

The Silicon Oscillating Accelerometer: A High-Performance MEMS Accelerometer for Precision Navigation and Strategic Guidance Applications

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ABSTRACT

The intercontinental ballistic missile (ICBM) and submarine-launched strategic missiles 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. Currently, the U.S. strategic missile arsenal relies on variants of the pendulous integrating gyro accelerometer (PIGA) to meet the high-performance, radiation-hard requirements of the weapon system.

Likewise, precision navigation systems, such as the currently deployed SSBN Ship Inertial Navigation Systems (SINS), employ highly specialized and complex electromechanical instruments that, like the PIGA, present a system life-cycle cost and maintenance challenge.

The PIGA and the Electromagnetic Accelerometer (EMA) demonstrate unsurpassed performance, however, their life-cycle cost has motivated a search for a high-performance, solid-state, strategic accelerometer.

The Draper Laboratory is currently in the process of developing the Silicon Oscillating Accelerometer (SOA), a MEMS-based sensor that has demonstrated in laboratory testing the part-per-million (ppm)/ μg scale-factor and bias performance stability required of precision guidance navigation applications.

The ICBM and SSBN applications have significantly different environmental, acceleration dynamic range, and resolution requirements that are best satisfied by optimizing the SOA geometry for each application. The design flexibility and wafer-scale fabrication methods of the silicon MEMS process enable manufacturing both

instrument designs with essentially zero incremental cost associated with the additional instrument assembly line. That is, the SOAs developed for the ICBM guidance and SSBN navigation applications share a common sensor package, electronics architecture, main housing and instrument assembly process. This paper will give an overview of the Draper SOA and compare and contrast performance data taken to date on both versions of the SOA.

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 of the weapon system, combined with the high acceleration levels and large velocity at reentry body deployment place an especially stringent performance requirement on the guidance system accelerometers. The SSBN SINS system requires similarly precise inertial performance from the navigation system accelerometers, although compared with the missile application, the SINS accelerometers enjoy a more benign operational environment and a smaller dynamic range requirement (Ref. [5]).

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.).

Typically, high-performance missile guidance applications require accelerometer bias stability on the order of 1 μg , and SF stability on the order of 1 ppm. The

SINS accelerometer requirements are similar to the ICBM/SLBM guidance requirements (see Table 1), however, the missile and SINS applications differ in two important aspects: 1) the reduced operational dynamic range of the SINS systems (maximum acceleration of 2 g), and 2) the very low readout noise specified for the SINS navigator processing.

Table 1. Typical SOA Performance Goals.

Parameter	Units	Missile Guidance	High-Performance Navigation
• Bias			
-- Long-Term Stability*	μg	1 - 100	1
-- Short-Term Stability**	μg	1 - 5	0.5
• Scale Factor			
-- Long-Term Stability*	ppm	1 - 100	10
-- Short-Term Stability**	ppm	1 - 5	5
-- Asymmetry	ppm	TBD	TBD
-- g ² (Compensated)	μg/g ²	0.1 - 0.2	1
-- g ³ (Compensated)	μg/g ³	TBD	TBD
• VRW	ft/s/√h	0.014 - 0.030	0.0014
• White Noise	μg/√Hz	10 - 22	1
• Misalignment			
-- Long-Term Stability*	arcsec	0.1 - 5	TBD
-- Short-Term Stability**	arcsec	0.1 - 2	0.4
• Vibration Rect.	μg/(grms) ²	<1	TBD
• Bandwidth	Hz	100	TBD
• Max DC Acceleration	g	15 - 120	2
• Peak Shock	g	70 - 170	TBD
*Long-term stability = 1σ over 90 days			
**Short-term stability = 1σ over 10 h			

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 every U.S. strategic missile deployed since the inception of ICBM weapon systems. The complexity of PIGA accelerometers and their specialized technologies, such as gas bearing wheels, ultrastable ball bearings, precision electromagnetic components, and “designer chemical” flotation fluids require a costly support infrastructure for production and system life-cycle maintenance. Likewise, the EMA deployed in the SSBM fleet SINS systems satisfies the accelerometer navigation performance parameters specified in Table 1, but like the PIGA the EMA is also a highly specialized design that requires a costly life-cycle maintenance infrastructure.

Consequently, the missile guidance community is seeking a low-cost alternative to the PIGA for next-generation high-performance missile systems, and a similarly simplified, low-maintenance accelerometer design for the next generation of SINS navigator systems. Both applications hold the important provision that performance remain uncompromised in candidate design alternatives.

