Session 4aPA

Physical Acoustics and Biomedical Acoustics: Session in Honor of David T. Blackstock I

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Chair's Introduction—8:00

Invited Papers

8:05

4aPA1. David T. Blackstock: Scholar, teacher, mentor, and gentleman. Mark F. Hamilton (Walker Dept. of Mech. Eng., The Univ. of Texas at Austin, 204 E Dean Keeton St., Austin, TX 78712, hamilton@mail.utexas.edu)

David T. Blackstock was born in Austin, Texas in 1930. After earning B.S. and M.S. degrees in physics at University of Texas at Austin he spent two years at Wright-Patterson Air Force Base, where he developed an interest in acoustics working under Henning von Gierke on hearing protection. He then joined F. V. Hunt's group at Harvard University and earned a Ph.D. in applied physics in 1960 with a doctoral thesis in nonlinear acoustics, ultimately his lifelong passion. Following three years at General Dynamics and seven years at University of Rochester, David returned to UT in 1970 to join its Applied Research Laboratories, and in 1987 he became Professor of Mechanical Engineering. Among David's legacies is his formulation of a convenient framework for implementing weak-shock theory. Combining analytical, computational, and experimental approaches, he proceeded to investigate acoustic saturation, finite-amplitude noise, suppression of sound by sound, parametric array in air, sonic boom, therapeutic ultrasound, and other fundamental problems in nonlinear acoustics. David was widely known as an exceptionally caring man, whether bringing Soviet scientists and their research to the attention of the West, teaching and mentoring graduate students, or through extensive service in the ASA and International Commission for Acoustics.

8:25

4aPA2. David T. Blackstock: Friend, husband, father. Stephen P. Blackstock (Appl. Res. Lab., Univ. of Texas at Austin, 10000 Burnet Rd., Austin, TX 78758, spb@arlut.utexas.edu)

David T. Blackstock, my father, was an exceptional and esteemed scholar, scientist, and teacher. He was an even more exceptional human being: a pillar of integrity, a kind and generous friend, a devoted husband, and a loving father. Like many in the audience, I learned so much from him. I have never understood how he had the energy to be so engaged in his research and teaching and, also, so attentive to his family. One of my older brother's childhood friends remarked, shortly after David's passing: "What made him so special was that he remained a good dad despite all the pressures of his professional life." In this talk, I'll explore this mystery, and I hope that, along the way, you'll get to know David Blackstock, the person, a little better. David taught many students how to be good scientists. He taught me how to be a good human being.

8:45

4aPA3. David Blackstock and the Applied Research Laboratories at The University of Texas at Austin (ARL:UT): Laying the Academic Foundation for an Applied Laboratory. Karl Fisher (Appl. Res. Labs., Univ. of Texas, 10000 Burnett Rd., Austin, TX 78758, kfisher@arlut.utexas.edu) and Clark Penrod (Appl. Res. Labs., Univ. of Texas, Austin, TX)

David T. Blackstock took a leave of absence from the University of Rochester in 1969 and returned to the University of Texas in his hometown of Austin. ARL:UT was extremely fortunate to have David accept a full-time appointment at the lab as a Faculty Research Scientist in 1970. Over the next fifty years, David nurtured and strengthened the bond between the academic and teaching environment on UT's main campus and the applied work conducted at ARL:UT. He helped establish coursework that has educated numerous ARL:UT staff members, many of whom had no prior knowledge of acoustics. David increased the recognition of ARL:UT's acoustic research by attracting internationally renowned scholars and by encouraging our staff to publish their work and take part in the ASA. David was a tireless mentor to our staff and students and created an enduring relationship between ARL:UT and the UT faculty. A truly fitting legacy left for a University Affiliated Research Center.

