Living With Sensors at APL

Isaac N. Bankman and Joseph J. Suter

The pursuit of the proximity fuze not only gave birth to APL in 1942, but also established the essential elements of the Laboratory's service in the realm of sensors, including the related science, technology, strategic contributions, technology transfer, production oversight, fielding, and interaction with military sponsors and soldiers. The comprehensive and focused approach that allowed the development of the proximity fuze is present today in many sensor projects as they evolve from initial concept to operational use in the field. In this article we present examples of recent projects that illustrate the diversity of sensor activities at APL, as well as the legacy of the Laboratory's first project.

INTRODUCTION

"Buck Rogers 110, common AA 47!" Messages such as this reverberated in the radio communications of the Pacific Fleet between January 1943 and the end of World War II. They reported the number of enemy planes downed with common anti-aircraft rounds and with the new rounds, whose utmost-secret fuze warranted their code name. Until then there were two types of common anti-aircraft rounds: those that detonated on impact, and those with a timer set manually to detonate at a selected time after firing.

The timer fuze was an improvement over the contact fuze, but still required a highly accurate estimate of the round's time of flight to its encounter with a maneuvering enemy plane.[1] It took typically 2400 rounds with the timer fuze to hit an airplane[2] because of uncertainties in the timing estimations, making our Pacific Fleet highly vulnerable to swarms of air attacks. A specialized sensor changed all that. The new, secret fuze equipped with a radio-frequency (RF) sensor made the Navy's 5-in. rounds much more effective than their common counterparts.

When first manufactured, the new fuze was already 3 to 4 times more effective than common fuzes, and at the end of the war, only about 400 rounds were used to down an enemy airplane. The sensor that allowed this advantage had a widespread and significant impact on the lives of many: it strengthened the Navy and protected the Marines, was used to develop the most effective army artillery rounds in the land warfare of their time, and was passed on to the British for defense against planes and V-1 bomb attacks. It also was the reason for founding APL in 1942.

A sensor that would detonate a shell within effective impact range from attacking aircraft, thought to be impossible by some, became an urgent quest in 1940 under the National Defense Research Committee. Exploratory efforts that included photoelectric, acoustic, and RF sensors were conducted by several institutions in the United States and Britain. The RF sensor soon proved to be the best for this application, and by the end of 1944, assembly lines were producing 40,000 proximity fuzes a day.[3]

The new fuze, also known as the variable time ("VT") fuze, detonated the shell at varying times after leaving the gun barrel, depending on the sensor's observations. More than 22 million VT fuzes were manufactured by August 1945. An estimated 1 million U.S. civilians and military personnel were involved in the research, development, and production of the proximity fuze and its use in the battlefield. When it was established in Silver Spring, Maryland, APL had 100 staff members, all working on the proximity fuze; by 1944 this number had reached 700.[3]

The development of the proximity fuze was a fundamental component of the Laboratory's contributions to the nation. This article highlights the legacy of the VT fuze and presents some recent projects that demonstrate APL's wide-ranging sensor activities involving technical aspects that were also addressed in the development of the VT fuze such as miniaturization, effective use of heterodyne detection, safety, and characterization of the environment.

FITTING IN

One of the most daunting challenges of the VT fuze was integration of a radar transmitter, its receiver, the battery plates, the battery fluid flask, safety devices, the igniter, and a self-destruction switch inside a cylindrical space of about a 4-cm diameter and 16-cm length within a 12.7-cm shell (Fig. 1). This was accomplished using the electronic component technology of the 1940s, with high enough integrity to withstand a 20,000-g acceleration at launch and centrifugal forces due to a rotation of 30,000 rpm in flight.[2] This remarkable miniaturization was paramount to the feasibility of the VT fuze. Today, APL is actively involved in miniaturized sensor development for diverse applications.

Microelectromechanical Systems

Microelectromechanical system (MEMS) sensors are, in general, mechanical structures manufactured by batch processing of a conventional semiconductor wafer yielding small-sized, low-cost, and reproducible features. A typical mechanical structure is designed around three or more layers of structural material, anchored to either the substrate or to each other using via holes in interleaved layers of a suitable sacrificial material that is dissolved away at the end of batch processing. Several structural geometries have been successfully implemented as a variety of MEMS sensors including diaphragms for pressure sensors, floating elements for accelerometers and gyroscopes, cantilevers for scanning-tunneling or atomic-force microscopy, resonators for RF circuit elements or magnetometers,[4] and moveable shutters for thermal control on microelectronic packages.[5]

At APL, Ben Givens, Dennis Wickenden, John Champion, Tom Kistenmacher, Jay Lamb, Robert
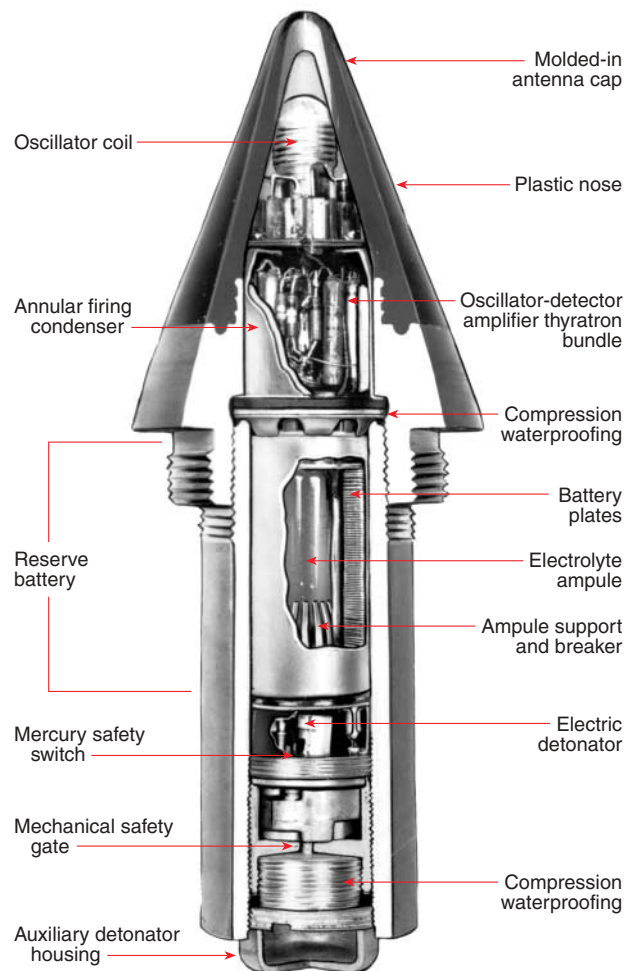

Figure 1. The VT fuze and its components.

Osiander, Doug Oursler, John Tucker, and Danielle Wesolek have been developing MEMS sensors for civilian and military applications for about 6 years. To date, the work has primarily concentrated on resonating mechanical devices where polysilicon is the structural material, using the fabrication services of either a commercial three-layer MEMS foundry or the Sandia SummitV five-layer facility. This approach leads to discrete devices that require separate electronics to control, drive, and sense the mechanical motion responsive to the driving force (e.g., pressure, electromagnetic field) to be measured.

Assembly complexity and the adverse effects of large parasitic capacitances can be reduced by placing the electronics on the same substrate in a fully integrated manner. However, the established techniques use interdigitated drive and sensing electrodes whose movements are restricted to a plane parallel to the die surface, and preclude easy adaptation to different methods of sensing movement. A potential solution is to use deep, reactive ion etching on MOSIS-type CMOS foundry structures,[6,7] yielding elaborate, high-definition structures

with performances comparable to their polysilicon or silicon-on-insulator equivalents.

The mechanical structures are composed of combinations of the polysilicon gate layer, interconnecting metal layers, and isolation dielectric layers used in standard CMOS processing. Typically, the top metal layer is employed to protect the electronic circuitry from the post-processing etching used to release the micromechanical structures. The metal layers are electrically connected in conventional comb-finger capacitive drive and sense structures so that the comb fingers function in the same way as their homogeneous polysilicon or silicon counterparts. However, metal layers in multiconductor comb fingers can also be selectively interconnected to form two sidewall capacitors between comb fingers whose capacitances change with motion perpendicular to the substrate surface.

The use of CMOS MEMS enables the development of complex micromechanical structures such as the combination of vibrating bar xylophone magnetometers; x-, y-, and z-axis accelerometers; and angular rate sensors with state-of-the-art capacitive sense performance on a single chip. The mask layout for a double vibrating bar magnetometer, complete with the sensing electronics, is shown in Fig. 2. The availability of such a technology facilitates rapid development of a wide variety of sensors with broad applicability to APL's potential needs.
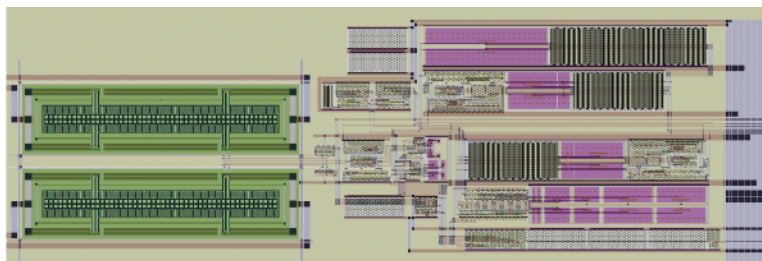
Expendable Underwater Transmissometer

Compact sensors are also under development for submarine applications. Kirk Decker, Thomas Murdock, Karen Rennich, Jason Stipes, and James Velky recently developed the Expendable Underwater Transmissometer that provides profiled, *in situ* water-quality measurements in support of various prototype imaging systems. This inexpensive device was specifically designed to fit into the probe compartment of a Sippican submarine-launched expendable bathythermograph (SSXBT), allowing existing onboard launch and data acquisition equipment to be exploited. The expendable transmissometer (SSXBX) can be launched using any of the signal ejectors aboard U.S. submarines. The design achieves a stable, low-cost SSXBX integrated into a low-profile, existing hydrodynamic shell and facilitates transition into a mass-produced package.

