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**Acoustic Scattering Processes for Target Discrimination**

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**I. Summary:** Objectives of this project include improving the understanding of acoustical scattering by objects near interfaces and related approaches for identifying signal features associated target responses. This project extends research examining the properties of scattering by targets at (or breaking through) a free surface at the top of a tank of water or partially buried in sand and targets illuminated by evanescent waves in fluids or by acoustic beams and scattering by objects in waveguides. The research also examines aspects of target responses (including low-frequency responses) to acoustic radiation forces of high-frequency sound or with other excitation methods. Aspects of the research involve the laboratory-based application and/or testing of synthetic aperture sonar (SAS) imaging methods. Sometimes we use synthetic data to produce SAS images and test imaging algorithms. This research will aid the understanding of how surfaces adjacent to targets alters their sonar images and responses and help in the development of methods for discriminating between natural acoustic clutter and man-made objects of interest. Thus this research is relevant to improving the use of acoustic scattering for object identification and improving naval capabilities with alternative modes of data acquisition.

**II. Introduction and Organization of this Report:** The majority of resources were used to support the activities of graduate students. The simplest way of summarizing the research was to compile in sequence edited versions of the Annual Reports submitted to ONR in 2016, 2017, 2018, and 2019. (Note, however, because of the depletion of grant funds the work in the report in 2019 was supported partially by a different ONR grant.) In this Final Report these edited Annual Reports are followed by information on three Ph.D. dissertations primarily funded by this grant.

**III. Annual Reports:** Note: Editing includes the removal of redundant or obsolete information.

## **Acoustic Scattering Processes for Target Discrimination (2016)**

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### **OBJECTIVES**

The objective of these grants is to improve the understanding and applications of acoustic scattering processes relevant to man-made objects in the shallow water environment. The current emphasis is on the interpretation of the effects on signatures of placing objects close to an interface. Synthetic aperture sonar, acoustic holographic images, spectral properties of scattering, and bistatic scattering are also examined. Other objectives involve improved understanding and modeling of scattering mechanisms including the applications of acoustic radiation force and other selective way of exciting oscillations of objects in water. Some prior work is reviewed in [1].

### **APPROACH**

The emphasis during FY16 was on laboratory-based experiments and on the documentation of prior experiments [2, 3, 4, 5]. The available facilities at Washington State University (WSU) include water tanks of various sizes and a special facility for generating evanescent acoustic wave-fields in water [6]. We have also gained insight from a prior investigation of gradient-enhanced coupling to target modes using an acoustic gradient produced by reflection of an acoustic wave off of a free surface. Experiments at WSU on modulated radiation force coupling were also partially supported by this grant.

The following graduated students were supported entirely or in part during FY16: V. Bollen (imaging and selected aspects of target physics); A. Gunderson (coupling to partially exposed targets and multipath issues, experiments with targets near a free surface or in sand and modeling of target physics); T. Daniel (target-physics experiments and modeling and radiation force and torque); and A. Fortuner (radiation force and torque experiments and set-up and modeling of other experiments).

During FY16 the following former WSU graduate students also contributed to this effort but without support from ONR grants to WSU during FY16: D. Plotnick (APL-UW) and L. Zhang (Univ. of Texas at Austin, now on the faculty of Univ. of Miss.). Aspects of the investigation of acoustic radiation force involved A. Abawi (HLS) and I. Kirsteins (NUWC).

## WORK COMPLETED

During the FY16 Plotnick submitted three manuscripts [2,3,4] based on his prior thesis work at WSU [5], and all three were published after review. Marston and Zhang submitted three manuscripts [7,8,9] related to radiation forces and torques and all of those have been published after review. One of those manuscripts [7] corrects a serious misconception that had been published by a different researcher [10] concerning the scattering of sound by viscoelastic objects in water. Gunderson submitted a manuscript related to his thesis research [11].

## RESULTS

(1) Multiple scattering effects in quasi-holographic monostatic SAS images: Plotnick's short EUSAR publication examines the cause of spurious image structure associated with multiple scattering from adjacent cylinders [2]. Previously related spurious images were reported and explained in quasi-holographic bistatic SAS images generated at WSU [12].

(2) CSAS imaging of vertically-oblique circular cylinders adjacent to flat surfaces: Plotnick's next paper [3] explains various CSAS image artifacts when a cylinder is made vertically oblique adjacent to flat a flat horizontal surface and viewed at grazing incidence [3]. He extended his prior research (carried out in collaboration with APL-UW) pertaining to the azimuthal dependence of the spectral response of a small aluminum cylinder next to a free surface viewed at grazing incidence [13]. Both the spectral response method and the imaging method provide simple ways of estimating the vertical tilt of certain targets based on backscattering data.

(3) Evanescent wave CSAS imaging: Plotnick's next paper [4] documents the procedure developed at WSU for monostatic evanescent wave CSAS imaging along with the interpretation of such images. This research was carried out in collaboration with Dr. T. M. Marston (APL-UW) who had initially explored that approach when he worked at WSU. The paper concerns the scattering by spheres and the imaging of sets of spheres. The paper also examines and documents bistatic imaging.

(4) Improved modeling of evanescent wavefields: Plotnick's paper [4] also reports one aspect of his improved modeling of evanescent wavefields associated with the reflection of acoustic beams incident on interfaces at sufficiently small grazing angles. Additional results are documented in his 2015 Ph. D. Thesis [5]. See also [14].

(5) Proof that absorbed power must be non-negative for scattering by passive targets: Early in 2016 a peer-reviewed publication appeared in the online journal *Wave Motion* [10] claiming that conditions producing negative absorbed power associated with scattering of sound by viscoelastic targets in water were "not fictional." When defending his assertion, the author of that paper claimed that the extra power in the scattered wave was supplied by shear waves in the target even though the only illuminating wave was an acoustic wave in water. Marston recognized that such claims violated basic energy conservation. In response to the claims in [10], Marston and Zhang published proofs [7] that various claims made in [10] were wrong. Disproving claims made in [10] is directly

relevant to the scattering of sound by targets in water since if the claims made in [10] were correct, the scattered wave could gain energy during the scattering process without any extra source of supplied energy.

(6) Complex-phase-shift analysis of absorbed power, scattering, and translational acoustic radiation forces on spheres: For sufficiently symmetric targets in water the scattering can be expressed using a partial-wave series. In analogy with quantum mechanical scattering it can be convenient to express partial-wave scattering amplitudes using complex partial-wave phase shifts. In the absence of absorption, the partial-wave phase shifts become real valued. Zhang and Marston developed this approach to the evaluation of absorbed power, scattering, and translational acoustic radiation forces on spheres [8]. The analysis concerned plane waves and Bessel beams, though some expressions in [8] pertain to arbitrary wavefields. Most of the analysis was done by Zhang and it extends some of the research associated with his 2012 Ph. D. Thesis at WSU. The results are also consistent with Marston and Zhang's results in [7].

(7) Backscattering enhancements for partially-exposed and proud spheres viewed at grazing incidence: Gunderson has continued his theoretical and experimental investigation of this topic. His research extends the prior research at WSU on scattering by partially-exposed solid cylindrical targets at grazing incidents [15,16]. Aspects of Gunderson's research generalize those of the prior investigations at WSU (concerning the scattering by cylindrical targets) to the case of spheres. These include: (a) the application of the Kirchhoff approximation [15] to modeling the evolution of scattering amplitudes associated with the uncovering of specular points, and (b) subsonic Franz-like wave backscattering enhancements for slightly-exposed targets [16]. (The Franz wave in water is guided by the surface of the target.) The corresponding experimental and theoretical results for spheres at a free surface are emphasized in his manuscript [11]. In addition he demonstrates the evolution of elastic wave backscattering contributions for spheres associated with the uncovering of coupling points. In his recent work he has also modified the Kirchhoff approach so as to account for an anomalous backscattering enhancement predicted to be present for vary large grazing angles from the computed exact scattering by a half-exposed rigid sphere at a free surface. This is described as the disc correction and is relevant when sensing objects at large grazing angles. See **Fig. 1**. Gunderson has also greatly improved the speed of his numerical integration used in his computational Kirchhoff approach. He has also performed several related supporting experiments and calculations during FY2016. This includes extending his work on displaying backscattering in the domain: (grazing angle) – (frequency). Gunderson has also displayed backscattering in the domain: (target-distance-from-interface) – (frequency); in that domain the coupling to low-frequency target modes is modulated by the Lloyd's mirror effect.

(8) Free-field bistatic scattering by elastic spheres (computational and theoretical): Gunderson investigated the issue of how to understand the angular evolution of the bistatic scattering since there is a significant bistatic component to the backscattering by a proud sphere.

(9) Acoustic color and CSAS imaging of a solid bi-cylinder: During FY16 Timothy Daniel started observations with a new category of target: a solid bi-cylinder made by epoxying together end-to-end circular cylinders made of aluminum and brass. This simple geometry should exhibit certain scattering properties present on more complicated targets because of the junction between dissimilar metals. This raises the complexity in the acoustic color plots and CSAS images even when the data is restricted to high  $ka$  values. See for example **Fig. 2** in which the junction between metals is evident in the image.

(10) CSAS imaging and acoustic color of vertically-oblique elastic cubes: During FY15 Bollen started investigating imaging and acoustic color properties of solid elastic cubes since they exhibit a combination of edge-diffractive and elastic responses [17]. Since we have previously examined how elastic scattering processes alter the SAS images of solid and hollow circular elastic cylinders in various configurations, it appeared appropriate to consider imaging less-symmetric elastic targets. We have begun this task using a solid stainless-steel elastic cube 6 cm wide on each side, previously used in scattering experiments here [17]. For the purpose of summarizing some of the results we define a reference position as shown in Fig. E1 of [17] in which diagonals on two of the opposite sides of the cube are horizontal and the top ridge (where two-other-of-the-sides meet) is initially horizontal. From that “neutral” position the top ridge may be vertically tilted to some specified vertical obliquity angle,  $\phi$ . To construct a free field CSAS image or a corresponding acoustic color spectral plot, with  $\phi$  fixed, the cube is spun around a vertical axis passing through the center of mass. The backscattering is monitored for a broad horizontal illuminating acoustic beam directed at the cube. While the measurements during FY15 emphasized the 6 cm steel cube, those during FY16 included a smaller brass cube. The imaging and acoustic color data for both reveal a superposition of edge-diffractive and elastic responses, though the angular dependence of the elastic responses depends on the type of cube. For example, while both exhibit high frequency backscattering enhancements associated with leaky Rayleigh-like waves, the velocity of the waves are different between steel and brass so the coupling mechanisms and associated cube orientations differ for the associated scattering enhancements.

(11) Acoustic color modeling for vertically-oblique cubes: From backscattering data acquired as described above the target response spectrum can be plotted. First, however, it is helpful to mention that in the time domain, much of the elastic contributions to the scattering occur much later in time than the purely-edge-diffractive features as well as the scattering from the thin lines used to position the target. The acoustic color data is displayed in the domain: frequency versus horizontal azimuthal angle. One result of that process is a splitting in the azimuthal domain of certain spectral features in a way that depends on the cube’s vertical obliquity angle  $\phi$ . This splitting is associated with edge diffraction and was modeled geometrically. Associated contributions to the scattering were also modeled using the Kirchhoff approximation.

(12) Modulated acoustic radiation force and Maxwell-stress excitation of low-frequency targets modes: During FY16 some of the new targets investigated at WSU by T. Daniel include an aluminum UXO model (borrowed from APL-UW) and an empty hollow

sphere. (WSU graduate student A. Fortuner also assisted with some of the experiments.) The experiments use a modulated high-frequency focused wave in water. Scanning the source facilitates the display of the target's low-frequency modal structure. Since that work is in cooperation with an ONR grant to Abawi (HLS) and Kirsteins (NUWC), it is anticipated that it will be summarized elsewhere. The excitation method uses the double-sideband suppressed-carrier approach of [18].

(13) Focused beam modification, vortex beams, and acoustic radiation torques: As a possible aid to the aforementioned radiation force experiments, A. Fortuner and T. Daniel investigated some of the ways the high-frequency focused wave could be modified using acoustic lenses machined from plastic. One of the machined lenses was designed to produce an acoustic vortex beam. Vortex beams transport angular momentum [9,19,20]. Fortuner and Daniel succeeded in demonstrating vortex beam generation and angular momentum transport by using the beam to: (a) stabilize the position of a floating sphere on the beam's axis, and (b) cause the sphere to spin around its axis when it was situated on the beam axis. The direction of the rotation agrees with the theory [19,20].

(14) Related student presentations at the Spring 2016 ASA meeting (Salt Lake City): Not listed here, there were four by current students and two related ones by Plotnick. The abstracts are published.

