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)	$\mu g/g^2$	0.1	0.2
g^3 (Compensated)	$\mu g/g^3$	TBD	0.005
Resolution	$\mu g/\sqrt{Hz}$	3	10
VRW	$ft/s/\sqrt{h}$	0.0042	0.014
Misalignment			
Repeatability	arcsec	0.1	5
Stability	arcsec	0.1	2
Vibration Rect.	$\mu g/(g\text{-rms})^2$	<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.

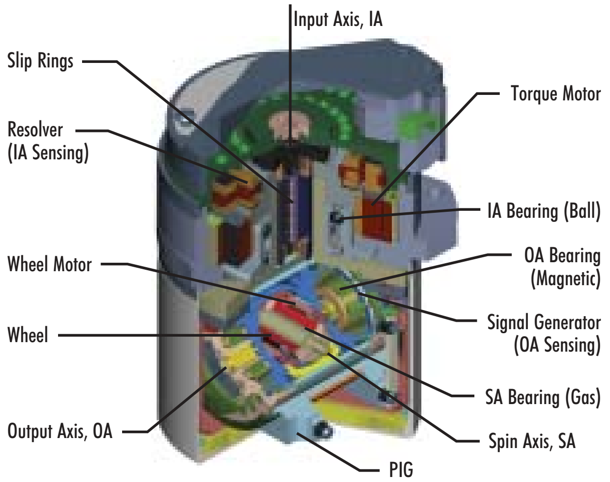

Figure 1. The 10 PIGA accelerometer.

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:

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(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.

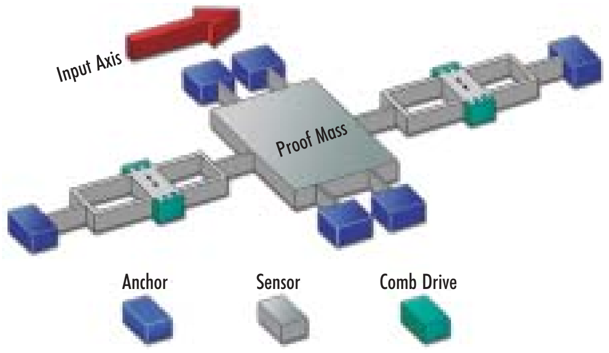

Figure 2. SOA schematic.

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.

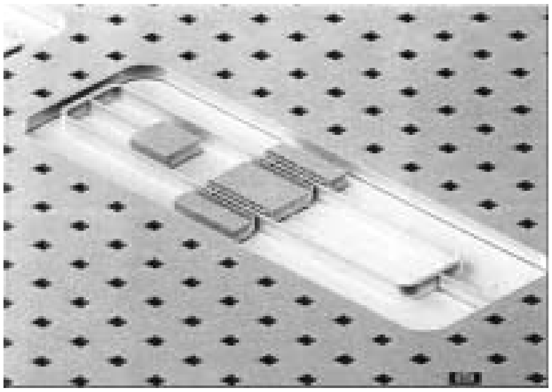

Figure 3. SOA oscillator detail.

The goal of the SOA design is to achieve a high SF, high Q resonator to meet the 1-µg/1-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

$$K = \frac{12\,EI}{L^3} + \frac{12P}{\pi^2 L} \tag{1}$$

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

$$f = \sqrt{\frac{2}{m}}\sqrt{\frac{12\,EI}{L^3} + \frac{12P}{\pi^2 L}} \tag{2}$$

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

Rearranging Eq. (2) gives

$$f = f_o\sqrt{1 + \frac{L^2}{\pi^2 EI}P} \tag{3}$$

where: f = resonant frequency
f_o = nominal unloaded (bias)
resonant frequency = $\sqrt{\frac{24\,EI}{m\,L^3}}$
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.

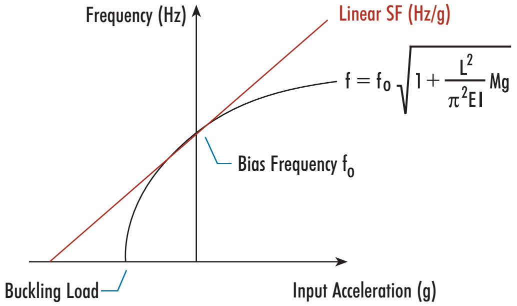

Figure 4. SOA frequency vs acceleration curve.

