AUDITORY AND ACOUSTIC RESEARCH AND DEVELOPMENT AT THE AIR FORCE RESEARCH LABORATORY

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Introduction

Since the days of the Wright brothers flying their first airplane, noise and its effects on hearing and communications have been an issue in the operation of aircraft. The Air Force Research Laboratory (AFRL) conducts auditory and acoustic research and development programs addressing unique Air Force needs relative to both air and ground operations. These programs have focused on two major areas—(1) bioacoustics in the development of noise exposure criteria, hearing protection, active noise reduction, voice communications, spatial auditory displays, and spatial hearing and (2) physical acoustics in the measurement, modeling, and propagation of aircraft noise. The acoustics research group at AFRL has been a leader in research and technology development including passive hearing protection, active noise reduction headsets and earplugs, 3-D audio displays, aircraft noise measurement and modeling, speech communication in noise, and national and international standards for over 60 years. This article is meant to give a flavor of the people and facilities at the AFRL acoustics group and the unique projects they are conducting. To understand the current and future research it is helpful to first review some history and legacy work of this group.

"The acoustics research program at the Air Force Research Laboratory has been active for more than sixty years."

A brief history

The acoustics research program at AFRL has been active for more than 60 years.[1] A report detailing the literature citations from this period would generate a substantial technical document and a complete review is beyond the scope of this article. The purpose of this section is to give a few examples of projects, large and small, that have helped make the group, facilities, and research programs what they are today. There are five primary core technical areas that have been, and continue to be, the focus of the AFRL acoustics group—(1) hearing conservation, (2) hearing protection, (3) speech communication, (4) spatial hearing and (5) noise measurement and community noise modeling.

AFRL's research investigating acoustics and the effects of noise on humans began with the arrival of Dr. Henning von Gierke from the Helmholtz Institute in 1947. Dr. von Gierke's dissertation (Doctor of Engineering, 1937) described the prediction of noise levels and spectrum from jet flow, both sheet flow and conical flow. Soon after Dr. von Gierke's arrival at Wright-Patterson, he was involved in the measurement of noise from the newly developed jet engines and the Air Force published the first hearing conservation regulation, AFR-160-3, "Precautionary Measures Against Noise Hazards," in 1948. This regulation required that exposures were never to exceed 95 decibels (dB) and were recommended to be kept below 85 dB. Later, in 1956, Dr. Horace (Hop) Parrack, an Air Force charter member of the National Academy of Sciences Committee on Hearing, Acoustics, and BioAcoustics (CHABA), led the establishment of the first recognized (military or non-military) comprehensive hearing conservation program.

AFRL has also been a leader in the development of both passive and active hearing protection technologies. Dr. von Gierke developed a lumped parameter model of passive circumaural hearing protectors which explained the basic relationship between attenuation and hearing protector design parameters such as mass, volume, and headband tension. The Air Force, working with Radio Corporation of America (RCA), designed and demonstrated a working active noise reduction (ANR) headset in 1956–1957.[2] This ANR headset project, led by Willard Meeker, RCA, used electron tube circuits about the size of a bread box, (Fig. 1), and also used a miniature microphone in the headset earcup. During this time, work on improved passive hearing protectors (both earmuffs and earplugs), and communication headsets was being led by Dr. Charles Nixon.

Work in physical acoustics (1959–1961), led by Dr. von Gierke, developed a broadband siren.[3] This siren design, capable of producing sound levels exceeding 170 dB Sound Pressure Level (SPL), would be later used in aircraft acoustic fatigue research and for human noise research involving the original seven NASA Mercury program astronauts (Fig. 2). The human tests were conducted to ensure the high levels of launch noise experienced in the Mercury space capsules did not adversely affect the astronauts.

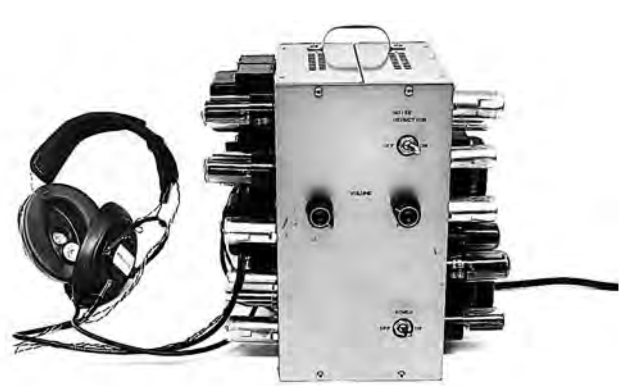

Fig. 1. Active noise reduction headset and electron tube electronics, circa 1957.