## **IMPACT/APPLICATIONS**

This research has implications to help explain the dependence of the evolution of acoustic signatures of objects of interest on the object's local environment. It may help in discrimination of those signatures from background acoustic scattering. The scattering by objects placed close to a free surface also has implications for understanding other situations of interest. The Franz wave backscattering enhancement [11, 16] is an example of a single-target multiple interaction with acoustic waves along with other multiple interaction mechanisms for a single-target identified in [3, 13].

## **RELATED PROJECTS**

Some of this work was in cooperation with UW-APL, NUWC, and HLS.

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## PUBLICATIONS

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P. L. Marston & L. Zhang, “Unphysical consequences of negative absorbed power in linear passive scattering: Implications for radiation force and torque,” *J. Acoust. Soc. Am.* 139, 3139–3144 (2016) [published, refereed].

L. Zhang & P. L. Marston, “Acoustic radiation force expressed using complex phase shifts and momentum-transfer cross sections,” *J. Acoust. Soc. Am.* 140, EL178–EL183 (2016) [published, refereed].

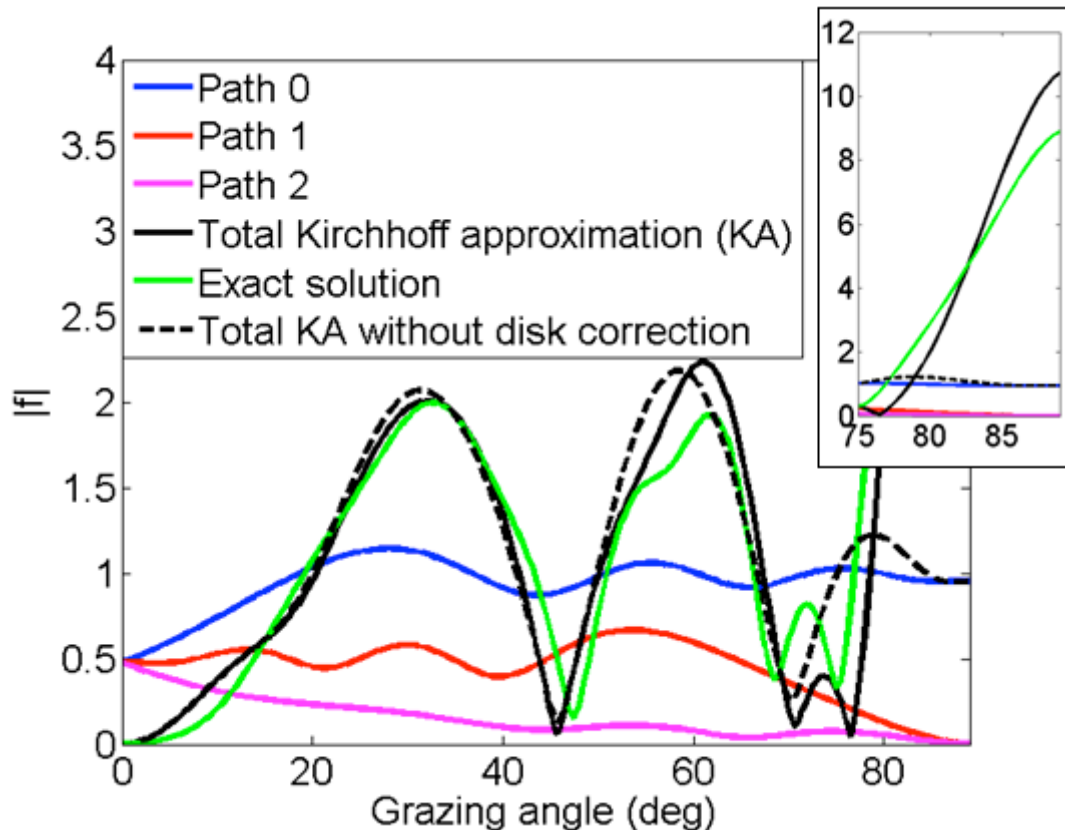
D. S. Plotnick & P. L. Marston, “Multiple scattering, layer penetration, and elastic contributions to SAS images using fast reversible processing methods,” *EUSAR 2016 - 11th European Conference on Synthetic Aperture Radar*, 3 pages (2016) <http://ieeexplore.ieee.org/document/7559430/> [published, refereed].

P. L. Marston & L. Zhang, “Optical and acoustical radiation torque and forces: overview, applications, and selected recent developments,” *META16 Conference, Proceedings*, ISSN: 2429-1390, pp. 764-765 (2016) (<http://metaconferences.org>) [published, refereed].

D. S. Plotnick, T. M. Marston, & P. L. Marston, "Circular synthetic aperture sonar imaging of simple objects illuminated by an evanescent wavefield," J. Acoust. Soc. Am. 140, XX-XX (2016) [accepted, refereed].

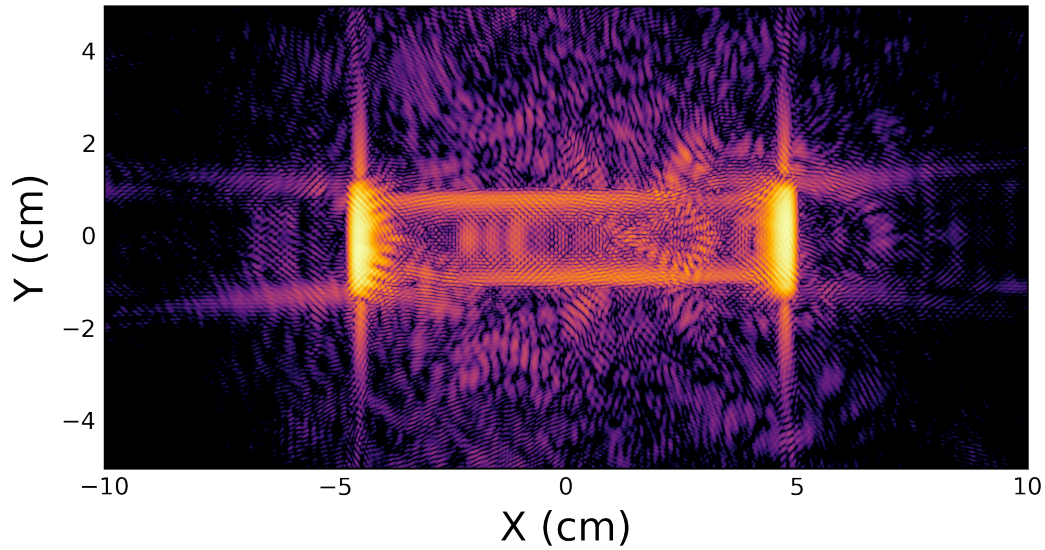
### HONORS/AWARDS/PRIZES

V. Bollen received the "First Prize Best Student Paper Award" in Underwater Acoustics for his presentation at the May 2016 meeting of the Acoustical Society of America.



**Figure 1.** This plot compares different solutions for the normalized backscattering amplitude expressed in terms of a form function  $|f|$  for the situation of a rigid sphere having  $ka = 10$ , half-exposed at a free surface. This amount of exposure was selected because there is an exact solution for the scattering. The horizontal axis plots the grazing angle. The green curve is the exact solution for a half exposed, rigid sphere. The solid black curve is the total Kirchhoff result, while blue, red, and magenta signify contributions from Paths 0, 1, and 2, respectively, in which Path 1 and 2 involve respectively one and two flat-surface reflections in addition to an interaction with the sphere. The dashed black curve is the Kirchhoff result without a disk correction that becomes important when the grazing angle is large. The inset shows the high grazing angle results over an extended range of  $|f|$ . The comparison demonstrates the importance of the disc correction at large grazing angles. Notice that in all of the theories, in the

*limit that the grazing angle vanishes, the backscattering vanishes. A similar behavior is expected for targets on flat sand viewed at vanishingly small grazing angles.*



**Figure 2.** CSAS images made at WSU of a solid bi-cylinder made by epoxying together end-to-end circular cylinders made of aluminum and brass. The diameter of each cylinder was 1 inch. The left-most part is a 3-inch long solid aluminum cylinder. The right-most part is a 1-inch long solid brass cylinder. The location of the aluminum-brass junction is clearly visible near the right end from the internal and external image structure.

## **Acoustic Scattering Processes for Target Discrimination (2017)**

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### **Major Goals:**

Objectives of this project include improving the understanding of acoustical scattering by objects near interfaces and related approaches for identifying signal features associated target responses. This project extends research examining the properties of scattering by targets at (or breaking through) a free surface at the top of a tank of water or partially buried in sand and targets illuminated by evanescent waves in fluids or by acoustic beams and scattering by objects in waveguides. The research also examines aspects of target responses (including low-frequency responses) to acoustic radiation forces of high-frequency sound. Aspects of the research involve the laboratory-based application and/or testing of synthetic aperture sonar (SAS) imaging methods. Sometimes we use synthetic data to produce SAS images and test imaging algorithms. This research will aid the understanding of how surfaces adjacent to targets alters their sonar images and responses and help in the development of methods for discriminating between natural acoustic clutter and man-made objects of interest. Thus the research is relevant to improving the use of acoustic scattering for object identification and improving naval capabilities with alternative modes of data acquisition.

A minor goal concerns the experimental demonstration of a form of sub-wavelength resolution acoustical imaging based on acoustic vortex beam scattering. The detection is sensitive to the topology of the scattered wave-fronts and uses a novel form of array-processing.

Most of the resources are devoted to the support of graduate students and consequently the experimental aspects are in keeping with projects suitable for Ph. D. Thesis documentation. Most of the experiments are carried out using tanks of water and associated acoustics transducers and data-acquisition hardware and electronics for which the operational and maintenance expenses are supplied by this grant through the support provided to students. In addition, with support from this grant some theoretical scattering research is carried out so as to contribute to the general field of understanding acoustical and optical scattering and radiation forces, where the optical component emphasis geometrical and topological aspects of wave propagation in common with acoustical wave physics. Some of the objectives such as the excitation of low-frequency responses are such that for the purpose of experimentation on scaled objects in water it has been useful to some alternative technologies and coupling mechanisms. For example, we

introduced the use of electromagnetic Maxwell stresses to excite and map-out the low frequency modal structure of objects in water.

One way to advance these objectives while at the same time promoting the STEM training is to (when feasible) enable graduate student involvement with researchers based at larger facilities. This includes: (a) student participation with Senior researchers visiting Washington State University from DoD facilities or other DoD supported research organizations; (b) student participation in ship-based data acquisition organized by larger DoD-funded research programs. With support from this grant both approaches are being used when the opportunities are available.

### **Accomplishments Under Goals:**

#### *A. Acoustical Imaging of Targets & Image Interpretation:*

With support from this grant, some of our tests of approaches to synthetic aperture sonar imaging of acoustical targets have been documented [1-3] including in a dissertation [4]. One of the important outcomes is that elastic responses of the targets are visible in the images and in many cases the underlying physical mechanisms associated those contributions to the acoustical image can be identified. These image contributions are superimposed on the usual image contributions associated with edge diffraction and specular reflection. Hence the claim that is sometimes heard that the frequency domains of “sonar imaging” and “structural acoustics” are “distinct” is an overly simplified claim and there can be potential advantages in incorporating structural-acoustics information in the interpretation of target images. One of the most striking examples concerns our SAS imaging of metal cubes over a variety of orientation angles since that simple example clearly reveals the full range of image contributions in a way that depends on the material properties of the different cubes viewed [4]. Also during this interval some of our prior imaging research was published including: (a) the interpretation of image contributions when viewing two adjacent targets viewed in such a way that multiple scattering between targets is significant [1]; (b) the interpretation of image contributions when viewing an inclined cylindrical target adjacent to a flat reflecting surface [2]; and (c) the interpretation of image contributions when viewing adjacent spheres illuminated by evanescent waves partially analogous to the case of targets buried in sand viewed at small grazing angles [3]. The results in [2] are significant in that image properties are found to reveal the inclination angle of the cylinder.

#### *B. Scattering Physics for Targets Adjacent to Flat Surfaces & Bistatic Scattering:*

This research was documented through publication [5] and a dissertation [6]. The publication concerned some very noticeable properties of the scattering by partially exposed spherical targets at a flat free surface viewed at variable grazing angles and variable exposures. For small exposures the backscattering is dominated by the Franz wave contribution that travels along the sphere’s surface and partially reflects from the interface. The publication also examines some methods of approximating the backscattering including the direct Kirchhoff approximation for rigid spheres that makes use of a method of images and a modification associated with the shadow region (the non-illuminated region) of the flat reflecting surface. These approximations are compared with the exact backscattering for a half-exposed rigid sphere and with measurements for solid spheres. The shadow region modification is found to be very significant at large

grazing angles when compared with the exact solution (in the grazing angle versus dimensionless frequency  $ka$  domain). The experiments (which were mostly at grazing angles below 30 degrees) showed that this approach is useful for modeling the evolution of the interference of the reflection contributions to the back-scattering as specular reflection regions are uncovered as the sphere becomes more exposed. The Kirchhoff approximation (even with the associated shadow modification) neglects to account for the elastic and Franz wave scattering contributions. Some aspects of the backscattering can be explained geometrically in the following domains displayed in [5]: (a) exposure versus time, (b) exposure versus frequency response, and (c) exposure versus grazing angle at fixed  $ka$ . The dissertation [6] includes measurements and discussion of the backscattering in the (d) grazing angle versus  $ka$  domain and (e) grazing angle versus time domain. This was also studied for solid cylinders viewed broadside where the evolution of records at different exposures is related to the uncovering of coupling regions for the excitation of guided elastic waves on the cylinder. Using the variable grazing angle data it was also possible to construct SAS images for which many of the bright regions could be explained geometrically. The dissertation [6] also shows that the backscattering from spheres in the exposure- versus- $ka$  domain is influenced by Lloyd's mirror interference and that there are some geometrically related regularities in the grazing angle versus  $ka$  domain. Several aspects of the aforementioned observations were also found for spheres partially exposed on sand, though in that case it is not possible to explore continuous variable exposure domains. One outcome of this study is that for simple targets such as spheres in the dimensionless frequency range of  $ka$  from 5 to 20 the target response can be strongly affected by the target exposure though there are certain geometrical regularities.

