

The Silicon Oscillating Accelerometer:

A MEMS Inertial Instrument for Strategic Missile Guidance

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ABSTRACT

The intercontinental ballistic missiles (ICBM) and submarine-launched ballistic missiles (SLBM) developed over the past 50 years have employed successive generations of increasingly accurate inertial guidance systems. The comparatively short time of guided flight and high acceleration levels characteristic of the ballistic missile application place a premium on accelerometer performance to achieve desired weapon system accuracy. To date, the accelerometer design of choice for strategic missiles has been the Pendulous Integrating Gyroscopic Accelerometer (PIGA) instrument, an accelerometer whose origins trace back to the German V2 rocket, and has been refined through several generations of development to achieve unsurpassed performance. The specialized technologies of PIGA accelerometers, such as gas bearing wheels, ultra-stable ball bearings, precision electromagnetic components, and "designer chemical" flotation fluids require a costly support infrastructure for production and system life-cycle maintenance.

Draper Laboratory is currently in the process of developing the Silicon Oscillating Accelerometer (SOA) a Microelectromechanical System (MEMS)-based sensor that has the potential to achieve the ppm/ μg performance stability required of the strategic missile application. The MEMS technology is inherently low cost and offers a rapidly expanding commercial business base to leverage and sustain accelerometer production and deployment in next-generation guidance systems.

The SOA belongs to the generic category of accelerometers known as Vibrating Beam Accelerometers (VBA), which sense acceleration by measuring the change in the resonant frequency of beam oscillators under the inertial loading of a proof mass. The SOA differs from conventional VBAs in one important respect; namely, the SOA is a silicon MEMS-based device, while VBAs are typically bulk-fabricated quartz devices.

The silicon MEMS process offers several advantages over quartz that enable superior accelerometer design features:

- (1) Semiconductor-grade, single-crystal silicon is a perfectly elastic structural material that can be produced with extremely low levels of impurities.
- (2) The MEMS process enables fabrication of very small (millimeter scale in the case of the SOA) resonator elements that are well isolated from the influence of parasitic instrument package stresses.
- (3) Capacitively based, electrostatic resonator actuation and sensing that offers greater design flexibility than the piezoelectric quartz technology.

This paper will give an overview of the Draper SOA and current performance data taken to date.

INTRODUCTION

SOA Applications and Performance Goals

The ICBM/SLBM strategic missile has the most demanding requirements of any inertial guidance application. The high degree of accuracy required, combined with the high acceleration levels and large velocity at reentry body deployment place an especially stringent performance requirement on the guidance system accelerometers.

Although there are many system-derived performance parameters specified for inertial-grade accelerometers (see Table 1), in broad terms, accelerometer performance can be characterized with two parameters: bias and scale-factor (SF) stability. Accelerometer bias is the dc offset indicated from the instrument output under zero applied acceleration. Scale factor is the instrument gain or sensitivity that relates the applied acceleration to the instrument output signal (e.g., V/g, Hz/g, etc.).

Table 1. SOA Performance Goals.

Parameter	Units	Boost	Reentry
Bias			
Repeatability	μg	1	100
Stability	μg	1	5
Mission Time	min	17	60
Scale Factor			
Repeatability	ppm	1	100
Stability	ppm	1	5
Mission Time	min	17	60
Asymmetry	ppm	TBD	TBD
g^2 (Compensated)	$\mu\text{g}/g^2$	0.1	0.2
g^3 (Compensated)	$\mu\text{g}/g^3$	TBD	0.005
Resolution	$\mu\text{g}/\sqrt{\text{Hz}}$	3	10
VRW	ft/s/ $\sqrt{\text{h}}$	0.0042	0.014
Misalignment			
Repeatability	arcsec	0.1	5
Stability	arcsec	0.1	2
Vibration Rect.	$\mu\text{g}/(g\text{-rms})^2$	<0.15	<1
Bandwidth	Hz	100	>100
Quantization	ft/s/count	0.0001	0.001
			-0.01
Maximum Acceleration	g	10	120



To date, strategic-grade performance has been achieved over the ICBM/SLBM mission times and hostile flight environments only in the PIGA, a highly refined instrument that has been employed successfully in U.S. strategic missile systems deployed since the inception of ICBM/SLBM programs. Unfortunately, the complexity of PIGA accelerometers (see Figure 1) and their specialized technologies, such as gas bearing wheels, ultra-stable ball bearings, precision electromagnetic components, and "designer chemical" flotation fluids require a costly support infrastructure for production and system life-cycle maintenance.

