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NONLINEAR ACOUSTICS: PROPAGATION IN A PERIODIC WAVEGUIDE AND SCATTERING OF SOUND BY SOUND

SECOND ANNUAL SUMMARY REPORT UNDER CONTRACT N00014-89-J-1109

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APPLIED RESEARCH LABORATORIES
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Research on nonlinear acoustics during the 12-month period ending 30 September 1990 is described. The two primary projects are (A) propagation in a periodic waveguide and (B) scattering of sound by sound. Project (A) is a combined theoretical and experimental study of acoustic Bloch waves in a rectangular, air-filled waveguide that is periodically loaded with reactive branch elements. A small-signal study of the system was done the previous year. This year second harmonic distortion was investigated. A quasilinear solution of the generalized Westervelt equation, with certain terms neglected, showed that although the fundamental Bloch wave is progressive, the second harmonic Bloch wave has both forward traveling and backward traveling components. Experimental measurements generally confirmed the theoretical predictions. In project (B) an analytical study was completed of the effect of various source boundary conditions on the scattered field. The project is mainly experimental, however. The tank facility (located in the Mechanical

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19. Engineering Department), where the experiments on scattering will be carried out, was completed. A series of three different experiments is planned. Besides the progress on Projects (A) and (B), some work was also done on (C) an upgrade of the Nonlinear Acoustics Laboratory, and (D) measurements of ellipsoidal focusing of spark-produced N waves.

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1. INTRODUCTION

The research carried out under Grant N00014-89-J-1109, which began 1 October 1988 and is the successor to Contract N00014-84-K-0574, is primarily in the field of nonlinear acoustics. The broad goal is to determine the laws of behavior of finite-amplitude sound waves, especially to find generalizations of the known laws of linear acoustics. This report is the second annual report under the Grant and covers the 12-month period ending 30 September 1990. The previous report (first annual report[1]) is referred to herein as 89-6.*

The following persons participated in the research:

Graduate students

C. E. Bradley, M.S. student in Mechanical Engineering

J. A. Ten Cate, Ph.D. student in Mechanical Engineering

Undergraduate student

M. J. Van Doren, senior in Mechanical Engineering

Senior personnel

M. F. Hamilton,† Mechanical Engineering Department, The University of Texas at Austin

J. Naze Tjøtta,‡ Research Fellow, on leave from Mathematics Institute, University of Bergen, Norway

W. M. Wright, Consultant, Physics Department, Kalamazoo College, Michigan

D. T. Blackstock, principal investigator

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*Numbers given in this style refer to items in the Chronological Bibliography given at the end of this report, e.g., 89-6 means the sixth entry in the list for 1989.

†Hamilton received no direct support from the Grant. However, he is co-supervisor of Ten Cate's Ph.D. research, which is described in Project B below.

‡Although Naze Tjøtta received no direct support from the Grant, she provided supervision for the theoretical portion of Ten Cate's Ph.D. research, which is described in Project B below.

2. PROJECTS

The following projects were active during the report period:

A. Propagation in a Periodic Waveguide

B. Scattering of Sound by Sound

C. Laboratory Upgrade

D. Miscellaneous

Primary effort was devoted to Projects A and B.

2.1 Propagation in a Periodic Waveguide

This is Bradley's project. Reported last year were theoretical and experimental results for acoustic Bloch wave propagation in a rectangular waveguide loaded with rigidly terminated side branches (see Sec. 2.2 in 89-6). Finite-amplitude as well as small-signal waves were investigated. The primary finding for small-signal waves was that the previously derived dispersion relation (Eq. 2.1 in 89-6) showed very good agreement with Bradley's measurements of attenuation and dispersion. Predictions from the nonlinear theory, which was based on Korpel's progressive spectral wave equation,[2] showed good *qualitative* agreement with some early measurements of the second harmonic behavior, but poor *quantitative* agreement (89-4). One of the problems was that the theoretical predictions failed to explain the strong second harmonic signal that was measured very close to the source (it was determined that the source itself was not to blame). A desire to improve the theoretical model led to this year's work, which began with a reexamination of the linear theory. The result was a better understanding of the structure of linear Bloch waves in a periodic waveguide and, in turn, the development of a more successful nonlinear theory.