The following were also studied [6]: (a) computation and understanding of bistatic scattering for spheres and cylinders in the scattering angle versus  $ka$  domain, (b) backscattering by a thick rubber spherical shell revealing reflection and guided-wave contributions.

### *C. Acoustic Radiation Force (ARF) & Maxwell Stress Excitation of Target Modes:*

The radiation force aspects are cooperative with DoD supported researchers who visited WSU in spring 2016 and concerns low-frequency (LF) modes. At that time experiments were carried out on a model aluminum UXO target in water and LF modes were successful excited using modulated ARF and Maxwell Stresses (MS). Since certain items were loaned during the experiments, during this FY the student involved (T. Daniel) continued experiments and verified ARF and MS excitation mechanisms using some simpler metallic shell targets. In addition some scaled aluminum UXO targets were fabricated at WSU for use in planned measurements. T. Daniel also carried out related experiments on the detection of LF modes of bubbles and certain LF bending modes. The latter experiments verified that an alternative ARF excitation could be used. In addition a new acoustical detection mechanism was verified as being capable of measuring LF resonance response curves in certain cases. T. Daniel also extended the understanding of some related aspects of the theory. During the summer of 2016, Daniel and another student (A. Fortuner) were also able to verify experimentally the production of acoustic radiation torque (ART) on spheres using a modified apparatus.

In related recent research Marston published some theoretical advances (sometimes with assistance from Prof. L. Zhang, now at Univ. of Mississippi). This

includes an alternative parameterization of ARF on spheres [7] and applications of that parameterization [8]. That included a generalization to objects in standing waves and new ways of approximating conditions giving vanishing LF-ARF [8]. Our additional related publications [9,10] correct some serious misconceptions that had been published by a different researcher. One corrects significant misconceptions concerning the scattering of sound by viscoelastic objects in water and also notes some relevant applications to ARF and ART [9]. The other [10] corrects implicit misconceptions concerning ARF and ART on cylindrical objects published by that researcher.

*D. Acoustic Beam Scattering Experiments:*

A form of high-resolution resolution imaging was demonstrated [4].

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**Results Dissemination**

*A. Publications appearing during the period of this report include:*

- [1] D. S. Plotnick & P. L. Marston (PLM), “Multiple scattering, layer penetration, and elastic contributions to SAS images using fast reversible processing methods,” EUSAR 2016 - 11th European Conference on Synthetic Aperture Radar, 3 pages (2016)  
<http://ieeexplore.ieee.org/document/7559430/>
- [2] D. S. Plotnick & PLM, “High frequency imaging and elastic effects for a solid cylinder with axis oblique relative to a nearby horizontal surface,” *J. Acoust. Soc. Am.* 140, 1525–36 (2016)
- [3] D. S. Plotnick, T. M. Marston, & PLM, “Circular synthetic aperture sonar imaging of simple objects illuminated by an evanescent wavefield,” *J. Acoust. Soc. Am.* 140, 2839–46 (2016)
- [4] PLM & L. Zhang, “Optical and acoustical radiation torque and forces: overview, applications, and selected recent developments,” META16 Conference, Proceedings, ISSN: 2429-1390, pp. 764-765 (2016) (<http://metaconferences.org>)
- [5] A. Gunderson & PLM, “Kirchhoff approximation for backscattering from a partially exposed rigid sphere at a flat interface,” *J. Acoust. Soc. Am.* 140, 3582–92 (2016)
- [6] L. Zhang & PLM, “Acoustic radiation force expressed using complex phase shifts and momentum-transfer cross sections,” *J. Acoust. Soc. Am.* 140, EL178–83 (2016)
- [7] PLM & L. Zhang, “Relationship of scattering phase shifts to special radiation force conditions for spheres in axisymmetric wave-fields,” *J. Acoust. Soc. Am.* 141, 3042–9 (2017)

[8] PLM & L. Zhang, “Unphysical consequences of negative absorbed power in linear passive scattering: Implications for radiation force and torque,” *J. Acoust. Soc. Am.* 139, 3139–44 (2016)

[9] PLM, “Comment on “Radiation forces and torque on a rigid elliptical cylinder in acoustical plane progressive and (quasi)standing waves with arbitrary incidence” [*Phys. Fluids* 28, 077104 (2016)],” *Physics of Fluids* 29, 029101 (2017)

*B. Professional Conference Presentations during this period:*

[1] Invited: P. L. Marston (PLM) & L. Zhang, “Optical and acoustical radiation torque and forces: overview, applications, and selected recent developments,” META16 Conference (Spain, July 2016) – (Presented by Marston.)

[2] T. D. Daniel, A. Fortuner, A. T. Abawi, I. Kirsteins, & PLM, “Modes of targets in water excited and identified using radiation pressure of modulated focused ultrasound,” 69th Annual Meeting of the APS Division of Fluid Dynamics, Portland, OR, Nov. 2016) (Presented by T. D. Daniel.)

[3] PLM & L. Zhang, “Acoustic radiation force expansions in terms of partial wave phase shifts for scattering: Applications,” 69th Annual Meeting of the APS Division of Fluid Dynamics, Portland, OR, Nov. 2016) (Presented by Marston.)

[4] Invited: T. D. Daniel, PLM, I. Kirsteins, & A. T. Abawi, “Modes of targets in water excited and identified using the radiation pressure of modulated focused ultrasound,” 172ST Meeting of the Acoustical Society of America (ASA), Honolulu, Nov. & Dec. 2016; 5TH Joint Meeting ASA & Acoustical Society of Japan. (Presented by T. D. Daniel.)

[5] Invited: V. Bollen, PLM, & D. S. Plotnick, “Circular synthetic aperture sonar images and aspect dependent spectral properties of solid elastic cubes,” 172ST Meeting of the Acoustical Society of America (ASA), Honolulu, Nov. & Dec. 2016; 5TH Joint Meeting ASA & Acoustical Society of Japan. (Presented by V. Bollen.)

[6] Invited: D. S. Plotnick, PLM, & T. M. Marston, “Sonar image reconstruction of objects near a reflective boundary,” 172ST Meeting of the Acoustical Society of America (ASA), Honolulu, Nov. & Dec. 2016; 5TH Joint Meeting ASA & Acoustical Society of Japan. (Presented by D. S. Plotnick.)

[7] Invited: PLM, “Insight into scattering and caustics from the evolution of glare points and wavefronts,” 16th Electromagnetic and Light Scattering Conference (Maryland, March 2017).

[8] Poster: Oli Jobe, David B. Thiessen & PLM, “Hyperbolic umbilic caustics from oblate water drops with tilted illumination: observations,” 16th Electromagnetic and Light Scattering Conference (Maryland, March 2017). (Presented by Marston, based on Jobe’s 2008 MS Thesis scattering experiments.)

*C. Dissertations:*

[1] Viktor Bollen, “Underwater Acoustical Scattering by Cubes and of Helical Beams,” Ph. D. Thesis (WSU, May 2017)

[2] Aaron Michael Gunderson, “Acoustic Scattering from Partially Exposed Spheres and Cylinders at a Flat Interface,” Ph. D. Thesis (WSU, May 2017)

*D. Media Interview:*

[1] P. L. Marston was interviewed concerning radiation force research by Emily Conover (Physics Reporter, Science News) in May 2017. Marston was quoted in her news article: “Quantum tractor beam could tug atoms molecules.”

<https://www.sciencenews.org/article/quantum-tractor-beam-could-tug-atoms-molecules?tgt=nr>

*E. Outreach Open-Access Publication to Increase Interest in Acoustical Physics:*

[1] P. L. Marston, "James Clerk Maxwell and the Physics of Sound," *Acoustics Today* 12(4), 20-28 (2016) <http://acousticstoday.org/wp-content/uploads/2016/12/Physics-of-Sound.pdf>

(Note: While not supported by any source, this is a form of outreach activity.)

*F. Journal Articles Accepted but not yet published at the time of the Annual Report:*

[1] Z. Gong, PLM, W. Li, & Y. Chai, "Multipole expansion of acoustical Bessel beams with arbitrary order and location," *J. Acoust. Soc. Am.* EL

[2] W. Li, Y. Chai, Z. Gong, & PLM, "Analysis of forward scattering of an acoustical zeroth-order Bessel beam from rigid complicated (aspherical) structures," *Journal of Quantitative Spectroscopy and Radiative Transfer*

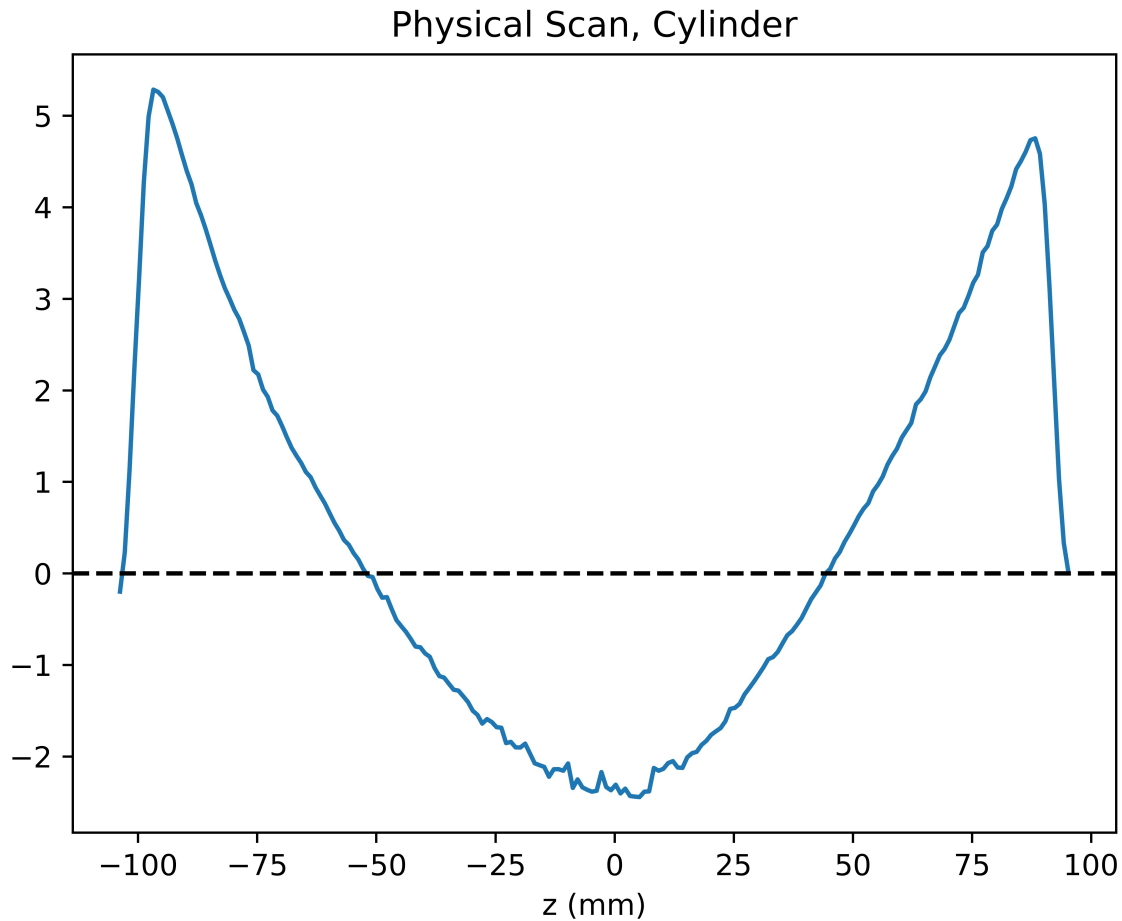
*G. Journal Articles Submitted (under review at the time of the Annual Report):*

[1] A. M. Gunderson, A. L. Espana, & PLM, "Spectral analysis of bistatic scattering from underwater elastic cylinders and spheres,"