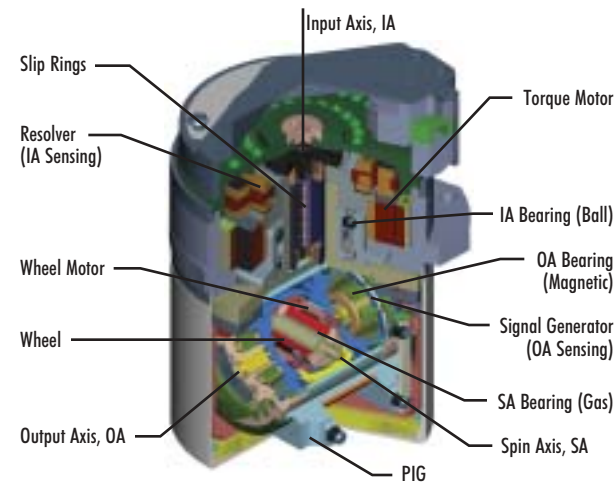


Figure 1. The 10 PIGA accelerometer.

Consequently, the strategic guidance community is seeking a lower cost, high-reliability alternative to the PIGA for next-generation ICBM/SLBM missile systems, with the important provision that performance remain uncompromised. Draper Laboratory is currently in the process of developing the SOA, a MEMS-based sensor that has the potential to achieve the ppm/ μg performance stability required of the strategic missile application. The MEMS technology is inherently low cost and offers a rapidly expanding commercial business base to leverage and sustain accelerometer production and deployment in next-generation guidance systems. The SOA belongs to the generic category of accelerometers known as VBAs, which sense acceleration by measuring the change in the resonant frequency of beam oscillators under the inertial loading of a proof mass. The SOA differs from conventional VBAs in one important respect; namely, the SOA is a silicon MEMS-based device, while VBAs are typically bulk-fabricated quartz devices.

The silicon MEMS process offers several advantages over quartz that enable superior accelerometer design features:

- (1) Semiconductor-grade, single-crystal silicon is a perfectly elastic structural material that can be produced with extremely low levels of impurities.
- (2) The MEMS process enables fabrication of very small (millimeter scale in the case of the SOA) resonator elements that are well isolated from the influence of parasitic instrument package stresses.

- (3) Capacitively based, electrostatic resonator actuation and sensing that offers greater design flexibility than the piezoelectric quartz technology.

In addition to the above design advantages, the small size inherent to MEMS sensors enables the development of a compact IMU for reentry body (RB) instrumentation. Table 1 shows a comparison of accelerometer performance specifications typical of strategic boost-only and reentry instrumentation requirements. Note that the performance requirements specified for reentry are five to ten times more relaxed than the boost phase requirements.

The next sections describe the operational principles of the SOA, the MEMS fabrication process, and some SOA performance data.

SOA Functional Description

The SOA developed by Draper Laboratory is a miniature silicon VBA fabricated using the silicon MEMS micromachining technology. Figure 2 is a schematic representation of the SOA sensor, showing a pair of double-ended tuning-fork oscillators connected to a common proof mass. These elements form a monolithic silicon structure that is supported above and anodically bonded to a glass substrate as shown.