The optical subsystem of the SSXBX includes a light-emitting diode (LED) source, projection optics, a measurement cylinder that contains the water under test, a retroreflector, receiving optics, and a photodiode detector. These components are configured in a "diverging collimated beam" arrangement that fits in the small available space. This approximates operation with a point light source using field stops on the focal planes of both the projector and receiver objective lenses. Light from the projector reflects back from the retroreflector, and the receiver detects the reflected light after two-way transmission through the water cylinder.

The electrical subsystem contains the LED driver, including an LED output stabilization circuit, the photodiode signal amplifier and data transmission circuitry, and a power supply circuit with battery power source for 15 min of operation. The mechanical subsystem contains the electro-optics housing, the combination nose/retroreflector housing, and the housing support frame. The optical, electrical, and mechanical subsystems (Fig. 3a) fit in a cylindrical volume approximately 24 in. long and 2 in. in diameter, and weigh no more than 1.5 lb.

After launch from a submarine (Fig. 3b), the SSXBT floats to the surface and releases the SSXBX probe, which begins profiling and descends gradually to the seafloor (Fig. 3c). The probe communicates its data to the submarine via the existing SSXBT junction box. The SSXBX provides an effective combination of performance, miniaturization in volume and weight, low cost, and reduced power dissipation. It is the first truly expendable transmissometer since it has a small footprint, is reproducible in mass quantities at low cost (less than $1500), and can be self-powered (e.g., battery, capacitor) for its operational lifetime. In addition, it delivers scientific-grade performance by providing improved accuracy capability over commercial alternatives. Validation tests against an established APL standard transmissometer indicate that the SSXBX performance matches the standard within 3% accuracy. Repeatability tests also show reliable performance in long-term operation.

X-Ray Scanning System

A biomedical application where compact design is particularly essential is the Advanced Multiple Projection Dual Energy X-ray Absorptiometry (AMPDXA) Scanning System that Harry Charles, Tom Beck (JHU Department of Radiology), Michelle Chen, Howard Feldmesser, and Tom Spisz are developing under funding by the National Space Biomedical Research Institute.[8] This is a precision scanner system for monitoring the deleterious effects of

Figure 2. Mask layout for a double vibrating bar magnetometer with sense electronics for fabrication using a standard CMOS foundry.
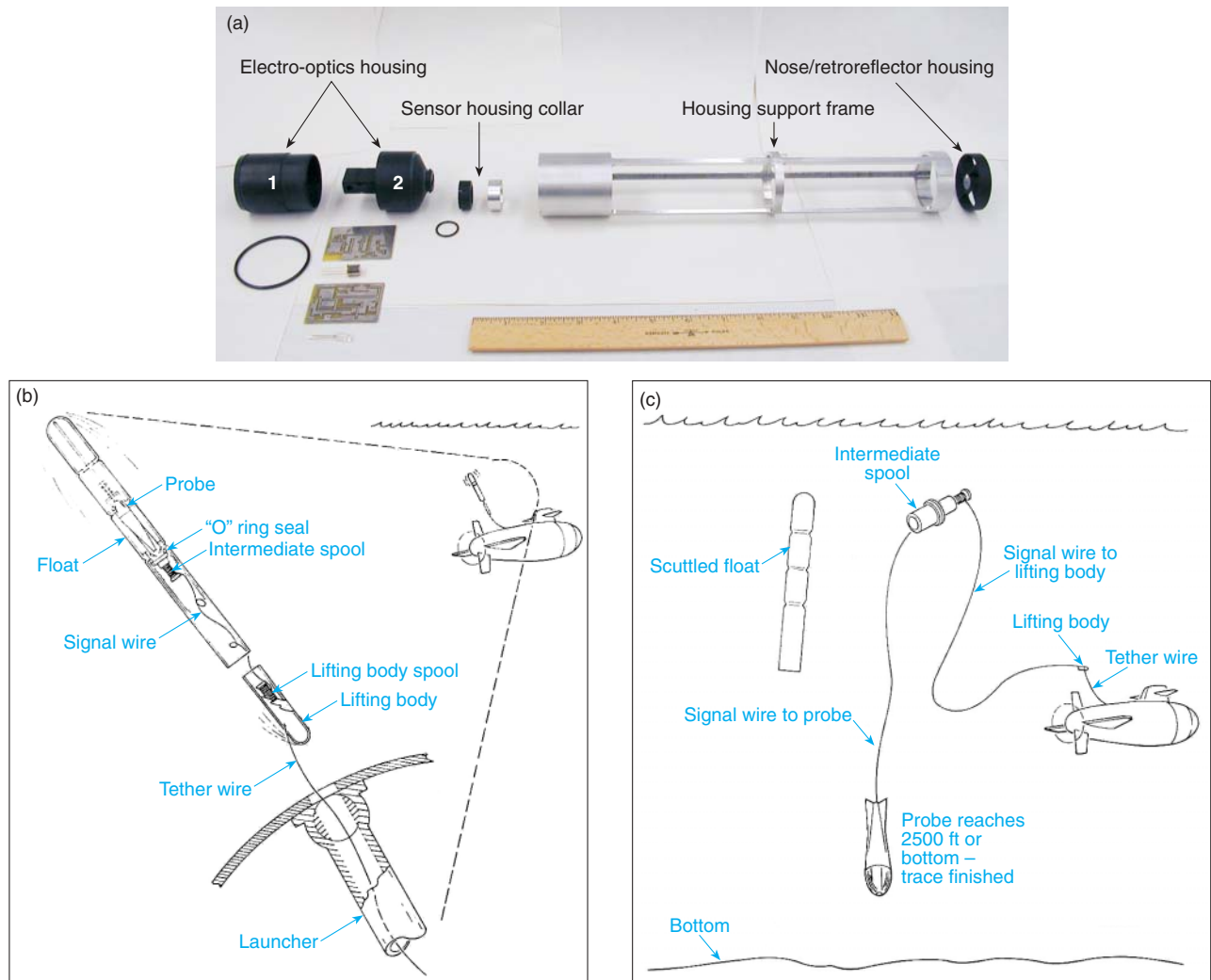
Figure 3. The Expendable Underwater Transmissometer: (a) main parts inside the probe, (b) start of a Sippican submarine-launched expendable bathythermograph deployment, and (c) fully deployed probe and connections to other parts.
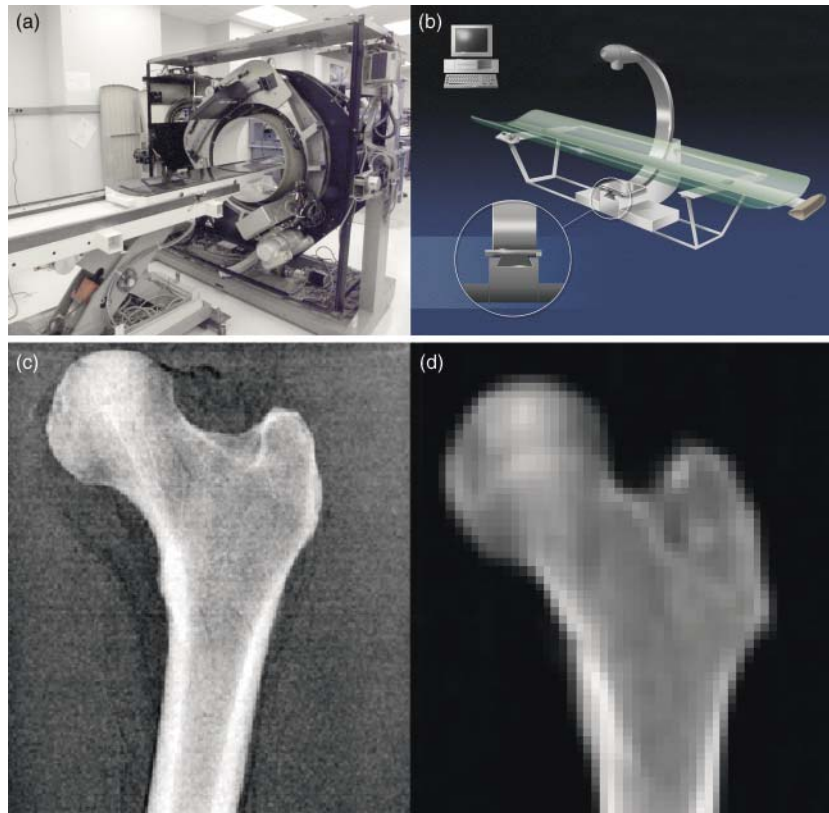
weightlessness on the human musculo-skeletal system during prolonged spaceflight. The scanner is designed to minimize volume and mass for space use while maintaining the required mechanical stability for high-precision measurement to detect changes of 1% in bone mass and geometry and 5% in muscle mass. The system is intended for use by astronauts in space to monitor their loss of bone and muscle mass and to regulate countermeasure doses dynamically.

