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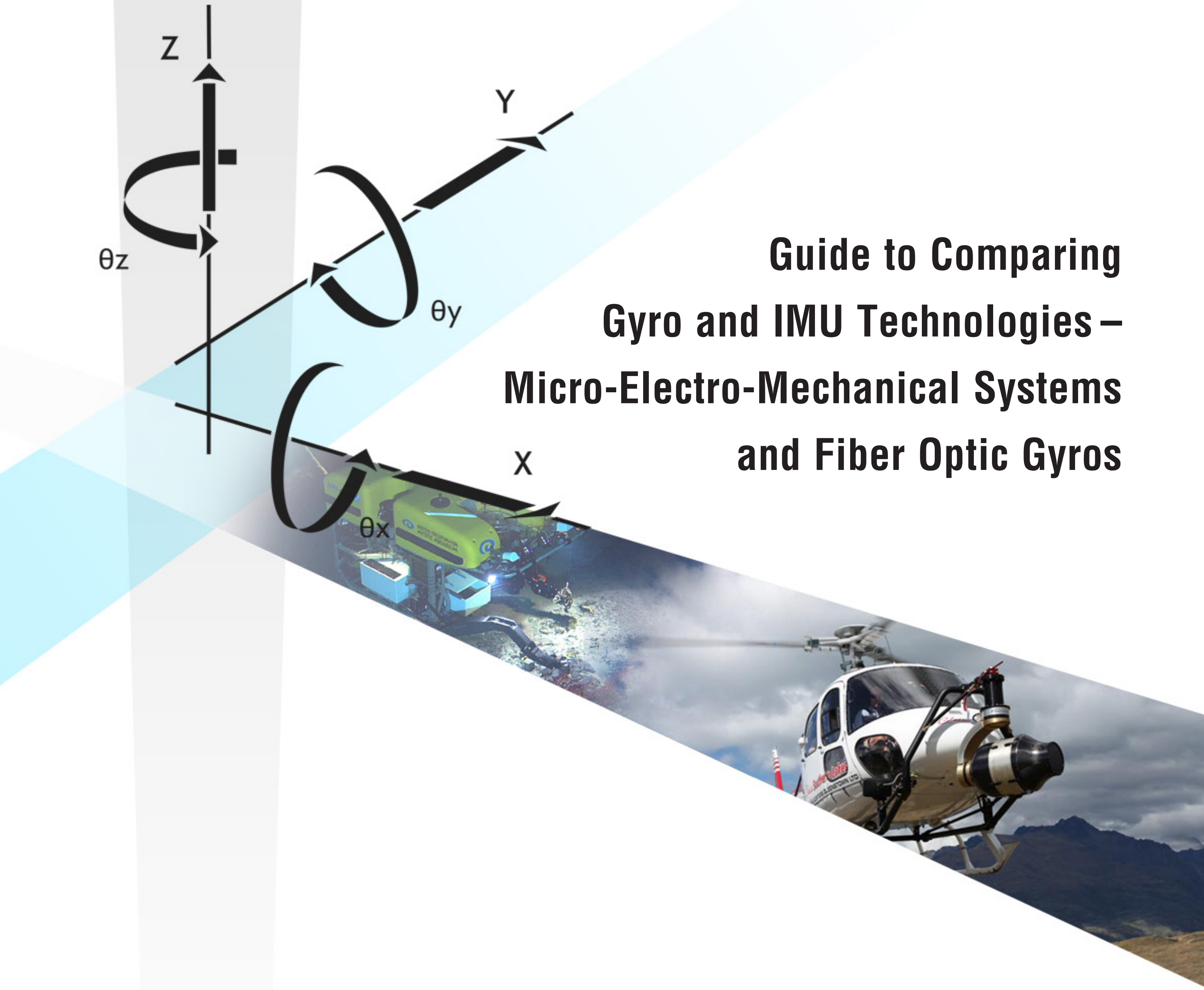


# Guide to Comparing Gyro and IMU Technologies – Micro-Electro-Mechanical Systems and Fiber Optic Gyros

KVH FOG
FIBER OPTIC GYRO

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## Abstract

Engineers designing gyro-stabilized systems for manned or unmanned applications must compare the attributes of various gyro technologies to determine which sensors offer the required performance parameters. Depending on the specifics of the application being designed, some performance criteria are more important than others. A reliable means of comparing common critical performance parameters is a necessary tool for designers and engineers. This paper compares gyro and inertial measurement technologies using distinct performance criteria of fiber optic gyros (FOGs) and FOG-based inertial systems, and micro-electro-mechanical systems (MEMS)-based gyros and MEMS inertial systems.  It focuses on the five key critical performance areas of industrial and tactical grade gyros, as well as current and trending applications for both FOGs and MEMS.