[2] O. Jobe, D. B. Thiessen, & PLM, "Hyperbolic umbilic caustics from oblate water drops with tilted illumination: observations,"

### **Technology Transfer & Related DoD Projects**

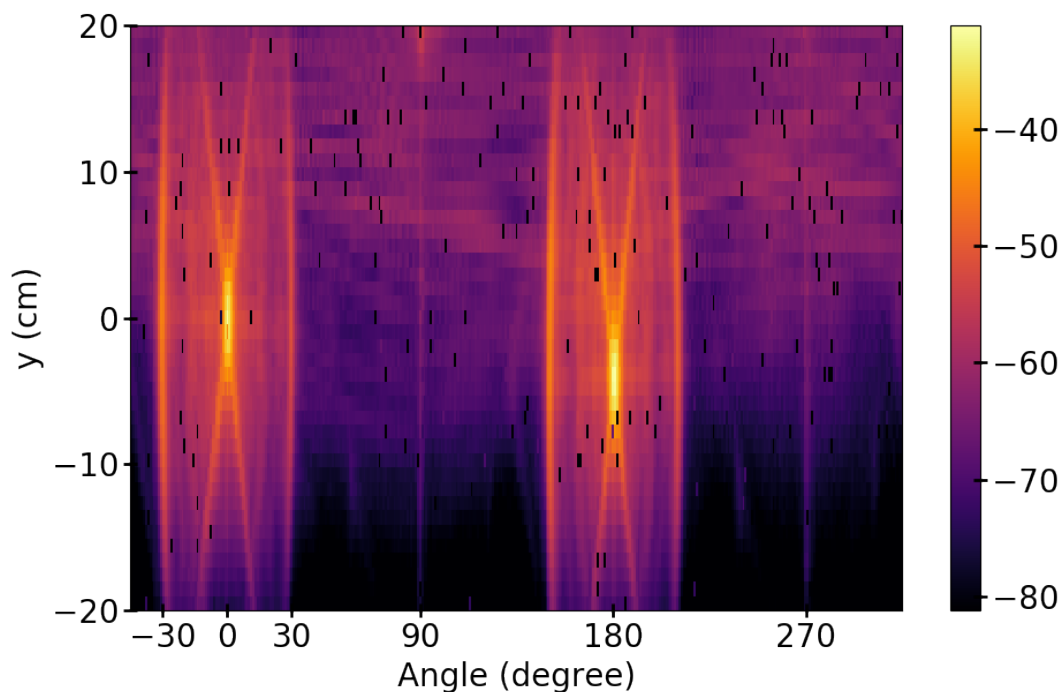
Contact the Principal Investigator for information.



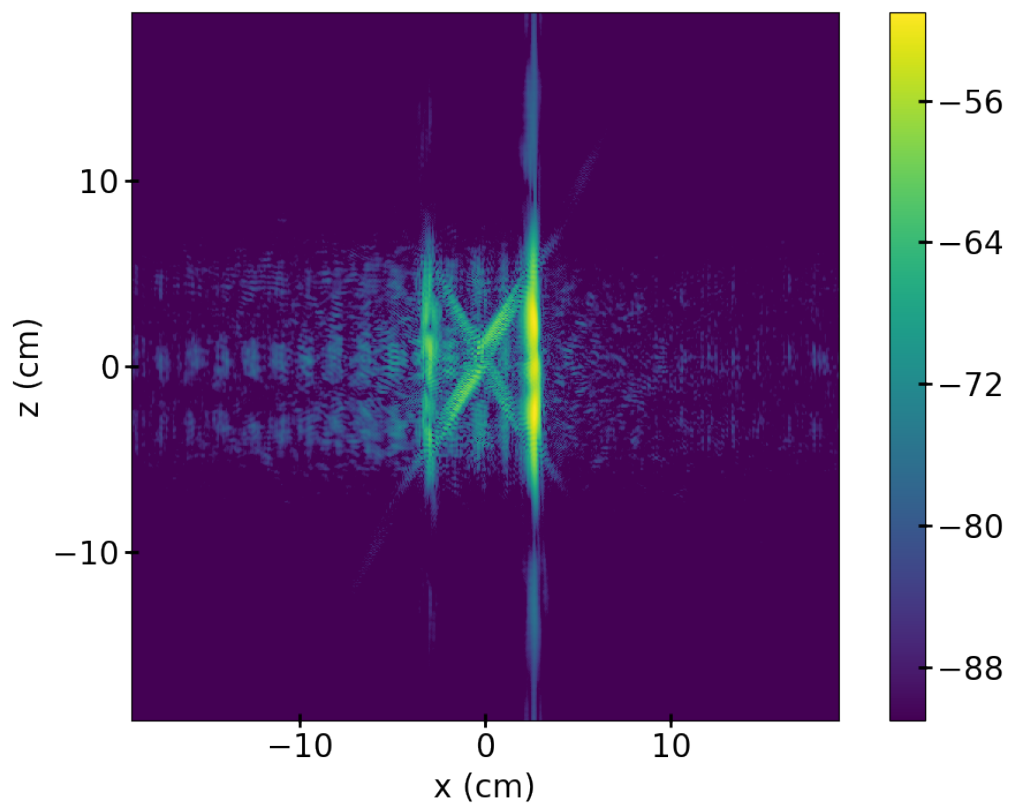
**Figure 1.** The result of a physical scan of a 1.5-inch diameter x 7.5-inch long solid aluminum cylinder in water for which a 1.5 MHz focused modulated beam excites the cylinder's mode at 3.91 kHz. The plot shows the magnitude of the velocity response, where the phase information has been preserved and is indicated by the sign of the response. This was done while scanning the focused ultrasound along the axis of the cylinder in 1 mm steps, which corresponds to the horizontal axis. This corresponds to the lowest bending mode of the target. The plot (recorded in June 2017) demonstrates that the radiation force excitation method can be used to detect a target's mode shape. The response vanishes when the focused beam is scanned beyond either end of the cylinder. The two zero crossings along the body of the cylinder correspond to nodes of the excited mode. (Data obtained and processed by T. Daniel at WSU.)



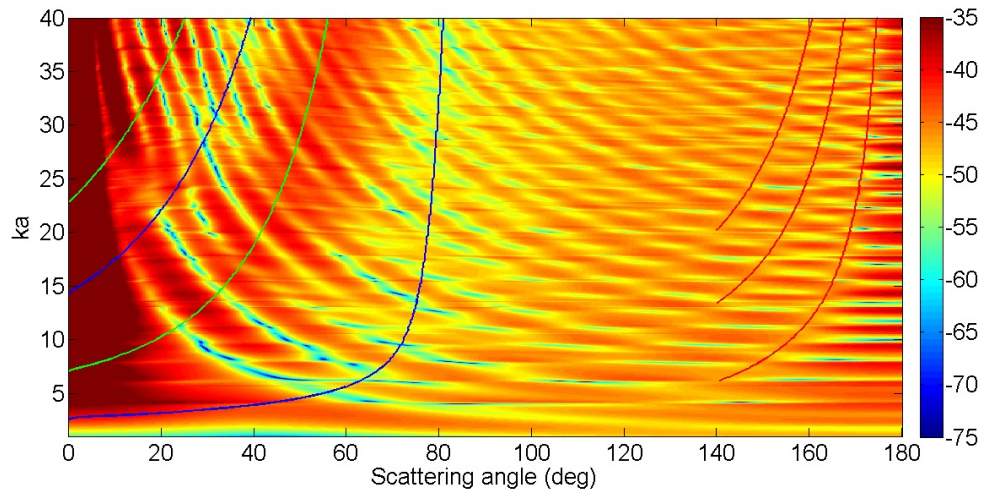
**Figure 2.** Volumetric CSAS image of a rigid cube based on synthetic data where the back-scattering scattering data was synthesized using the a Kirchhoff approximation approach documented in V. Bollen's 2017 Ph. D. Thesis. The image is shown here only for one perspectives, though images for other perspectives can also be constructed.



**Figure 3.** Average back-scattering amplitude of a cylindrical scan of a slightly tilted steel cube at each transducer location  $y$  in a vertical scan. (The illumination was a short acoustic pulse.) The vertical axis pertains to the transducer height of the scan, whereas the horizontal axis is the aspect angle. The black marks are data points where the signal dropped during the experiment. At  $0^\circ$ , the face side of the cube, there is a bright reflection from said face. The bent vertical lines near  $\pm 30^\circ$  are the Rayleigh waves coupling into the steel cube. The edge side faces and support wires can also be seen at  $\pm 90^\circ$ . The X-pattern is the splitting of the face side associated with edge-diffraction by the cube. In principle the data is sufficient for the construction of a volumetric CSAS image. (From V. Bollen's 2017 Ph. D. Thesis.)



**Figure 4.** Ordinary CSAS image from the data set in Figure 3 obtained by considering only the data acquired with a transducer location  $y = -4$  cm. The bright region on the left is from the specular reflection from the cube's face. The X-pattern in the image is from the cube's Rayleigh wave contributions to the scattering. It would not be present if the cube were rigid. (From V. Bollen's 2017 Ph. D. Thesis.)



**Figure 5.** Bistatic spectrum for a 20 mm diameter copper sphere in water, using the exact scattering solution. Results are plotted in terms of absolute target strength TS, with the color bar showing the amplitude in dB where the vertical axis is dimensionless frequency  $ka$  where  $a$  is the sphere radius and  $k$  is the acoustic wave-number. The superposed arcs correspond to loci in the scattering angle versus  $ka$  domain predicted by physical acoustics models. For example the red arcs are predicted minima in the near-backward amplitude associated with axial-focusing of the backscattering (also known as glory scattering). The blue loci model amplitude minima associated with destructive interference between a specular reflection and a (near-side) Rayleigh wave contribution to the scattering. The green loci model amplitude ridges associated with constructive interference. (The calculations are documented in A. M. Gunderson's 2017 Ph. D. Thesis. The range of TS displayed is such that in the forward direction the display is saturated.) Information of this type is useful for interpreting mono-static data for targets near interfaces and is potentially useful for calibrating bistatic scattering measurements. See the subsequent publication in *J. Acoust. Soc. Am.*

## Acoustic Scattering Processes for Target Discrimination (2018)

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### Accomplishments Under Goals:

*A. Acoustical Imaging of Targets & Image & Signature Interpretation:* With support from this grant, during the current period some of our tests of approaches to synthetic aperture sonar imaging of acoustical targets have been abstracted and presented [1]. Specifically T. Daniel was able to identify the cause of easily observed image features in SAS images associated with the elastic responses of circular cylinders. This was done for compositions of solid cylinders not previously investigated. His investigation included the identification of the aspect-angle-dependent frequency response or “acoustic color” as well as the explanation of features present in the time-aspect-angle domain. This included the case of a bimetallic cylinder having bonded aluminum and brass ends. The aluminum-brass junction is taken to be representative of junctions present in real targets.

During the current period we submitted and published [2] our measurements of the high-frequency backscattering by a submerged empty rubber shell. These experiments reveal phenomena relevant to understanding signatures of naval interest. They demonstrated for the first time that such a shell supports a guided wave that circumnavigates the shell and contributes to the backscattering signature. The measurements and analysis also show how reverberations of sound across the thickness of the shell contribute to the backscattering [2,3]. This situation was also used in by Gunderson and Isakson for the verification of FEM calculations [2,3].

During the current period we designed and verified the successful operation of a negative buoyancy target having a prompt frequency-dependent response resulting in a high-frequency backscattering enhancement. That target may be useful for assessing the selective properties of the sonar of dolphins or of manmade high-frequency sonar systems. The frequency selective enhancement mechanism is related to one originally proposed and modeled in research directed by Marston [4,5] though the material selection and target shape differ for ease of fabrication. The relevant dimensionless frequency range is typically  $ka > 45$ . The mechanism identified would not be degraded if the target rests on the seafloor though the consequences of complete burial are not yet known.

*B. Scattering Physics for Targets Adjacent to Flat Surfaces & Bistatic Scattering:* As previously discussed [6] understanding bistatic scattering in the free-field is directly relevant to understanding target responses of some targets resting on the seafloor where reflections of target-scattered waves by the seafloor are significant. That is also the case for targets near a free-surface and for some situations of targets in a boundary waveguide. During the current period we published our new way of displaying and understanding the computed bistatic scattering for spheres and cylinders in the scattering angle versus  $ka$  domain [7].

Scattering by target in what we refer to a boundary waveguide corresponds to the situation where a target is in a waveguide but the source and receiver are external to the

waveguide. Sound reaches the target from the source by passing through one of the walls of the waveguide and similarly sound passes through one of the walls of the waveguide to reach the receiver (which may be located at the source in the usual case of monostatic scattering). Multiple reflections within the waveguide modify the frequency response and time domain response of the target. Some evidence for this modification was found for a target in a mud-layer on sand in data acquired during the 2014 BayEx measurements [8]. With support of the present grant a partial experimental simulation of this situation was built and explored by Fortuner [9]. One of the waveguide boundaries is a free surface and the other is a flat thin plastic sheet of PMMA. A target was selected having only a weak free-field frequency dependence so that the waveguide modification of the frequency response was obvious. The major waveguide modifications of the target's SAS image were also modeled.