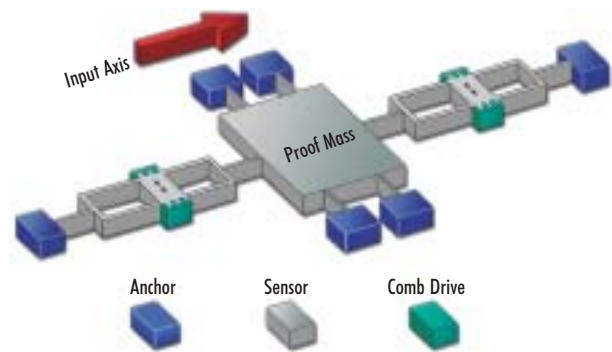


Figure 2. SOA schematic.

The SOA input axis lies in plane as indicated in Figure 2; under acceleration, the proof mass axially loads the two resonator pairs. The vibration frequency of each resonator changes under the applied load. This frequency change is measured and serves as the indicated acceleration output of the SOA. Note that the resonators are arranged so they are loaded differentially by the proof mass. That is, one resonator is placed in tension, the other in compression. This differential design doubles the sensitivity or scale factor of the accelerometer and furnishes a cancellation of error sources common to both resonators.

The resonators are excited by an electrostatic comb drive,^{[1],[2]} similar to that used in Draper's micromechanical tuning-fork gyro (TFG). The comb drive has both inner and outer motor stator combs that are fixed to the glass substrate. The outer motor combs apply the drive force, the inner motor combs sense the drive amplitude and frequency. A detail of the comb geometry is shown in Figure 3.



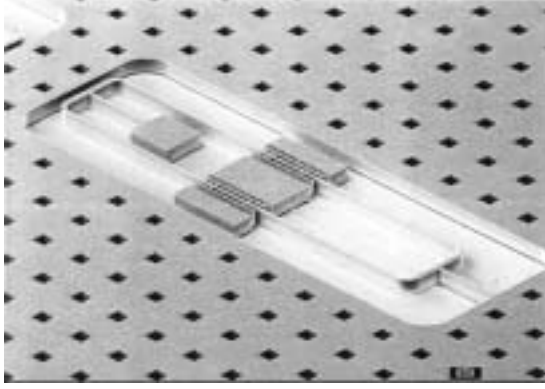


Figure 3. SOA oscillator detail.

The goal of the SOA design is to achieve a high SF, high Q resonator to meet the 1- $\mu\text{g}/1\text{-ppm}$ strategic-grade performance requirements. Large SF is desirable because it decreases the degree of frequency stability required to resolve a given acceleration level. For example, 0.1-mHz frequency stability is required of a 100-Hz/g SF unit to resolve 1 μg . A 10-Hz/g unit has a ten times more restrictive frequency stability requirement (10 μHz) to resolve the same 1- μg input.

It can be shown^[3] that the lateral stiffness of an axially loaded beam with fixed ends is

$$K = \frac{12EI}{L^3} + \frac{12P}{\pi^2L} \quad (1)$$

where: K = stiffness
 E = Young's modulus
 I = moment of inertia
 L = beam length
 P = axial load

If a lumped mass is supported between two beams, the natural frequency of the mass-beam system as a function of axial load is given by

$$f = \sqrt{\frac{2}{m} \sqrt{\frac{12EI}{L^3} + \frac{12P}{\pi^2L}}} \quad (2)$$

where: f = resonant frequency
 m = mass of lumped oscillator

Rearranging Eq. (2) gives

$$f = f_0 \sqrt{1 + \frac{L^2}{\pi^2 EI} P} \quad (3)$$

where: f = resonant frequency
 f_0 = nominal unloaded (bias)

$$\text{resonant frequency} = \sqrt{\frac{24EI}{mL^3}}$$

m = resonator mass
 L = beam length
 E = Young's modulus
 I = beam inertia
 P = applied axial load

Note that the frequency versus applied acceleration load relationship in the SOA is nonlinear, as indicated by Eq. (3) and shown in Figure 4.