9:05

4aPA4. David Blackstock and the Acoustical Society of America: Sixty-five years of commitment. Marcia Isakson (Appl. Res. Labs., The Univ. of Texas at Austin, 10000 Burnett Rd., Austin, TX 78758, misakson@arlut.utexas.edu) and Elaine Moran (Acoust. Society of America, Melville, NY)

David Blackstock and the Acoustical Society of America (ASA) have had a long history together. David attended his first ASA meeting in 1955 and became a member in 1959. Throughout his career, the ASA provided David with a place to publish and form collaborations. David more than repaid the ASA with service as the chair of meetings, technical and administrative committee service and as the Society's vice president and president. In 1993, he was awarded the Gold Medal, the ASA's highest honor. However, David's true service to the ASA is to the student and early career members of the Society. David coordinated the Students Meet Members for Lunch (SMMfL) initiative from 2002 to 2019. This program has paired numerous students with members of the Society. David's students from the University of Texas at Austin, the University of Rochester and Pennsylvania State University have been recognized by the Society with numerous awards and medals. In 2004, David was also recognized with the first ASA student council award for mentorship. In 2019, the ASA student council officially recognized David's commitment to students by renaming the mentorship award after him. Because of David's commitment to the Society and its future, his ASA legacy will never be forgotten.

9:25

4aPA5. David Blackstock and the University of Rochester. Diane Dalecki (Univ. of Rochester, 210 Goergen Hall, P.O. Box 270168, Rochester, NY 14610, dalecki@bme.rochester.edu)

This presentation provides perspective on David T. Blackstock at the University of Rochester in Rochester, NY. Dr. Blackstock's interactions with the University of Rochester began early in his academic career. In the early 1960's, he was an associate professor in the Department of Electrical Engineering at the University of Rochester for several years. Beginning in 1970, he moved to The University of Texas at Austin for his long academic career with the Applied Research Laboratories and the Department of Mechanical Engineering. Then in 1987, enabled through collaborations with Dr. Edwin L. Carstensen, Dr. Blackstock returned to Rochester to spend his summers at the University of Rochester. That same year, he became a visiting member of the Rochester Center for Biomedical Ultrasound directed by Dr. Carstensen. Dr. Blackstock continued to spend summers at the University of Rochester for several decades. Summers with Dr. Blackstock were filled with engaging scientific discussions, research collaborations, and interactions with many students and faculty in various departments. During the summer, he regularly taught his Fundamentals of Acoustics course and, during select years, his Nonlinear Acoustics course. Dr. Blackstock's longtime engagement with the University of Rochester greatly impacted the careers and lives of many students and faculty.

9:45–10:00 Break

10:00

4aPA6. Early works of David Blackstock in nonlinear acoustics: A view from the former Soviet Union. Lev Ostrovsky (Appl. Mathematics, Univ. of Colorado, 1111 Eng. Dr., ECOT 225, Boulder, CO 80309, lev.ostrovsky@gmail.com)

This presentation outlines some moments in the development of modern nonlinear acoustics in the 1960s–1980s, in which Professor David Blackstock played a significant role. In those times of limited contacts between the American and Soviet scientific communities, David was the first to notice our works in the area. He initiated and supported our contacts, first by regular mail (no Internet at that time!) and then, when it became possible, by inviting us to the USA. Our areas of common interest included, among others, radiation and diffraction of nonlinear acoustic beams, horn antennas, and parametric arrays. A few examples of parallel developments in these areas will be described.

10:20

4aPA7. David Blackstock and the physics of nonlinear sound beams. Thomas G. Muir (Appl. Res. Labs, Univ. of Texas, P.O. Box 8029, Austin, TX 78713, muir@arlut.utexas.edu) and Mark F. Hamilton (Appl. Res. Labs, Univ. of Texas, Austin, TX)

In the 1970s, David Blackstock and his students and colleagues examined nonlinear sound beams both theoretically and experimentally. Two noteworthy articles in JASA resulted from this research, one by Shooter, Muir and Blackstock (1974) and another by Lockwood, Muir and Blackstock (1973). Of particular interest was the generation of highly directive radiation at harmonics of the source frequency that at moderate source levels decreased in beamwidth with harmonic order. Additional sidelobes were also observed in the harmonics. The main lobe in both the fundamental and the harmonics eventually broadened with increasing source level as shock waves