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

$$f = f_o\left[1 + \frac{1}{2}SP - \frac{1}{8}S^2P^2 + \frac{1}{16}S^3P^3 - \cdots\right] \tag{4}$$

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

Equation (4) can be rewritten as

$$f = f_o + K_1 g + K_2 g^2 + K_3 g^3 - \cdots \tag{5}$$

where: $K_n = K_1 b_n (K_1/f_o)^{n-1}$ (Hz/g^n)
$b_n = b_{n-1}\,(3-2n)/n$
$K_1 = f_o\,(S/2)$
$b_1 = 1$
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_o). The linearized SF is dependent on resonator dimensions, Young's modulus, and the mass of the resonator (m) and proof mass (M)

$$K_1 = \frac{M}{8\pi}\sqrt{\frac{L}{EIm}} \tag{6}$$

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/°C), as it is an order of magnitude larger than silicon's TCE (2.5 ppm/°C), the parameter that would control the resonator dimensional stability. Given the square root relationship, the linear SF temperature coefficient is approximately 25 ppm/°C, indicating that 0.01°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_o)

$$K_2 = -\frac{1}{2}\frac{K_1^2}{f_o} \tag{7}$$

$$K_3 = \frac{1}{2}\frac{K_1^3}{f_o^2} \tag{8}$$

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/g^2 and 0.0125 Hz/g^3. Normalizing these coefficients by dividing by the linear SF gives 2500 µg/g^2 and 12.5 µg/g^3, respectively.

Compensating these coefficients to the sub-µg level is feasible because their stability will be of the order of the linear SF and bias. Differentiation of Eqs. (7) and (8) gives

$$\frac{\Delta K_2}{K_2} = 2\frac{\Delta SF}{SF} - \frac{\Delta f_o}{f_o} \qquad (9)$$

$$\frac{\Delta K_3}{K_3} = 3\frac{\Delta SF}{SF} - 2\frac{\Delta f_o}{f_o} \qquad (10)$$

Note that 1-µg performance implies a resonator frequency stability (Δf/f) on the order of 5 ppb (given a 100-Hz/g per side SF and 20-kHz nominal frequency unit). Combined with the 1-ppm SF requirement, this implies that the above SF nonlinearity coefficients should be stable to approximately 2 to 3 ppm. This high degree of stability should enable compensating the raw nonlinear coefficients to sub-µg levels (although measuring the higher-order g-coefficients will require careful centrifuge testing). Additionally, the net SOA g^2 coefficient and other even-order terms will be reduced as the g^2 contribution from each resonator will be common mode differenced in the net SOA output.

SOA Electronics

Figure 5 shows the SOA electronics block diagram. As mentioned above, the SOA employs an electrostatic comb drive to excite the resonators and to pick off the resonator displacement.

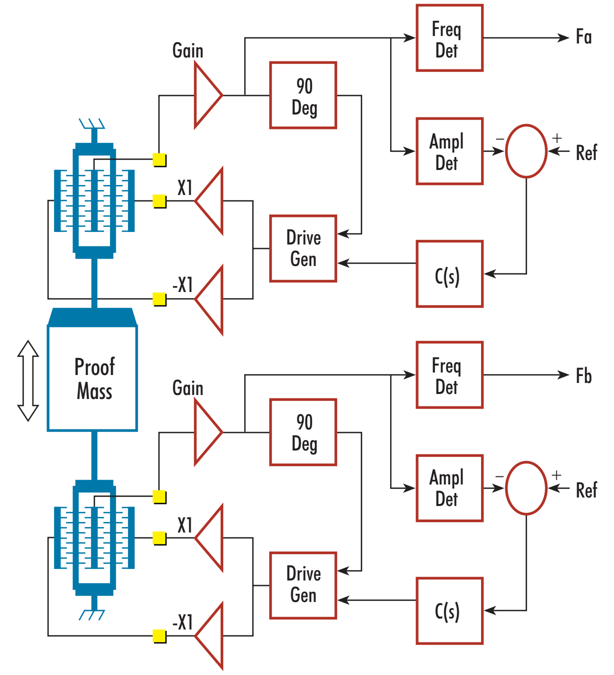

Figure 5. SOA electronics block diagram.

