Minneapolis, Minnesota
NOISE-CON 2005
2005 October 17-19

NASA Glenn Research Center Acoustical Testing Laboratory: Five Year Retrospective

Beth Cooper
NASA John H. Glenn Research Center at Lewis Field
21000 Brookpark Rd. MS 86-10
Cleveland, OH 44135
Beth.A.Cooper@grc.nasa.gov
http://acousticaltest.grc.nasa.gov

James Akers
Paul Passe
Analex Corporation
NASA John H. Glenn Research Center
at Lewis Field
21000 Brookpark Rd. MS 333-1
Cleveland, OH 44135

ABSTRACT

In the five years since the NASA Glenn Research Center (GRC) Acoustical Testing Laboratory (ATL) opened its doors in September, 2000, it has developed a comprehensive array of services and products that support hearing conservation goals within NASA and industry. The ATL provides acoustic emission testing and noise control engineering services for a variety of specialized customers, particularly developers of equipment and science experiments manifested for NASA's manned space missions. The ATL aggressively supports the vision of a low-noise on-orbit environment, which facilitates mission success as well as crew health, safety, and comfort. In concert with these goals, the ATL also produces and distributes free educational resources and low-noise advocacy tools for hearing conservation education and awareness. Among these are two compact discs of auditory demonstrations (of phenomena in acoustics, hearing conservation, and communication), and presentations, software packages, and educational materials for use by engineers, audiologists, and hearing conservation stakeholders. This paper highlights ATL's construction, history, technical capabilities, and current projects, as well as some of the unique educational resource materials that are distributed by the ATL.

1. INTRODUCTION

The International Space Station (ISS) is an on-orbit international laboratory that provides scientists, researchers, and engineers from around the world with scientific research opportunities in microgravity. Although simple investigations of fluid interfaces and combustion processes, for example, can be addressed in small, contained experiments, more complex and challenging investigations require dedicated facilities to contain fluids and products of combustion in a controlled and safe environment. One such dedicated laboratory facility manifested for the ISS is the Fluids and Combustion Facility (FCF), a two-rack microgravity research facility recently developed at NASA's Glenn Research Center for the USA's Laboratory Module of the ISS. This modular, multi-user, permanent microgravity science laboratory will make it possible for researchers on the ground, with the assistance of the astronauts in space, to schedule and perform studies of how fluids and flames behave in the absence of gravity.

The Acoustical Testing Laboratory at the NASA John H. Glenn Research Center at Lewis Field was established in late 2000 specifically to support the low-noise design and acoustic emissions verification process for the FCF. This paper provides a brief chronology of the evolution of the ATL over this five-year period, from its beginnings as a newly-constructed

anechoic chamber to the full-service laboratory that today provides a comprehensive range of services for the broader noise control and hearing conservation technical community. Over its five-year history, ATL has intentionally expanded its charter beyond acoustic emissions testing to include expert acoustical engineering consulting, technical training, and the development and distribution of educational resources in support of low-noise product design and occupational hearing conservation. It is the authors' intention in this paper to capture and document ATL's milestones and accomplishments, to provide a roadmap that references ATL-relevant publications and tangible products, and to acknowledge the diverse group of industry and academic collaborators who have made fundamental contributions to these successful efforts.

2. NASA'S QUEST FOR A QUIET ON-ORBIT WORK ENVIRONMENT

Space flight hardware and science experiment payloads must meet stringent acoustic emission requirements that support hearing conservation, speech communication, and mission safety goals[1]. These requirements also prevent noise-induced vibrations from deteriorating the on-orbit microgravity environment. In addition to limiting sound levels in the on-orbit environment, hearing loss prevention among the flight (astronaut) crew is promoted by means of a comprehensive hearing conservation program managed by the Audiology and Hearing Conservation Clinic (AuHCon) at NASA's Johnson Space Center[2].