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were formed. Eventually finite-amplitude absorption became significant, acoustic saturation set in, and the medium did not permit further increase in amplitude. David's application of weak-shock theory to model this process was validated by underwater acoustic experiments at the Applied Research Laboratories Lake Travis Test Station involving transducers driven at high intensities, at several hundred kilohertz, with waveforms and beams measured at ranges of several hundred meters. The results provided guidance for many applications, ranging from audio frequency tools in ocean acoustics to ultrasonic biomedical instruments now used worldwide in diagnostic and therapeutic applications. [Work supported by ARL:UT.]

10:40

4aPA8. David Blackstock and the parametric array in air. Joseph Pompei (Holosonics, 400 Pleasant St., Watertown, MA 02472, fjpompei@holosonics.com) and Mark F. Hamilton (Appl. Res. Labs., The Univ. of Texas at Austin, Austin, TX)

In 1971, Peter Westervelt and David Blackstock attended a Navy meeting on underwater acoustics. Following mention of rumored failed attempts to create a parametric array in air, Peter offered reasons why it should not be expected to work in air. David, sitting nearby, said to him "Bulls**t Peter!," to which Peter responded "Alright, you prove it!" After returning to Austin, David proceeded to do just that with master's student Mary Beth Bennett, whose experiments resulted in their 1975 JASA paper "Parametric array in air." In the 1990s, Joseph Pompei, then a master's student and former engineer at Bose, became interested in the airborne parametric array. His vision was to use the technology to make a practical directional loudspeaker and enable new ways to control sound. Facing similar skepticism from the audio industry, Pompei responded with a doctoral dissertation demonstrating the first high performance, low distortion parametric loudspeaker. The main technical challenges he overcame were developing correct signal processing methods and creating an ultrasonic transducer and amplifier with adequate bandwidth, power and fidelity. Now commercially successful as the "Audio Spotlight" by Holosonics, it has proved successful in digital signage, museums, retail displays, libraries, and similar places that require well localized sound.

11:00

4aPA9. Propagation of plane acoustic noise of finite amplitude. Frederick M. Pestorius (Appl. Res. Labs., Univ. of Texas at Austin, 8102 West Court, Austin, TX 7759, fmpestorius@gmail.com)

I was Professor Blackstock's first doctoral student at the University of Texas. I arrived at Texas having been away from serious academic work for six years while serving on submarines. David took me under his guidance and proposed an investigation of the propagation in air of plane finite-amplitude noise waveforms. The work was both theoretical and experimental, and the results obtained were valid both before and after shock formation. Starting with David's formulation of weak shock theory, we included Kirchhoff tube wall attenuation and dispersion because the experimental work was done in a pipe. The 96-foot pipe possessed an anechoic termination to permit the study of traveling waves. The theoretical model is unique in that it combines the effects of nonlinear distortion as well as tube wall attenuation and dispersion, and it is valid for input waveforms of arbitrary shape. The model was implemented in FORTRAN code and uses FFTs, relatively new at the time, to alternate between the time and frequency domains at each step along the propagation path. We initially tried to solve this problem analytically, but that effort failed in a sea of algebra. Outstanding agreement with the measured waveforms was obtained.

11:20

4aPA10. Reflecting on David Blackstock's contributions to understanding nonlinear propagation of jet noise. Kent L. Gee (Dept. of Phys. and Astronomy, Brigham Young Univ., N281 ESC, Provo, UT 84602, kentgee@byu.edu)

In 2002, my Ph.D. advisor, Vic Sparrow, and I began to research a problem in physical acoustics that had been relatively untouched for many years: modeling the nonlinear propagation of noise from high-speed jets. Without a steady progression of recent research to rely on, and flummoxed by seemingly nonphysical approaches to the problem by others, I found myself revisiting papers and reports authored by David Blackstock and his students in the 1970s: Pestorius, Anderson, Webster, and others. Within these reports, I found both critical insights and direction. In this talk, I will review David's foundational contributions to nonlinear jet noise propagation and some meaningful interactions.