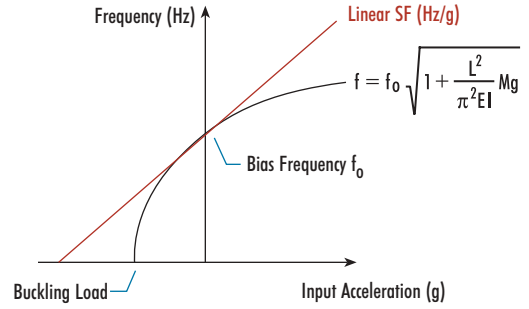


Figure 4. SOA frequency vs acceleration curve.

A series expansion of Eq. (3) can be used to determine the linearized SOA SF (the slope about zero acceleration in Figure 4) and higher order g-coefficients

$$f = f_0 \left[1 + \frac{1}{2} SP - \frac{1}{8} S^2 P^2 + \frac{1}{16} S^3 P^3 - \dots \right] \quad (4)$$

where $S = L^2/\pi^2 EI$.

Equation (4) can be rewritten as

$$f = f_0 + K_1 g + K_2 g^2 + K_3 g^3 - \dots \quad (5)$$

where: $K_n = K_1 b_n (K_1/f_0)^{n-1}$ (Hz/gⁿ)
 $b_n = b_{n-1} (3-2n)/n$
 $K_1 = f_0 (S/2)$
 $b_1 = 1$
 g = acceleration

Note that the values of the g^2 and g^3 coefficients (K_2, K_3) are controlled by the linear SF (K_1) and bias frequency (f_0). The linearized SF is dependent on resonator dimensions, Young's modulus, and the mass of the resonator (m) and proof mass (M)

$$K_1 = \frac{M}{8\pi} \sqrt{\frac{L}{EI m}} \quad (6)$$

The SF stability of the SOA will be largely controlled by the Young's modulus sensitivity to temperature ($\Delta E/E/\Delta T = -50$ ppm/ $^\circ\text{C}$), as it is an order of magnitude larger than silicon's TCE (2.5 ppm/ $^\circ\text{C}$), the parameter that would control the resonator dimensional stability. Given the square root relationship, the linear SF temperature coefficient is approximately 25 ppm/ $^\circ\text{C}$, indicating that 0.01 $^\circ\text{C}$ temperature control will maintain better than 1-ppm SF performance.

From Eqs. (4) and (5), the values of the g^2 and g^3 coefficients (K_2, K_3) can be expressed by the linear SF (K_1) and bias frequency (f_0)

$$K_2 = -\frac{1}{2} \frac{K_1^2}{f_0} \quad (7)$$

$$K_3 = \frac{1}{2} \frac{K_1^3}{f_0^2} \quad (8)$$

For a 100-Hz/g (per side) SF, 20-kHz nominal bias frequency unit, Eqs. (7) and (8) project g^2 and g^3 coefficients of 0.25 Hz/g² and 0.0125 Hz/g³. Normalizing these coefficients by dividing by the linear SF gives 2500 $\mu\text{g}/g^2$ and 12.5 $\mu\text{g}/g^3$, respectively.



The contribution of phase noise in the drive frequency electronics can also be estimated. The PSD of the oscillator phase noise is approximately equal to the PSD of the amplitude noise divided by the peak amplitude.

At resonance, the phase noise is related to frequency noise by

$$\phi_f = \phi_p \frac{d\omega}{d\phi} = \phi_p \frac{\omega_n}{2Q} \quad (17)$$

where: ϕ_f = frequency noise PSD
 ϕ_p = phase noise PSD
 ω_n = nominal resonant frequency
 Q = Q of resonator

The high Qs achieved in the SOA oscillators (~100,000) significantly reduce the frequency noise in the output from phase jitter. The net frequency noise in the SOA readout is dominated by oscillator amplitude noise. Consequently, frequency readout resolution is improved with increasing bias voltage and decreasing drive amplitude.