Many of NASA's on-orbit noise emission requirements documents make use of noise criteria (NC) curves, which limit spectral shape as well as the overall noise emission level, as the basis for governing noise emission of individual payloads, racks and entire laboratory modules. In addition to the NC-like limits on continuous noise, intermittent noise is subject to a progressive scale that trades A-weighted sound level against duration of exposure. Most payloads generate a combination of continuous and intermittent noise according to an elaborate operational timeline associated with the function of the experiment process taking place inside the payload. This typically involves noise generated by various combinations of such sound sources as fans, pumps, motors, gas and fluid handling systems, hard drives, cameras, and combustion processes. Payload acoustic emissions must be test-verified before launch to show compliance with the applicable criterion; during this process measurements must be acquired on each face of the payload at all operating conditions that are expected to occur on orbit[3].

Payload noise emissions must be minimized in the context of a myriad of other design requirements that constrain the weight, volume, structural, heat transfer, and safety aspects of the payload's design as well as all noise control approaches and materials. In order to ensure the success of a low-noise design process, noise emission testing must be a frequent and iterative element of that process. Therefore, the development of a noise control plan for FCF required a dedicated in-house anechoic laboratory environment that would allow convenient access to repeatable and accurate noise measurements throughout the life of the project, in addition to hosting the final rack-level verification tests in a hemi-anechoic configuration.

3. ATL: SUPPORTING LOW-NOISE DESIGN OF SPACE FLIGHT HARDWARE

The ATL and its state-of-the-art PC-based data acquisition system were designed and built in less than one calendar year, from project inception in February of 2000 to its grand opening in September of that year [4,5,6]. The combined NASA-contractor team included anechoic chamber manufacturer Eckel Industries and acoustical consultant David Nelson of Nelson Acoustical Engineering, who developed a multi-channel enhancement to National Instruments' Sound Power System software to customize it to the ATL's unique needs[7]. Other enhancements were subsequently added, including a scanning sound intensity system, developed as a diagnostic tool to identify noise emission leaks and "hot spots," by a team of student interns from Brigham

Young University[8]. In addition, collaborative arrangements with the GRC Structural Dynamics Laboratory introduced additional capabilities, including specialized diagnostic techniques and measurements producing accelerometer, modal hammer, and shaker data.

Although the FCF project provided the motivation and the funding for ATL, the laboratory quickly became a NASA-wide resource that now provides all payload developers with the opportunity to actively integrate noise control strategies into their designs, right from the start. The ATL is unique among NASA facilities as the only full-service convertible hemi-anechoic chamber agency-wide that is dedicated to supporting the development and qualification of space flight hardware. ATL's state-of-the-art acoustical and operational capabilities are comparable to those of well known acoustical laboratories in the commercial sector.

In March of 2003, the ATL's ISO 17025-compliant quality system, developed with the assistance of Jeff Schmitt of JGS Consulting, was awarded accreditation by the National Voluntary Laboratory Accreditation Program (NVLAP Code 200557-0) for sound power level determinations per ISO 3744 and ANSI S12.54[9]. As FCF's low-noise design process proceeded from small-scale component tests through sub-assembly and assembly-level hardware testing, the ATL team began to develop the specifics of the procedures that would be employed for the final verification tests on the two full racks[10,11]. These tests, performed early 2005, were based on ISO 11201, for which the ATL was awarded NVLAP accreditation in December of 2004[12]. Selected highlights of the ATL's acoustic emissions testing operations are shown in Figure 1.

4. PROVIDING EDUCATION AND RESOURCES FOR PAYLOAD DEVELOPERS

The ATL enthusiastically promotes a shared vision of a low-noise on-orbit environment that contributes to mission success and crew health, safety, and comfort. Toward this end, client testing services now combine expert low-noise design and noise control services with a progressive testing program that iteratively quantifies and addresses noise emissions of successively larger scale assemblies, thus facilitating the ongoing prediction of full-rack noise emissions using a test-verified analytical model. Acoustical engineering services assist clients with materials selection, noise budgeting, and design strategies. To further the assimilation of low-noise ideals within NASA's on-orbit hearing conservation and noise control community, educational resources and training are offered for ISS stakeholders. ATL has sponsored the development of a library of customized training courses for NASA-associated payload developers who have projects in stages as early as concept definition. The most popular of these courses taught by Nelson Acoustical Engineering is an annual low-noise design training workshop that includes lecture sessions, lab tours, case studies, and in-class design reviews.

