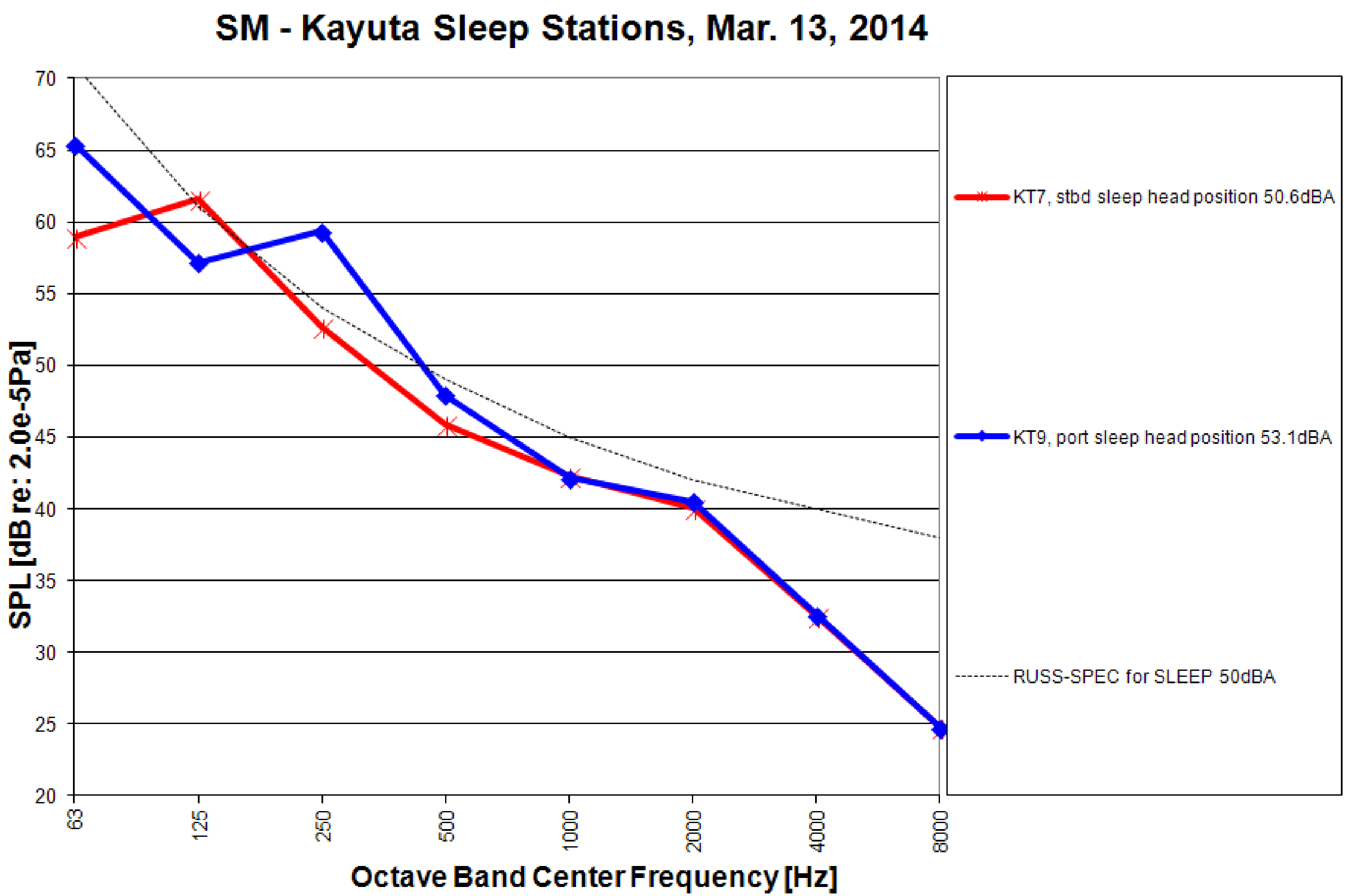
US Segment Acoustics – Node 1 and A/L