*C. Acoustic Radiation Force (ARF) & Maxwell Stress Excitation of Target Modes:* The modulated radiation force aspects are cooperative with DoD supported researchers who visited WSU in 2017 & 2018 and concern low-frequency (LF) target modes. We took measurements of the excitation of target modes and extended our prior models of the coupling with the emphasis on situations where targets are displaced from the focus of the ultrasonic beam. The WSU-based theoretical approach is to split the theory into a LF-part in which FEM (done by Abawi at HLS) is used to compute target mode shapes while approximation methods are used to calculate the radiation stress distribution (on the target's surface) of an ultrasonic beam. In support of this approach the same approximation methods were applied to situations in which exact solutions are available [10]. A reversal of the LF response phase discovered as an elastic disk was scanned away from the source was successfully modeled. In addition the relevance of adjacent targets and boundaries was investigated and those experiments clarify when mode coupling becomes relevant. It is possible to excite a particular target without strongly exciting modes of adjacent targets if their spacing is sufficient.

*Related theory development & testing:* One of our DoD collaborators suggested that we apply an expansion method previously introduced by Marston to the case of our focused sound beam and T. Daniel has reduced the problem to a single numerical integration. Marston published papers developing a different expansion method revealing fundamental ARF properties [11,12] on aluminum. Marston also expanded his early work on Maxwell stress coupling with conducting spheres [13].

*References & Selected Publications:*

[1] TD Daniel, SM Smith, & PL Marston (PLM), "Backscattering enhancement due to weakly damped, leaky, guided waves on cylinders and associated images," <https://doi.org/10.1121/1.5036085>

[2] AM Gunderson, TD Daniel, PLM, & MJ Isakson "Observation and modeling of acoustic scattering from a rubber spherical shell," J. Acoust. Soc. Am. 143, 3036-3046 (2018)

[3] AM Gunderson, T Daniel, PLM, & MJ Isakson, "Late backscattering enhancement from a rubber spherical shell associated with waveguide coupling and propagation," J. Acoust. Soc. Am. 142, 2498 (2017).

[4] G Kaduchak, DH Hughes, & PLM, "Enhancement of the backscattering of high-frequency tone bursts by thin spherical shells associated with a backwards wave: Observations and ray approximation," J. Acoust. Soc. Am. 96, 3704-3714 (1994).

- [5] PLM, "Negative group velocity Lamb waves on plates and applications to the scattering of sound by shells," *J. Acoust. Soc. Am.* 113, 2659-2662 (2003).
- [6] AM Gunderson & PLM, *J. Acoust. Soc. Am.* 140, 3582–92 (2016).
- [7] AM Gunderson, AL Espana, & PLM, "Spectral analysis of bistatic scattering from underwater elastic cylinders and spheres," *J. Acoust. Soc. Am.* 142, 110–115 (2017).
- [8] KL Williams, *J. Acoust. Soc. Am.* 140, EL504 (2016).
- [9] AR Fortuner & PLM, "Laboratory simulation of backscattering by a hemisphere in a boundary wave-guide with an external source," <https://doi.org/10.1121/1.5036093>
- [10] PLM & TD Daniel, "Geometric approximation of radiation stress projections for canonical objects," *J. Acoust. Soc. Am.* 143, 1718 (2018); <https://doi.org/10.1121/1.5035596>
- [11] PLM, "Finite-size radiation force correction for inviscid spheres in standing waves," *J. Acoust. Soc. Am.* 142, 1167–1170 (2017); <https://doi.org/10.1121/1.5000236>
- [12] PLM, "Phase-shift expansions for approximate radiation forces on solid spheres in inviscid-acoustic standing waves," *J. Acoust. Soc. Am.* 142, 3358-3361 (2017); <https://doi.org/10.1121/1.5016031>
- [13] PLM, "Humblet's decomposition of electromagnetic angular momentum applied to conducting spheres in the Hagen-Rubens approximation for terahertz radiation torque," 17th ELS (2018).

## Results Dissemination

### *A. Publications appearing during the period of this report include:*

- [1] Z. Gong, P. L. Marston (PLM), W. Li, & Y. Chai, "Multipole expansion of acoustical Bessel beams with arbitrary order and location," *J. Acoust. Soc. Am.* 141, EL574–EL578 (2017).
- [2] A. M. Gunderson, A. L. Espana, & PLM, "Spectral analysis of bistatic scattering from underwater elastic cylinders and spheres," *J. Acoust. Soc. Am.* 142, 110–115 (2017).
- [3] W. Li, Y. Chai, Z. Gong. & PLM, "Analysis of forward scattering of an acoustical zeroth-order Bessel beam from rigid complicated (aspherical) structures," *Journal of Quantitative Spectroscopy and Radiative Transfer (JQSRT)* 200, 146-162 (2017).
- [4] O. Jobe, D. B. Thiessen, & PLM, "Hyperbolic umbilic caustics from oblate water drops with tilted illumination: observations," *JQSRT* 202, 147-153 (2017).
- [5] PLM, "Finite-size radiation force correction for inviscid spheres in standing waves," *J. Acoust. Soc. Am.* 142, 1167–1170 (2017).
- [6] PLM, "Phase-shift expansions for approximate radiation forces on solid spheres in inviscid-acoustic standing waves," *J. Acoust. Soc. Am.* 142, 3358-3361 (2017).
- [7] A. M. Gunderson, T. D. Daniel, PLM, & M. J. Isakson "Observation and modeling of acoustic scattering from a rubber spherical shell," *J. Acoust. Soc. Am.* 143, 3036-3046 (2018); <https://doi.org/10.1121/1.5038256>

### *B. Professional Conference Presentations during this period:*

- [1] Best Underwater Acoustics Student Paper 2nd Prize: AM Gunderson & PLM, "Kirchhoff approximation for scattering from solid spheres at flat interfaces: Improved description at large grazing angles, *J. Acoust. Soc. Am.* 141, 3700 (2017); 173st Meeting of the Acoustical Society of America (ASA), Boston, June 2017; Joint Meeting ASA & European Acoustical Society.

- [2] V Bollen, T Daniel, & PLM, "Creating synthetic aperture images using experimental and simulated backscattering of solid elastic cubes," *J. Acoust. Soc. Am.* 141, 3700 (2017); same meeting as [1].
- [3] AM Gunderson, AL Espana, PLM, "Bistatic scattering from underwater elastic spheres and cylinders: Interference and resonance phenomena," *J. Acoust. Soc. Am.* 141, 3700 (2017); same meeting as [1].
- [4] Invited: P. L. Marston & L. Zhang, "Acoustic radiation force expansions in terms of partial-wave scattering phase shifts: Extended applications," *J. Acoust. Soc. Am.* 141, 3463 (2017); same meeting as [1].
- [5] Z Gong, PLM, Y Chai, & W Li, "T-matrix method implementation for acoustic Bessel beam scattering from elastic solids and shells," *J. Acoust. Soc. Am.* 141, 3506 (2017); same meeting as [1].
- [6] PLM, L Zhang, DB Thiessen, & TD Daniel, "From modulated acoustic radiation forces and liquid column stabilization to radiation torques and special force conditions," (in Proceedings of) *Acoustofluidics 2017: The 14th Conference on Acoustofluidics*, 2 pages (San Diego, Aug. 2017); <https://cbmsociety.org/conferences/acoustofluidics-2/>
- [7] AT Abawi, IP Kirsteins, PLM, & T Daniel, "On target excitation by modulated radiation pressure," *J. Acoust. Soc. Am.* 142, 2498 (2017); 174th Meeting of the Acoustical Society of America (ASA), New Orleans, Dec. 2017.
- [8] AM Gunderson, T Daniel, PLM, & MJ Isakson, "Late backscattering enhancement from a rubber spherical shell associated with waveguide coupling and propagation," *J. Acoust. Soc. Am.* 142, 2498 (2017); same meeting as [7].
- [9] PLM, "Humblet's decomposition of electromagnetic angular momentum applied to conducting spheres in the Hagen-Rubens approximation for terahertz radiation torque," 17th Electromagnetic and Light Scattering Conference (Texas A&MU, March 2018); abstract archived at: <https://www.giss.nasa.gov/staff/mmishchenko/ELS-XVII/>
- [10] PLM & L Zhang, "Insight into Radiation Forces on Spheres from Partial Wave Phase Shifts," ELS-XVII & LIP2018 joint meeting (Texas A&MU, March 2018); 3-page abstract archived at: <https://sites.google.com/a/tamu.edu/lip2018/programme/contributed-abstracts>
- [11] SM Smith, TD Daniel, JC Stotts, & PLM, "Investigation of negative group velocity harmonic waves associated with backscattering of ultrasound off submerged cylindrical shells," Showcase for Undergraduate Research and Creative Activities (SURCA), WSU April 2018; abstract archived at: <https://surca.wsu.edu/>
- [12] Invited: TD Daniel, PLM, AT Abawi, & IP Kirsteins, "Target response in a focused, modulated sound field: Modeling and experiment," 175th Meeting of the Acoustical Society of America (ASA), Minneapolis, May 2018; <https://doi.org/10.1121/1.5035674>
- [13] Invited: PLM, "Quantitative ray methods for scattering by tilted cylinders," same meeting as [12]; <https://doi.org/10.1121/1.5036084>
- [14] TD Daniel, SM Smith, & PLM, "Backscattering enhancement due to weakly damped, leaky, guided waves on cylinders and associated images," same meeting as [12]; <https://doi.org/10.1121/1.5036085>
- [15] AR Fortuner & PLM, "Laboratory simulation of backscattering by a hemisphere in a boundary wave-guide with an external source," same meeting as [12]; <https://doi.org/10.1121/1.5036093>

[16] PLM & TD Daniel, Geometric approximation of radiation stress projections for canonical objects," same meeting as [12]; <https://doi.org/10.1121/1.5035596>

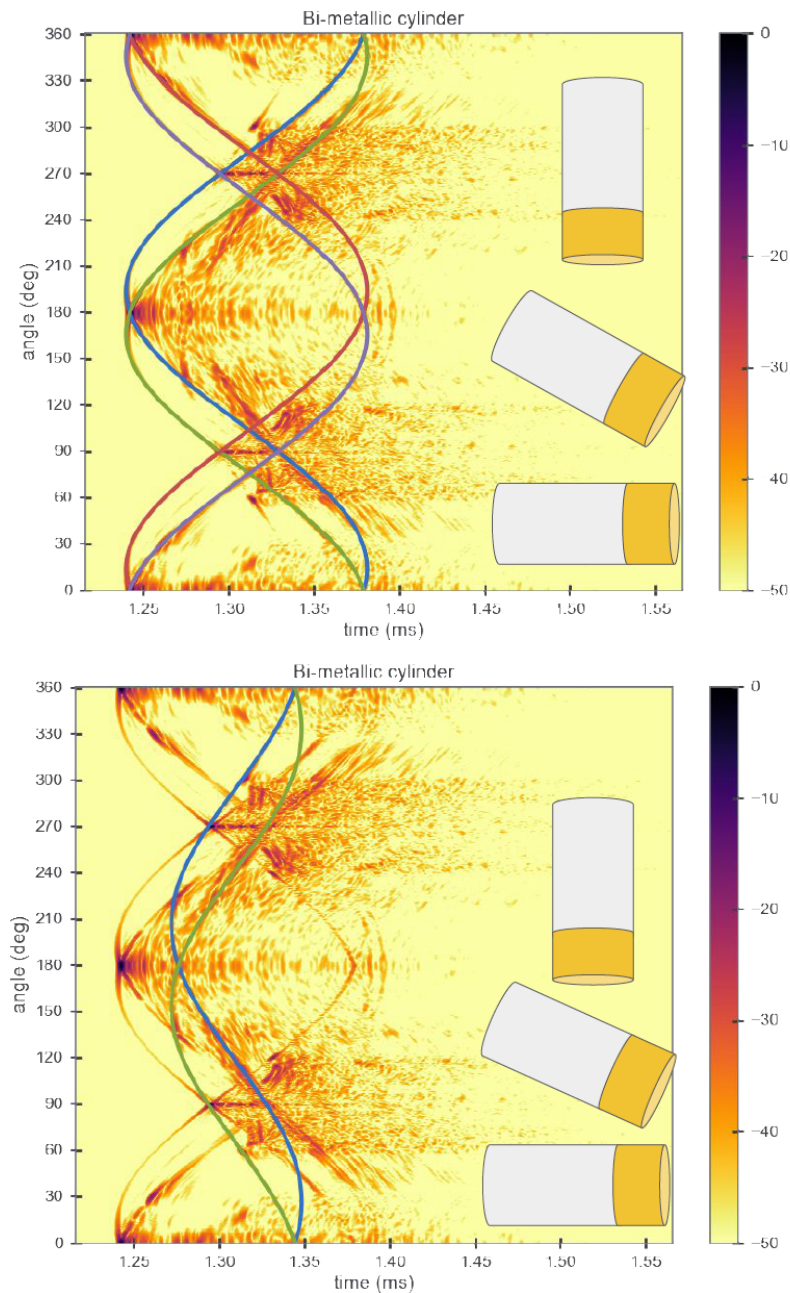
[17] PLM, "Radiation force on spheres in standing waves in ideal fluids: Improved simple approximation for material dependence," same meeting as [12]; <https://doi.org/10.1121/1.5035595>