The Draper Laboratory is currently in process of developing the SOA a Microelectromechanical Systems (MEMS)-based sensor that has demonstrated the ppm/μg performance stability required of the SINS navigator and missile applications. The MEMS technology is 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, as opposed to VBAs, which typically are 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, and 3) capacitively based, electrostatic resonator actuation and sensing, which offers greater design flexibility than the piezoelectric quartz technology.

The SSBM navigation and missile guidance applications have significantly different environmental, acceleration dynamic range, and resolution requirements that are best satisfied by optimizing the SOA geometry for each application. The design flexibility and wafer-scale fabrication methods of the silicon MEMS process enable manufacturing both instrument designs with essentially zero incremental cost associated with the additional instrument assembly line. That is, both versions of the SOA share a common sensor package, electronics architecture, main housing and instrument assembly process.

The next sections describe the operational principles of the SOA, the MEMS fabrication process, and present a summary of performance data taken to date on both the

missile guidance and SSBN navigation versions of the SOA.

SOA Functional Description

The SOA developed by Draper Laboratory is a miniature silicon VBA fabricated using silicon MEMS micromachining technology. Figure 1 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.

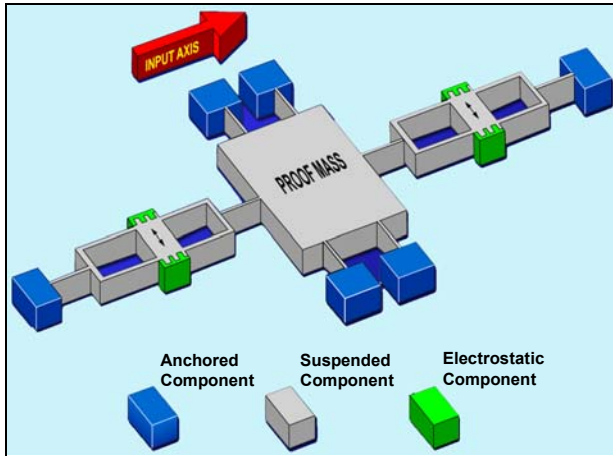


Figure 1. SOA Schematic.

The SOA input axis lies in plane as indicated in Figure 1; 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 (Refs. [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 2.

The goal of the SOA design is to achieve a high scale factor, high Q resonator to achieve high-performance. Large scale factor is desirable because it decreases the degree of frequency stability required to resolve a given acceleration level. For example, 0.1-mHz frequency

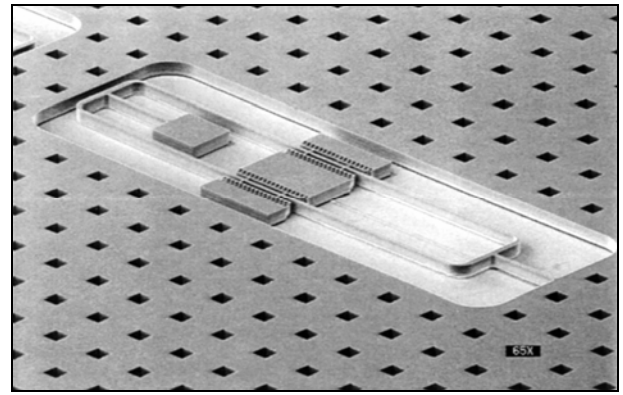


Figure 2. SOA Oscillator Detail.

stability is required of a 100-Hz/g SF unit to resolve 1-μg. A 10-Hz/g unit has a 10 times more restrictive frequency stability requirement (10 μHz) to resolve the same 1 μg input.

It can be shown (Ref. [3]) that the lateral stiffness of an axially loaded beam with fixed ends is:

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

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:

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

where

f = resonant frequency
m = mass of lumped oscillator

Rearranging [2] gives:

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

where

f = resonant frequency
f₀ = nominal unloaded (bias) 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 [3] and shown in Figure 3.

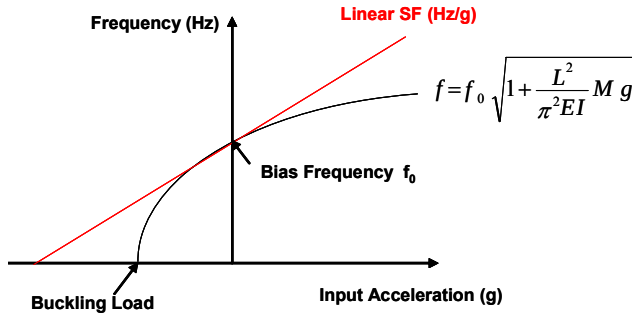


Figure 3. SOA Frequency vs. Acceleration Curve.