## Introduction

Gyroscopes are essential for navigation, guidance, and stabilization and/or pointing of many manned and unmanned systems designed for commercial, industrial, and military applications. From game controllers to smartphones, and from remote stabilized weapons to driverless vehicles, gyros and inertial measurement units (IMUs) perform a number of vital navigation, guidance, and positioning functions within these systems.

With the tremendous variety of applications comes an equally wide array of performance grades in gyros and IMUs. Consumer grade gyros such as those used in video game controllers, smartphones, tablets, and automobile airbag systems exist on the low-end of both performance and cost. More demanding applications such as weapons systems, driverless vehicles, and navigation in GPS/GNSS-denied environments require a much higher grade of performance. The performance capabilities and accuracy requirements determine which technology is integrated into a specific system.

## Grading Performance in Gyros

Gyro and IMU accuracy can be roughly divided into performance grades according to bias stability specifications, with the lowest grade being used for consumer products, and the highest performing grades being used for mission critical strategic applications. A bias stability measurement tells you how stable the bias of a gyro is over a certain specified period of time. In general, the lower the bias stability the lower the errors will be when integrating the gyro output over time. A gyro with lower bias stability will lead to lower errors in position estimates for an inertial measurement unit. As might be expected, the performance grade of a gyro or IMU also determines its comparative cost.

Table 1.

**Gyro Grades Based on Bias Stability**

| Performance Grade | Bias Stability |
|---|---|
| Consumer | 30-1000°/hr |
| Industrial | 1-30°/hr |
| Tactical | 0.1-30°/hr |
| High-end Tactical | 0.1-1°/hr |
| Navigation | 0.01-0.1°/hr |
| Strategic | 0.0001-0.01°/hr |

The intended application is also an important consideration when evaluating gyro performance grades. Lower performance gyros such as quartz and silicon MEMS gyros are typically used in consumer, industrial, and tactical grade applications such as smartphones, smart munitions, and tactical mid-course guidance. More precision-oriented applications such as torpedoes, air/land/sea navigation, geo-referencing mapping and surveying, and autonomous surface or subsurface navigation require performance grades found in high performance FOGs, ring laser gyros (RLGs), and mechanical gyros. For the purposes of this paper, we will focus on fiber optic gyros and micro-electro-mechanical systems gyros.

## Gyro Technology Types

### Fiber Optic Gyros (FOGs)

FOGs use the Sagnac effect, which utilizes counter-propagating optical beams and interferometry to measure rotation. FOGs have solid state, all fiber or hybrid fiber construction. Moderately priced, these gyros are typically used for industrial and high-tactical grade applications, and provide good price to performance value.

### Micro-Electro-Mechanical Systems (MEMS) Gyros

These gyros use the Coriolis Effect, which is based on vibrating mass deflection resulting from rotation. MEMS can be quartz or silicon based in construction and their benefits are low cost, small size/weight. MEMS are typically used in consumer to industrial grade applications.

## Key Gyro Performance Factors

This paper will look at five critical areas in which industrial/tactical grade gyros must outperform consumer grade gyros while maintaining small form factor and low cost. These areas are:

1. Noise or Angle Random Walk (ARW) - The average error that occurs as a result of high frequency white noise.
2. Bias Offset Error - A stationary gyro can incorrectly register some rotation; this is called bias offset error. Its deviation from zero is typically given at 25°C for an ideal environment (i.e. no temperature change, vibration, shock, or magnetic field applied).
3. Bias Instability - Instability of the bias offset at any constant temperature and ideal environment.
4. Temperature Sensitivity - Bias offset and absolute scale factor (SF) of a gyro will vary slightly with temperature changes. This can be improved with calibration.