The review of the linear theory proved to be quite illuminating. The detailed structure of Bloch waves was worked out and a new expression of the Bloch wave function, referred to here as the convolution expression, was derived. Bloch wave functions can be expressed in a variety of ways, but the convolution expression aids qualitative understanding of the structure of the Bloch wave and is ideally suited to the nonlinear analysis. Let h be the (spatial) period of the structure, and let $\psi(z)$ represent the pressure wave function in a single cell $-h/2 < z < h/2$ of the structure. It is found that the Bloch wave function $p(z)$ for the complete structure is expressed as the convolution of $\psi(z)$ with a phase weighted lattice function,

$$p(z) = \psi(z) * \sum_{n=-\infty}^{+\infty} \delta(z - nh) e^{jqnh}, \tag{2.1}$$

where q is the wave number of the Bloch wave. The convolution of the cell wave function with each delta function in the lattice simply places an appropriately phased copy of the cell wave function in every other cell of the structure. The cell wave function itself is composed of a forward traveling or f wave and a backward traveling or g wave:

$$\psi(z) = \begin{cases} 0 & z < -h/2, z > h/2 \\ fe^{jkz} + ge^{-jkz} & |z| < h/2. \end{cases} \tag{2.2}$$

Equation 2.1 shows the Bloch wave function to be a string of identical but delayed copies of the compound wave field that exists in a single cell.

The Bloch wave function is completely determined by q and g/f. While q is found from the previously derived and experimentally verified dispersion relation (Eq. 2.1 in 89-6), g/f, the relative amplitude (and phase) of the f and g waves, is found in terms of impedances:

$$g/f = \frac{Z_{Ba} - Z_{oa}}{Z_{Ba} + Z_{oa}}.$$

Here Z_{Ba} and Z_{oa} are the acoustic impedances of the waveguide with and without the side branches, respectively. Note that Z_{Ba} depends upon frequency and various waveguide dimensions. The acoustic pressure field measured at two points in a cell provided sufficient information to find g/f. Figure 2.1 shows that the theoretical and experimental results are in excellent agreement.

Next consider the nonlinear case. Because the Bloch wave function is composed of compound wave fields, our use last year of Korpel's progressive wave equation as the model equation for finite amplitude Bloch waves was not really appropriate. We therefore shifted this year to the generalized Westervelt equation,[4] which is valid for compound flow. A quasilinear analysis was employed in which the fundamental field is represented by its convolution expression. The solution of the equation for the second harmonic, found by using a discrete Green's function, is as follows:

$$p_2(z) = G_o(z) * \sum_{n=-\infty}^{+\infty} \delta(z - nh) e^{2jnq_1h}, \tag{2.3}$$

where q_1 is the Bloch wave number for the fundamental. The function $G_o(z)$ is the second harmonic response due to the presence of the fundamental field in a single cell,

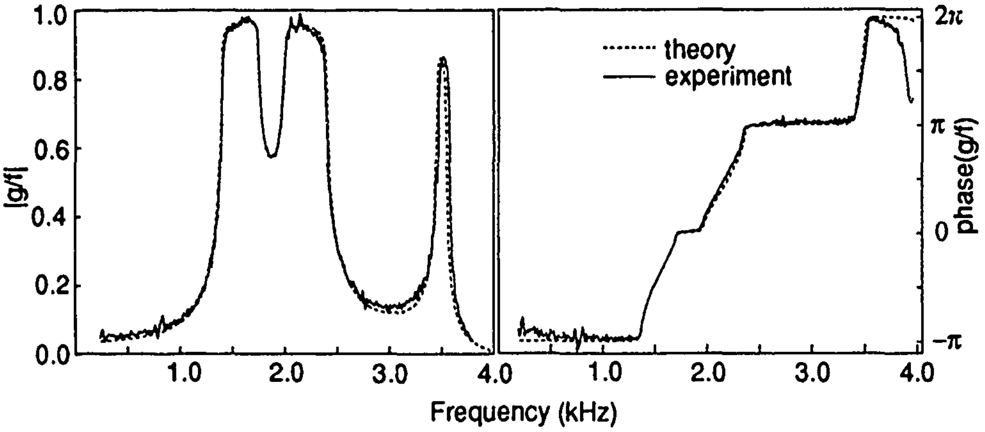

FIGURE 2.1
The magnitude and phase of $\dot{g}/f$.