11:40–12:00
Open Mic

Session 4pPA

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Applied Research Labs, University of Texas, P.O. Box 8029, Austin, TX 78713

Chair's Introduction—1:30

Invited Papers

1:35

4pPA1. David T. Blackstock—An international perspective. Michael Vorlaender (IHTA, RWTH Aachen Univ., Kopernikusstr. 5, Aachen 52056, Germany, mvo@akustik.rwth-aachen.de)

The international acoustics community looks back with deep appreciation on the great lifetime achievement of David T. Blackstock. Always interested in international scientific exchange, he was especially involved in the International Commission for Acoustics (ICA) since the 1980s. Without his contributions to understanding across the Iron Curtain, we would not have such harmonious cooperation in acoustics today. This applies not only to the open and trusting cooperation at international conferences, but also to the establishment of firmly rooted support for individual researchers and students who have to work under difficult conditions. This paper looks at David Blackstock's involvement in the ICA, and describes the structures of international collaboration that he was instrumental in initiating.

1:55

4pPA2. David T. Blackstock and kidney stone lithotripsy. James A. McAteer (Dept. of Anatomy, Cell Biology, and Physiol., Indiana Univ. School of Medicine, Indianapolis, IN), Michael R. Bailey (Ctr. for Industrial and Medical Ultrasound, Appl. Phys. Lab, Univ. of Washington, 1013 NE 40th St., Seattle, WA 98105, bailey@apl.washington.edu), and Lawrence A. Crum (Ctr. for Industrial and Medical Ultrasound, Appl. Phys. Lab, Univ. of Washington, Bellievue, WA)

For the past 25 years, David Blackstock served as External Advisor to an NIH Program Project Grant (PPG) dedicated to improving shock wave lithotripsy (SWL) of kidney stones. Invented in the 1980s, SWL revolutionized stone management, eliminating the need for open surgery. As a truly noninvasive surgery, SWL remains the flagship of medical acoustic therapies. Study of its engineering, bioeffects, and physical mechanisms of action helped make SWL safer and more effective and led to new modalities of diagnostic and therapeutic ultrasound. Dr. Blackstock's role in this effort cannot be overstated. He was a regular participant in our series of in-depth, two-day, semiannual meetings where in addition to reviewing new data related to his areas of expertise in shock wave propagation and nonlinear acoustics he absorbed, dissected, and eloquently critiqued research in the broad array of fields (e.g., clinical urology, renal vascular physiology and pathology, fracture mechanics, and more) otherwise unrelated to his experience. Dr. Blackstock had the ability to learn on the spot and then add incisive, valuable suggestions based on his expertise, intuition, and critical thinking. He kept us focused. He elevated our thinking. He stimulated our creativity and encouraged us toward new ideas. Work supported by NIH-P01-DK043881.

2:15

4pPA3. David Blackstock: Distortion of shock waves and breaking of kidney stones. Robin O. Cleveland (Eng. Sci., Univ. of Oxford, Old Rd. Campus Res. Bldg., Oxford OX3 7DQ, United Kingdom, robin.cleveland@eng.ox.ac.uk)

This talk will discuss how the seminal work that David Blackstock carried out in nonlinear acoustics for underwater and atmospheric applications contributed to the understanding of the medical use of shock waves for breaking of kidney stones. David's expertise lead to him acting as an external advisor for two decades to a NIH funded programme in shock wave lithotripsy; that contribution will be covered elsewhere in the session. I will present the weak shock theory that describes how nonlinear pulses distort when undergoing geometrical spreading. The theory will then be applied to the first clinically approved lithotripter, that employed a spark to generate a shock wave and an ellipsoidal reflector to focus that into the body. Inside the reflector the shock wave undergoes spherical spreading, reflection and then spherical convergence. It will be shown that nonlinear distortion inside the reflector results in variations in phase and amplitude across the mouth of the reflector which then impact the focusing of the shock wave onto a kidney stone. I will reflect on David's role as a Ph.D. supervisor and his mentorship of acousticians young and old.