A series expansion of [3] can be used to determine the linearized SOA scale factor (the slope about zero acceleration in Figure 3) and higher order g-coefficients:

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

where $S = L^2 / \pi^2 E I$.

Equation [4] can be rewritten as:

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

where

$$\begin{aligned}
 K_n &= K_1 b_n (K_1 / f_0)^{n-1} \text{ (Hz/g}^n\text{)} \\
 b_n &= b_{n-1} (3-2n)/n \\
 K_1 &= S/2 \\
 b_1 &= 1 \\
 g &= \text{acceleration}
 \end{aligned}$$

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):

$$K_1 = \frac{M}{8 \pi} \sqrt{\frac{L}{E I m}} \quad [6]$$

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/°C), as it is an order of magnitude larger than silicon's thermal coefficient of expansion (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 [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, [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.

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 [7] and [8] gives:

$$\frac{\Delta K_2}{K_2} = 2 \frac{\Delta SF}{SF} - \frac{\Delta f_0}{f_0} \quad [9]$$

$$\frac{\Delta K_3}{K_3} = 3 \frac{\Delta SF}{SF} - 2 \frac{\Delta f_0}{f_0} \quad [10]$$

Note that 1- μg performance implies a resonator frequency stability ($\Delta f / f$) on the order of 5 ppb (given a 100-Hz/g per side SF and 20-kHz nominal frequency unit). Combined with 1-ppm SF stability, 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 calibrating the higher-order g-coefficients will require precision 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 4 shows the SOA electronics block diagram. As mentioned above, the SOA employs an electrostatic comb

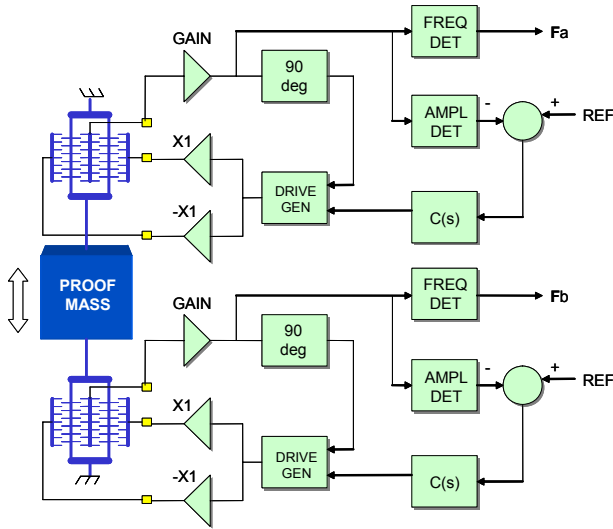


Figure 4. SOA Electronics Block Diagram.

drive to excite the resonators and to pick off the resonator displacement. The electrostatic drive force is given by:

$$F = \frac{1}{2} \frac{dC}{dx} V^2 \quad [11]$$

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 (Ref. [4]) that if the resonator is modeled as a linear plus cubic stiffness element, the resonator frequency dependence on amplitude is given by:

$$f = f_o \left[1 + \frac{3}{8} \frac{K_3}{K} X^2 \right] \quad [12]$$

where

f = frequency at amplitude x
f_o = nominal resonant frequency
K = linear stiffness of resonator
K₃ = cubic stiffness coefficient
x = drive amplitude

The stability requirement on the drive amplitude can be determined by differentiating [12] to get:

$$\frac{\Delta f}{f_o} = \frac{3}{4} \frac{K_3}{K} X^2 \frac{\Delta x}{x} \quad [13]$$

From [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 K₃ 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 Ref. [1], the capacitance across a set of engaged comb drive fingers is given by:

$$C = 2 N \alpha \epsilon_o \frac{t}{g} L \quad [14]$$

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:

$$\frac{dC}{dx} = 2 N \alpha \epsilon_o \frac{t}{g} \quad [15]$$

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:

$$\phi_f = f_o \left(\frac{3}{4} \frac{K_3}{K} X \right) \phi_A \quad [16]$$

where

φ_f = frequency PSD in Hz/√Hz
x = nominal drive amplitude
φ_A = amplitude noise PSD
f_o = nominal resonant frequency
K₃/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:

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

where

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

The high Q's 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 Sensor Design, Fabrication, and Screening

The ICBM application and the SSBN SINS system have significantly different environmental, acceleration dynamic range, and resolution requirements as mentioned above (Table 1). The SOA instrument can be easily adapted to either application by adjusting the SOA MEMS sensor element geometry for the specific operating acceleration range required. Figure 5 is similar to Figure 3 and shows the load vs. acceleration curve for two different SOA designs: a higher g-capable design suitable for ICBM/submarine-launched ballistic missile (SLBM) environments and a lower g design tailored for the more benign SINS environment. Note that the higher sensitivity (higher SF) SINS design has a correspondingly lower buckling load. This is a consequence of beam mechanics and is a fundamental design trade-off in selecting SOA acceleration sensitivity.

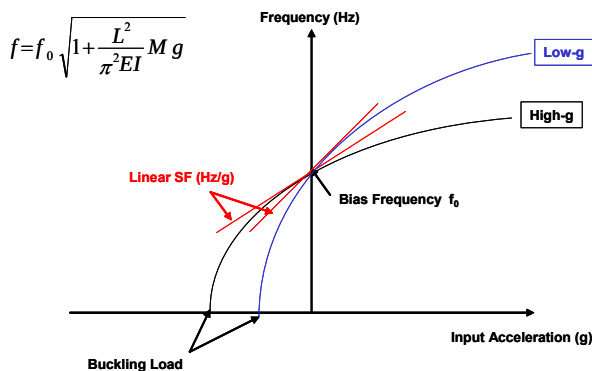


Figure 5. SOA Dynamic Range.

The geometries of the two different SOAs are optimized for each application by adjusting oscillator and proof mass geometry. The advantages of the silicon MEMS design approach is apparent as two different applications can be serviced with only the incremental expense of the MEMS photo-maskset needed to fabricate the application-specific SOA sensor element. The design flexibility and wafer-scale fabrication methods of the silicon MEMS process enable manufacturing both instrument designs with essentially zero incremental cost associated with the additional sensor design. That is, both versions of the SOA share a common sensor package, electronics architecture, main housing, and instrument assembly process. The only difference between the two instrument assembly processes is the use of a different MEMS photo-maskset in the fabrication of the SOA sensor element.

Draper uses the silicon-on-glass dissolved-wafer process to fabricate the SOA (Refs. [6]), a mature MEMS fabrication process that Draper employs elsewhere in MEMS-based inertial technology (Ref. [2]).

The main process steps of the dissolved wafer process are illustrated in Figure 6. The starting wafers used in processing are a boron-doped epitaxial silicon layer grown on an undoped silicon handle layer. The thickness of the epitaxial layer determines the final thickness of the silicon device layer. The first process step is to etch mesas in the epitaxial silicon layer; this step defines the eventual operating air gap between the suspended silicon sensor element structures and the glass substrate.

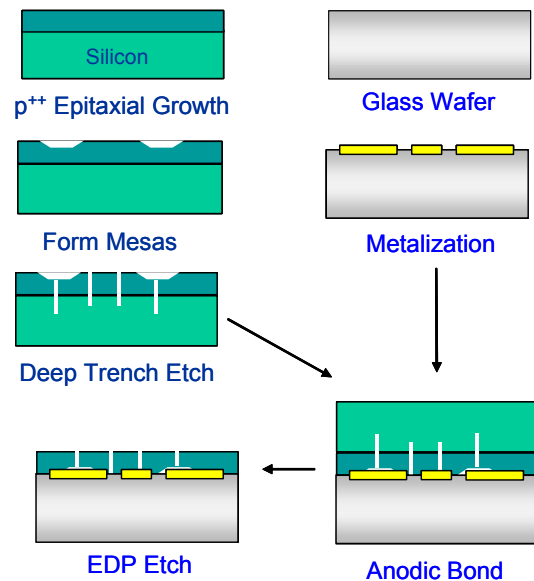


Figure 6. SOA Fabrication Process.

The device structural layer is then photolithographically patterned on the silicon and the wafers are etched using high-aspect-ratio micromachining in a Reactive ion Etch (RIE) machine. This step forms the 2-D geometry of the

SOA silicon sensor element. Recent advances in RIE etching technology have enabled a very high degree of feature size control (e.g., beam width uniformity, side wall perpendicularity, etc.) in MEMS processing, a critical factor affecting as-built SOA sensor performance.