SOA MEMS Fabrication

For micromachining inertial instruments, Draper Laboratory employs the silicon-on-glass bulk dissolved-wafer process. The main process steps are illustrated in Figure 6. This process has been used in other inertial sensor fabrication. First, mesas are etched in the silicon wafer to form the gap between the suspended structures and the substrate. This process is done using potassium hydroxide with a silicon dioxide etch mask. Once the SiO₂ etch mask is removed, the silicon wafers undergo boron diffusion to form the etch stop layer; device thickness is determined by the depth of the boron diffusion. The device structural layer is then photolithographically patterned on the silicon, and wafers are etched using high-aspect-ratio micromachining in an inductively-coupled plasma (ICP) machine. Wafers are then anodically bonded to glass substrates that have been metallized with the SOA electrode pattern. Finally, the silicon wafer is dissolved in an anisotropic wet etchant such as ethylenediamine pyrocatechol (EDP), to remove all but the heavily-boron-doped layer of silicon.

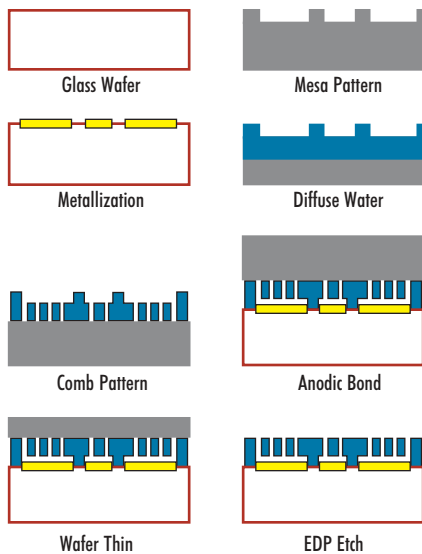


Figure 6. SOA fabrication process.

A scanning electron micrograph (SEM) of the SOA oscillator flexure and oscillator mass is shown in Figure 7; the structure thickness is 12 μm. Data from the SEM showed that the initial SOA oscillator flexure widths were, on average, three tenths of a micron larger than designed. This oversize can be corrected during fabrication of future devices, but test data contained here are for devices of this slightly wider flexure width.

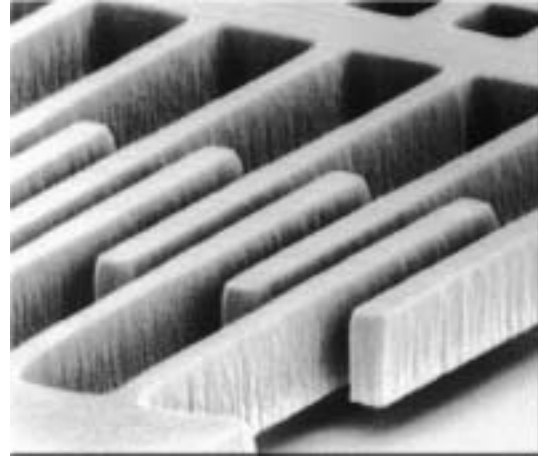


Figure 7. SOA oscillator detail.

SOA Fabrication Screening

The first phase in assessing the viability of newly fabricated SOAs is to individually test the two SOA oscillators in air at a probe station. SOA test articles fabricated with a 3.5-, 4.0- and 4.5-μm flexure width were used to confirm that the in-phase oscillator drive mode (i.e., the "Hula" mode) frequency is at least 10% lower than the out-of-phase drive mode for a wide range of beam geometry fabrication variation. A separation of at least 10% between the drive mode and the parasitic hula mode is desired to ensure that the hula mode does not interfere with the oscillator drive loop.

After probe testing, SOAs with satisfactory performance are packaged and integrated with preamplifier electronics. The SOA sensor is vacuum sealed in an aluminum oxide leadless ceramic chip carrier (LCCC), which is in turn bonded to a preamplifier alumina substrate for interfacing to breadboard electronics. The residual pressure achieved in the LCCC after vacuum seal is less than 1 mTorr, which ensures high oscillator Q factors. A plot of Q vs pressure for a typical SOA is shown in Figure 8.