The magnitude of the drive force is given by

$$F = \frac{1}{2}\frac{dC}{dx}V^2 \qquad (11)$$

where: F = drive force
dC/dx = comb position sensitivity
V = applied voltage

The drive amplitude stability furnished by the electronics is critical to maintaining nominal resonator frequency stability. The resonator beams stiffen with lateral deflection, causing a dependence of the resonant frequency with drive amplitude. This nonlinear stiffening effect introduces a bias uncertainty from the resonator drive amplitude instability.

It can be shown[4] that if the resonator is modeled as a linear plus cubic stiffness element, the resonator frequency dependence on amplitude is given by

$$f = f_o\left[1 + \frac{3}{8}\frac{K_3}{K}x^2\right] \qquad (12)$$

where: f = frequency at amplitude x
f_o = nominal resonant frequency
K = linear stiffness of resonator
K_3 = cubic stiffness coefficient
x = drive amplitude

The stability requirement on the drive amplitude can be determined by differentiating Eq. (12) to get

$$\frac{\Delta f}{f_o} = \frac{3}{4}\frac{K_3}{K}x^2\frac{\Delta x}{x} \qquad (13)$$

From Eqs. (12) and (13), it can be seen that a small drive amplitude will minimize the resonator frequency variance from drive amplitude instability and noise. An alternate means of maximizing frequency stability is to minimize the amount of nonlinear stiffening, i.e., design a resonator with a low K_3 coefficient.

The resolution or noise floor of the SOA can be estimated by calculating the amplitude and phase noise associated with the sense comb frequency readout. From Reference [1], the capacitance across a set of engaged comb drive fingers is given by

$$C = 2N\alpha\varepsilon_o\frac{t}{g}L \qquad (14)$$

where: C = capacitance
ε_o = permittivity of air
N = number of teeth per side
α = fringing factor
t = comb finger thickness
g = air gap between fingers
L = engaged length of fingers

The capacitance sensitivity to position (i.e., engaged length) is given by

$$\frac{dc}{dx} = 2N\alpha\varepsilon_o\frac{t}{g} \qquad (15)$$

where dC/dx = sensitivity to position.

Equation (12) gives the relationship between resonator amplitude and frequency, which gives the resonator frequency power spectral density (PSD) as

$$\phi_f = f_o\frac{3}{4}\frac{K_3}{K}X\phi_A \qquad (16)$$

where: ϕ_f = frequency PSD in Hz/√Hz
x = nominal drive amplitude
ϕ_A = amplitude noise PSD
f_o = nominal resonant frequency
K_3/K = stiffness coefficient ratio

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

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

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 SiO_2 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.

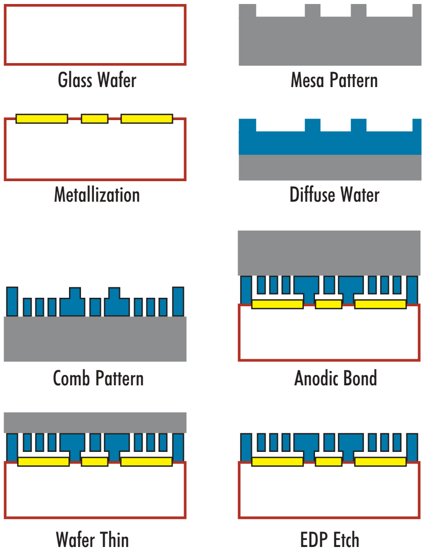

Figure 6. SOA fabrication process.

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.