5. Shock and Vibration Sensitivity - Shock and vibration can be modeled as noise and bias offset in the gyro output, causing inaccuracies too large to accommodate. These inaccuracies are not easily improved with calibration.

### 1. Noise or Angle Random Walk (ARW)

The output of a gyro includes a broadband, random (white) noise element. ARW describes the average deviation or error that will occur as a result of this noise element, and can be obtained from the Allan Variance value (refer to *Figure 1*) at the 1-sec crossing time (IEEE-STD-952: "Specification Format Guide and Test Procedure for Single-Axis Interferometric Fiber Optic Gyros").

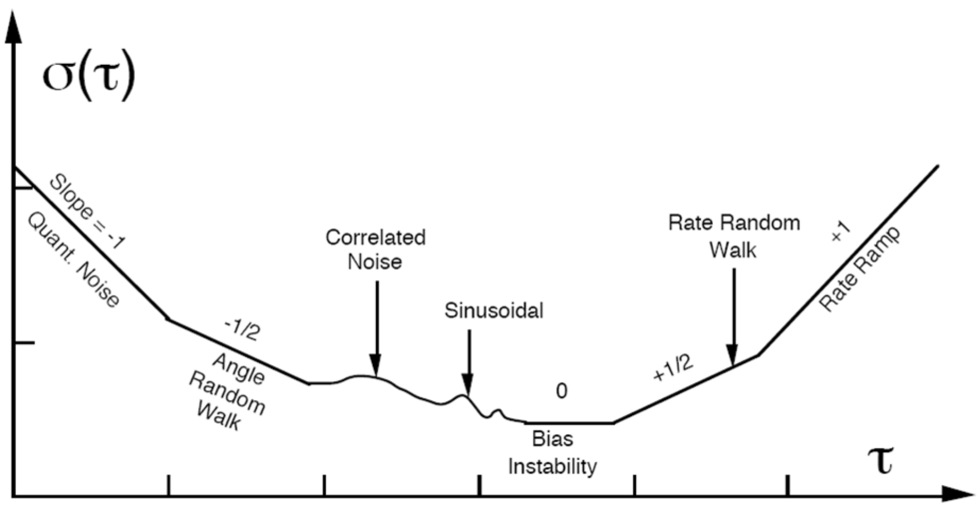
At short averaging times (horizontal axis of the Allan Variance plot), sensor noise dominates and is given as the -½ slope. Major contributors to random noise are the active elements of the gyro such as the laser diode and photo diode in a FOG, and the silicon or quartz vibrating beam and detection electronics in a MEMS gyro. There are large noise performance differences among the various FOG and MEMS gyro suppliers, so designers typically pay extra attention to this parameter. Too much gyro noise results in loss of application precision and accuracy in the rate or position measurement.

### 2. Bias Offset Error

Bias is any nonzero sensor input when the input is zero. A mathematical model is used to calibrate and compensate for fixed errors such as bias (offset) and input/output scale factor variations.

Figure 1.

**Log Allan Deviation Plot from IEEE-STD-952**



### 3. Bias Instability (Constant Temperature)

This is the stability of the bias offset at any constant temperature and ideal environment. Bias instability is best measured using the Allan Variance (IEEE-STD-952) measurement technique and is the fundamental method of deriving performance specifications for all major gyro types including FOGs, MEMS, and RLGs.

The standard definition of bias instability used by inertial sensor manufacturers is the minimum point on the Allan Variance curve - the lower this value, the better the bias performance (refer to *Figure 1*). Allan Variance is intended to estimate stability due to noise processes, and not that of systematic errors such as temperature, shock, or vibration effects.

While a gyro's constant bias offset could potentially be calibrated out, bias instability introduces an error that may not be easy to calibrate. Due to bias instability, the longer a gyro operates, the greater its accumulated rate or position error. Low bias instability is critical for applications requiring excellent accuracy over long periods, such as autonomous vehicle navigation. Bias instability is therefore very critical in the gyro selection process.