The bone fracture risk upon returning to planetary gravity levels can also be estimated using the measurements. The AMPDXA measures bone mineral density (BMD) and separates soft tissue into fat and muscle. These measurements can be used to derive structural properties such as cross sections and moments of inertia. Multiple projections, coupled with axial translation, provide three-dimensional imaging with sensitivity and resolution suitable for accurate structural analysis. Such analysis results, used in conjunction with bone models and estimated loads, can determine the fracture risk.

The main activities of the AMPDXA project include instrument development, algorithm development for BMD image extraction and structural analysis, and bone reconstruction and modeling. The clinical test system and the planned space prototype are shown in Figs. 4a and 4b. Initial tests aimed at verifying principles and theoretical expectations have produced promising results and indicate that significant improvement in image quality over a conventional, new commercial DXA system can be achieved (Figs. 4c and 4d). The BMD image of the AMPDXA has higher resolution, and the mass distribution in a projected thickness of a femur slice contains much more structural detail than the conventional DXA.

Using three or more projections about the bone axis, the AMPDXA allows measurement of structural properties that are independent of patient position

Figure 4. Advanced Multiple Projection Dual Energy X-ray Absorptiometry (AMPDXA) Scanning System: (a) clinical test system, (b) illustration of planned space prototype, (c) image of the femur immersed in water obtained with developed AMPDXA, and (d) image of the femur in water obtained with conventional DXA.

The Doppler shift of the signal returning from the target played a major role in the operation of the VT fuze.[2] The signal returning from the target was beaten against the transmitted signal within the miniature vacuum-tube receiver module. Specialized detection techniques determined with remarkable accuracy the distance to the target and ignited the fuze. The Doppler effect, which conveys information on the relative motion of the target or its parts, is the basis of numerous sensor applications at APL today.

Doppler Processing in Radar Guided Missiles

Anti-air radar-guided missiles typically use Doppler processing to discriminate moving targets from stationary or slow-moving objects. Radar returns from natural surfaces, collectively known as clutter, are commonly much stronger than the return from the target itself. Chaff, i.e., bundles of metal strips that separate and form a cloud of radar reflectors when launched from an aircraft, can also produce a radar return much larger than the aircraft's. To discriminate the target signal from such large interfering signals, the missile employs bandpass filters, tuned to the expected target Doppler frequency, to attenuate signals at other frequencies. Digital RF processors usually use fast Fourier transform techniques to implement this filtering.

In addition to chaff, a variety of electronic countermeasures (ECM) have been developed over the years to hide or mask the target signal. Wideband noise jammers, which cover the region of the Doppler spectrum containing the target, can obscure the target return if sufficiently strong. False Doppler targets, also known as "velocity gate stealers," can confuse the Doppler processor, causing it to select a signal at the wrong frequency and provide a false estimate of target velocity. Missile receiver designers have responded to such measures with home-on-jam modes, rapid re-acquisition logic, and other electronic counter-countermeasures (ECCM). The battle between ECM and ECCM designers began shortly after the birth of radar and continues to this day.

APL has made numerous contributions on both sides of the electronic battle since it began development of Navy radar-guided missiles in the 1950s. During the Vietnam War, ECM and tactics to counter North

such as maximum and minimum moments of inertia for bending or torsion in any plane. Initial experimental measurements with different sets of three projections showed that the principal moments of inertia could be determined within 3 to 4%. Instrument improvements and additional projections (above three) can reduce this number further. The AMPDXA may also have Earthbound clinical and research applications such as monitoring the effect of aging and disuse on bone integrity, screening for osteoporosis, and monitoring osteoporosis drug therapy.

TELLING BEATS

In the quest for an effective VT fuze, as noted earlier, several physical phenomena were considered to determine proximity to the target. In particular, acoustic, photoelectric, and RF techniques were studied and initial experiments were conducted.[3] Acoustic and photoelectric techniques were found to be sensitive to environmental and background effects and were also difficult to implement in a fully automated manner. Gradually, the RF sensor emerged as the one that could operate with the desired sensitivity and without operator assistance.

Vietnamese surface-to-air missiles and protect U.S. pilots were developed under a program led by Alvin Eaton. Captive-carry exercises, using actual missile guidance sections, have been conducted under the leadership of Lex Hughes since the early 1980s to help characterize multipath and clutter returns from ocean, desert, and mountainous terrain. Models of multipath and clutter, as well as various types of ECM, have been incorporated by Bob McDonald, Mike Leumas, Mark Smalley, Jeff Dumm, and others into detailed six-degree-of-freedom missile simulations to assess missile performance in the presence of such electromagnetic interference.
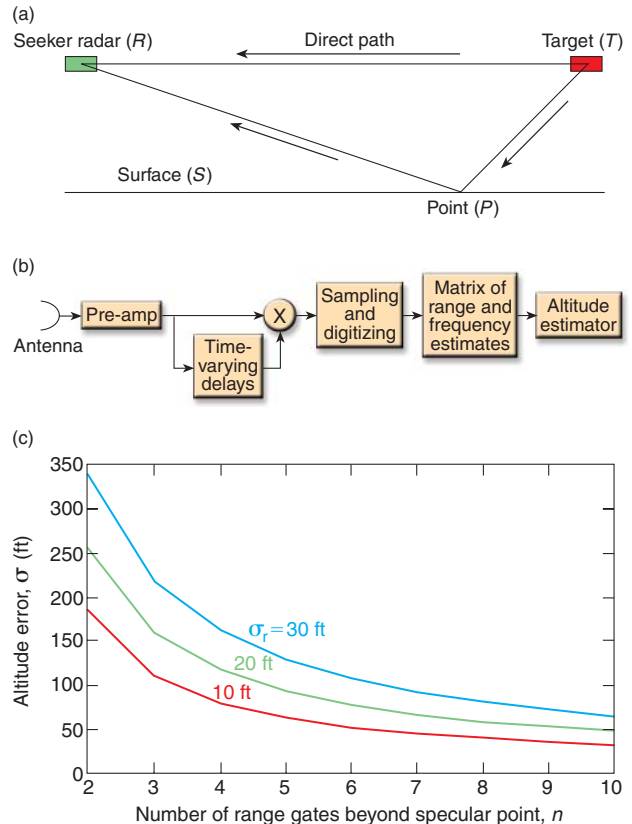
Diffuse Multipath Estimation

The use of range and Doppler processing is essential in techniques that Richard Pavek developed for estimating the altitude of targets bearing certain ECM. These techniques are especially designed for air-to-air seekers. When targets are flying at low altitudes, in addition to the direct radar path, surface bounce introduces additional indirect paths (Fig. 5a). In such cases, multipath is usually sufficient to deprive the seeker of accurate information about target elevation angle, and consequently its altitude.

Two different techniques designed to address the diffuse multipath problem deal with two different cases: the repeater countermeasure[9] and the broadband noise emission.[10] In the repeater ECM, emission begins at the seeker radar (R) and reaches the target's repeater (T). Some of its energy travels directly back to the seeker radar and some scatters to the surface (S) before arriving at the seeker radar. In the noise ECM case, emission begins at the target noise jammer (T), where the backscatter travels on both the direct and indirect paths to the seeker radar receiver. At low altitude, the emission from each of these countermeasures usually causes the direct path and the dominant multipath signals to be unresolvable in range, Doppler shift, and angle. Furthermore, the countermeasure can engage a terrain bounce technique by purposely directing the emission toward a point (P) on the surface, causing the seeker to track well ahead of the target.

The new APL techniques, Diffuse Multipath Estimation (DME) for repeaters and DME for noise emissions, use information that is typically untapped by other algorithms. Unlike most methods that attempt to mitigate or suppress the effects of multipath in a low-altitude setting, these two DME techniques actually exploit the diffuse multipath, and thus need not assume that the familiar specular return is the only significant signal coming from the surface. They also exploit the alternative hypothesis in which diffuse returns from other surface locations, while weaker, should also be measurable. DME algorithms infer the target's altitude by examining the interrelationship between range and

Doppler measurements taken across the surface and from the direct path return. In addition, other available seeker and target information is used to complete a geometric model and form a range-Doppler image of the surface.

In the case of DME for repeaters, the target altitude is estimated using known geometrical relations between the target and the seeker's radar, especially once direct path measurements have yielded range and closing velocity without much terrain distortion. Altitude estimation in DME for noise ECM is similar, except that an autocorrelation receiver (Fig. 5b) is needed to extract the information because the arriving signal's waveform is unknown to the receiver. The received noise is the sum of continuous broadband random processes, each delayed and frequency shifted as it scatters from various locations on the surface. The technique yields a theoretical altitude error (Fig. 5c) for the selected radar parameters. These errors represent elevation angle accuracy that is much less distorted than that of standard radar monopulse techniques when the terrain or sea surface has strong multipath. These techniques make possible, and optimize, a compromise between the resolution and

Figure 5. Diffuse multipath estimation: (a) illustration of direct and indirect paths, (b) block diagram of an autocorrelation receiver, and (c) error of altitude estimation (standard deviation) as a function of the number of radar range gates beyond the specular point on the surface for three accuracy levels in the estimation of the indirect path (σ_r).

the signal-to-noise ratio (SNR). Resolving specular from diffuse returns is easiest at a large number n of range gates from the specular point, whereas achieving SNR in a diffuse cell is easier at small n because scattered amplitudes generally decline with n.