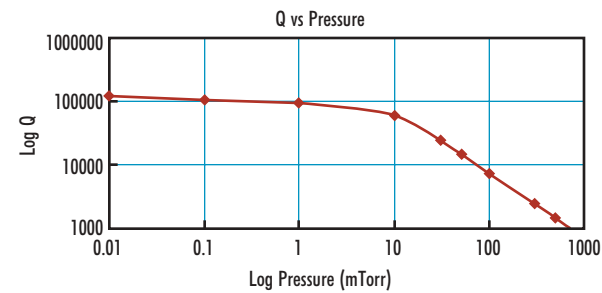


Figure 8. Q vs pressure relationship.



SOA Performance Test Data

Figure 9 shows an Allan Variance or Green's chart plot of an SOA. The standard deviation of indicated acceleration indicating SOA uncertainty is plotted against data averaging time. Note that the slope of the curve in the initial short averaging time periods is minus one half on a log scale, characteristic of instrument white noise. The equivalent white noise PSD can be calculated from a point on the minus one half slope line from

$$\sigma^2 = \frac{2\phi}{T} \quad (18)$$

where: σ = acceleration standard deviation
 ϕ = white noise PSD
 T = averaging time

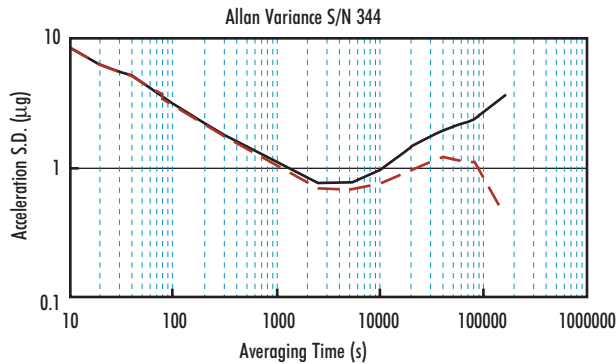


Figure 9. SOA Allan Variance.

The data from Figure 9 in the white noise region indicate, from Eq. (18), a white noise PSD of $23 \mu\text{g}/\sqrt{\text{Hz}}$. The equivalent velocity random walk coefficient is $0.031 \text{ ft/s}/\sqrt{\text{h}}$.

Note from Figure 9, that the SOA acceleration uncertainty drops below $1 \mu\text{g}$ over averaging times that extend over approximately 1000 s. The region between approximately 2000 s and 10,000 s represents the "bucket" of the SOA, where minimum instrument uncertainty is achieved over this data averaging period. For longer periods of time, uncertainty starts to increase, representing long-term drift and instability in the instrument. Note that Figure 9 shows two data curves that are initially coincident, but begin to diverge at longer averaging times. The solid curve that increases monotonically after 10,000 s is raw, uncompensated SOA output. The dashed curve was developed by applying a long-term drift compensation model to the SOA output.

Figures 10 and 11 show SOA bias and SF uncertainty. The data shown in these figures are 5-min (600-s) averaged data and are uncompensated SOA output. The data shown extend over a roughly 20-h period and show standard deviations in SF and bias of 3 ppm and $5 \mu\text{g}$, respectively.

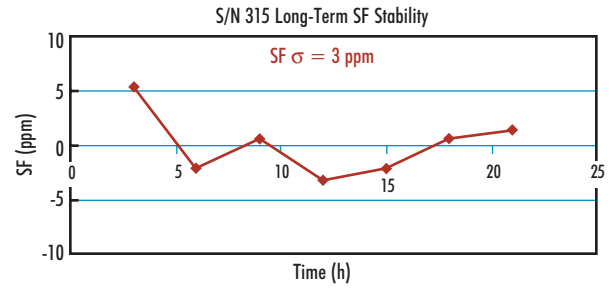


Figure 10. SOA SF stability.