Fig. 2. High intensity noise test at AFRL, circa 1960.

In the late 1960's, AFRL conducted the first and only study of the effects of airbag deployment on the human auditory system. These data were used to estimate the hearing damage risk (1-2%) from airbag deployment. During the 1960's, the effects of high levels of infra-sound on human auditory, vestibular, and cognitive function were also investigated. At that time, rapid progress was being made in air transportation and consideration was being given to the US development of supersonic transport. Dr. Nixon's work on human responses to sonic boom[4] was instrumental in the US policy decisions to prohibit commercial supersonic flights over the continental US. At the personnel level, a young Air Force Lieutenant, David Blackstock, had many debates with Dr. von Gierke regarding non-linear acoustics. Later, the Acoustical Society of America would separately award both men the Gold Medal, Dr. Blackstock for "contributions to the understanding of finite-amplitude sound propagation and worldwide leadership in nonlinear acoustics," in 1993 and to Dr. von Gierke for "contributions to bioacoustics, psychoacoustics, vibrations, and for leadership in national and international acoustical standards," in 1999.

The 1970's brought development of speech recognition systems, speech synthesis systems, custom molded communication earplugs, community noise mapping from aircraft operations, a voice communication research facility, Voice Communication Research and Evaluation System (VOCRES), shown in Fig. 3, and new work on active noise reduction headsets. AFRL human temporary threshold shift (TTS) studies were instrumental in adoption of the equal energy principle (i.e., the 3 dB per doubling time-intensity trading relationship for noise exposure). Led by Lieutenant Colonel Daniel Johnson and Captain Mark Stephenson, these studies showed that human TTS was essentially equal for exposures as short as 1 second at 130 decibels, A-weighted (dBA) and as long as 48 hours at 80 dBA (i.e., equal energy) . Coincident with the technology developments and pioneering research was the development of national and international standards in physical acoustics, bioacoustics, and noise, led by Dr. von Gierke.

The 1980's brought AFRL's development of the world's first real-time system for presenting synthetic spatial audio cues, (i.e., a 3-D audio display). This display was developed using the AFRL Auditory Localization Facility (ALF) shown

Fig. 3. Voice communication research and evaluation system (VOCRES), circa 1987.

Fig. 4. Auditory Localization Facility (ALF), circa 2004.

in Fig. 4. This facility enabled fast and accurate collection of head-related transfer functions (HRTFs) which were important to synthetic 3-D audio displays. Additionally, the ALF was used to compare human localization performance in a real environment with the synthetic spatial auditory display environment. At this time, AFRL also expanded their research efforts investigating the effects of electronic noise and radio interference on speech intelligibility, where both the talker and listener were in operationally relevant high levels (>100 dB) of broadband, ambient, acoustic noise.

In the 1990's, AFRL collaborated with the US Navy/US Marine Corps and NASA to conduct flight tests of 3-D audio displays on a Navy/Marine Corps AV-8B Harrier and a NASA Glenn Research Center OV-10 Bronco. These were the world's first flight tests of a synthetic 3-D audio system.[5] Basic research was initiated investigating the effect of spatial auditory cures on aurally-guided visual search. The initial experiments demonstrated that the human auditory system was very effectively guiding the visual gaze of the subject. The results showed a decreased reaction time in locating and discriminating a small (<1°) target from 30 seconds without the spatial auditory cue to 1.5 – 2 seconds with spatial auditory cueing. The results were also dependent on the visual field of view, with smaller, more restricted field of views receiving a larger benefit from the addition of spatial auditory cueing. During the 1990's, AFRL also collaborated with the US Navy to conduct measurements of flight deck operational noise on US Navy aircraft carriers. The results of these noise measurements showed noise levels from 130-148 dB and brought a new focus to developing new hearing protection devices with improved noise attenuation and new programs in hearing protection research that included investigations of the potential impacts of bone conducted noise.