[18] AR Fortuner, TD Daniel, & PLM, "Acoustic vortex beam created with a continuous phase ramp lens and resulting radiation torque response of a sphere," same meeting as [12]; <https://doi.org/10.1121/1.5036051>

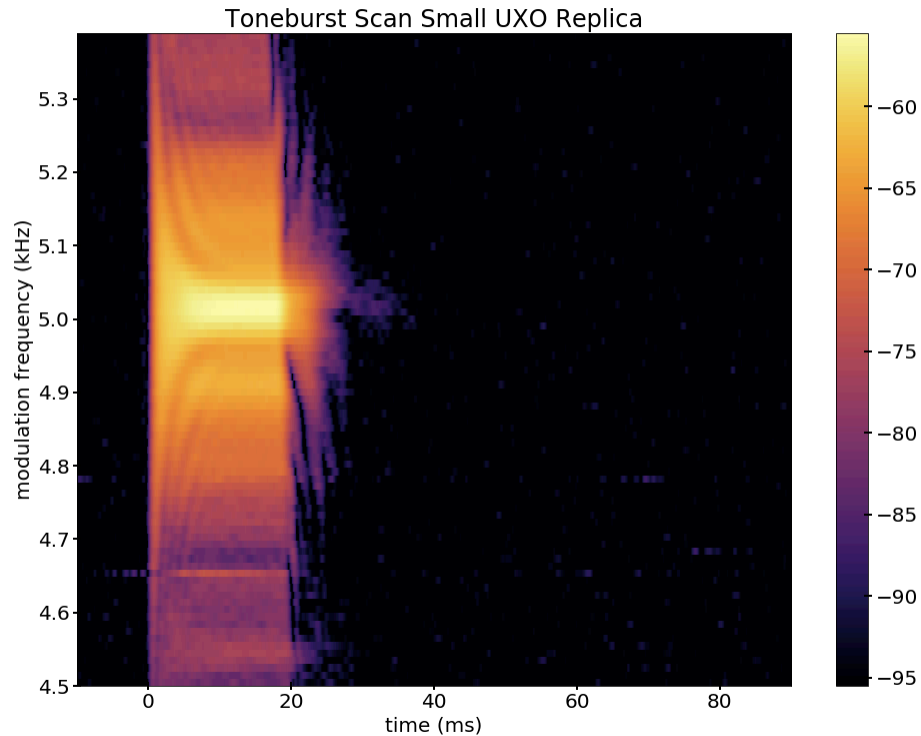
[19] Invited: Z Gong, PLM, & W Li, Potential of theoretical approach and T-matrix method for designing numerical acoustical tweezers toolbox," same meeting as [12]; <https://doi.org/10.1121/1.5035675>

### **Technology Transfer & Related DoD Projects**

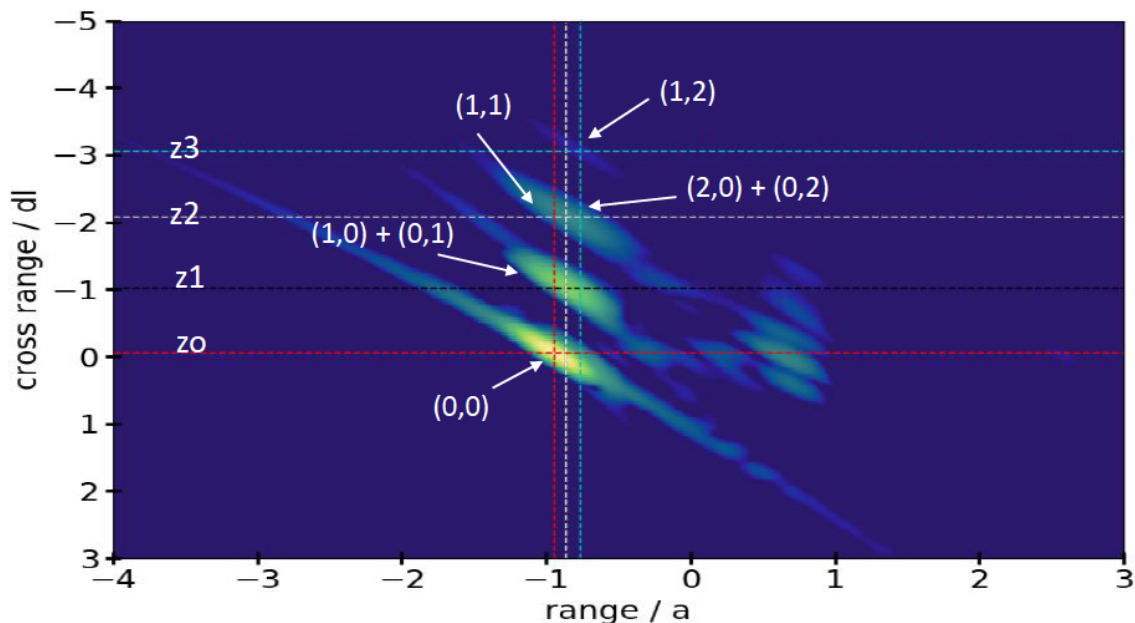
Contact the Principal Investigator for information.



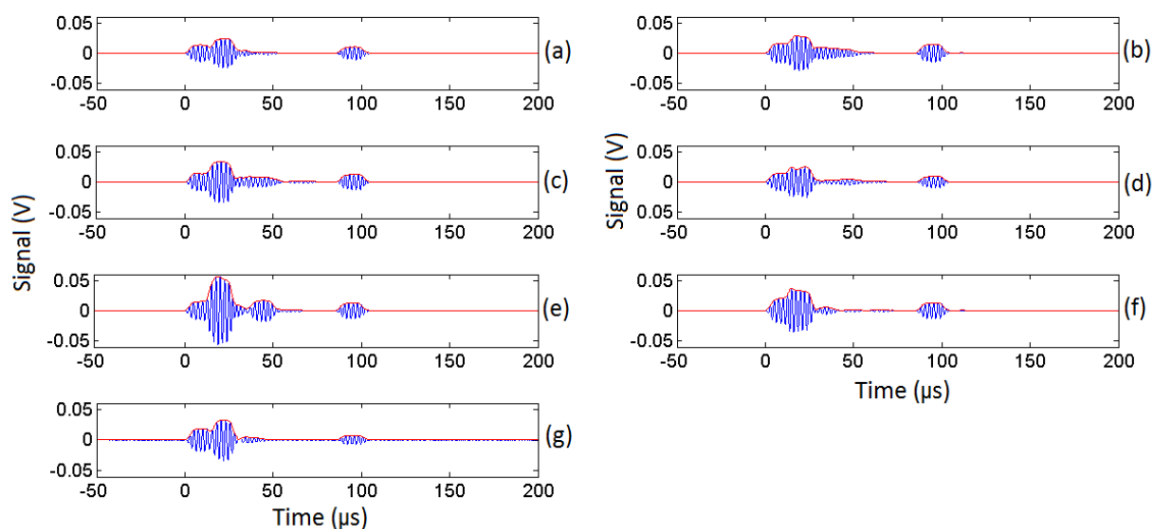
**Fig. 1.** Both the upper and lower figures show the same data for the envelope of the time-domain acoustic short-burst backscattering by a bimetallic solid cylinder made of a short brass cylinder bonded to a longer aluminum cylinder. The vertical axis is the orientation angle. Cylinder orientation (for a source on the the left) is shown in the diagrams on the right. Regions with strong echoes are compatible with ray theory. On the upper figure the theoretical timing arcs for echoes from the external corners are superposed while in the lower figure the timing arc(s) from the bimetallic junction is shown. Comparing both figures shows the junction signature is visible as are other elastic features.



**Fig. 2.** Excitation of a low frequency mode of a scaled UXO model by way of modulated radiation pressure (MRP). The horizontal axis is time after the excitation of the MRP tone burst. The vertical axis is the frequency of the excited mode. The color indicates the magnitude of the laser-Doppler-vibrometer (LDV) signal indicating the UXO response. A picture of the UXO model is in the 2017 Report. The figure shows that when driven in the region of the resonance near 5 kHz, the UXO response remains large after the end of the exciting burst and subsequently decays. For an abstract describing the experiment, see: T. D. Daniel, P. L. Marston, A. T. Abawi, & I. P. Kirsteins, “Target response in a focused, modulated sound field: Modeling and experiment,” *Journal of the Acoustical Society of America* 143, 1739 (2018); <https://doi.org/10.1121/1.5035674>



**Fig. 3.** SAS image of the acoustic specular reflection from an impenetrable hemisphere in a horizontal boundary waveguide. The image was produced by vertically scanning a source-receiver transducer (located outside the waveguide) and by processing the data using the quasi-holographic processing method previously introduced at WSU. The direct specular reflection is labeled  $(0, 0)$  and it involves no reflection from the waveguide walls. It is the brightest image. The weaker adjacent image labeled  $(1, 0) + (0, 1)$  involves degenerate paths a single reflection from the wall of the waveguide. The vertical offset of that image is correctly described using a type of ray theory. The cross-range coordinate is normalized by the waveguide width ( $dl$ ) while the range coordinate is normalized by the hemisphere radius ( $a$ ). The offsets of some weaker images, labeled  $(1, 1)$ ,  $(2, 0) + (0, 2)$ , and  $(1, 2)$ , were also identified and modeled using ray theory. Those images involved additional wave-guide wall reflections. For an abstract describing the experiment, see: A. R. Fortuner & P. L. Marston, "Laboratory simulation of backscattering by a hemisphere in a boundary wave-guide with an external source," *Journal of the Acoustical Society of America* 143, 1855 (2018); <https://doi.org/10.1121/1.5036093>



**Fig. 4.** Backscattering of a tone burst from an empty rubber spherical shell in water. The late echo (which is delayed nearly by 100 microseconds from the initial echo) is from a wave guided circumferentially around the backside of the sphere by the rubber. These echoes are a new acoustic guided wave manifestation. (This phenomena will not be limited to empty rubber shells.) The different records are for different orientations of a seam present in the rubber shell. See: A. M. Gunderson, T. D. Daniel, P. L. Marston, and M. J. Isakson, “Observation and modeling of acoustic scattering from a rubber spherical shell,” *Journal of the Acoustical Society of America* 143, 3036-3046 (2018); <https://doi.org/10.1121/1.5038256>

## Acoustic Scattering Processes for Target Discrimination (2019)

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### Accomplishments Under Goals:

#### *A. Acoustical Imaging of Targets & Image & Signature Interpretation:*

During the current period we obtained improved measurements on our first negative buoyancy target having a prompt frequency-dependent response resulting in a high-frequency backscattering enhancement. That target may be useful for assessing the selective properties of the sonar of dolphins or of manmade high-frequency sonar systems. The frequency selective enhancement mechanism is related to one originally proposed and modeled in research directed by Marston [1,2] though the material selection and target shape differ for ease of fabrication. The relevant dimensionless frequency range is typically  $ka > 45$ . The mechanism identified would not be degraded if the target rests on the seafloor though the consequences of complete burial are not yet known. Some measurements of the prompt highly-frequency dependent response are shown in **Fig. 1**.

#### *B. Scattering Physics for Targets Adjacent to Flat Surfaces & Bistatic Scattering:*

Scattering by target in what we refer to a boundary waveguide corresponds to the situation where a target is in a waveguide but the source and receiver are external to the waveguide. Sound reaches the target from the source by passing through one of the walls of the waveguide and similarly sound passes through one of the walls of the waveguide to reach the receiver (which may be located at the source in the usual case of monostatic scattering). Multiple reflections within the waveguide modify the frequency response and time domain response of the target. Some evidence for this modification was found for a target in a mud-layer on sand in data acquired during the 2014 BayEx measurements [3]. With support of the present grant a partial experimental simulation of this situation was built and explored by Fortuner [4]. One of the waveguide boundaries is a free surface and the other is a flat thin plastic sheet of PMMA. A target was selected having only weak free-field frequency dependence so that the waveguide modification of the frequency response was obvious. The major waveguide modifications of the target's SAS image were also modeled. During this period Fortuner improved his modeling measurements of the test target to verify our claim that specular processes are dominant as shown in **Fig. 2**. This has made it possible to improve our experimental resolution of waveguide and multiple-scattering effects. During this period Fortuner also advanced our models of relevant aspects of bistatic scattering and assisted with experiments in support of our modulated radiation force measurements.