Laser Radar in Ballistic Missile Defense

Radar and passive infrared (IR) sensors can locate the warhead of a separating ballistic missile in some cases. However, recent ballistic missiles that deploy countermeasures such as decoys, jammers, chaff, and flares present a serious challenge for these two sensors. A solution is to include a ladar in the seeker of the interceptor missile and use the advantages of an optical active sensor system. To study the feasibility and added value of ladar on a seeker, Isaac Bankman investigated ladar sensors and developed models of the ladar signatures of ballistic missile parts.[11] These models are used in algorithm development for ladar discrimination. The signature models take into account the properties and mechanism of ladar sensors, including their angular, range, and Doppler measurements as well as the structural, optical, and dynamic properties of the target objects.

Long-range ballistic missiles pass from the exo-atmosphere, and the reentry vehicle (RV) is typically spin-stabilized to keep it on its intended ballistic trajectory. Discrimination of the RV must be accomplished at very large distances from the target and therefore must be based on a sensing mechanism that is not diffraction-limited. Range-Doppler ladar provides informative RV signatures from such distances and has good potential for discrimination.

For observing and discriminating ballistic missile parts, the large translational Doppler shift due to the closing velocity is disregarded, and the observed object is represented by a set of rotational Doppler spectra in consecutive range bins. When the RV is spinning, points that move toward the receiver increase the laser frequency and those that move away decrease it. This Doppler broadening is small in range bins at the tip of the RV and becomes larger toward the base where rotational radii are larger (Fig. 6a). In addition to radius, the spectral broadening in each range bin is a function of the spin rate, aspect angle, and half tip angle of the RV cone shape. Figure 6b shows the model output obtained with the same parameters as the experimental signature of Fig. 6a. Ladar signatures of diverse objects in separating ballistic missiles can be simulated with this model (Figs. 6c and 6d).

When the RV is not spinning, the signature is reduced to a total power in each range bin known as the "range profile." Both types of signatures convey information and can be used for discrimination of the RV. Models and algorithms developed at APL address RV discrimination using ladar range-Doppler signatures and range profiles at arbitrary aspect angles. The change

in an object's signature during an engagement provides additional discrimination potential.
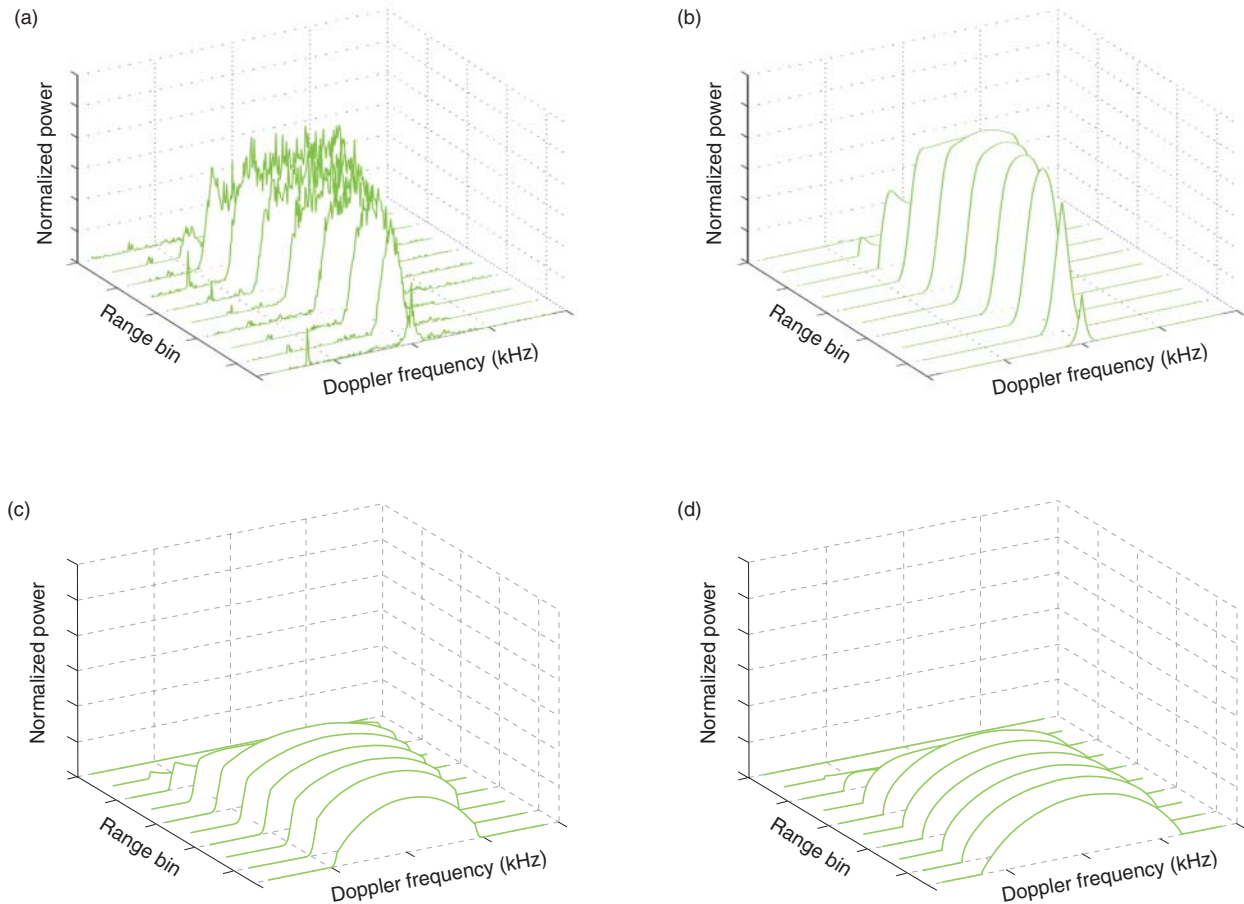
SAFETY

To safeguard personnel handling the round and loading the guns, the VT fuze had to include a highly effective safety device. This meant that the fuze had to be armed only after it had left the gun muzzle on its way to the target. The main safety device was a "mercury unshorter switch."[2,3] The switch, 0.6 cm in diameter and 1 cm long, included two cylindrical chambers. The inner chamber, which contained mercury, had a porous wall through which mercury could pass into the outer chamber only when driven by a force of sufficient magnitude. While inside the inner chamber, the mercury formed part of a circuit that shorted and disarmed the fuze. When the projectile was fired, the centrifugal force due to the spin forced the mercury to the outside chamber and armed the fuze. This required mercury with a very high purity level; the highest-grade commercial mercury was further purified by distillation for use in the VT fuze. Today, the safety of military and civilian personnel is one active area of APL work, and a wide range of techniques is in use for the development of sensors for safety.

Terahertz Sensor for Land Mine Detection

One of the most pressing issues for the safety of soldiers and civilians today is land mine detection. David Kohler, Robert Osiander, Joe Miragliota, Paul Schuster, and Jane Spicer have started to develop and investigate a sensor for mine detection using an ultra-fast terahertz laser system. The part of the electromagnetic spectrum between millimeter waves and far IR is referred to as "terahertz radiation" or "T-rays." This spectral range, 0.1 to 10.0 THz, can be used for high-resolution remote subsurface imaging with spatial and depth resolution better than 1 mm, enabling differentiation of mines from other objects of similar size. Terahertz sensors are good candidates for an alternative that complements ground-penetrating radar for mine detection. Furthermore, the spectral information of the transmitted and/or scattered radiation in a terahertz system may be used to identify materials such as plastics or explosives.

An effort in this area addressed the best terahertz source and the imaging capabilities of such a system. The propagation and penetration of terahertz radiation in soil under different environmental conditions and the spectroscopy of different explosives are also under investigation. A laboratory terahertz system was constructed at APL, while feasibility measurements were performed with a terahertz system at the Rensselaer Polytechnic Institute in collaboration with X-C. Zhang.

Experiments conducted at a SNR of 70 dB indicated that radiation could be detected after transmission

(a)

Normalized power

Range bin

Doppler frequency (kHz)

(b)

Normalized power

Range bin

Doppler frequency (kHz)

(c)

Normalized power

Range bin

Doppler frequency (kHz)

(d)

Normalized power

Range bin

Doppler frequency (kHz)

Figure 6. APL laser radar signature model (Ref. 11) used in ballistic missile defense: (a) Experimental ladar range-Doppler signature of a spinning cone recorded at the Army Advanced Measurements Optical Range. (b) Output of the APL model for the same spinning cone and aspect angle. (c) Simulated ladar range-Doppler signature of a rotating frustum. (d) Simulated ladar range-Doppler signature of a rotating cylinder. The aspect angle and spin rate of the frustum and cylinder are the same as those of the cone in (a).

through 3 cm of moist sand, although terahertz radiation is strongly scattered by the sand (16.5 dB/cm) and attenuated by the water content (8.2 dB/cm per weight percent of water). These experiments also showed that the best results can be obtained at frequencies between 0.1 and 1.0 THz, which can be easily generated with a moderately short laser pulse (150 fs) and a biased GaAs emitter. Efforts are under way to increase the efficiency of terahertz radiation generation for this wavelength band.