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i.e., the response due to $\psi(z)$, and is composed of both forward *and* backward traveling Bloch wave components. The excitation of *bidirectional* second harmonic Bloch waves by the fundamental Bloch wave accounts for the large on-source second harmonic level that was measured last year. The present theory is thus an improvement over the progressive wave theory.

A model incorporating the effects of truncation of the periodic waveguide and second harmonic generation in the source region was developed, and an analytical, closed form result was found (the series in Eq. 2.3 can be summed). The functional form of $G_o(z)$ was derived by assuming that the locally generated second harmonic due to nonlinear interaction of the fundamental f and g waves is negligible. A comparison of the theoretical result and a measurement is shown in Fig. 2.2. The agreement is seen to be fairly reasonable (90-3, 90-8).

Bradley's work seems to be the first that has ever been done on nonlinear acoustical Bloch waves. The only other research of which we are aware on nonlinear Bloch waves is in nonlinear optics^5 and is generally for the case of small dispersion. Dispersion is definitely not small for the Bloch waves in Bradley's system.

2.2 Scattering of Sound by Sound

The purpose of this project, which is Ten Cate's Ph.D. topic, is to perform an experimental check of the Tjøtta's predictions concerning scattering of sound by sound. This year Ten Cate concentrated on getting the new tank facility in the Department

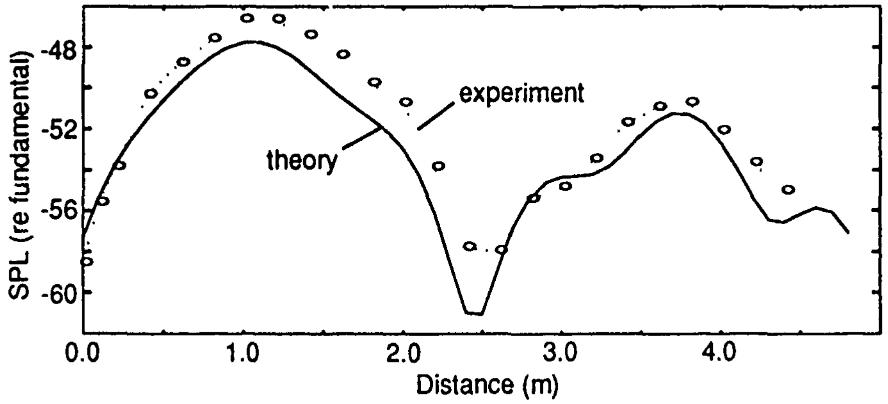

FIGURE 2.2

Amplitude of the second harmonic Bloch wave as a function of distance. Fundamental Bloch wave frequency is 680 Hz and source level is 133 dB.

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of Mechanical Engineering (see Sec. 2.3 in 89-6) ready for measurements. However, together with the Tjøttas, he also submitted a paper, which is a complete account of some earlier reports (89–8, 89–9), to *J. Acoust. Soc. Am.* (90–8).

The paper with the Tjøttas, "Effects of boundary conditions on the nonlinear interaction of sound beams," has relevance to Ten Cate's upcoming scattering of sound by sound measurements. In practically all treatments of radiation and propagation of finite-amplitude waves, the second order field is presumed to be zero at the source(s) of the primary field(s).[4] The theoretical and numerical work in the present paper shows that the actual (nonzero) boundary conditions on the second order field have effects that are *not* negligible. Figure 2.3 shows computed sum (top) and difference (bottom) frequency fields for an interaction that results in the scattering of sound by sound. The geometry of the transducers and the crossed beams they generate is shown by the insert in the center of the figure. The boundary conditions in question are those assumed on the horizontal dashed line, which represents the plane of the sources. The dash-dash-dot patterns that peak at 45° (top left and lower right) represent the classical product directivity. The separate curves shown in the insets show the effects of different boundary conditions imposed on the second order field. The four boundary conditions are as follows: (1) rigid wall, (2) rigid wall with source motion included, (3) pressure release wall, and (4) pressure release wall with source motion included.* The results show that (1) it is mostly the scattered sound that is affected by changing the boundary conditions, and (2) the difference caused by