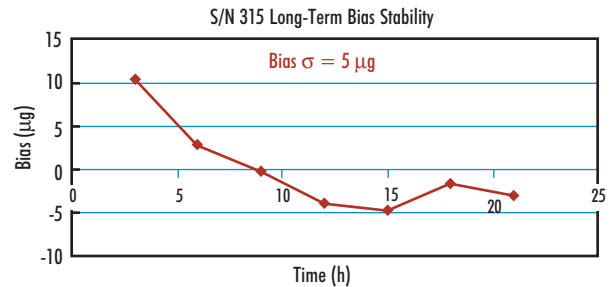


Figure 11. SOA bias stability.

Conclusions

Draper Laboratory is currently in the process of developing the SOA, a MEMS-based inertial-grade sensor. Performance data acquired to date approach the levels needed for strategic guidance missions, both for traditional boost phase only guidance, and an emerging generation of reentry phase instrumentation applications.

The MEMS technology is inherently low cost and offers a rapidly expanding commercial business base to leverage and sustain accelerometer production and deployment in next-generation guidance systems.

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(clockwise from here)



- Paul A. Ward
- Bernard M. Antkowiak
- Richard D. Elliott
- Jeffrey T. Borenstein
- Ralph E. Hopkins
- Michael D. DePiero
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Biographies

Paul A. Ward

is currently a Principal Engineer and Microelectronics Group Leader at Draper Laboratory. He has been the Principal Electrical Engineer for many challenging projects, including ppm-level radiation test systems, electron-spin and nuclear-magnetic resonance precision signal references, resonator and interferometer fiber-optic gyroscopes, and most recently, micromechanical instrument electronics. He is the Principal Engineer for Draper's micromachined gyroscope and accelerometer electronics, including application-specific integrated circuits (ASICs). He was nominated for the 1992 and 1993 Draper Distinguished Performance Awards, and received the 1994 Draper Distinguished Performance Award along with others for their work on the micromechanical gyroscope and electronics. He received the 1997 Draper Distinguished Performance Award for his work on a commercially viable yaw rate sensor instrument. In addition, he has received numerous Draper Recognition Awards, as well as the 1996, 1997, and 1998 "Best Technical Patent" Awards. He holds 14 U.S. patents, has several patents pending, and has co-authored numerous papers. Mr. Ward is a member of Eta Kappa Nu, IEEE, and ARRL. He received BS and MS degrees in Electrical Engineering from Northeastern University.

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is a Senior Member of the Technical Staff, Microelectronics Design, and is currently Principal Investigator of the High-Performance Pendulous Accelerometer and Electronics Task Leader for the Multimission INS/SOA. He is involved in all aspects of the design and development of accelerometer instrument electronics, and provides technical support to other critical task areas, such as sensor design and fabrication and instrument and system packaging. Responsibilities include technical oversight for the electronics designs, generation of electronics requirements and specifications from the system level flow down, leading the actual electronics design and implementation, and conducting sensor/electronic integration and assessment. This work is essential in extending the performance of these accelerometers to the requisite levels for tactical and strategic applications. His experience includes hardware and software design, sensor physics, data acquisition and analysis, sensor and instrument design, electronics architecture development, instrument test and evaluation, instrument error modeling, and signal processing. Before joining the microelectronics group, he worked in the Test and Analysis group. Accomplishments included the development of custom test electronics and the test approaches needed to characterize, develop, and model MEMS gyroscopes, accelerometers, and microphones. He designed custom low-noise electronics and methods to measure the Brownian noise limits of Draper's pendulous accelerometer design. He has one patent pending in the MEMS area, and has co-authored several technical papers on Draper's inertial MEMS technology. Mr. Elliott received a BS in Engineering Technology from Northeastern University (1990) and a BS in Electrical Engineering (1997) from Boston University.