2:35

4pPA4. Bridging shock: Blackstock's general solution for propagation of finite-amplitude sound waves. Kenneth G. Foote (Woods Hole Oceanographic Inst., 98 Water St., Woods Hole, MA 02543, kfoote@whoi.edu), Allan D. Pierce (Retired, East Sandwich, MA), and Mark F. Hamilton (Walker Dept. of Mech. Eng., The Univ. of Texas at Austin, Austin, TX)

Reflections are offered on D. T. Blackstock ["Connection between the Fay and Fubini solutions for plane sound waves of finite amplitude," *J. Acoust. Soc. Am.* **39**, 1019–1026 (1966)]. This work treats the propagation of planar finite-amplitude sound waves. It nominally links the Fourier-series-based solution of Fubini for the pre-shock condition, and the distant, post-shock solution of Fay. However, addressing the transition region between these two required solving the entire problem, which Blackstock did with aplomb. This additionally enabled specification of undetermined factors in the Fay solution, statement of an explicit bound on the applicability of the solution, and generalization to cylindrical and spherical waves. Hallmarks of Blackstock's work are evident: scholarly mindfulness of historical precedent, meticulous analysis that inevitably advanced understanding of nonlinear acoustic phenomena, and elegance in presentation, which was, moreover, pedagogically convincing.

2:55

4pPA5. How graduate work with David T. Blackstock led to a lifelong obsession with wave equations. Thomas L. Szabo (Biomedical Eng., Boston Univ., 44 Cummington Mall, Boston, MA 02215, tlszabo@bu.edu)

As one of David T. Blackstock's first graduate students at the University of Rochester (1966), I quickly admired his elegant style of normalizing and solving equations and was baffled by his frequent allusions to great acousticians and mathematicians of the past. Shortly after my arrival, he submitted his transient solution to the viscous wave equation to J.A.S.A. We planned a summer research project (1967) to validate his solution experimentally. He also introduced me to advanced methods for solving equations. David told me there was no general transient solution to this equation, which inspired my determination to solve it. My data confirmed his predictions leading to my first published paper. I left Rochester with an M.S. and afterwards, I filled several notebooks with unsuccessful equations. Eventually, after ten years in ultrasound imaging, I chose the University of Bath for its excellent PhD program in nonlinear acoustics. David visited me there in 1990 and we discussed his 1985 general solution to the Burgers equation. Later at Bath, twenty-three years after beginning, aha moments led me to more general and causal solutions to both linear and nonlinear viscous wave equations for frequency power law media and papers, cited a thousand times.

3:15–3:30 Break

3:30

4pPA6. David Blackstock and the experimental explanation of the spikes on sonic boom waveforms. Allan D. Pierce (Retired, PO Box 339, 399 Quaker Meeting House Rd., East Sandwich, MA 02537, allanpierce@verizon.net)

The present paper discusses an extremely clever experiment perforrmed by David Blackstork and his student Bruce Davy at Rochester in the early 1970s. In the late 1960s people were puzzled by some anomalous features in the measured waveforms of sonic booms recorded at the ground during flyovers of supersonic aircraft. The waveforms were supposed to look like the letter N, but that was not always the case. Sometimes there were strange upward reaching spikes just behind the leading and trailing shocks and in other instances the wavefront was rounded. There were a lot of explanations kicking around, and the present author and David Blackstock came up with the idea that it was somehow caused by imperfect focusing of wavefonts after traveling through regions of higher sound velocity. During our discussions, Blackstock came up with the remark, ''Let's talk experiment.'' What resulted was an experiment that would have been worthy of Lord Rayleigh. The paper that reported this, titled ''Measurements of the Refraction and Diffraction of a Short *N*-Wave by a Gas-Filled Soap Bubble,''appeared in *J. Acoust. Soc. Am.* in March 1971. Besides really nailing down the physical phenomena responsible for the spikes on sonic boom waveforms, it illustrated a wealth of physical concepts and experimental techniques. The present talk discusses the background of the paper, the physics that it used, and the influence it had on subsequent research.