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*The fifth curve is for a nonphysical boundary condition, included in order to reference previous work.[6]

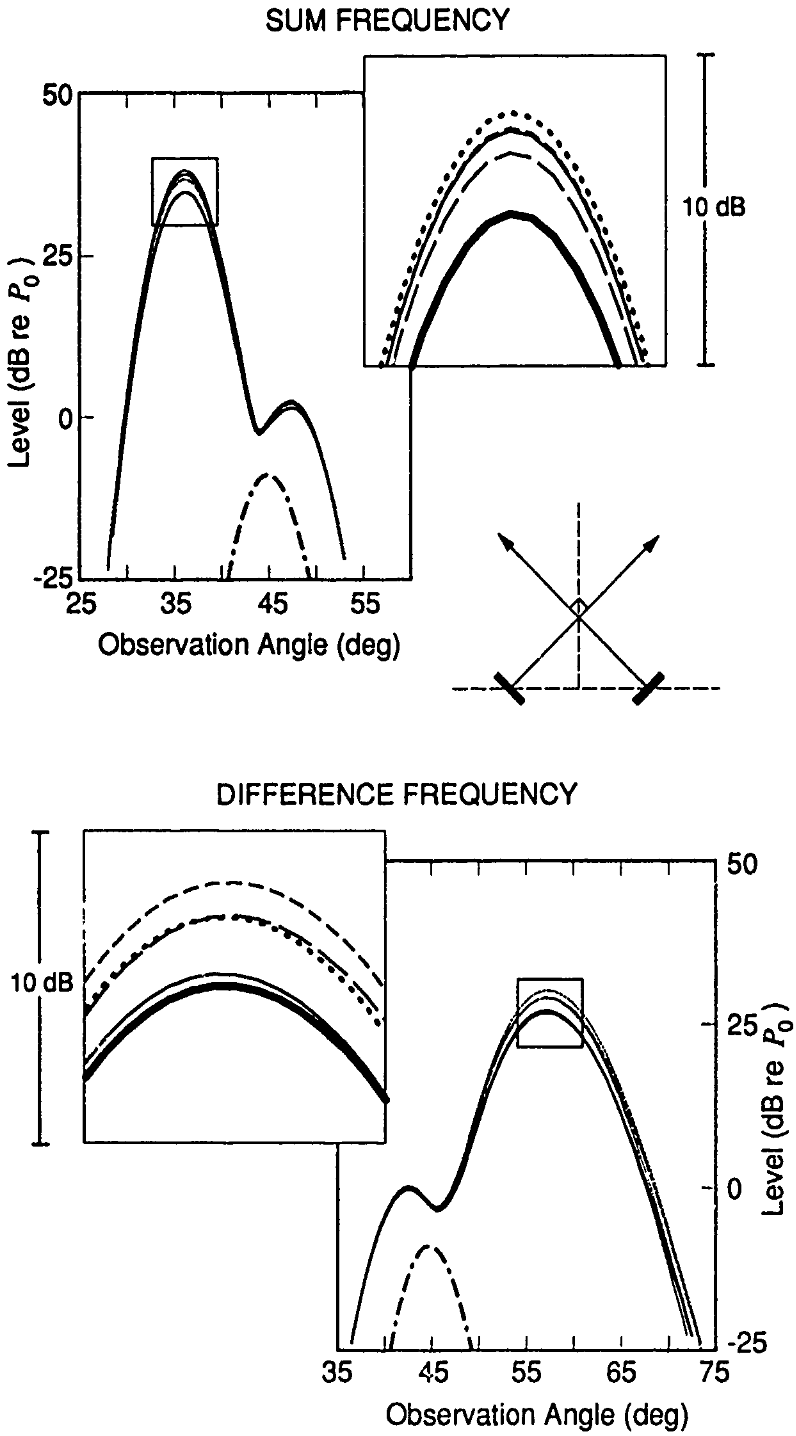

FIGURE 2.3
Beam patterns of scattered sound for various source boundary conditions.