To supplement these training courses and provide resources for stakeholders who wish to participate in a low-noise advocacy process within their own organizations, ATL, in partnership with Nelson Acoustical Engineering, has developed a series of auditory demonstrations that are intended to convey the challenges to speech communication that are presented by various parameters of the acoustical environment. The effects of interior background noise, reverberation, and break-through noise from adjacent spaces on speech intelligibility are simulated using conversational vignettes to demonstrate the frustrating and problematic results of inadequate or inappropriate design standards, whether in an on-orbit or ground-based environment. The compact disc, *Auditory Demonstrations II: Challenges to Speech Communication and Music Listening*, was released in 2004 and is available on request via the ATL website (http://acousticaltest.grc.nasa.gov) [13]. An animated version of selected demonstrations will be released as ***Animated*** *Auditory Demonstrations II: Challenges to Speech Communication and Music Listening* in early 2006. Also included in both of these collections are recordings of several styles of music that have been filtered to simulate progressive noise-

induced hearing loss that can be predicted to result over a career-long exposure to workplace noise. The series of *Auditory Demonstrations* CDs, including an earlier (1997) release (*Auditory Demonstrations in Acoustics and Hearing Conservation*) is shown in Figure 2.

Currently, in the summer of 2005, the ATL is undertaking a new initiative to develop the capability of characterizing the noise emission and performance characteristics of cooling fans that may have applications in space flight hardware, particularly as NASA prepares to pursue new deep space exploration missions. This fan noise characterization initiative is intended to be a collaborative program, with multiple industry partners, which will produce an extensive database of fan design information that has heretofore been sorely missing from the payload developer's arsenal of design tools. An automated fan plenum apparatus has been built and tested for ATL by JGS Consulting in partnership with Nelson Acoustical Engineering and will be operational at ATL at the time this paper is delivered in the fall of 2005[14,15].

5. SUPPORTING HEARING CONSERVATION ON-ORBIT AND ON EARTH

In addition to providing technical support to payload developers, ATL has developed an acknowledged expertise in the multidisciplinary field of hearing conservation and has provided a variety of specialized services to NASA's flight crew hearing conservation program. For instance, customized medical illustrations, as shown in Figure 3, have contributed substantially to educational briefings and materials for flight crew and flight surgeon education.

Many of ATL's resources and products initially developed in support of NASA's manned space missions are equally applicable to ground-based hearing conservation programs, both at NASA and in the wider hearing conservation community. Most are available as free downloads or via on-line request on the ATL's website. These resources include activity sheets for elementary and middle school students on topics that include noise-induced hearing loss and acoustics, hearing conservation workshops for medical personnel, and design guides and other resources related to industrial noise control and the promotion of a low-noise workplace[16,17,18].

One such resource is MACSUG, a software program that facilitates the teaching of manual audiometry in a classroom environment, such as one associated with a course approved by the Council for Accreditation in Occupational Hearing Conservation (CAOHC) for training and certifying occupational hearing conservationists. MACSUG (which stands for Microprocessor Audiometer Computer Simulator User Gizmo) simulates an audiometer's graphic interface, as shown in Figure 4, and allows the instructor to coach and drill groups of students on the correct procedure for conducting audiometry by displaying both the patient's input and the audiometer's output on a projection screen. MACSUG, which was developed in collaboration with the Audiology and Hearing Conservation Clinic (AuHCon) at the NASA Johnson Space Center, was distributed for beta testing by several CAOHC Course Directors in November of 2003 and is expected to be released publicly by mid-2006.

In early 2004, the ATL released JeopEARdy, another hearing conservation training resource developed in collaboration JSC's AuHCon[19]. JeopEARdy is a unique interactive game, as shown in Figure 5, which is most commonly used by an instructor in a classroom setting as part of an OSHA-required annual hearing conservation training session. As a PowerPoint® application, it may be easily customized by the end user to meet the needs of the specific audience. Single copies of JeopEARdy are available to hearing conservation educators via an on-line product request form on the ATL website.