To demonstrate the feasibility of terahertz radiation to image small, buried dielectric objects, a neoprene grommet was embedded in 0.5 cm of sand and scanned under the terahertz beam. (Neoprene is typical of the materials used to encase nonmetallic mines.) The resulting image (Fig. 7) shows that it is possible to resolve features of the order of millimeters such as the hole in the grommet. Present efforts also focus on the identification of explosives and explosive residues using terahertz spectroscopy under funding by a Multi-University Research Initiative from the Army Research Office.

Molecularly Imprinted Polymers for Explosive Detection

Detection of explosives and explosive residues using novel chemical techniques is addressed by George Murray, Dave Lawrence, and Paul Schwartz in collaboration with the University of Maryland. Available techniques require large, complex, and expensive instruments such as liquid or gas chromatographs coupled with mass-spectroscopic or chemiluminescent detection. These instruments also require highly skilled operators and involve difficult maintenance procedures. The transport of their samples is associated with extensive documentation and an increase in the possibility of contamination.

Immunoassay tests are available for sensing some explosives but are cumbersome to use and have short shelf lives. Sensors based on optical fibers or self-contained optical devices are small, simple, and portable but are not selective enough because of the lack of chemically specific recognition elements needed for their transduction. The production of a selective and sensitive transduction
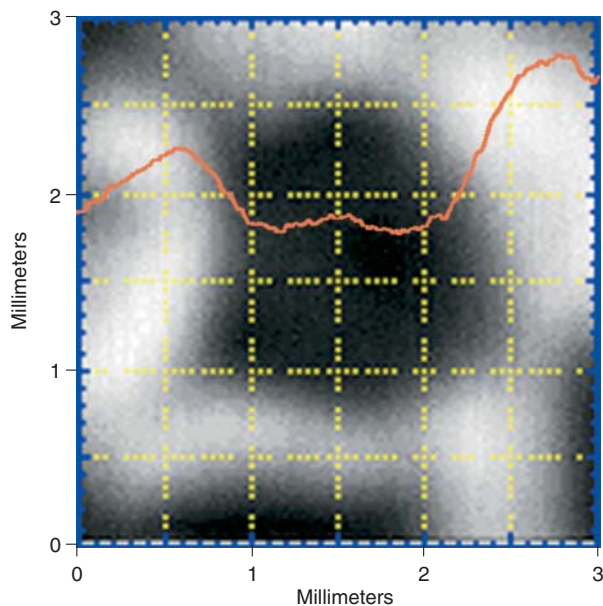
Figure 7. Terahertz image of a neoprene grommet embedded in 0.5 cm of sand. Neoprene is a land mine material that is difficult to detect.

mechanism for the detection of explosive vapors can contribute considerably to a broad range of applications.

The required transduction specificity may be obtained with molecularly imprinted polymers (MIPs), which can be used to synthesize materials for selective chemical sensors. MIPs are produced by first building a complex of a target molecule and associated attached binding molecules that can be incorporated into a polymer.[12] Charge transfer complexes are formed between molecules with complementary electronic structures using Van der Waals forces. The association can result in a spectroscopic transition that removes an electron from the highest occupied molecular orbital of the donor molecule to the lowest unoccupied molecular orbital of the acceptor molecule. The result can be a net transfer of charge from one molecule to the other, with the production of a pair of ions held together by electrostatic attraction. The excited state complex or "exciplex" can decay by photon emission back to the ground state. This results in two new spectroscopic transitions whose emission wavelengths are longer (red-shifted) than the wavelengths of the parents. These red-shifted emissions occur only when the two molecules are associated.

Sensors based on MIPs can be tailored to detect a specific explosive molecule and, if desired, can be directed toward a group of chemically similar compounds. The same methodology can be applied to provide an array of sensors covering the full range of explosive chemicals. The sensors can then be used as portable detectors for forensic investigations, as implanted *in situ* sensors, or as part of a sensor array for continuous monitoring.

APL has evaluated a variety of electron donors for the detection of dinitrotoluene, trinitrotoluene, and trinitrobenzene. Initial donors such as allylpyrrolidine and allylpiperdine were found to function and be polymerizable. Higher levels of red-shifted emission are obtained with vinyl-substituted zinc tetraphenyl-porphyrin and buckminsterfullerene.

The polymer matrix is initially formed at a relatively high crosslink level to ensure the most favorable conditions for retention of the cavity "memory" once the template is removed. A subsequent grinding step is employed to maximize surface area and allow access by the various reagents and samples. Consequently, a solution of the monomer, self-assembled complexes, divinylbenzene crosslinker, and various amounts of a suitable solvent (0–50 weight percent of alcohol porogen) is made. In each case, the crosslinked polymer is washed, ground to a uniformly fine powder, then continuously eluted with nonpolar solvents to remove the unreacted monomer. Sieves are used to sort the particles. A suitable solvent (acetone) is used to swell the polymer, allowing greater access to the imprinting molecule. A large fraction of the template is removed, leaving cavities that become template-specific.

A 16-channel imaging land mine detector prototype (Fig. 8a) that operates with fiber-optic sensors coated with MIPs (Fig. 8b) has been designed, engineered, and fabricated. It is currently undergoing testing and evaluation. The imaging detector supplies forced draft air to the optrode, supports optical detection, and provides heated air to facilitate clearing the detectors after a positive test. The controls and output of this 16-channel detector are provided by a laptop computer using a software package running under LabView.

Assessment of Concrete Structures

A particularly important safety concern in the civilian world is the system of bridges and highways that carries a continuous multitude of vehicles and people. This makes cost-effective and efficient ways of assessing the structural condition of deteriorating bridges and other concrete structures essential. The primary cause of bridge deck deterioration is the corrosion of the reinforcement, also called rebar. Bridge decks are currently monitored with periodic visual inspection by trained personnel, or with individual sensor measurements based on electrical resistance methods that estimate the likelihood of corrosion. However, measurements with such sensors are destructive in nature since the concrete must be drilled for electrical connections to be established with the rebar. Furthermore, the available monitoring information is often too little, too late. Modal Analysis Processing (MAP), developed by Dave Blodgett, is a nondestructive technique that allows rapid assessment of the rebar bonding state in existing reinforced concrete structures.

The MAP system takes advantage of the acoustic modal (resonance) properties of rebar in the concrete structure
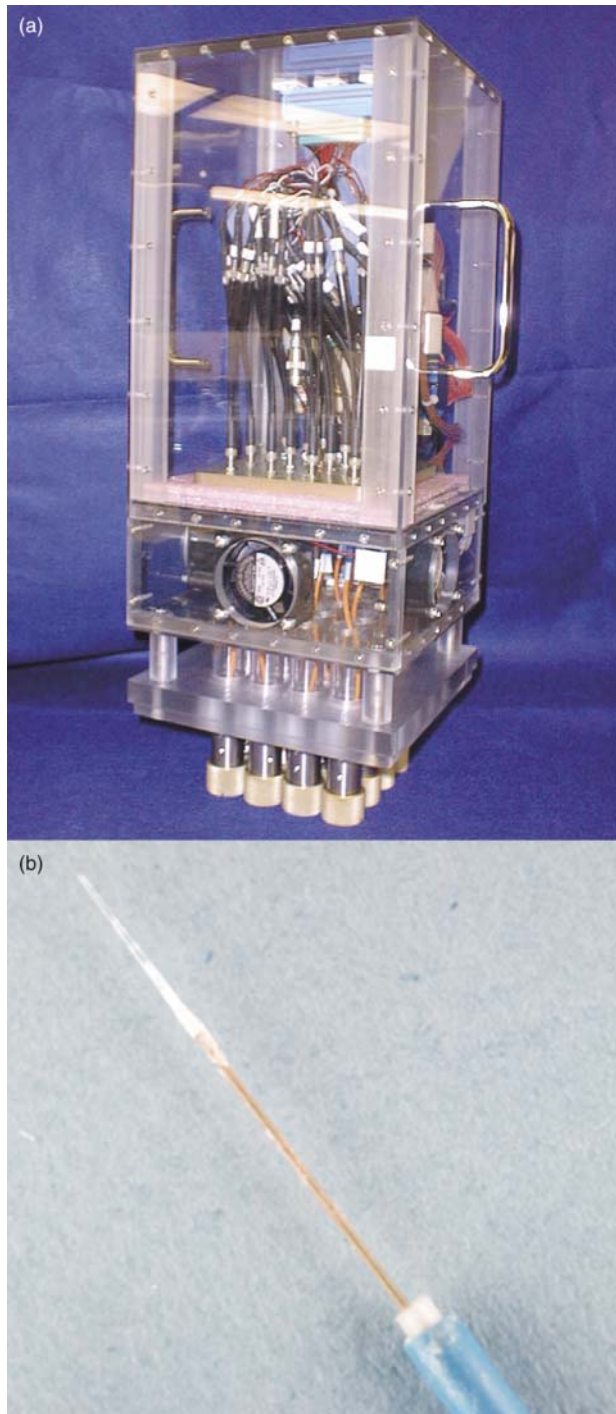
Figure 8. Explosive detection with chemical sensors: (a) a 16-channel land mine imaging detector and (b) a fiber-optic sensor coated with MIPs.

in order to determine if significant corrosion has occurred. In the absence of corrosion, the rebar is well bonded to the surrounding concrete; however, as corrosion begins to occur, sections of the rebar separate or disbond from the concrete. The degree of disbond is assessed by monitoring the resonant properties of these sections.