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is Group Leader of the MEMS Fabrication Group at Draper Laboratory. He has 15 years of experience in semiconductor processing and devices, micromachining, and MEMS. Dr. Borenstein has developed novel micromachining process technologies with applications in inertial guidance and navigation, acoustic and chemical sensing, and biomedicine. He is currently Task Leader of the MEMS Process and Radiation Hardness component of the strategic-grade SOA program. He is co-Principal Investigator on the Center for Integration of Medicine and Innovative Technology (CIMIT) Tissue Engineering project aimed at microfabrication of vascularized tissues for organ replacement, and is developing polymer MEMS and other advanced micromachining process technologies. Dr. Borenstein has published 40 papers and holds two U.S. patents with six pending. He is a member of the American Physical Society, the Tissue Engineering Society, the Materials Research Society, and the Electrochemical Society. Dr. Borenstein received a PhD in Physics from the State University of New York at Albany.

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is a Principal Member of the Technical Staff at Draper Laboratory where he is responsible for the design and development of inertial instruments and sensors. Currently, he is Technical Director of the Silicon Oscillating Accelerometer (SOA) development program, a high-performance silicon MEMS VBA targeted for strategic-grade applications. He has also been involved in the development of navigation and tactical-grade MEMS gyroscopes and accelerometers. Mr. Hopkins holds two patents and has authored several papers on MEMS sensors. He is a current member of the AIAA Guidance, Navigation, and Control Technical Committee. He received BS and ME degrees in Mechanical Engineering from Rensselaer Polytechnic Institute and an ME in Engineering Mechanics from Columbia University.

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is a Senior Member of the Technical Staff in the Mechanical Design Group at Draper Laboratory. He is responsible for conceptual, preliminary, and detailed mechanical design/integration for inertial instrument, system, and environmental test facilities. He has served as Task Leader for the SOA program for the past 3 years, focusing primarily on MEMS sensor to strategic instrument development and test. His past assignments have covered a wide range of hardware design tasks for inertial instrument, system, and test support, including the mounting ring assembly for the Inertial Pseudo-Star Reference Unit (IPSRU) Phase 2 to Phase 3 upgrade, and several gyro/accelerometer precision mounting fixtures for both single- and multi-axis rate table testing. As Task Leader in the Navy's Deep Submergence Rescue Vehicle (DSRV) program, he was responsible for all mechanical requirements involved in the design, test, and integration of several critical propulsion systems. Before joining Draper, he was employed by the Electronics Research Laboratory at Northeastern University where he designed kinematic mechanisms and ejection devices in support of sounding rocket research. Prior to this, he was a Captain in the U.S. Air Force assigned to the Air Force Geophysics Laboratory, Hanscom AFB and was responsible for the design, development, and integration of scientific balloon and sounding rocket payloads. He is a member of the Tau Beta Pi Engineering Society and the American Society of Mechanical Engineers (ASME), and received a BS in Mechanical Engineering from Norwich University (1982).

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is Laboratory Technical Staff and Group Leader in Draper Laboratory's Systems Engineering and Evaluation Directorate. He is responsible for the design and testing of a wide range of micromechanical gyroscopes, accelerometers, hydrophones, microphones, angular displacement sensors, chemical sensors, and biomedical devices. He holds 20 patents with 12 additional in application. He was given Draper's Best Patent, Best Publication, and Distinguished Performance Award for his work on the tuning-fork gyro, the first silicon micromechanical gyroscope to demonstrate resolution better than 100 deg/h in 60 Hz. Dr. Weinberg received BS, MS, and PhD degrees in Mechanical Engineering from MIT.

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joined Draper in 1959 and is currently in the Systems Integration, Test, and Evaluation Division. He has worked in the development programs for Navy Polaris and Trident and for Air Force Minuteman and Peacekeeper guidance systems, primarily in the accelerometer and gyro instrument design and test. Experience also includes over 25 years in management with Section Chief and Associate Director positions and Task Leader for the A-10 GPS/IDM Integration Test Program. Currently, Mr. Miola's primary responsibility is the test and evaluation of the SOA 3 accelerometer design. He received a BS in Engineering (1959) and an MS in Electrical Engineering from Northeastern University.