6. OUTREACH TO THE EDUCATIONAL AND TECHNICAL COMMUNITY

ATL maintains an ongoing program of hosting summer interns who are majoring in acoustics or in a field related to hearing conservation and has also provided opportunities for high school

students and teachers to complete career shadowing and in-service training requirements. In 2003, the ATL hosted a collaborative project with the Cleveland Institute of Music's Audio Engineering Department, which required the use of an anechoic chamber to research optimal microphone placement for instrumental music recordings. The ATL frequently hosts tours for groups of students, teachers, industry professionals, and the general public. In 2003, ATL organized and hosted a tour of several of GRC's acoustics facilities for attendees at NoiseCon 2003. The conference, which was held in Cleveland and co-sponsored by ATL and the Glenn Research Center, included numerous special sessions and plenary speakers dedicated to ISS hearing conservation and noise control topics[20,21,22]. More information on ATL's history, capabilities, services and free publicly-distributed resources, may be found on the ATL website (http://acousticaltest.grc.nasa.gov). These outreach activities are highlighted in Figure 6.

ACKNOWLEDGEMENTS

Thanks to the aggressive championing of a low-noise on-orbit environment by those who are developing, testing, and reviewing science experiment payloads for the ISS, flight crew members are able to carry out their research in a quiet work environment, free from the risks of noise-induced hearing loss and communication interference that can pose risks to on-orbit safety and productivity. Among the ATL team, these goals have motivated the development of a wide range of hearing-conservation-related products and services that offer benefit to the broader noise control and hearing conservation community. The authors would like to acknowledge the contributions of ATL team members who have collaborated on this diverse collection of projects.

Funding for the ATL's construction and major ongoing support was provided by GRC's Microgravity Sciences Division and the FCF Project Office and associates (Bob Zurawski, Bob Corban, Terry O'Malley, Frank Gati, Dave Francisco, and Dennis Rohn). The ATL's construction partners at Eckel Industries (Alan Eckel and Jeff Morse) and sound intensity system project team at Brigham Young University (Scott Sommerfeldt and students Kent Gee, Lance Locey, and Gordon Dix) have been instrumental in the ongoing evolution of the physical facility. Jeff Schmitt (JGS Consulting) coached the ATL team through the development and accreditation of its ISO17025-compliant quality system and has been the driving force behind many of the hardware and process customizations that have simplified and automated ATL's operations. David Nelson (Nelson Acoustics) has been an invaluable adjunct to the ATL staff in every aspect of the ATL's design and operation since the early conceptual stages as well as nearly every product development and training project. The recent successful culmination of FCF's thorough and rigorous low-noise design process is a credit to the FCF design team at Northrop Grumman Information Technologies, including acoustics team members Judy Young and Eugene Krejsa as well as technical leads Brian Finley, Marty O'Toole, and Jim Birchenough. An ongoing succession of summer interns, including Karen Shandera (Penn State) and medical illustrator Nicholas Hawes (Cleveland Institute of Art) have all contributed fresh ideas and skills to the eclectic mix of projects that are continually launched and completed over the course of one or more summers. Dick Danielson, JSC's Manager for Audiology and Hearing Conservation, has been an inspired collaborator on many of the hearing conservation training projects and products. The Acoustics Working Group at NASA Johnson Space Center (Jerry Goodman and Chris Allen as well as Eric Phillips and Greg Pilkinton of the Boeing Company) continues to provide valuable guidance as ATL actualizes its vision of providing low-noise design and noise control services and training for payload developers. Finally, the authors would like to acknowledge the management support and encouragement of Kim Otten and the Analex Corporation, and of Rick Manella, John Taylor, and Dan Gauntner of the NASA GRC Engineering Development Division.

REFERENCES

[1] Beth Cooper, Richard Danielson, Jonathan Clark, and Christina Stevens, "Global Auditory Concerns for Individual Needs: Expanding the Hearing Conservation Universe to the International Space Station," Proceedings of the 2002 NHCA Conference (National Hearing Conservation Association, 2002)

[2] Richard Danielson and Christina Stevens, "Overview of Hearing Conservation Programs for the International Space Station and NASA Flight Personnel," Proc. NoiseCon 2003 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2003)

[3] David Nelson, "Noise Emission Testing Requirements for Spaceflight Hardware," Proc. NoiseCon 2003 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2003)

[4] Beth Cooper, Alan Eckel, Trent Butcher, and David Nelson, "New Acoustical Testing Laboratory at NASA," Sound & Vibration. Dec. 2000: 10-18.