The patterned 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), which removes the silicon handle layer. The boron doping in the epitaxial layer stops the chemical etching action of the EDP, leaving the finished device layer array on the glass wafer substrate. Individual SOA sensors are then diced and screened prior to packaging.

The first screening step performed on the SOA MEMS sensor die is a particle and defect inspection, followed by electrical probing for proper resistance and continuity. Units passing this step are “wiggle tested” by energizing the oscillator elements to verify oscillator freedom at the expected drive frequency.

After probe testing, SOAs with satisfactory performance are packaged and vacuum sealed in an aluminum oxide leadless ceramic chip carrier (LCCC). The residual pressure achieved in the LCCC after vacuum seal is less than one mTorr, which ensures high oscillator Q factors. A plot of Q vs. pressure for a typical SOA is shown in Figure 7, indicating that oscillator drive Q's on the order of 100,000 are achieved with this process. The packaged SOA is mated to a front-end preamplifier electronics module and subsequently mounted in an instrument main housing assembly. The final SOA instrument assembly is shown in Figure 8.

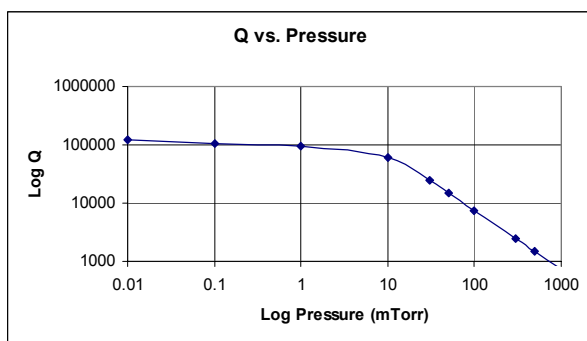


Figure 7. Q vs. Pressure Relationship.

Missile Guidance and SINS SOA Performance Test Data

Both versions of the SOA demonstrate the performance required for their respective applications. As mentioned above, the SINS SOA is tailored with a higher sensitivity



Figure 8. SOA Instrument.

to exploit the reduced dynamic range environment of the SSBN application. The SINS SOA sensor design also incorporates design features to maximize longer time scale drift stability.

The contrast in the performance of both versions of the SOA is best captured by the acceleration resolution capability demonstrated via the noise PSD plots shown in Figure 9. Note that both units have a white noise floor on the order of $10^{-11} \text{ g}^2/\text{Hz}$, however, the SINS design maintains the resolution capability over longer time scales (i.e., lower frequency bands). The missile guidance SOA shows a noise PSD that starts to break upward with a $1/f$ signature in the 10^{-1} Hz to 10^{-2} Hz decade. The SINS SOA shows the white noise floor extending another decade or two before exhibiting a $1/f$ signature.

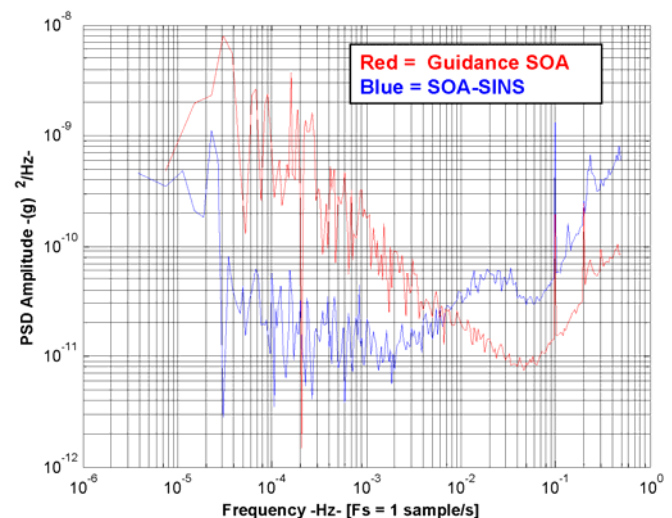


Figure 9. SOA Acceleration Noise PSD.