*C. Acoustic Radiation Force (ARF) & Maxwell Stress Excitation of Target Modes:* The modulated radiation force aspects are cooperative with DoD supported researchers who visited WSU in 2017 & 2018 and concern low-frequency (LF) target modes. We took measurements of the excitation of target modes and extended our prior models of the coupling with the emphasis on situations where targets are displaced from the focus of

the ultrasonic beam. The WSU-based theoretical approach is to split the theory into a LF-part in which FEM (done by Abawi at HLS) is used to compute target mode shapes while approximation methods are used to calculate the radiation stress distribution (on the target's surface) of an ultrasonic beam. In support of this approach we applied the same approximation methods to situations in which exact solutions are available [5]. During this period we made several advances including the following: (a) Modeling relevant aspects of focused wave-fields: By using an expansion method previously introduced by Marston in our case of focused sound beams, T. Daniel has reduced the wave-field computation problem to a single one-dimensional numerical integration. During this period his results were submitted, peer-reviewed and published [6]. See **Fig. 3**. (b) Lens design and testing to produce the improved focused wave-fields: We needed a longer-focal-length transducer submersible to greater depth than the commercial one we had been using. As a first step we designed a solid- low-loss-polymer lens for producing a longer focal-length ultrasonic beam (15 cm). It is likely capable of deep deployment. We designed this lens to be corrected for spherical aberration. That required the machining of a non-spherical-concave surface. The lens was machined at the WSU Technical Services Shop on a computer controlled milling machine. We verified that this lens design when coupled to a circular flat PZT plate produces a high-quality 710 kHz focused ultrasonic beam, **Fig. 4**. Beginning late August 2018 we used this source to drive a wider range of elastic modes on a wider range of targets than we had done with the prior commercial source. (c) Modes excitation on some large targets either recently fabricated or not previously deployed: The simplest example is a solid aluminum cylinder having  $L/D = (13.75 \text{ inches})/(2.75 \text{ inches}) = 5$  scaled to cylinders previously studied in low-frequency scattering experiments at WSU. This cylinder is large-enough to be deployed in outside-the lab experiments & small enough to be testable at WSU. In agreement with theory, the solid cylinder has an easily observed mode near 2100 Hz and the observed mode shape has the expected form (**Fig. 5**).

(d) Maxwell Stress research: The oscillating electromagnetic Maxwell Stress approach was verified with one of the newly constructed targets. In a different aspect of Maxwell Stress research Marston gave a new analysis of electromagnetic Maxwell torques on imperfectly conducting spheres [7].

*D. Other research:* Marston prepared and presented an invited review of quantitative ray methods for scattering by cylinders [8] and presented some acoustic radiation force calculations in preliminary form that were subsequently peer-reviewed and published [9].

*References & Selected Publications:*

- [1] G Kaduchak, DH Hughes, & PL Marston (PLM), "Enhancement of the backscattering of high-frequency tone bursts by thin spherical shells associated with a backwards wave: Observations and ray approximation," *J. Acoust. Soc. Am.* 96, 3704-3714 (1994).
- [2] PLM, "Negative group velocity Lamb waves on plates and applications to the scattering of sound by shells," *J. Acoust. Soc. Am.* 113, 2659-2662 (2003).
- [3] KL Williams, *J. Acoust. Soc. Am.* 140, EL504 (2016).
- [4] AR Fortuner & PLM, "Laboratory simulation of backscattering by a hemisphere in a boundary wave-guide with an external source," *J. Acoust. Soc. Am.* 143, 1855 (2018), <https://doi.org/10.1121/1.5036093>

- [5] PLM & TD Daniel (TDD), "Geometric approximation of radiation stress projections for canonical objects," *J. Acoust. Soc. Am.* 143, 1718 (2018); <https://doi.org/10.1121/1.5035596>
- [6] TDD, F Gittes, IP Kirsteins & PL Marston, "Bessel beam expansion of linear focused ultrasound," *J. Acoust. Soc. Am.*, 144, 3076–3083 (2018). <https://doi.org/10.1121/1.5080602>
- [7] PLM, "Humblet's angular momentum decomposition applied to radiation torque on metallic spheres using the Hagen-Rubens approximation," *Journal of Quantitative Spectroscopy and Radiative Transfer* 220, 97–105 (2018) DOI: 10.1016/j.jqsrt.2018.08.019
- [8] PLM, "Fermat's principle, Fresnel zones, and ray methods for high-frequency signatures of elastic cylinders in water," *J. Acoust. Soc. Am.*, 144, 1873 (2018).
- [9] PLM, "Phase-shift derivation of expansions for material and frequency dependence of progressive-wave radiation forces and backscattering by spheres," *J. Acoust. Soc. Am.*, 145, EL39–EL44 (2019); <https://doi.org/10.1121/1.5087646>

## Results Dissemination

### *A. Publications appearing during the period of this report include:*

- [1] PL Marston (PLM), "Humblet's angular momentum decomposition applied to radiation torque on metallic spheres using the Hagen-Rubens approximation," *Journal of Quantitative Spectroscopy and Radiative Transfer* 220, 97–105 (2018) DOI: 10.1016/j.jqsrt.2018.08.019
- [2] TD Daniel, F Gittes, IP Kirsteins & PL Marston, "Bessel beam expansion of linear focused ultrasound," *J. Acoust. Soc. Am.*, 144, 3076–3083 (2018). <https://doi.org/10.1121/1.5080602>
- [3] PLM, "Phase-shift derivation of expansions for material and frequency dependence of progressive-wave radiation forces and backscattering by spheres," *J. Acoust. Soc. Am.*, 145, EL39–EL44 (2019); <https://doi.org/10.1121/1.5087646>

### *B. Professional Conference Presentations during this period:*

#### (a) Invited:

- [1] T. D. Daniel, I. P. Kirsteins, & P. L. Marston, "Expansion of linear focused sound fields using Bessel beams," *J. Acoust. Soc. Am.*, 144, 1932 (2018), <https://doi.org/10.1121/1.5068458>
- [2] P. L. Marston, "Fermat's principle, Fresnel zones, and ray methods for high-frequency signatures of elastic cylinders in water," *J. Acoust. Soc. Am.* 144, 1873 (2018), <https://doi.org/10.1121/1.5068241>
- [3] P. L. Marston, "Phase-shift based expansions for material and frequency dependence of scattering and of radiation forces," *J. Acoust. Soc. Am.* 144, 1896 (2018), <https://doi.org/10.1121/1.5068311>

#### (b) Other:

- [1] Ivars Kirsteins, Ahmad Abawi, Philip Marston, & Timothy Daniel, "An examination of the scaling rules for sound emissions from targets excited by point-like forces," *J. Acoust. Soc. Am.* 144, 1811 (2018), <https://doi.org/10.1121/1.5067991>
- [2] Ahmad Abawi, Ivars Kirsteins, Philip Marston, & Timothy Daniel, "Scattering from multiple elastic targets using the coupled finite element/boundary element method," *J. Acoust. Soc. Am.* 144, 1810 (2018), <https://doi.org/10.1121/1.5067988>

[3] Aubrey L. Espana, Daniel Plotnick, Kevin Williams & P. L. Marston, “Multiple scattering effects for a solid cylinder with axis oblique relative to a nearby horizontal surface,” *J. Acoust. Soc. Am.* 144, 1811 (2018), <https://doi.org/10.1121/1.5067994>

*C. Ph. D. Dissertations:*

Timothy Derek Daniel, Jr.

Title:

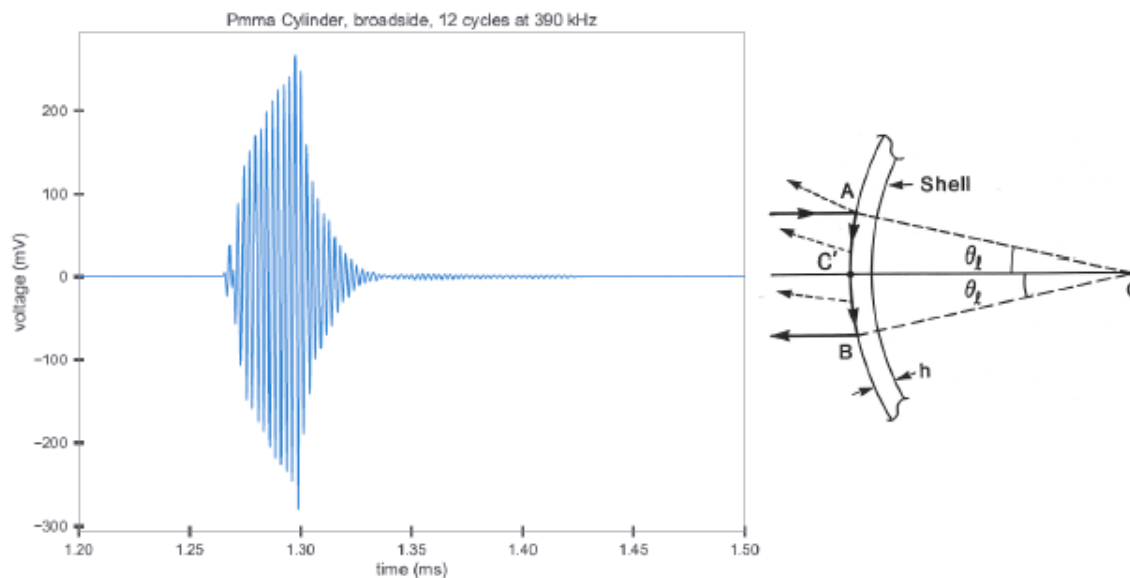
I. Harmonic Stress Excitation of Modes of Solid Objects

II. Analysis and Scattering of Focused Acoustic Beams

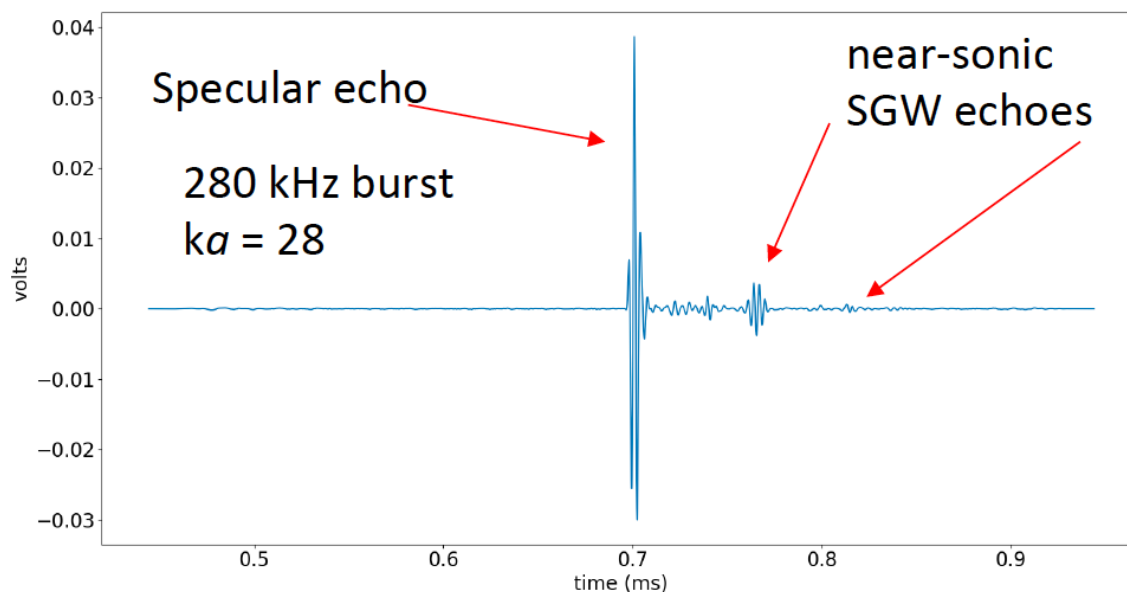
III. High Frequency Scattering by Truncated Solid Cylinders (Washington State University, Pullman, Submitted May 2019)