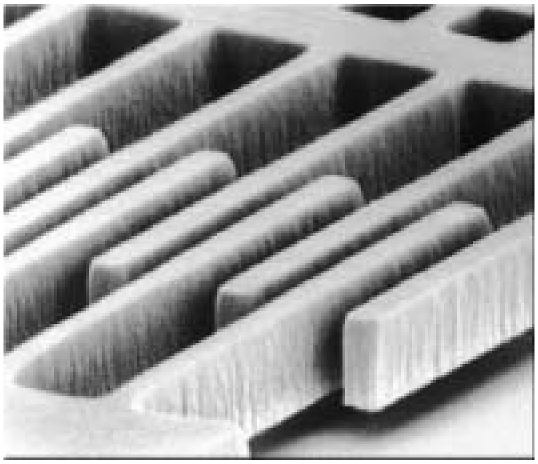

Figure 7. SOA oscillator detail.

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.

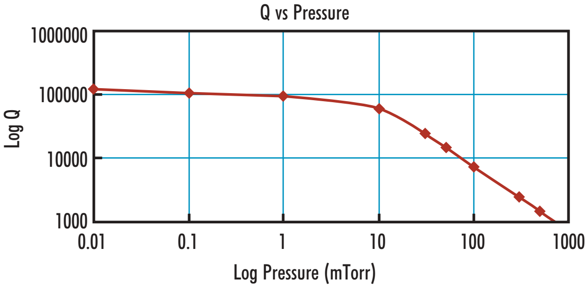

Figure 8. Q vs pressure relationship.

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

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

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

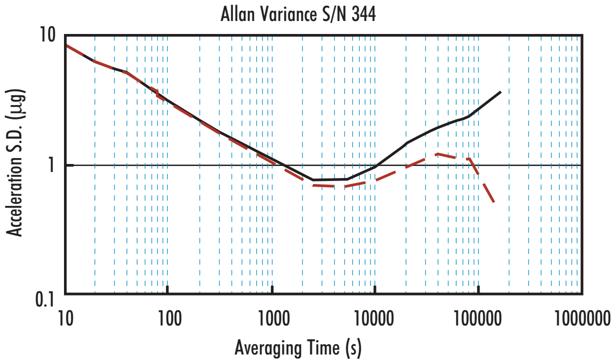

Figure 9. SOA Allan Variance.

The data from Figure 9 in the white noise region indicate, from Eq. (18), a white noise PSD of 23 µg/√Hz. The equivalent velocity random walk coefficient is 0.031 ft/s/√h.

Note from Figure 9, that the SOA acceleration uncertainty drops below 1 µg 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 µg, respectively.

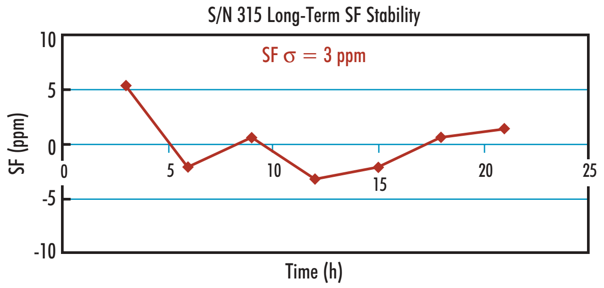

Figure 10. SOA SF stability.

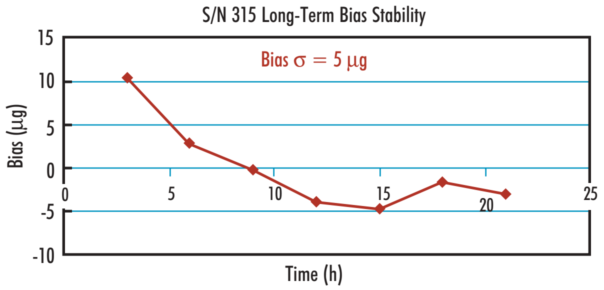

Figure 11. SOA bias stability.

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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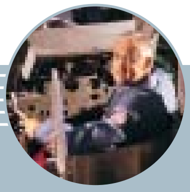

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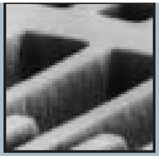

(clockwise from here)

Biographies

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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 in the Mechanical Design and Analysis Division at Draper. Since joining Draper in 1983, he has worked on a broad range of analysis and testing on structural systems. His current research interests include state space modeling of high-speed rotating structures to determine active control requirements. He has a BS in Mechanical Engineering from the University of Lowell and an MS in Mechanical Engineering from Worcester Polytechnic Institute.

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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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