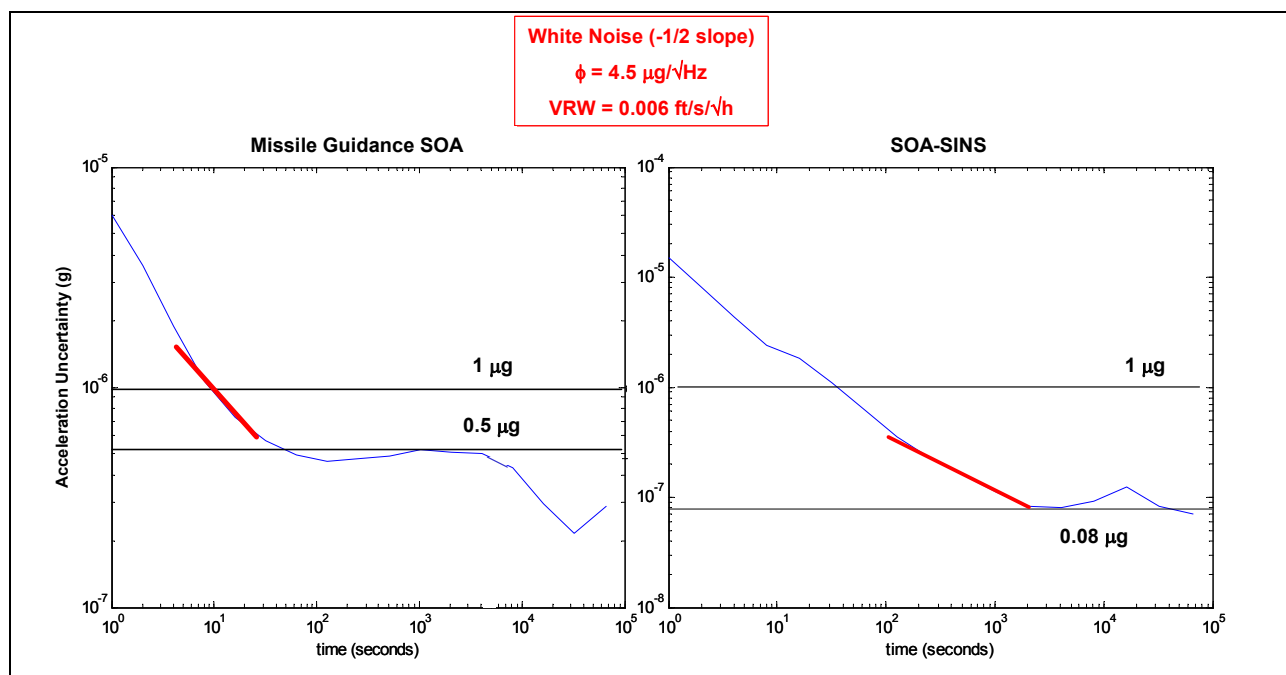


Figure 10. SOA Allan Variance.

This 1/f (or “flicker”) noise is indicative of an acceleration drift instability that limits the net resolution capability of the accelerometer. This is also characterized by the Allan variance charts calculated from the PSD measurements shown in Figure 10. The missile guidance SOA resolution is limited to 0.5 μg , which is achieved over 100-s averaging times. Longer averaging times do not further improve resolution in the missile guidance SOA because of the 1/f drift instability, but the low-frequency extension of white noise floor of the SINS SOA enables 80 nano-g resolution, which is achieved after 1000 s of averaging.

The Allan variance plots the standard deviation of indicated acceleration against data averaging time. The white noise floor of the corresponding PSD can be determined from the portion of the Allan variance having a minus one half slope on the log scale. The equivalent white noise PSD can be calculated from a point on the minus one half slope line from:

$$\sigma^2 = \frac{\phi}{2T} \quad [18]$$

where

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

The data from both versions of the SOA (Figure 10) in the minus-one-half slope region indicates (from [18]) a white

noise PSD of 4.5 $\mu\text{g}/\sqrt{\text{Hz}}$, which is equivalent to a velocity random walk coefficient of 0.006 $\text{ft/s}/\sqrt{\text{h}}$.

Figure 11 shows SOA bias and SF uncertainty measured on a missile guidance SOA in a 2-position test, and Figure 12 shows SF and bias uncertainty measured on an SOA-SINS unit in a 4-position test. The SF and bias data shown in these figures is uncompensated SOA output and are the average values over a 30-min dwell as determined from 1-s averaged data. The data shown extend over a roughly 3-day period and show 1 σ standard deviations in SF and bias of 0.56 ppm and 0.92 μg , respectively, for the missile guidance SOA. The quieter SOA-SINS unit demonstrates 1 σ uncertainty in SF and bias of 0.14 ppm and 0.19 μg , respectively.