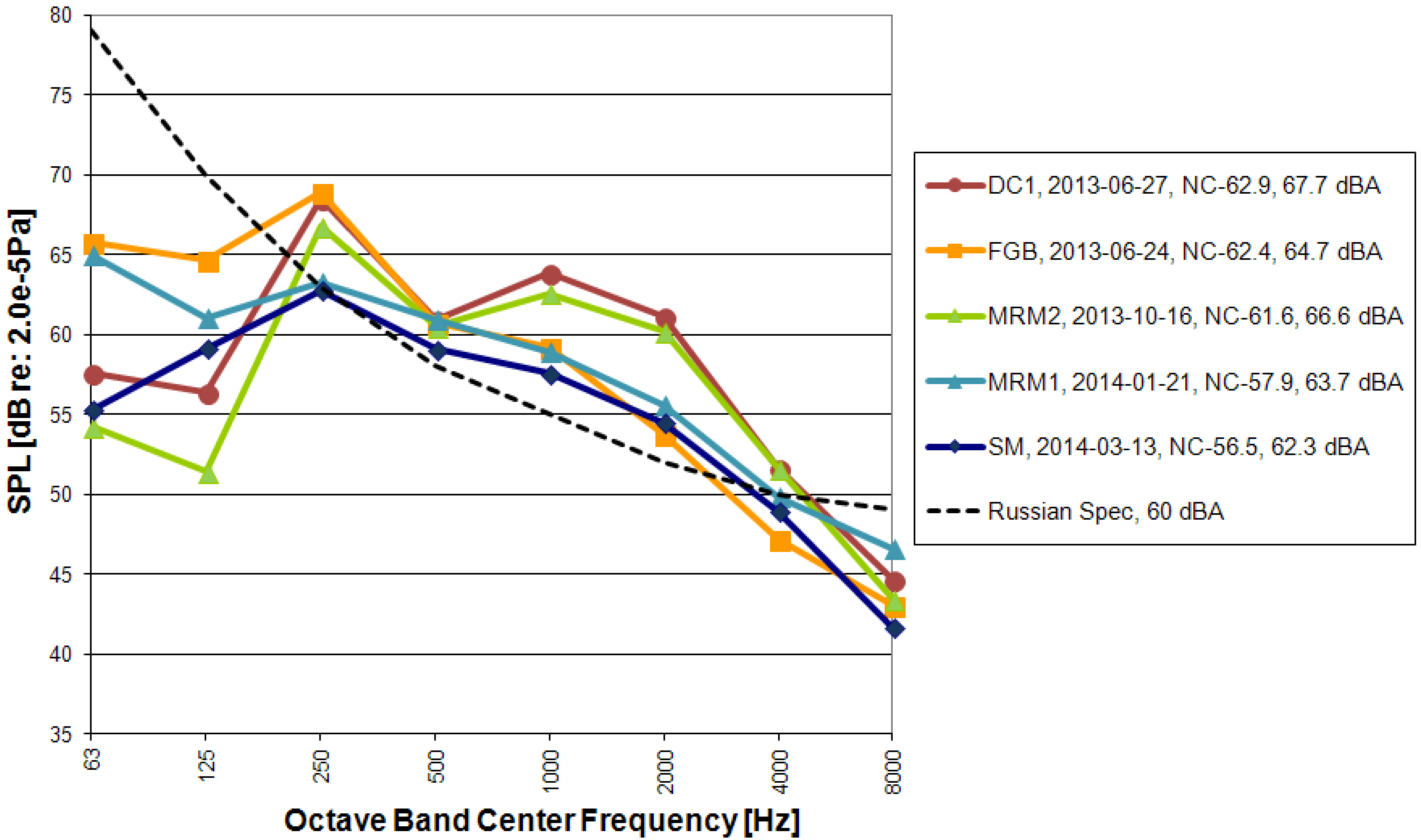
US Segment Acoustics – IP Modules and Cupola