### 4. Temperature Sensitivity

Gyro performance degrades over temperature. Parameters sensitive to temperature include noise, bias offset, and scale factor (sensitivity). System integrators should characterize all these parameters over temperature to confirm that gyro performance meets system targets. The smaller the uncalibrated temperature sensitivity is, the better the calibrated performance. For example, KVH FOGs have internal temperature calibration tables for bias offset and scale factor correction versus temperature.

### 5. Shock and Vibration Sensitivity

Gyro performance (noise and bias offset) also degrades under vibration and shock input, and vibration and shock-induced errors are not easily calibrated. Vibration performance is important in many industrial and military applications in which gyros must perform accurately in the presence of random vibration and/or shock input caused by numerous factors such as engines or gunfire. To help minimize vibration issues, designers locate the gyro where vibrations are dampened and utilize anti-alias and decimation filtering. The more resistant a gyro is to vibration, the more reliable the performance and the more freedom the designer has for gyro location within the system. FOGs are inherently not sensitive to vibration due to using a light source whereas MEMs use a mechanical structure and are more prone to vibration sensitivity.

Provided in *Table 2* are the performance parameters of currently manufactured gyros. Likewise, *Table 3* is a performance sample of currently manufactured inertial measurement units including both MEMS and FOGs.

## Overview of FOGs

Fiber optic gyros offer high performance in the five key parameters vital for navigation, control, and stabilization. These are low angle random walk; small bias offset error; excellent bias instability (low drift); reduced temperature sensitivity; and reduced shock and vibration sensitivity. FOGs are solid state sensors which makes these gyros extremely robust and reliable. In terms of cost vs. performance, FOGs offer an excellent value. Through design and process improvements KVH continually reduces the size and weight of the FOGs and IMUs as well as increasing performance. These process improvements also reduce cost making the FOG a more affordable choice in lower cost applications in which the cost may have previously been prohibitive.

## Traditional and Trending Applications for FOGs and FOG-based IMUs

With the superior ARW and thermal bias stability of FOGs, this technology is often the choice of engineers designing high-speed platform stabilization in land, sea, and

Table 2.

### GYRO FOG vs. MEMS Performance

| Performance | Units | Specification | Specification |
|---|---|---|---|
| Technology | | FOG | MEMS |
| Input Rate (maximum) | ± °/sec | ± 490 | ± 400 |
| Angle Random Walk (25°C) | °/h/√Hz | ≤ 0.667 | ≤ 9 |
| Bias Offset (25°C) | ± °/h | ± 2 | ± 250 |
| Bias Instability (constant temp) | °/h, 1σ | ≤ 0.05 | ≤ 1 |
| Bias Full Temp (≤ 1 °C/min) | °/h, 1σ | ≤ 1 | ≤ 10 |
| Bias Vibration Rectification | °/h/grms | ≤ 0.3 | ≤ 1 |
| SF Non-Linearity (max rate, 25°C) | ppm, 1σ | ≤ 50 | ≤ 50 |
| SF Full Temp (≤ 1 °C/min) | ppm, 1σ | ≤ 200 | 200 |
| Bandwidth (-3dB) | Hz | 440 | 262 |
| Physical | | | |
| Dimensions (max) | mm (inches) | 45.7 Dia x 22.9 h<br>(1.8 x 0.9) | 45.7 l x 38.1 w x 20.32 h<br>(1.8 x 1.5 x 0.8) |
| Weight (max) | kg (lbs) | 0.11 (0.24) – 1 axis<br>0.17 (0.38) – 2 axes | 0.05 (0.11) |
| Electrical | | | |
| Input Voltage | VDC | +5 & ±8 to ±15.75, ±5% | +5 ±10% |
| Power Consumption (max) | Watts | 4 | 1.5 |
| Data Interface | Digital | RS-422 | RS-422 |
| Data Rate | Hz | 1000 | 2000 |

= high-end tactical grade gyro performance (ARW ≤ 6 °/h/√Hz = 0.1 °√h, Bias Offset ± 10 °/h
Bias Instability ≤ 1 °/h-1σ, Bias Temp ≤ 1 °/h-1σ, Bias Vibe ≤ 1 °/h/grms, SF Temp ≤ 200 ppm-1σ)

Table 3.