### **Technology Transfer & Related DoD Projects**

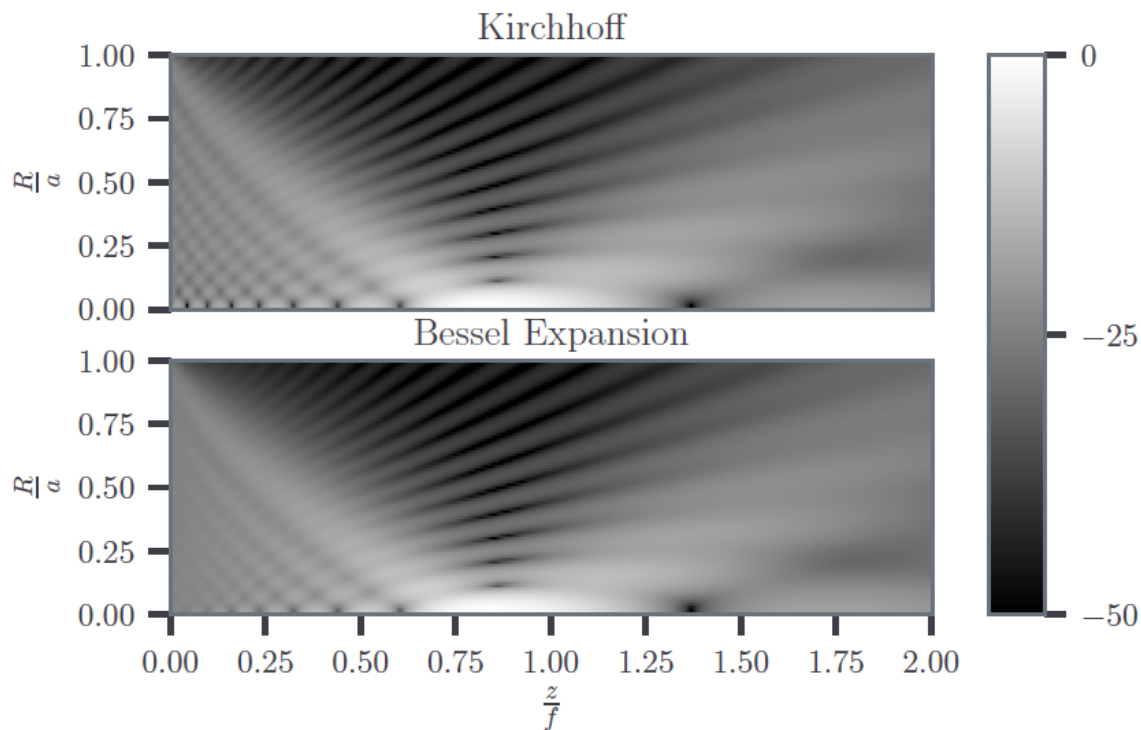
Contact the Principal Investigator for information.



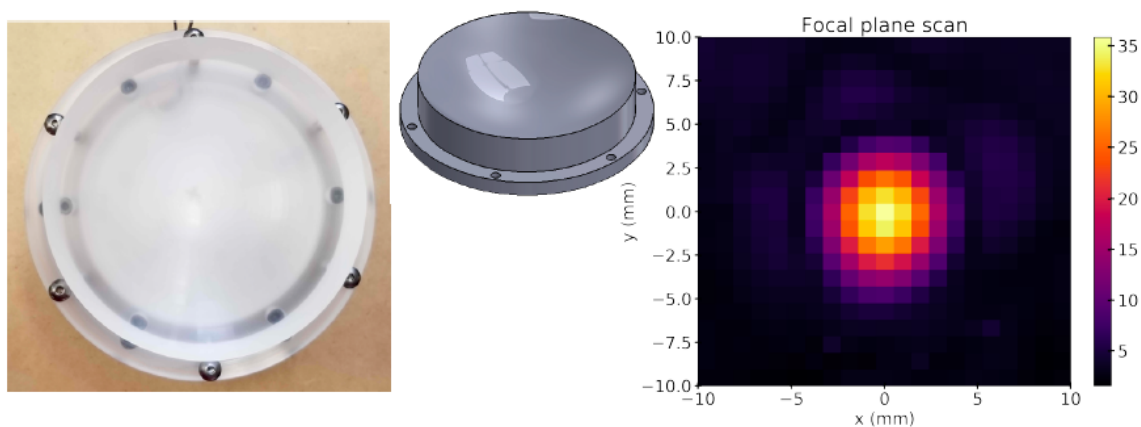
**Fig. 1: (Left)** Backscattering of a 390 kHz 12-cycle-long tone-burst by an empty 2.5-inch dia. acrylic cylindrical shell viewed broadside. The gradual buildup of the echo followed by a long ring-down (after the end of the incident burst) indicates a high-Q resonant feature. Both effects are well-suppressed 50 (or more) kHz above or below 390 kHz. **(Right)** Backwards-guided-wave ray diagram believed to be associated with this enhancement. This diagram was previously proposed & confirmed at WSU for a high-frequency signature enhancement observed for spherical steel shells [1,2].



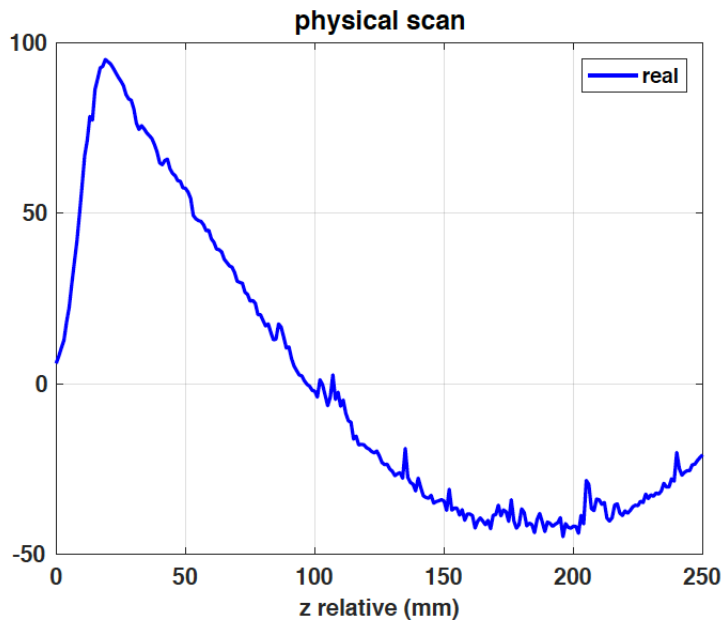
**Fig. 2:** Backscattering of a short tone-burst by an empty thin-walled polymer shell in water revealing the dominance of the specular echo. The weak delayed echo is from a surface guided wave SGW that circumnavigates around the backside of the shell.



**Fig. 3:** A comparison of a two-dimensional calculation of the magnitude of the complex pressure for a focused acoustic wave-field. The vertical axis is a normalized distance from the focal axis. The upper figure uses direct numerical integration. The bottom figure uses a novel Bessel beam expansion method. From our publication: TD Daniel et al., *J. Acoust. Soc. Am.*, 144, 3076–3083 (2018).



**Fig. 4: Left & Center:** Diffraction-limited ultrasonic lens corrected for spherical aberration. The material is a low-loss solid polymer. The focal length is 150 mm and the outer diameter of the lens element is 3.44 inches. **Right:** Focal-plane scan demonstrating high-quality focused 710 kHz wave-field having a wavelength of 2.1 mm. This is one of the lenses is being used for measuring target responses to modulated ultrasonic radiation force. It can be scaled up to longer focal-length or larger lens diameters if needed.



**Fig. 5:** The figure shows the evolution of a laser-vibrometer signal for a solid circular cylinder in water. It gives an empirical mode shape identification obtained by exciting the 13.75 inch (349.25 mm) long solid aluminum cylinder at resonance (near 2200 Hz) and scanning the source transducer in Fig. 4 along the cylinder's axis at a fixed range. The horizontal axis  $z$  is the distance from the start of the scan. The start was approximately 15 mm beyond the end of the cylinder. The vertical axis shows the phased response. There is an initial rise when the focus of the beam becomes centered on the antinode of this mode at the left end of the cylinder. There is a weaker antinode of opposite phase near  $z = 190$  mm near the cylinder's mid-plane. The antinode of this mode at the cylinder's right end is outside the scan range of the positioner used. The phasing is such that the imaginary part of the response was weak. The data was acquired at WSU. The ultrasound source was excited with only moderate excitation amplitude and an analogous hydrophone response (also indicative of the mode shape) was recorded also.

#### **IV. Information on Aaron Michael Gunderson's Ph.D. dissertation (2017).**

ACOUSTIC SCATTERING FROM PARTIALLY EXPOSED SPHERES AND CYLINDERS AT A FLAT INTERFACE, Ph. D. dissertation (Washington State University, Pullman, WA, May 2017).

Abstract: Scattering by partially exposed objects breaking through an interface is profoundly different from scattering by the same objects in a free field environment. The presence of the interface both adds additional scattering paths, and can strongly modify or remove preexisting paths, depending upon the level of exposure and grazing angle. Acoustic scattering by partially exposed spheres and cylinders through an interface is considered in the time and frequency domains. Scattering from a handball (a rubber, hollow spherical shell) is also considered, and results are compared to those from solid spheres. Experimentally acquired results are compared to several theoretic models, including the Kirchhoff approximation, partial wave series solutions, ray theory, and finite element simulations. The Kirchhoff approximation has previously been applied to backscattering from a rigid cylinder at a free surface [K. Baik and P.L. Marston, *IEEE Journal of Oceanic Engineering* 33, 386-396 (2008)], and the analogous process for a rigid sphere is developed here. Scattering path contributions are identified based on timing models and frequency content, and target elastic resonances and interference phenomena are discussed. Two different interfaces are considered in experiments and models: an air-water interface (free surface) and a sand-water interface. Comparisons and distinctions are made between the results at the two interfaces, which are shown to become similar in the low grazing angle limit. Smooth, continuous transitions in scattering amplitude are shown to correlate with scattering path coupling points becoming exposed as the target is lowered through the interface. Scattering in the low target exposure limit is shown to be dominated by Franz wave contributions (surface-guided, non-elastic waves). This contrasts with high exposure and free field scattering signatures from spheres and cylinders, in which the Franz contribution is highly diminished and is not a significant contributor. Bistatic scattering from free field spheres and cylinders is also considered, in the context of understanding the bistatic scattering paths from these targets at partial exposure through an interface. Results from this work have direct applications to understanding the scattering from partially exposed objects resting on or buried within a seafloor environment.

Dissertation document URL and document ID are unavailable at the time of this report.

## V. Information on Viktor Bollen's Ph.D. Dissertation (2017)

UNDERWATER ACOUSTICAL SCATTERING BY CUBES AND OF HELICAL BEAMS, Ph. D. dissertation (Washington State University, Pullman, WA, May 2017).

Abstract: Acoustic scattering is the study of the reflections of sound by objects, which is used to detect and identify said objects underwater. This dissertation has two parts; the first part discusses the topological properties of helical beams. An acoustic helical, or vortex, beam has a null down its axis of propagation and a phase ramp. In this dissertation, the modulation and direct measurement of the beam's helicity, and the forward and back-scattering by a small solid sphere were examined. Moreover, for the forward scattering a helicity sensitive detector was used, and for the nearly monostatic backscattering the source transducer was turned into a helicity sensitive receiver in post-processing. Since there is a rapid phase change across the null of the beam, sub-wavelength imaging of said null is possible. The experimental results were compared to a Kirchhoff-integration based simulation of the beam and its backscattering.

The second part covers the backscattering by solid cubes. Two cubes, one brass and one steel, were insonified underwater in a tank and their backscattering measured using Synthetic Aperture Sonar (SAS). Cubes were chosen as the target due to their sharp corners and flat faces, making it easy to measure aspect dependent backscattering, such as Rayleigh waves. Rayleigh waves couple into the face of the cube at a material dependent angle, called the Rayleigh angle, and are retro-reflected back to the source. Similar, to the helical beam, the backscattering of the cube was compared to Kirchhoff-integration simulations. The specular response was isolated from elastic effects using the simulations, which determined the cause of a splitting of the backscattered signal from the face of a forward tilted cube. Target images were also constructed using Fourier back-projection methods from the SAS scans.

Dissertation document URL and document ID are unavailable at the time of this report.

**VI. Information on Timothy Derek Daniel, Jr.'s Ph.D. Dissertation (2019)**

I. HARMONIC STRESS EXCITATION OF MODES OF SOLID OBJECTS

II. ANALYSIS AND SCATTERING OF FOCUSED ACOUSTIC BEAMS

III. HIGH FREQUENCY SCATTERING BY TRUNCATED SOLID CYLINDERS

Ph. D. dissertation (Washington State University, Pullman, WA, July 2019).

Contact the grant Principal Investigator for final Abstract. This Dissertation was supported in part by ONR Award N00014-19-1-2039.

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| <b>14. ABSTRACT</b><br>The purpose of this investigation was to improve the understanding of the way that sound in water interacts with various types of targets in situations similar to those encountered in underwater acoustics. The emphasis was on situations relevant to the use of sonar systems in shallow water. Laboratory methods were developed and tested for displaying the scattering of sound, including partially-exposed targets. Some of the work concerned bistatic scattering. Much of the research was in the intermediate frequency range where geometrically motivated ray based methods were helpful even when elastic responses were significant. Signal processing methods used included synthetic aperture sonar. Some of the research concerns the scattering by beams of sound (including vortex beams) and the response to acoustic radiation force of beams and other selective ways of exciting oscillations of objects in water. |                         |  |   |  |  |
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