[5] Beth Cooper, "Design and Construction of a Convertible Hemi/Anechoic Acoustical Laboratory for Testing Space Flight Hardware at the NASA Glenn Research Center," Proc. NoiseCon 2000 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2000)

[6] Beth Cooper, "Creating a Quiet Work Environment in Space," Testing Technology Intl -- Aerospace. (2002).

[7] David Nelson, "A Computer-Based Acoustical Measurement System for NASA Glenn Research Center," Proc. NoiseCon 2003 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2003)

[8] Gordon Dix, Kent Gee, and Scott Sommerfeldt, "Design and Implementation of an Acoustical Scanning System at the ATL of NASA GRC," Proc. NoiseCon 2003 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2003)

[9] Jeff Schmitt, "The Design of a Quality System to Support NASA Glenn Research Center Acoustical Testing Laboratory," Proc. NoiseCon 2003 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2003)

[10] George Douzos, Eugene Krejsa, and Judy Young, "Testing and Noise Control for FCF Project Fluids and Combustion Facility," Proc. NoiseCon 2003 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2003)

[11] James Akers, Paul Passe, and Beth Cooper, "Challenges in Acoustic Testing of ISS Payloads: Lessons Learned at the NASA Glenn Research Center Acoustical Testing Laboratory," Proc. NoiseCon 2003 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2003)

[12] James Akers, Paul Passe, and Beth Cooper, "Acoustic Emissions Verification Testing of International Space Station Experiment Racks at the NASA Glenn Research Center Acoustical Testing Laboratory," Proc. NoiseCon 2005 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2005)

[13] Beth Cooper, David A. Nelson, and Richard W. Danielson, "Auditory Demonstrations II: Challenges to Speech Communication and Music Listening," Proc. NoiseCon 2004 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2004)

[14] Jeff G. Schmitt, David A. Nelson, and John Phillips, "An Automated System for the Acoustic and Aerodynamic Characterization of Air Moving Devices," Proc. NoiseCon 2005 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2005)

[15] David A. Nelson, William Butrymowicz, and Chris Thomas, "Effect of Discharge Duct Geometry on Centrifugal Fan Performance and Noise Emission," Proc. NoiseCon 2005 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2005)

[16] Beth Cooper and Richard Danielson, "Integrating Noise Measurement and Noise Control Engineering Into Hearing Conservation Training Programs," Proc. NoiseCon 2001 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2001)

[17] Richard Danielson and Beth Cooper, "Promoting a noise control program: Resources for successfully advocating a low-noise environment," Proc. InterNoise 2002 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2002)

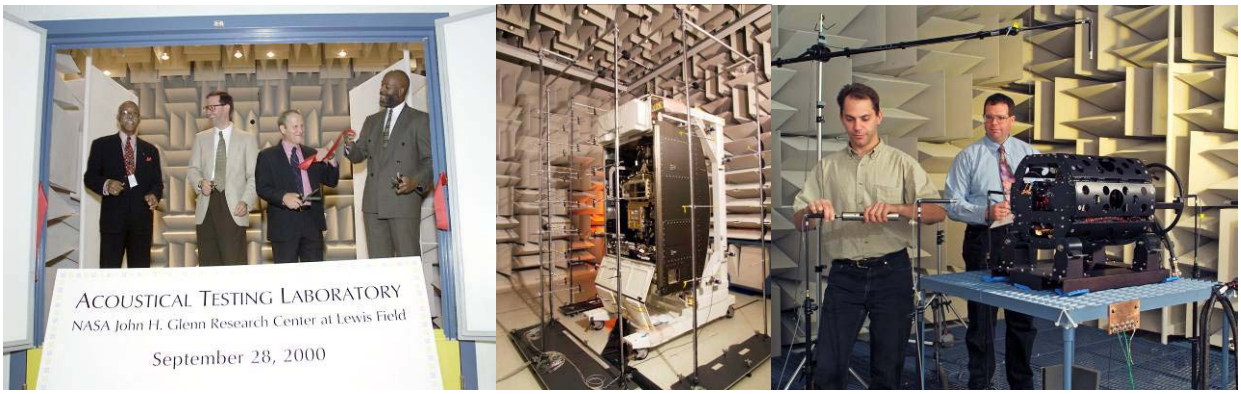
[18] Beth Cooper, "Considering an Engineered Noise Control Solution?" CAOHC Update. Part 1. Winter 2000/2001: 1, 9. Part 2. Spring 2001: 1, 7-8. Part 3. Fall 2001: 5-6.