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varying the boundary conditions seems to be, at most, 5 to 6 dB. Also discussed in the paper is the relevance of boundary conditions to second harmonic generation and to parametric receiving and transmitting arrays.

The rest of Ten Cate's time was spent with the new tank facility in the Mechanical Engineering Department. The custom, computer-controlled positioning system was assembled and put in place over the tank. The receive system includes computer-controlled x, y, z (vertical), and θ (about z axis) movement. The system is closed loop (with feedback to hold desired position). The transmit system includes a completely manual control but with computer readout of position.

Although the positioning system was mostly complete when received, some work was required to make it usable. Two types of receiver PVDF hydrophones will be utilized, needle type and membrane type. Some machining had to be done. The membrane hydrophones required a somewhat specialized mount to provide some tilt capability. The ultrasonic sources required individually machined holders. The motor drives, power sources, and associated equipment had to be rack mounted and the entire system checked out. Connecting and interfacing the Macintosh II to the motor controller, Berkeley Axis Machine or BAM, took some time as well. The BAM is a computer itself and its programming language had to be learned. Work is currently being done to make the software package LabVIEW communicate with the BAM and other instruments that will be used in the experiments.

Ten Cate also spent considerable time "tuning" the motion of each of the axes after everything was assembled and functioning. He aimed for repeatability on the order of 100 μm. Repeatability is a measure of how close one can return to a given position. For reference, the PVDF membrane hydrophone used in the tank has a thickness of 25 μm. Electronic damping and stiffness are added to each axis for the best motion profile, given the mass of the sources and the system parts being moved. Unfortunately, the method for arriving at the correct damping and stiffness is essentially one of trial and error. Ideally, one desires smooth motion that produces quick and accurate arrival at a chosen position.

It is expected that the actual experiments will be well under way before the end of the present report period. Preliminary qualitative experiments are just now being started. Three types of experiments are planned: (1) reexamination of second harmonic generation from a circular piston source, (2) examination of the effects of pulse length on a Gaussian source, and (3) measurement of the scattering of sound by sound.

2.3 Laboratory Upgrade

The first goal in the upgrade of our Nonlinear Acoustics Laboratory was to assemble a basic computer controllable data acquisition system. This task was completed last year (see Sec. 2.5 in 89-6). The heart of the system is a realtime digitizer (Tektronix RTD 710A), an arbitrary function generator (Wavetek model 275), software to acquire, process, and display data (National Instruments LabVIEW), and a general purpose interface bus (GPIB). The last two items enable our Macintosh II computer to exercise control over the instruments. This year we added important components to the system: a bandpass filter (Krohn Hite model 3202), an audio power amplifier (Hafler Pro 500), and a high voltage dc power supply (Glassman EH20P). Two more items, a powerful spectrum analyzer (Hewlett Packard 35660A) and an A-D/D-A board (National Instruments NB-M10-16XH-42), will be purchased by the end of the report period. The A-D/D-A board, to be added to the Mac II, will increase the dynamic range of the entire system to 96 dB and perform certain other operations. Not all of the instruments are used in every experiment, of course. For example, the high voltage supply is intended only for our investigations with sparks. Each instrument is, however, capable of being an integral part of any given computer-controlled measurement.

We also began the development of a small water tank facility for experiments in the megahertz frequency range. This facility is not intended to compete with the larger, more elaborate, and high precision tank facility recently constructed in the Mechanical Engineering Department on the main campus of the University (see Sec. 2.3 in 89-6). Since the small tank will be located at ARL:UT, it will provide us a more convenient means with which to carry out small-scale experiments with high frequency beams on such topics as reflection and transmission at an interface. (It will be recalled that Cotaras's study of reflection and transmission was limited to theoretical calculations, largely because an airborne experiment proved too difficult; see Sec. 2.1 in 89-6.)