Current efforts

The new millennium brought exciting and challenging projects run by an excellent cadre of scientists and engineers using world-class acoustics facilities and instrumentation. The multi-disciplinary researchers include experts in audiology, biomedical engineering, human factors engineering, human factors psychology, mechanical engineering, physics, and speech and hearing science. This team is focused on researching the fundamental underpinnings of human auditory perception of simple and complex sound (including speech) and the effects of noise to optimize the design of auditory interfaces, acoustic models, and communication technologies. The laboratory also hosts visiting scientists. National Research Council (NRC) post-doctoral fellows and laboratory personnel mentor and host undergraduate and graduate students in science and engineering. Additional collaborations are facilitated via educational partnership agreements, cooperative

Fig. 5. High Intensity Noise Emulation Facility, circa 2008.

research and development agreements with industry, international scientist and engineer exchange programs, and international data exchange and project agreements.

The group uses a variety of laboratories and equipment to conduct their programs of research and development. The major facilities include the Auditory Localization Facility, the Voice Communication Research and Evaluation System, the high intensity noise emulation facility, the Aeroacoustic Research Complex (ARC), advanced speech perception laboratory, and the Integrated Visualization Platform. The latter is unique in that part of it is located in the AFRL acoustics building and the other part is located at Wright State University, and enables advanced auditory interface development and assessment in distributed virtual environments. The Integrated Visualization Platform is owned and operated by Wright State University (WSU), and daytaOhio.

Auditory Localization Facility (ALF)—Fig. 4

- 4.26-meter-diameter geodesic sphere inside an anechoic chamber
- 277 loudspeakers
- Simulates complex real-world auditory environments
- Can present 16 sounds simultaneously from selected or all locations
- Research in spatial hearing and virtual auditory display technologies

High Intensity Noise Emulation Facility—Fig. 5

- Capable of generating broadband noise environments up to 142 dB SPL
- Supports development of advanced active noise reduction technologies
- Supports establishment of noise exposure criteria for intense noise fields
- Used to assess speech intelligibility in intense noise fields

Aeroacoustics Research Complex—Fig. 6

- Dedicated facility for acoustic measurements of fixed and rotary winged aircraft for determining the noise source characteristics in-flight
- 2 - 300 ft towers, 800 ft apart
- 56 - microphones and data acquisition channels
- 5 - meteorological systems
- Low ambient background noise (< 20dB SPL(A))
- Supports research on in-flight source noise, weather effects on noise propagation

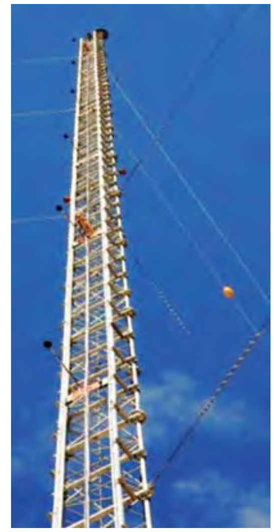

Fig. 6. Tower at the Aeroacoustic Research Complex (ARC).

Advanced Speech Perception Laboratory—Fig. 7

- Stimulus generation system capable of driving a reconfigurable array of up to 21 loudspeakers
- Up to 21 acoustic sources can be presented simultaneously
- Located inside an anechoic chamber with a low frequency cut-off at 150 Hz

- Designed to investigate advanced methods for improvement of speech intelligibility
- Research conducted in speech intelligibility, spatial hearing, and sound source localization

Integrated Visualization Platform (A WSU/daytaOhio Facility)—Fig. 8

- Multiple distributed immersive facilities depicting a common, synchronized virtual environment
- A 4-wall large-screen data wall at daytaOhio, a 4-wall immersive facility at Wright State University, and a 5-wall immersive facility located in AFRL's Battlespace Acoustic Branch
- Multimodal display systems including stereoscopic visualizations, 3-D audio and haptic/tactile displays
- Research platform designed for evaluating the effectiveness of advanced displays and technologies in operationally-relevant scenarios

Fig. 7. Advanced speech perception laboratory.

Bioacoustics

The AFRL acoustics group has a very strong commitment to basic research. The Air Force Office of Scientific Research gives special recognition to a top small percentage of the funded research teams. The bioacoustics group has been awarded "STAR Team" status from 2002-2011 (the award is normally made for a grant period of approximately 3 years and can be made at the beginning of a grant). The work is centered on the analysis and processing of complex acoustic scenes. This includes efforts in speech perception and spatial hearing in complex multi-source auditory environments and investigations of the relative effects of energetic and informational masking in such environments. Additional basic research focuses on the investigation of bone/tissue conducted noise and the relation between the perception of air conducted and bone/tissue conducted stimuli, in loudness judgment linearity, localization error, and temporary threshold shift.