The two key components of the MAP system are the generation of resonant modes in the rebar and the detection and processing of the vibrations associated with the rebar resonance. The resonant modes of the disbonded rebar are excited by putting a standard audio speaker in contact with the structure. Audio tones from the speaker couple acoustic energy into the concrete, where they can interact with the rebar and induce flexural vibrations. These induced vibrations cause the rebar to behave like an embedded acoustic source. The largest vibrations occur at resonant frequencies of the flexural modes in the rebar. The vibrations from the rebar, in turn, couple acoustic waves into the concrete that propagate back to the concrete surface. Detection of the surface vibrations is accomplished using either a laser vibrometer or an accelerometer. Coherent processing of the accelerometer or vibrometer signals, such as with a lock-in amplifier, allows the frequency-dependent vibration amplitudes to be accurately processed.

Field tests have been coordinated with the Maryland State Highway Association on two separate bridges to determine the suitability of the MAP system to field environments. The first sets of tests were conducted on a 70-year-old bridge (Fig. 9). The high-frequency vibrations between 2500 and 7000 Hz in Fig. 9a indicate the presence of disbonded rebar. Such vibration frequencies are much too high to be attributed to the concrete structure itself. The MAP results shown in Fig. 9b are significantly different and do not contain the high-frequency vibrations, suggesting that this section of the bridge is in good condition. These two findings were later confirmed by destructive analysis of the bridge sections, as shown on the right in Figs. 9a and 9b.

CHARACTERIZING THE ENVIRONMENT

The effects of the atmospheric environment on the VT fuze were determined by firing projectiles under varying weather conditions and at varying altitudes. The effects of clouds were determined experimentally in such studies. Since then, various effects of the environment on remote sensing systems have been studied at APL with specialized experiments as well as advanced analytical models. Both the RF and electro-optical properties of the environment are addressed in such studies. In some cases, the characterized environment is not on Earth.

Optical Techniques for Atmospheric Remote Sensing

The study of radar and electro-optical remote sensing system performance requires a comprehensive characterization of the atmosphere. Climatology research, meteorology, and atmospheric hydrology as well as detection of harmful chemical vapors, atmospheric pollutants, and chemical and biological aerosols also
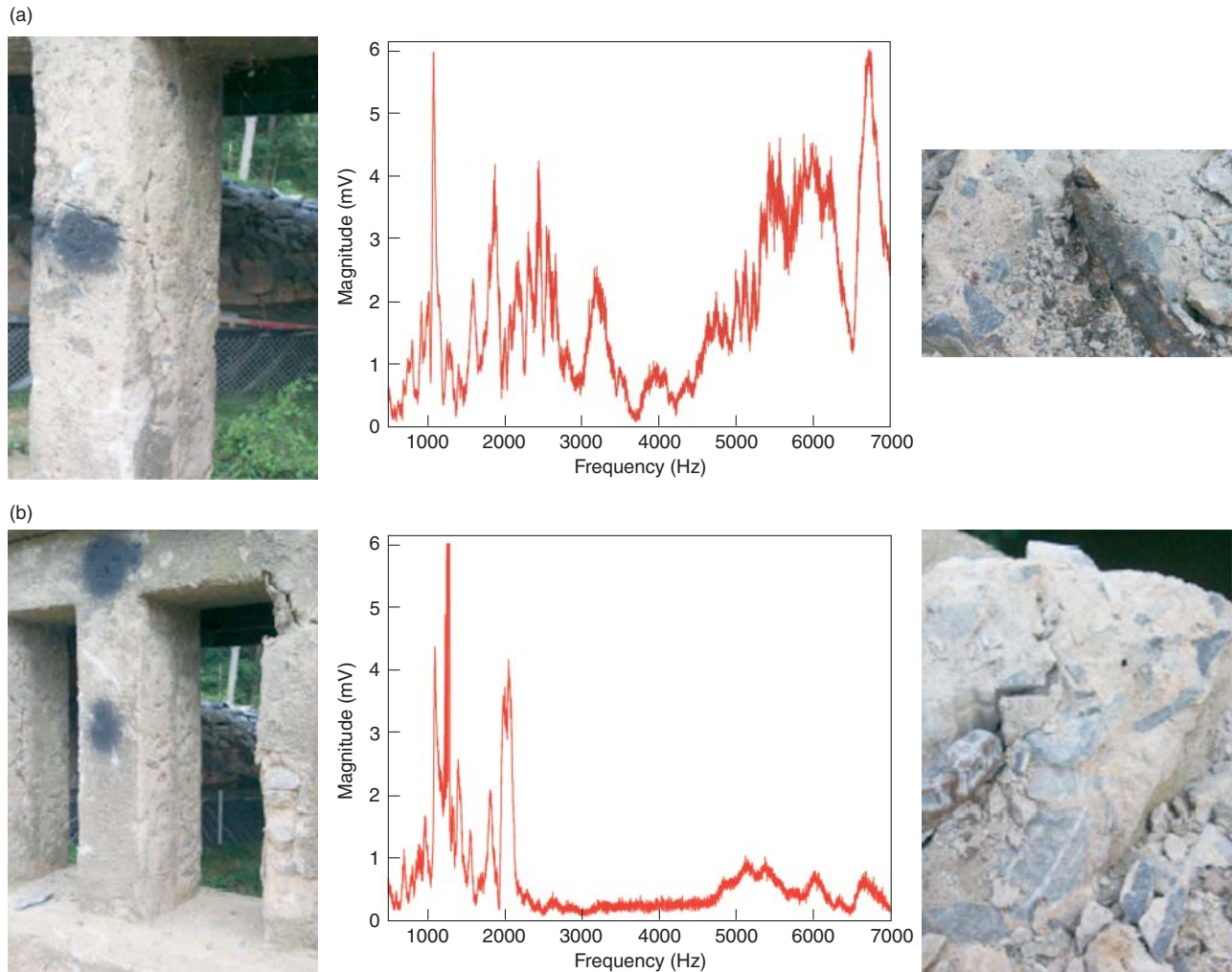
Figure 9. MAP system for assessment of concrete structures: (a) resonance spectrum (center) of a concrete structure (left) with corrosion, and inner part (right), removed after test, showing corrosion; (b) resonance spectrum (center) of a concrete structure (left) without corrosion, and inner part (right), removed after test, showing no corrosion.

depend on atmospheric conditions and can benefit from atmospheric characterization techniques. In many applications, atmospheric characterization must be accomplished in real time to provide information to an ongoing process. In particular, characterization of the lower atmosphere or troposphere is of greatest importance to these applications.

To address atmospheric characterization, Michael Thomas, Matthew Banta, Craig Mitchell, David Terry, and Sue Walts developed a suite of optical sensors and related data analysis techniques. The instruments are passive remote sensing systems that are preferable to active systems in many settings since the former do not require a radiation source and enable covert operation. Passive systems use only a receiver and sense the thermal and/or scattered solar radiation. They cost typically much less than active systems and do not involve the eye exposure hazard encountered in active systems. The passive receiver is often a spectrometer or a camera that is radiometrically calibrated. The spectroradiometer

provides spatially averaged, spectrally resolved information, whereas the camera provides spatially resolved, spectrally averaged information.

An example of innovative atmospheric characterization at APL is the estimation of vertical temperature and humidity profiles. The measurement of spectrally resolved down-welling radiance within the atmosphere is a powerful and relatively new tool for atmospheric profiling.[13–15] However, the current technique for extracting vertical profiles of temperature and humidity from down-welling radiance is numerically intensive. APL developed a new procedure for a more efficient estimation of vertical profiles within the troposphere. An initial low spatial resolution vertical temperature profile is obtained by examining the wavelength locations of certain spectral features of uniformly mixed gases. The specific spectral features are chosen based on the temperature insensitivity of the spectral line being probed. With this information, more detailed profiles of temperature and humidity can then be obtained more efficiently.

The procedure was tested using a midwave spectroradiometer (BOMEM MR154) operated at 4.0 to 5.5 μm on clear days and nights against balloon-sonde measurements with encouraging results.[16] The spectral measurements always included local measurements of temperature and humidity using a simple probe. The algorithm for obtaining the temperature profile was applied to the data using a vertical transmittance model based on the HITRAN database of atmospheric spectral lines. Figure 10a compares the temperature profile measured by the balloon-sonde with the temperature profile estimated with the APL technique. The balloon-sonde profile took 2 h to collect as opposed to the 2-min observation time of a spectroradiometer. Thus multiple measurements by the spectroradiometer were collected during the balloon's ascent. The low spatial resolution temperature profiles can be obtained in real time.