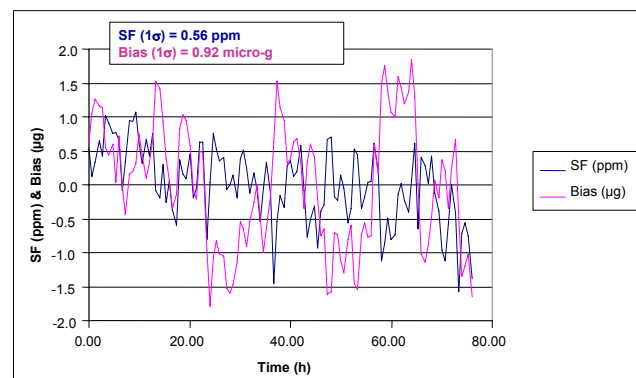


Figure 11. Missile Guidance SOA SF and Bias Stability.

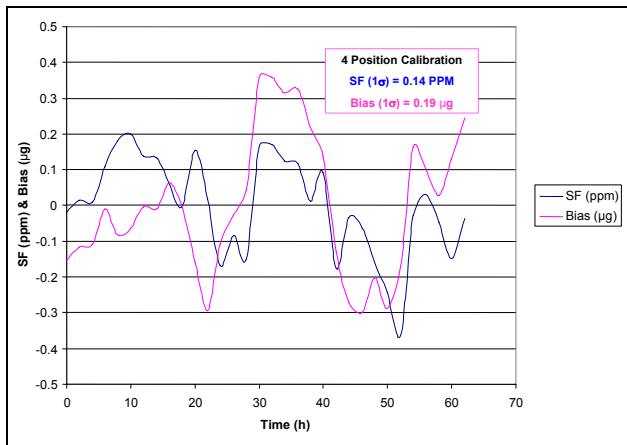


Figure 12. SOA-SINS SF and Bias Stability.

The SOA also demonstrates sub-ppm and sub- μg performance across multiposition tumble tests. The following error model was used to fit the tumble data:

$$a_{\text{ind}} = \frac{f}{SF} = \text{Bias} + a_i + K_2 a_i^2 + K_3 a_i^3 + K_{im} a_i a_m + K_{mm} a_m^2 + K_{io} a_i a_o + K_{oo} a_o^2 \quad [19]$$

where

- a_{ind} = indicated acceleration output
- f = net (differenced) SOA frequency output
- SF = SOA scale factor (Hz/g)
- Bias = SOA bias frequency
- a_i = input axis applied acceleration
- a_m, a_o = cross axis applied accelerations
- K_2, K_3 = second and third order SF nonlinearity
- K_{im}, K_{io} = cross-axis coupling coefficients
- K_{mm}, K_{oo} = cross-axis nonlinearity coefficients

Table 2 shows the nominal values of the above parameters for the SOA as determined in a 16-position tumble test. Note that a value for the K_{mm} and K_{oo} coefficients can not be extracted from a single orientation, multiposition tumble. The contribution of these terms is absorbed in the nominal values of bias and the K_2 coefficient. Table 2 also shows the 1σ variation in the coefficients during the tumble, a test that takes 9 hours to complete.

Figure 13 is a plot of the residual (i.e., the difference between the actual SOA output and the fitted error model) for multiposition tumble tests about the instrument's two cardinal axes. Note that the 1σ standard deviations of the residuals are less than $1 \mu\text{g}$ (0.95 and $0.79 \mu\text{g}$) and the residual plot does not show a systematic variation with table angle, an indication that there is not a major unmodeled error term present in the sensor.

Table 2. Multiposition Tumble Results.

Parameter	Tumble about OA		Tumble about MA	
	Nominal Value	Std. Dev. (1σ)	Nominal Value	Std. Dev. (1σ)
Bias	797.965 Hz	0.354 μg	797.724 Hz	0.295 μg
Scale Factor	126.697 Hz/g	0.989 ppm	126.722 Hz/g	0.822 ppm
K_2	121.33 $\mu\text{g}/\text{g}^2$	0.652 $\mu\text{g}/\text{g}^2$	117.49 $\mu\text{g}/\text{g}^2$	0.542 $\mu\text{g}/\text{g}^2$
K_3	6.167 $\mu\text{g}/\text{g}^3$	1.324 $\mu\text{g}/\text{g}^3$	0.24 $\mu\text{g}/\text{g}^3$	1.10 $\mu\text{g}/\text{g}^3$
K_{im}/K_{io}	-7.293 $\mu\text{g}/\text{g}^2$	0.629 $\mu\text{g}/\text{g}^2$	-6.65 $\mu\text{g}/\text{g}^2$	0.523 $\mu\text{g}/\text{g}^2$
Misalignment	2.34 mrad	0.295 μrad	28.3 mrad	0.245 μrad