The applied research program focuses on developing innovative technologies and procedures and transitioning them to field use. Frequently these products have application not only for Air Force use, but also for use by the Army, Navy,

Fig. 8. Integrated Visualization Platform—left: 4-wall large-screen data wall at daytaOhio, a 4-wall immersive facility at Wright State University, and a 5-wall immersive facility located in AFRL's Battlespace Acoustic Branch; middle: multimodal display systems including stereoscopic visualizations, 3-D audio and haptic/tactile displays; right: research platform designed for evaluating the effectiveness of advanced displays and technologies in operationally-relevant scenarios.

Fig. 9. F-35 Lightning II (Joint Strike Fighter), ground run-up noise measurement—left: the aircraft; right: the crew and some of the near-field sensors

Fig. 10. F-35 Lightning II, flyover noise measurement—clockwise from upper-left: the crew; flyover and tower sensors: ground sensors.

Marine Corps, and civilian sectors. Some examples of recent in-house and contract-developed technologies include the Attenuating Custom Communication Earpiece System (ACCES), high performance active noise reduction earplugs, helmets specifically designed to reduce bone conducted noise, tactical hearing protection (earplugs or earmuffs with active electronics to provide ambient listening, communication, and localization capabilities while protecting from continuous and impulsive noise—frequently also providing a radio communication interface), low-cost head orientation system, for dismounted airmen and soldiers, and spatial auditory symbology.

Recent work in ASA/ANSI standards include significant work on hearing protection standards S12.6, S12.42, S12.68, and on the speech intelligibility standard S3.2. Additional work has been accomplished in NATO Task Groups on impulse noise, active noise reduction, and improved hearing protection.

Physical acoustics

The efforts in physical acoustics are focused on the accurate measurement, modeling, and propagation of aircraft noise. The two major applications of the products from these efforts are community noise assessments and mission planning. Most recently an extensive program was conducted to measure F-35 Lightning II (Joint Strike Fighter) ground run-up near-field and far-field noise, flyover noise, and cockpit noise. The ground run-up, shown in Fig. 9, and flyover noise, shown in Fig. 10, data collection was conducted at Edwards Air Force Base in California. Recently, the Aeroacoustic Research Complex (ARC), Fig. 8, became operational and is being used to collect noise data on several aircraft. A collaborative effort between AFRL and NASA also uses the ARC for data collection and analysis.

The propagation modeling effort has recently focused on adding capabilities to accurately propagate directional sources and handle non-linear propagation. This effort, the Advanced Acoustic Model (AAM), was a collaboration among the Strategic Environmental Research and Development Program (SERDP), AFRL, US Navy, Wyle Laboratories, and Penn State University. Validation studies for AAM are currently being conducted using data from very far-field (1 to 7 miles) measurement locations. A second SERDP sponsored effort is refining the process to estimate noise from jet flow characteristics. This effort is a collaboration among SERDP, Penn State University, NASA Glenn, NASA Langley, Wyle Laboratories, General Electric Aircraft Engines, and AFRL. AFRL sponsors the development of many new technologies via Small Business Innovative Research (SBIR) contracts. One example is the