Another example of a new technique for characterizing the atmosphere is the passive radiometric measurement of clouds. The optical depth of clouds can be characterized by measuring their IR radiance. To accomplish this, experimental measurements are conducted with two IR cameras that yield spatially resolved images of cirrus clouds in the longwave and midwave IR bands. Radiance models of ice clouds are developed to assist image analysis. A model for the bulk optical properties of the ice type-Ih that compose cirrus clouds was developed as part this effort. The results are valuable for computer simulations of atmospheric radiance. An example longwave image is presented in Fig. 10b. The atmospheric path radiance to the cloud can be determined by measuring the radiance away from the cloud. Knowledge of the path radiance also yields an estimate of the path transmittance. The IR spectroradiometer is used to determine cloud temperature; cloud emittance is estimated by using the measured information.

## Contamination Measurements and Sensors

Quartz crystal microbalances (QCMs) have been used for over 25 years as monitors of molecular contamination of the environment. In satellites, QCMs have measured film deposition on sensitive surfaces such as optical mirrors, thermal radiators, and solar arrays. Recently, Manny Uy, Russell Cain, Bliss Carkhuff, Richard Cusick, Harry Eaton, and Chris Eddins used QCMs in a cryogenically cooled IR space telescope and in the seeker of a missile to measure optical contamination from outgassing materials.[17] The former was the first time that a QCM was used at cryogenic temperatures (20 K). The latter was the first application where QCMs were miniaturized to fit inside the confined space of a missile seeker. In both instances, APL conducted significant development in microcircuits and other areas for the QCM design to meet mission requirements. For example, the miniaturization of microcircuitry reduced
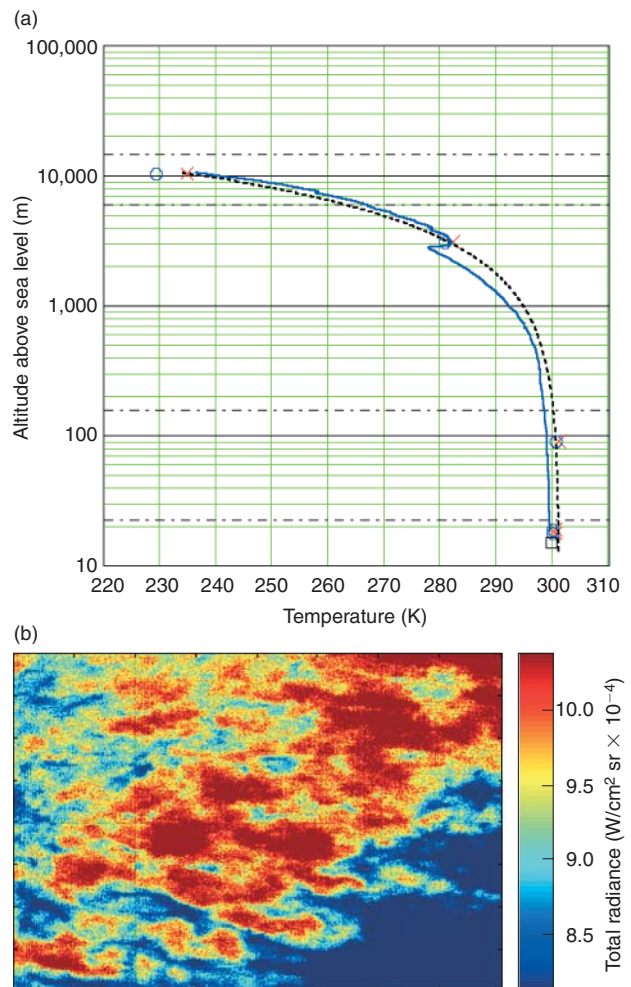
Figure 10. Optical techniques for atmospheric remote sensing. (a) Comparison of balloon-sonde measurement of the vertical temperature profile (solid curve) with spectroradiometer measurement (×'s and ○'s) and a model fit (dotted curve). A thermocouple measurement of air temperature near the spectroradiometer is indicated by □. Measurements collected at night on 2 August 1999. (b) Longwave image of high-altitude cirrus clouds covering 5.0° in azimuth (horizontal) and 3.3° in elevation (vertical).

QCM power consumption from 12.0 W to only 1.1 W for the missile seeker application.

The QCM uses two carefully matched quartz crystals, one under the other, with only one exposed to the outside environment. The difference in frequency between the two crystals, i.e., the beat frequency, is a very sensitive indication of the contamination mass deposited on the exposed crystal surface. QCMs can measure contamination with angstrom thickness resolution, providing the possibility of sensing monolayers of contamination.[18] Typical QCMs are shown in Fig. 11. The beat frequency, which is proportional to the mass of contamination accumulated on the sensing area, is electronically recorded in a digital electronic counter. The counter is then updated at a rate sufficient to resolve the dynamics of the contamination history.
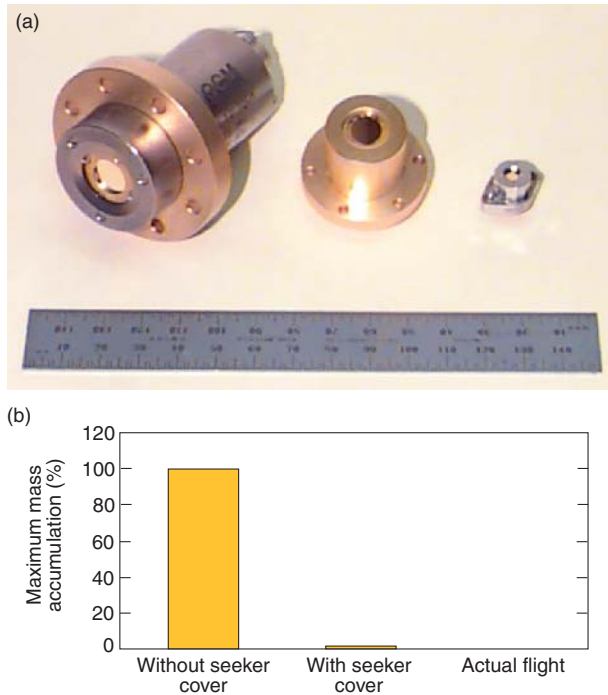
Figure 11. (a) A commercial QCM used in space experiments (left), cryogenic QCM (center), and miniature QCM for a missile seeker (right). (b) Chart showing the percentage of maximum mass accumulation as measured by the QCM before and after a seeker cover was installed to protect the missile seeker from contamination during ground testing. The third data point shows zero contamination during the actual missile flight test.

The theory and use of QCMs to measure satellite contamination and outgassing materials have been studied extensively.[19,20] The most common outgassing materials measured by QCMs are residual solvents and plasticizers (carbon or silicon-based volatile condensable materials) from nonmetallic components on a spacecraft. These types of contamination become visually opaque under ultraviolet irradiation from the Sun and are the cause of solar array power loss in orbit. They can also occur on the lenses of optical telescopes.

Knowledge of these outgassing phenomena and their effect on performance in orbit are essential for building reliable space and missile missions. As shown in Fig. 11b, the QCMs inside a missile seeker indicated severe contamination from components in the seeker housing during qualification testing in APL's wind tunnel, which led to the installation of a seeker cover and another ground test. The second ground test showed minimal contamination. This was later validated with an actual missile test carrying a similarly QCM-equipped seeker, which showed no contamination during the entire launch and intercept phases.

TECHNOLOGY TRANSFER AND FUTURE CHALLENGES

One of the main factors in the timely introduction of the VT fuze to the armed forces was undoubtedly the swift and effective transfer of know-how from APL to manufacturers. In its first project, APL was committed to the on-site development of the prototype and its manufacture by industry. The Laboratory worked actively with companies, conveying not only the design but also valuable experience for the success of the product. APL/industry interaction is increasingly active.

Technology transfer, the formal process of transferring inventions to industry, is an important facet of federally funded R&D. The Bayh-Dole Act set the basic public policy in this regard by allowing universities and federally funded research institutions to retain the title to their inventions. The Johns Hopkins University is intensely involved in technology transfer as demonstrated by the many technology licenses it has created over the past few years. Industry can access APL's innovations and use them to develop new products and industrial processes. Our encouraging approach to technology transfer, combined with a multitude of sensor projects at APL, has created a diverse portfolio of sensor technologies. Over 25% of APL's intellectual property portfolio consists of sensor inventions. Early success stories of technology transfer to industry cover a broad range of sensors including the Digital Solar Altitude Detector, the Space Based Contamination Measurements Sensor for spaceflight applications, and video surveillance technologies for examining the content of containers.

APL is also expanding its role as a leader in sensor innovations by spearheading the National Next Generation Sensors Initiative (NGSI) to help companies take advantage of federal and university research to develop new products and processes. The goal is to increase U.S. competitiveness by ensuring that U.S. companies have the benefit of the most advanced R&D in each area of sensor technology and that the time from idea to market is reduced to the greatest extent possible.[21] NGSI combines the needs, talents, and resources of three groups— companies that use sensors to manufacture products; manufacturers of sensors; and federal, university, and private R&D laboratories—in a collaborative effort to improve the productivity of industry. APL's role in NGSI is to work with the broad user community to identify sensor technology needs, match needs with technology or technical expertise, and facilitate collaborative research projects.