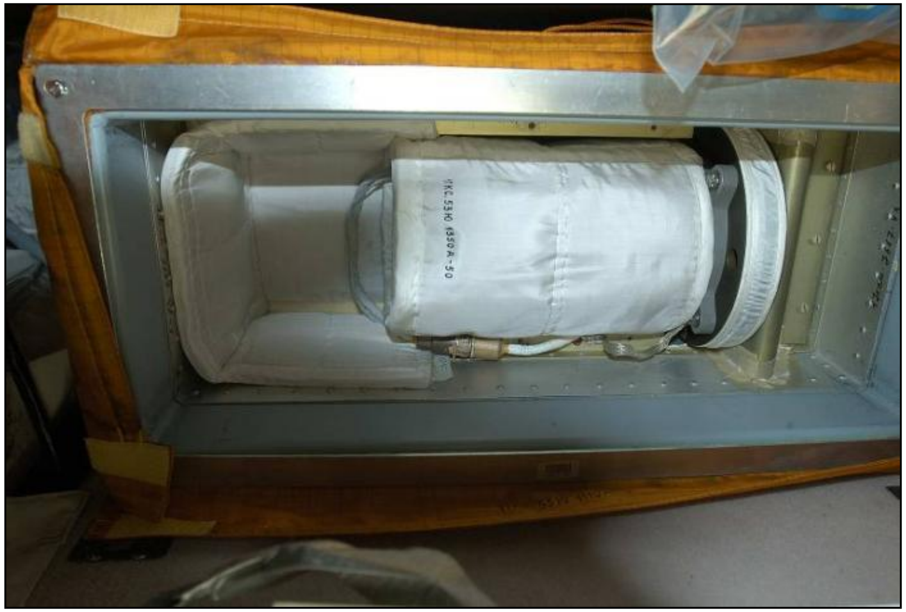
SM Sleep Station Noise Levels - March 13, 2014