The tank itself has been constructed. Designed and built of 1/2″ lucite by Van Doren, it has external dimensions 23.5″ x 12.5″ x 12.2″. Three threaded holes are provided for side or bottom mounting of transducers or spark sources. A spark source has also been constructed,* and a PVDF needle hydrophone has been purchased.

The proposal for a continuation of the grant includes plans for equipping the tank with hydrophone positioning apparatus and necessary electronics for sending and receiving signals. It is hoped that the positioning apparatus can also be used for positioning a microphone in our airborne experiments with sparks. Initially we

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*Funds for building the spark source came from NIH. The tank may also be used for some experiments relevant to medical ultrasonics.

had expected to obtain the positioning apparatus during the present year (see Sec. 2.5 in 89-6), but a one-year postponement became attractive when we learned that a highly skilled person, Youseph Yazdi, will be joining our group as a graduate student in September 1990. Yazdi has had a great deal of experience in designing and using tanks of this sort, and his expertise should be invaluable in completing the facility next year.

2.4 Miscellaneous

The project on ellipsoidal focusing (see Sec. 2.4 in 89-6) continued at a very slow pace because of lack of a student this year. Our consultant, Wayne M. Wright, spent some time rebuilding the microphone preamplifier, which had fallen on hard times, and improving on some of the measurements reported last year (89-2, 89-3). He will complete the draft of a journal article on the ellipsoidal focusing measurements before the end of the present report period.

Other activities included presenting papers on evanescent waves (90-1), laboratory demonstrations in nonlinear acoustics (90-2), absorption of finite-amplitude sound (90-6), and finite-amplitude waves in porous material (90-7).

3. SUMMARY

During the current report period, 1 October 1989 - 30 September 1990, we have been occupied primarily with two projects, (A) propagation in a periodic waveguide, and (B) scattering of sound by sound. Work has also been done on (C) upgrade of the Nonlinear Acoustics Laboratory and (D) some miscellaneous items. Project (A) is a combined theoretical and experimental study of acoustical Bloch waves in a rectangular, air-filled waveguide that is periodically loaded with reactive branch elements. Although a small-signal study of this system had been completed the previous year, discrepancies between theory and experiment for finite-amplitude waves prompted a review of the linear theory. The review led to a new theoretical expression for the nonlinearly generated second harmonic Bloch wave. The theoretical prediction is now in better agreement with our measurements. Project (B), although mainly experimental, produced a journal article this year on the effect of various source boundary conditions on the scattered field. The Mechanical Engineering Department tank facility, where the experiments on scattering will be carried out, has been completed. A series of three different experiments is planned to begin before the end of the present report period. The main goal of Project (C), to make possible a variety of computer-controlled experiments, was achieved last year. Additional equipment was purchased this year to expand the scope of the experiments that can be done. Work was also begun on a small water tank for experiments in the megahertz frequency range. Miscellaneous items under Project (D) include work on ellipsoidal focusing and presentation of various papers.

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and
Predecessor Contract N00014-84-K-0574 (ended 9-30-88)

Code

B = chapter in a book
J = journal publication
JS = submitted for journal publication
O = oral presentation
P = paper in a proceedings
T = thesis or dissertation
TR = technical report

ONR Grant/Contract

1109 = N00014-89-J-1109, began 10-1-88
0574 = N00014-84-K-0574, ended 12-31-88
0867 = N00014-75-C-0867 ended 8-31-84

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[a] Hamilton's support for this work came from Contract N00014-85-K-0708.

[b] Primary support for this work came from University of Rochester, NIH Grant CA 39241.

[c] Partial support for this work came from a grant from Bureau of Engineering Research, College of Engineering, The University of Texas at Austin.

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[§] Although no specific grant or contract can be cited, it is appropriate to acknowledge ONR because its support of research in physical acoustics at U. T. Austin has played an important role in the development of the University's graduate acoustics program.

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[d] Primary support for this work came from Applied Research Laboratories IR&D program and Texas Advanced Research Program.

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[e] Partial support for this work came from Applied Research Laboratories IR&D program.

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