[19] David Byrne, "A New Hearing Conservation Training Resource Developed by NASA John H. Glenn Research Center." NHCA Spectrum. 21 (3) 2004.

[20] Jerry Goodman, "International Space Station Acoustics," Proc. NoiseCon 2003 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2003)

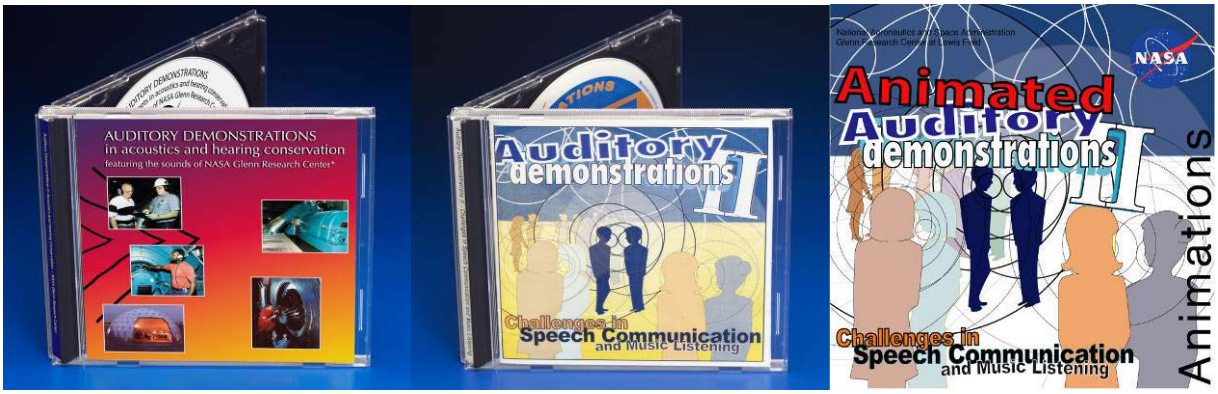
[21] Greg Pilkinton, "ISS Acoustics Mission Support," Proc. NoiseCon 2003 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2003)

[22] Chris Allen and Jerry Goodman, "Preparing for Flight – The Process of Assessing the ISS Acoustic Environment," Proc. NoiseCon 2003 (Inst. of Noise Control Engineering of the USA, Inc., Washington, DC, 2003)



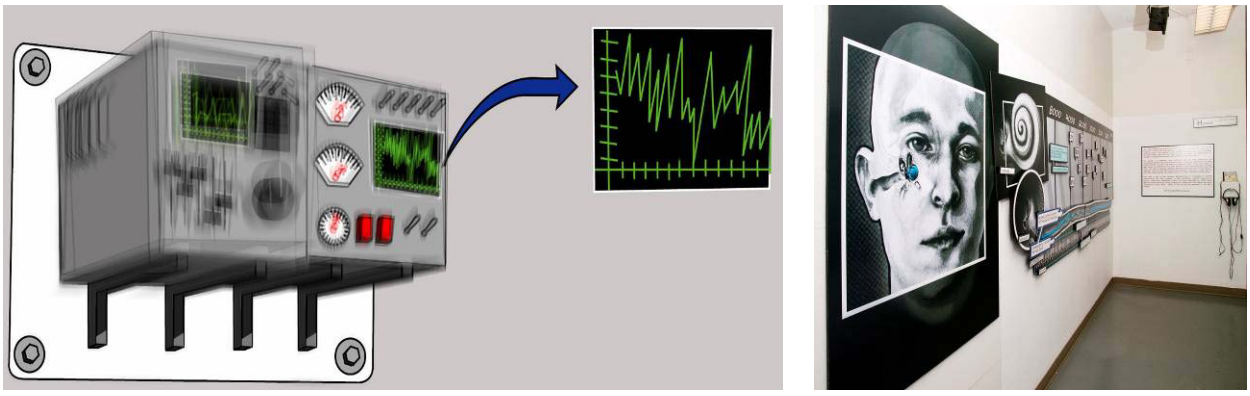
(a) (b) (c)

Figure 1. Since its grand opening in 2000 (a), the ATL has provided acoustic emissions testing services for the Fluids and Combustion Facility (b) as well as FCF subassemblies and smaller space flight payloads (c).