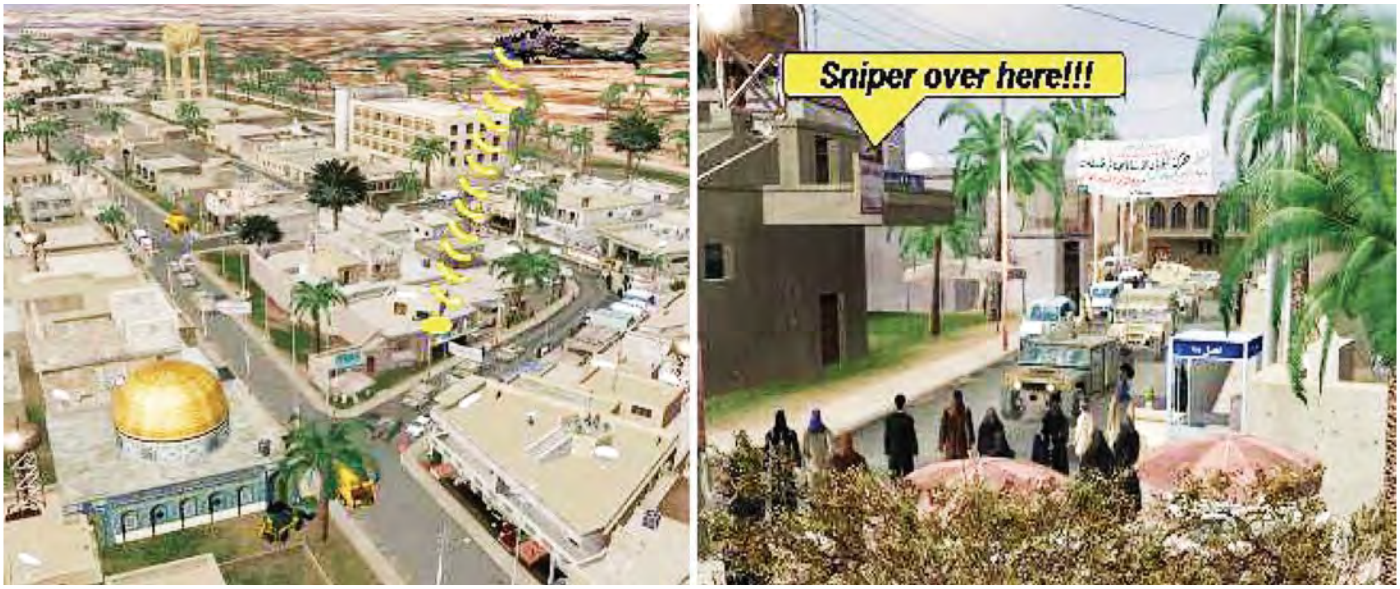

Fig. 11. Pictorial concept of application of audio annotation—left: helicopter sensing and transmission; right: sound annotation to the soundscape.

development of a near-field acoustic holography measurement and analysis technology. This technology will scan a full scale jet plume and provide the 3-D noise radiation profile. Applications include quantifying near-field noise exposure for maintenance personnel, identification of noise sources in the plume, and development and validation of jet noise reduction technologies. Another example of an AFRL SBIR contract effort is the development of techniques to capture, analyze, and re-synthesize 3-D soundscapes. The product of this effort will be used in investigating the effects of local soundscape on the community perception of noise from aircraft operations and in the mitigation or reduction of the perceived noise.

Emerging efforts

Future directions involve the integration of auditory technologies with future visual display systems for presenting large amounts of data for rapid and accurate decision making. Spatial auditory displays and enhanced communication will be applied in Unmanned Air Vehicle (UAV) operations and airborne and ground command and control. Investigation and leveraging of the interactions of cognition with auditory perception in decision making will also be addressed. Two focus areas are—(1) audio annotation where advanced audio displays are used for referencing critical events in simulated operational environments, a concept shown in Fig. 11 and (2) net-centric communications where the results of multi-talker speech perception research is exploited to improve the effectiveness of communications in a highly integrated multi-channel voice communication network environment. In physical acoustics, AFRL will investigate the interactions, modeling, and validation of weather and terrain with linear and non-linear propagation of directional sources. Additional standards work will focus on the establishment of new standards for fast Fourier transforms (FFT) analyzers, spatial audiometry, speech level measurement, and the measurement of impulsive noise for hearing damage risk assessment.

Summary

The AFRL acoustics research group is an exciting place to work on cutting edge projects in bioacoustics and physical acoustics with freedom to explore innovative solutions to complex problems. The acoustic research facilities are among the best in the world. The researchers are a group of excellent scientists and engineers developing new technologies protecting and enhancing the performance of military personnel. Many of the AFRL developed technologies have had significant application and use in the civilian sector.

AFRL has been a leader in the development of hearing conservation and hearing protection for over 60 years. AFRL researchers have pioneered the establishment of continuous noise exposure criteria and national and international standards for noise measurement, measurement of hearing protector performance, and speech communication.

Major technology developments and related scientific findings include: passive hearing protector technologies, hearing conservation programs, active noise reduction headsets, broadband sirens, acoustic fatigue, community noise mapping, studies of airbag noise, lateral attenuation of aircraft flyover noise, atmospheric modeling, infrasound, bone conduction, sonic boom measurement, human response to sonic booms, communication earplugs, speech communication in noise, hearing protector measurement standards, active noise reduction earplugs, 3-D audio display technologies, and an auditory artificial horizon for aircraft.**AT**

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