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



Ventilation System Noise Controls



Air Conditioning System (CKB) Noise Controls

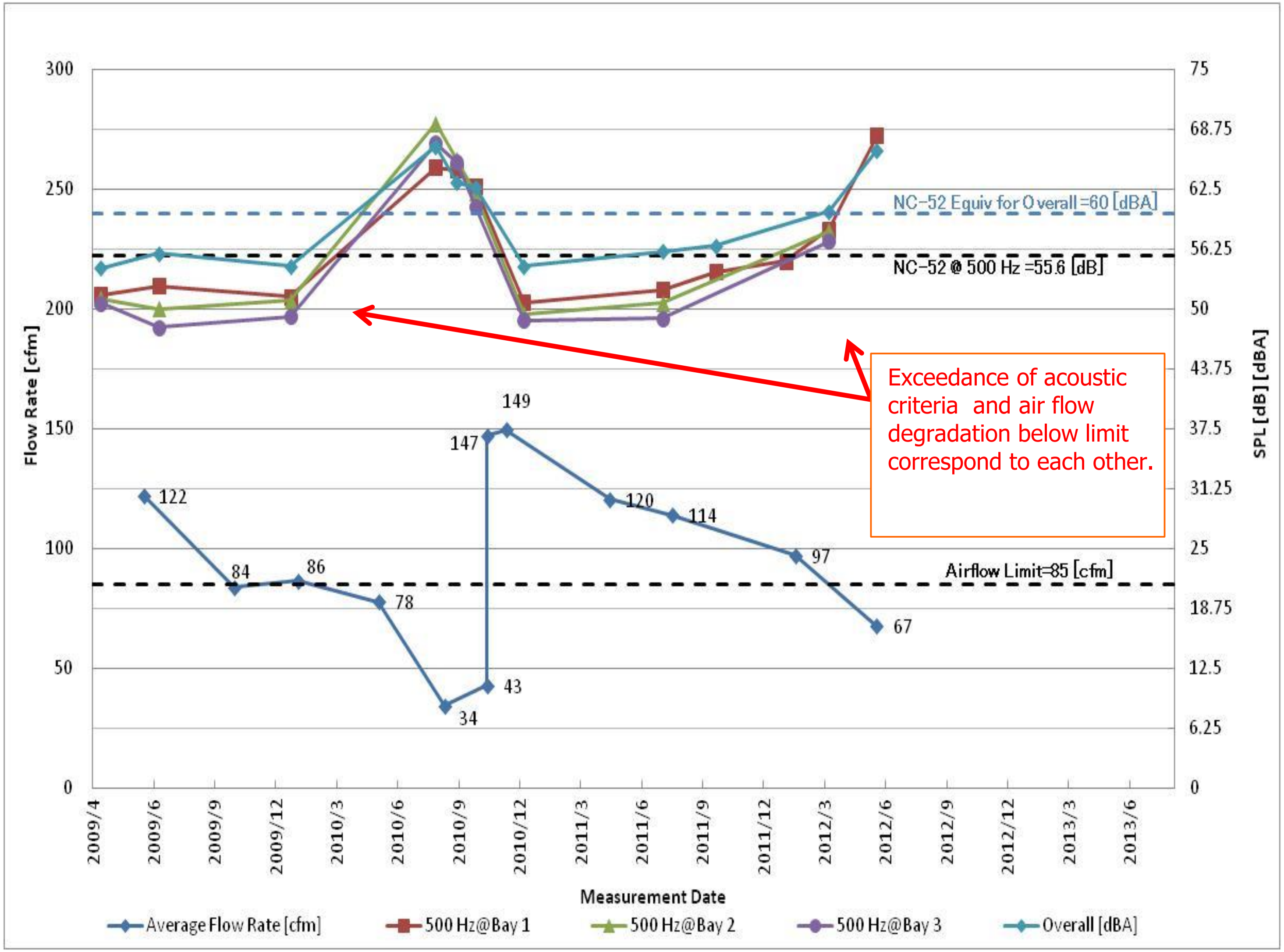
Vozdukh System Noise Controls

Adapter, shock absorber, and soft soundproof cover installed

Upon crew initiative, additional soundproofing device installed

JEM Ops Status – July, 2012

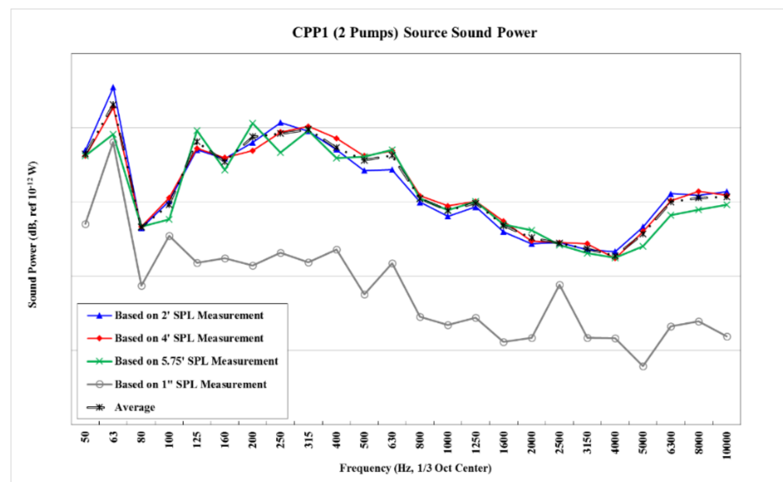
- Comparison of the noise level and the air flow still shows good correspondence.

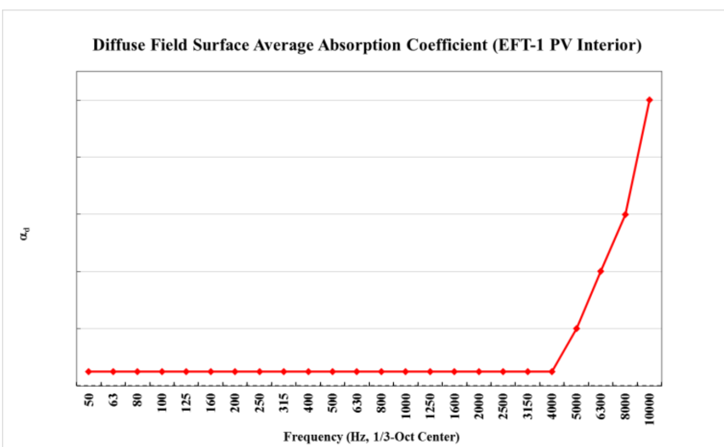


CPP1 SPL Measurement and Source Sound Power

- 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.

$$L_p(r) = L_w + 10log_{10}\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right)$$





Cabin SPL due to Allocated Noise Source Powers