Interaction among sectors of the sensor industry has been cumbersome despite the necessity for effective collaborations that can meet the challenges of increasingly shorter product cycle times, a reduction in the time from idea to market, and the demand for innovation in an era of reduced R&D resources. NGSI utilizes the seamless and efficient power of the Internet to quickly initiate and advance information exchange and mutually beneficial relationships. All virtual and real-time associations within the NGSI community are further enhanced by annual conferences.

As stated by the DoD Director of Defense Research and Engineering, "*Continued improvements in performance will only be possible by miniaturization, automation, sensor integration, sensor fusion, digitization, and seamless information distribution.*"[21] Smaller, smarter, and more reliable and rugged sensors for security applications are in development. Networking of large sensor systems (sensor fusion) and miniaturization (nanoscale sensors) are being studied. More versatile, less expensive "e-noses" for medical diagnosis, quality control in the food and chemical industries, and chemical and biological agent detection are in development as well.

In the field of space exploration, APL is developing sensors and sensor systems for space missions that will lead to a better understanding of the effects of long-duration human spaceflight and the possible establishment of a robotic/engineering "outpost." Space-based sensors will also further the understanding of space weather through solar, radiation belt, and ionospheric mapping.

CONCLUDING REMARKS

Following the legacy of the VT fuze that saved the lives of many soldiers 60 years ago and helped win World War II, APL is involved in many other sensors that can help save or preserve the lives of military personnel and civilians. The APL commitment to this mission manifests itself in the lives and careers that many staff members devote to sensors and their problems, solutions, hardware, and software.

In the 1940s, APL produced a specialized sensor that reached the limits of engineering and technology at that time. In the 21st century, the performance of many sensing devices, as currently designed, will approach the fundamental limits of physics. In addition to the technology improvements stated above,[21] APL will also investigate new physical phenomena and new ways of exploiting known phenomena to develop new sensors and sensing mechanisms. The pursuit of this great challenge, fueled by the resourcefulness of APL scientists and engineers, is the seminal step of innovation. The Laboratory also addresses the needs of industry by carefully examining manufacturing feasibility, complexity, and cost. Close collaboration among government, APL, and commercial institutions will facilitate the practical application of sensors and expedite the development of the next generation of sensors and sensor systems.

REFERENCES

[1]"Variable Time Fuze Major Secret Ordnance Development," Navy Department Press Release (20 Sep 1945).
[2]Colley, D., "Deadly Accuracy: The Making of the Least Appreciated Technological Breakthrough of World War II—The Proximity Fuze," *Invention and Technology*, 44–50 (Spring 2001).
[3]"APL and the VT Fuze," *APL Tech. Dig.*, 18–22 (Sep–Oct 1962).
[4]Wickenden, D. K., Champion, J. L., Givens, R. B., Kistenmacher, T. J., Lamb, J. L., and Osiander, R., "Polysilicon Xylophone Bar Magnetometer," in *Proc. SPIE, vol. 3876, Micromachined Devices and Components V*, pp. 267–273 (1999).
[5]Garrison Darrin, A. M., Osiander, R., Champion, J. L., Swanson, T., Douglas, D., and Grob, L. M., "Variable Emissivity Through MEMS Technology," in *Proc. ITHERM 2000*, pp. 264–270, IEEE (2000).
[6]Xie, H., and Fedder, G. K., "A CMOS Z-Axis Capacitive Accelerometer with Comb-Finger Sensing," in *Proc. 13th Ann. Int. Micro Electro Mechanical Systems Conf.*, Miyazaki, Japan, pp. 496–501 (2000).
[7]Parameswaram, M., Robinson, A. M., Blackburn, D. L., Gaitan, M., and Geist, J., "Micromachined Thermal Radiation Emitter from a Commercial CMOS Process," *IEEE Electron Device Lett.* **12**, 57–59 (1991).
[8]Charles, H. K. Jr., Beck, T. J., Feldmesser, H. S., Magee, T. C., Spisz T. S., and Pisacane, V. L., "Precision Bone and Muscle Loss Measurements by Advanced, Multiple Projection DEXA (AMPDXA) Techniques for Spaceflight Applications," *Acta Astronaut.* **49**(2–10), 447–450 (2001).
[9]Pavek, R. E., *Diffuse Multipath Estimation of Sinusoidal ECM*, F2A-91-0-531, JHU/APL, Laurel, MD (30 Aug 1991).
[10]Pavek, R. E., *Diffuse Multipath Estimation of Broadband Noise ECM*, F2A-91-0-532, JHU/APL, Laurel, MD (30 Sep 1991).
[11]Bankman, I. N., "Analytical Model of Doppler Spectra of Coherent Light Backscattered from Rotating Cones and Cylinders," *J. Opt. Soc. Am. A* **17**, 465–476 (2000).
[12]Wulff, G., and Sarhan, A., "Use of Polymers with Enzyme-Analogous Structures for the Resolution of Racemates," *Angew. Chem. Int. Ed.* **11**(2), 341–346 (1972).
[13]Smith, W. L., Revercomb, H. E., Howell, H. B., Huang, H-L., Knuteson, R. O., et al., "GHIS-The GOES High-Resolution Interferometer Sounder," *J. Appl. Meteor.* **29**, 1189–1204 (1990).
[14]Feltz, W. F., Smith, W. L., Knuteson, R. O., Revercomb, H. E., Woolf, H. M., and Howell, H. B., "Meteorological Applications of Temperature and Water Vapor Retrievals from the Ground-Based Atmospheric Emitted Radiance," *J. Appl. Meteor.* **37**, 857–875 (1998).
[15]Smith, W. L., Feltz, W. F., Knuteson, R. O., Revercomb, H. E., Woolf, H. M., and Howell, H. B., "The Retrieval of Planetary Boundary Layer Structure Using Ground-Based Infrared Spectral Radiance Measurements," *J. Atmos. Oceanic Technol.* **16**, 323–333 (1999).
[16]Thomas, M. E., and Banta, M. D., "Passive Remote Sensing of the Atmosphere by a Ground Based Spectroradiometer," in *Proc. Int. Geoscience and Remote Sensing Symp.* (24–28 Jul 2000).
[17]Uy, O. M., Cain, R. P., Carkhuff, B. G., Cusick, R. T., and Wood, B. E., "Miniature Quartz Crystal Microbalances for Spacecraft and Missile Applications," *Johns Hopkins APL Tech. Dig.* **20**(2), 199–213 (1999).
[18]Wood, B. E., Green, B. D., Uy, O. M., Cain, R. P., and Thorpe, J., "Materials Outgassing Effects and Satellite Contamination Database," in *Proc. AIAA 38th Aerospace Science Mtg.*, Reno, NV (2000).
[19]Green, B. D., Wood, B. E., and Uy, O. M., *Satellite Contamination and Materials Outgassing Knowledgebase—An Interactive Database Reference*, NAS8-98215, NASA (Oct 2000).
[20]Uy, O. M., Green, B. D., Galica, G. E., Boies, M. T., Wood, B. E., et al., "Outgassing of Optical Baffles and Primary Mirror During Cryogen Depletion of a Space-Based Infrared Instrument," in *Proc. Optical Systems Contamination and Degradation: Effects, Measurements, and Control (AM304)*, SPIE, San Diego, CA (30 Jul–4 Aug 2000).
[21]*Dual Use Science and Technology Program, Fiscal Year 1998 Report to Congress*, Department of Defense, pp. 1–7 (Mar 1999).

THE AUTHORS

ISAAC N. BANKMAN, a member of the APL Principal Professional Staff, is Supervisor of the Imaging and Laser Systems Section in ADSD's Electro-Optical Systems Group. He received a B.S. in electrical engineering from Bosphorus Univeristy, Turkey, in 1977, an M.S. in electronics from the University of Wales, Britain, in 1979, and a Ph.D. in biomedical engineering from Technion University, Israel, in 1985. He joined APL in 1990 and worked on signal processing algorithms for transient detection, image processing algorithms for object recognition, and image registration algorithms. In the past 6 years he has developed analytical models of ladar and radar signatures of ballistic missile parts and related discrimination algorithms. His recent work also includes ladar sensing and laser communication in marine applications, image analysis for missile guidance, and radar and passive IR fire control systems for ship self-defense. His e-mail address is isaac.bankman@jhuapl.edu.

JOSEPH J. SUTER received his B.S. (1977) in physics from the Free University of Amsterdam, the Netherlands, and his M.S. (1980) in physics from Michigan State University. He also received an M.S. (1982) in electrical engineering from the University of Maryland and a Ph.D. (1988) in materials science and engineering from The Johns Hopkins University. During the last 20 years, Dr. Suter has led a variety of technical programs including sensors and communication systems, atomic and quartz frequency standards, advanced power sources, and space flight technologies. In addition, he worked in the APL Office of Technology Transfer as Director of Technology Programs, licensing electronic and communication technologies. Recently, Dr. Suter was appointed the Assistant Department Head of the Research and Technology Development Center. He has (co)-authored over 55 publications which have appeared in various *IEEE Transactions*, *Cryogenics*, the *Journal of Physics D*, the *Journal of Non-Crystalline Solids*, and the *Journal of Applied Physics*. His e-mail address is joseph.suter@jhuapl.edu.