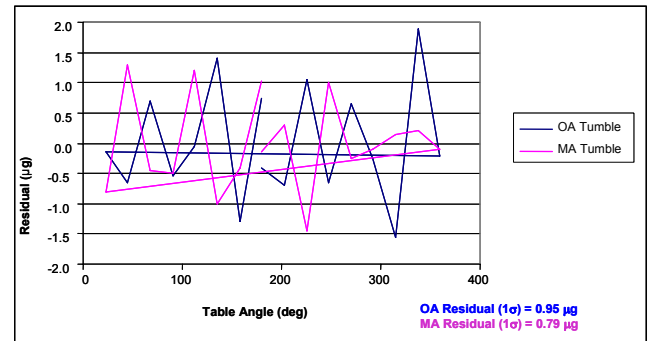


Figure 13. Multiposition Tumble Residuals.

Finally, Figures 14 and 15 show long-term (30-day) SF and bias stability measured on two SOA-SINS units (S/Ns 028 and 063). The better of the two units demonstrates a 1σ SF stability of 0.73 ppm and a 1σ bias stability of approximately $2 \mu\text{g}$ over 30 days.

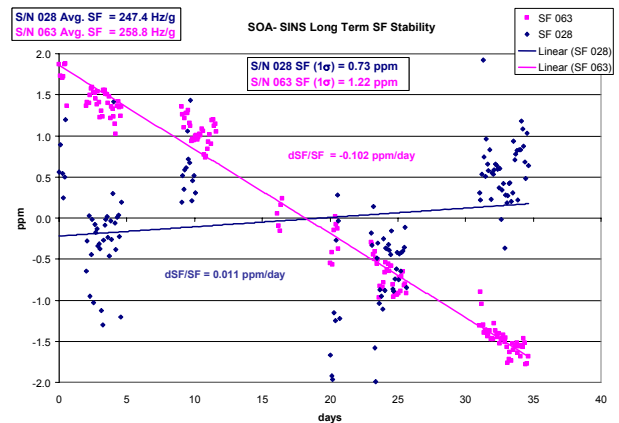


Figure 14. Long-Term SOA-SINS SF Stability.

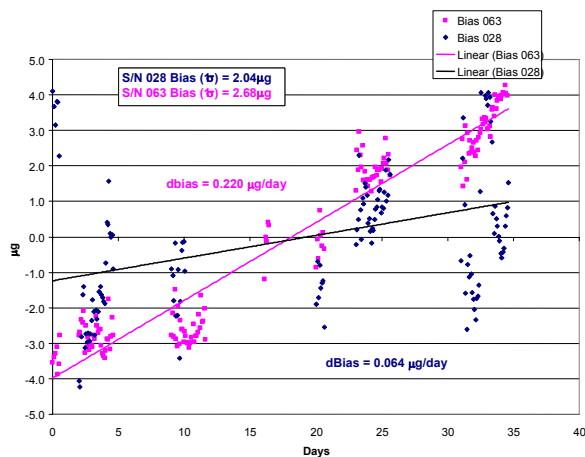


Figure 15. Long-Term SOA-SINS Bias Stability.

CONCLUSIONS

Draper Laboratory is currently in process of developing the SOA, a MEMS-based inertial-grade sensor. Performance data acquired to date meet goals for missile guidance missions and for high-performance navigation applications such as the SLBM SINS navigation systems.

The missile and SSBN applications have significantly different environmental, acceleration dynamic range, and resolution requirements that are best satisfied by optimizing the SOA geometry for each application. The design flexibility and wafer-scale fabrication methods of the silicon MEMS process enable manufacturing both instrument designs with essentially zero incremental cost associated with the additional instrument assembly line. That is, both versions of the SOA share a common sensor package, electronics architecture, main housing, and instrument assembly process.

The MEMS technology is low cost and offers a rapidly expanding commercial business base to leverage and sustain accelerometer production and deployment in next-generation strategic system applications. Integration of the SOA with mixed-signal application-specific integrated circuit (ASIC) electronics offers the promise of a low-cost, small-size, low-power, and high-reliability strategic grade instrument.

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