3:50

4pPA7. From laboratory-scaled experiments to numerical predictions of sonic boom level variability due to atmospheric turbulence. Philippe Blanc-Benon (CNRS, LMFA UMR 5509 CNRS Ecole Centrale Lyon, 36 Ave. Guy de Collongue, Ecully 69134, France, philippe.blanc-benon@ec-lyon.fr)

Supersonic flights of aircraft through the atmosphere create shock waves called "sonic booms." Atmospheric turbulence affects the perceived loudness of sound at the ground level, mainly by changing its amplitude and rise time, which are significant factors in determining the acceptability of supersonic flight. Some authors compared theoretical predictions of sonic boom distortion to sonic boom recordings, but such analyses are limited because the parameters of turbulence cannot be measured accurately enough to allow detailed quantitative comparisons. In the 1990s David Blackstock showed that laboratory scaled experiments using N-waves produced by electrical sparks and a downscaled atmosphere offer an attractive alternative to field measurements since both the acoustic source and the turbulence can be controlled (Lipkens and Blackstock, JASA 1998, Lipkens and Blanc-Benon, CRAcadSci Paris 1995). Following this research, we developed at Ecole Centrale de Lyon two experimental setups to study separately the influence of temperature or random velocity fluctuations on the waveform distortion in relation to the occurrence of random caustics at large distances of propagation (Blanc-Benon, Lipkens, Dallois, Hamilton, and Blackstock, JASA 2002). The aim of this paper is to present recent experimental results obtained using optical interferometry and numerical predictions based on the nonlinear KZK propagation equation.

4:10

4pPA8. David Blackstock and the reflection and refraction of finite amplitude waves. Victor W. Sparrow (Penn State, 201 Appl. Sci. Bldg., University Park, PA 16802, vws1@psu.edu)

In honor of David Blackstock, this presentation recalls his contributions regarding nonlinear acoustics in the areas of reflection and refraction. Some of this is well documented and other pieces are not. For example, in his 1960 Ph.D. dissertation David was the first to recognize Pfriem's pressure amplification equation would apply to finite amplitude plane-wave reflection from a rigid surface. Acoustic pressure MORE than doubles for finite amplitude rigid surface reflection, and it is the variational sound speed that exactly doubles. And this result provides a basis for an understanding of oblique reflection and the formation of finite amplitude Mach stems. Further, the work of David's Ph.D. student Frederick Cotaras on finite amplitude refraction from 1989 will be highlighted in addition to other contributions as time permits.

4:30

4pPA9. David T. Blackstock's *Fundamentals of Physical Acoustics.* Won-Suk Ohm (School of Mech. Eng., Yonsei Univ., 50 Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea, ohm@yonsei.ac.kr)

One can hardly imagine that a book, written on a subject as complicated as physical acoustics, could serve as both an introductory text for beginning students and a serious reference for experts. *Fundamentals of Physical Acoustics* by David T. Blackstock is one such book. Nearly 40 years in the making, the book has its roots in the class notes that Blackstock had written for courses on acoustics throughout his academic career. Sitting in his Acoustics I course as a first-year graduate student at University of Texas at Austin in 1994, I was (gratefully in retrospect) one of those many guinea pigs whom Professor Blackstock tested his manuscript on. What came out of this long and arduous journey is a book that is not only battle tested and combat proven, but also praised nowadays as a modern classic in physical acoustics literature. In this talk, I share my experience with this book, now as a professor who has used the book for graduate-level acoustics courses for the last 14 years. Its pedagogical philosophy, unique structure, real-world drawn problems, adaptability to a MOOC (massive open online course), and last but not least, his lucid and elegant writing style will be highlighted.

4:50–5:10
Open Mic