(a) (b) (c)

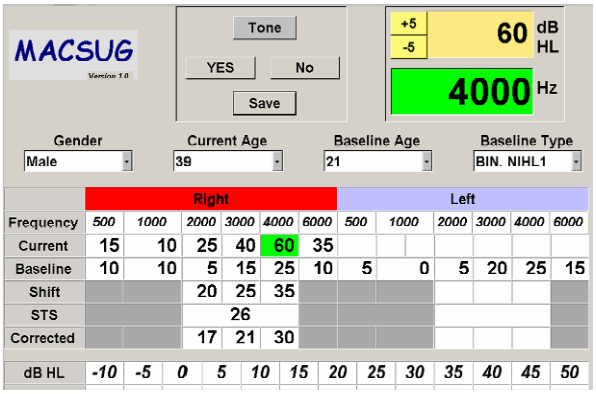
Figure 2. The ATL has produced a series of auditory demonstration products that illustrate basic concepts in acoustics and hearing conservation (a) and various challenges to speech communication and music listening (b). An animated version of selected tracks from *Auditory Demonstrations II* is scheduled for release in early 2006 (c).



(a) (b)

Figure 3. The ATL has supported the flight crew hearing conservation program for the International Space Station by developing educational outreach materials, including scientific (a) and medical (b) illustrations that are targeted to NASA's unique astronaut and program management audience.

(a)

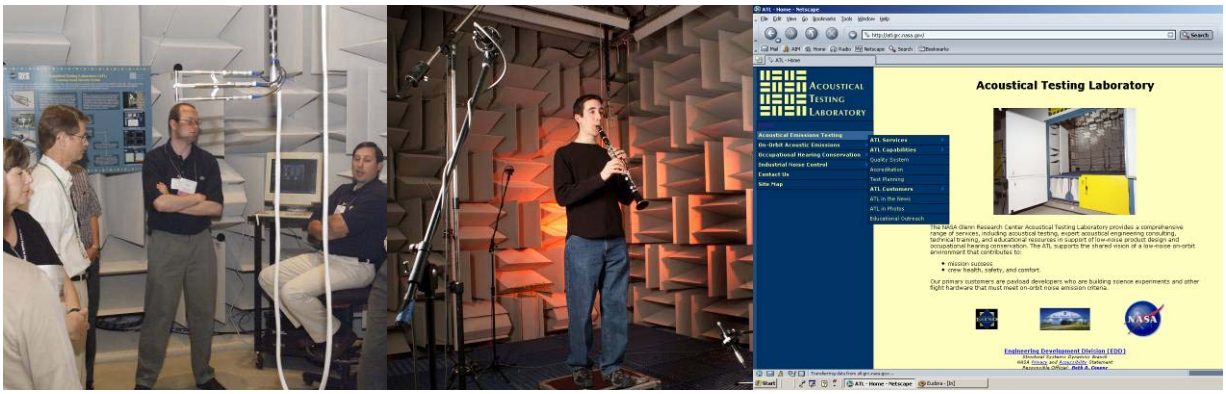


(b)

Figure 4. MACSUG (a) is an ATL-developed software program that simulates an audiometer's graphic interface (b). It may be used to teach manual audiometry and audiogram review in a classroom environment.

(a) (b) (c)

Figure 5. ATL's educational outreach products are widely used in the general hearing conservation community (a). JeopEARdy is a PowerPoint® -based training game (b) that reinforces concepts taught in OSHA-mandated hearing conservation training (c). It may be easily customized to meet the needs of local audiences.



(a) (b) (c)

Figure 6. The ATL's outreach programs include summer internships for college students, including those from Brigham Young University shown here demonstrating their scanning sound intensity system during a tour hosted for NoiseCon 2003 attendees (a), collaborations with local universities with audio engineering programs (b), and an extensive website (http://acousticaltest.grc.nasa.gov) that offers a wealth of free educational resources (c).