## IMU – FOG vs. MEMS Performance

| Performance | | | |
|---|---|---|---|
| **Gyros** | **Units** | **Specification** | **Specification** |
| Technology | | FOG | MEMS |
| Input Rate (maximum) | °/sec | ± 490 | 400 |
| Angle Random Walk (25°C) | °/hr/√Hz | ≤ 0.7 | ≤ 9 |
| Bias Offset (25°C) | °/hr | ± 2 | ± 250 |
| Bias Instability (constant temp) | °/hr, 1σ | ≤ 0.05 | ≤ 1 |
| Bias vs. Temp (≤ 1°C/min) | °/hr, 1σ | ≤ 1 | ≤ 10 |
| Bias Vibration Rectification | °/hr/grms | ≤ 0.3 | ≤ 1 |
| SF Non-Linearity (max rate, 25°C) | ppm, 1σ | ≤ 50 | ≤ 50 |
| SF vs. Temp (≤ 1°C/min) | ppm, 1σ | ≤ 200 | 167 |
| Bandwidth (-3dB) | Hz | ≥ 440 | 262 |
| Misalignment | mrads | ± 0.4 | ± 1 |
| **Accelerometers** | | | |
| Technology | | MEMS Silicon | MEMS Silicon |
| Input Limit (max) | g | ± 10 | ± 10 |
| Velocity Random Walk (25°C) | mg/√Hz | ≤ 0.12 | 0.1 |
| Bias Offset (25°C) | mg | ± 2 | Not specified |
| Bias Instability (constant temp) | mg, 1σ | ≤ 0.05 | 0.05 |
| Bias Full Temp (≤ 1°C/min) | mg, 1σ | ≤ 1 | 2 |
| Bandwidth (-3dB) | Hz | 200 | 262 |
| Misalignment | mrads | ± 1 | ± 1 |
| **Physical** | | | |
| Dimensions (max) | mm (inches) | 88.9 Dia x 73.7 h (3.5 x 2.9) | 45.7 l x 38.1 w x 20.32 h (1.8 x 1.5 x 0.8) |
| Weight (max) | kg (lbs) | 0.7 (1.45) | 0.05 (0.12) |
| **Electrical** | | | |
| Power Consumption (max) | Watts | 8 | ≤ 2 |
| Initialization Time (valid data) | secs | ≤ 1.5 | ≤ 5 |

= high-end tactical grade gyro performance (ARW ≤ 6 °/h/√Hz = 0.1 °/√h, Bias Offset ± 10 °/h

aerial systems including mission-critical weapons platform stabilization. FOGs are used in motion sensing, pointing, stabilization, and navigation for unmanned and manned applications, GNSS/INS integration systems, payloads for Unmanned Aerial Vehicles (UAVs), long-range optical and sensor systems, and high-accuracy inertial navigation systems. FOG-based IMUs with low bias offset and excellent thermal bias stability are typically the choice for such demanding applications as antenna, optical equipment and laser system pointing and stabilization, GNSS-aiding, unmanned vehicle stabilization and navigation, EO/FLIR, land, sea, aerial mobile mapping and surveying, flight control, and altitude, heading and reference systems (AHRS).

Some emerging applications for high performance FOGs and FOG-based IMUs include autonomous platforms for land, air, and sea that require excellent thermal bias stability. Such autonomous and robotic systems include, but are not limited to, oil and gas exploration, ocean floor mapping, search and rescue operations, security and law enforcement support, wildfire control and monitoring, military operations support multipliers, humanoid systems, and industrial material handling. In addition, FOGs' excellent ARW makes them ideal for augmented reality systems used for such applications such as sports (America's Cup races and NFL football) and virtual map overlays in real time used by first responders and law enforcement.

The future of driverless vehicle technology requires the superior bias and scale factor stability offered by high performance FOGs and FOG-based IMUs. These applications include driver-assist systems for self-parking, collision avoidance, and auto-braking, as well as vehicle-to-vehicle applications such as safe road trains and connected driver systems. In military applications, driverless cargo convoys rely on the same situational awareness technology.

## Overview of MEMS

Micro-electro-mechanical systems gyros offer smaller size and weight and less power consumption than other gyroscopes. MEMS are capable of withstanding high non-operating shock levels, and in general offer a lower cost than other gyro technologies. The weaknesses of MEMS gyros and inertial systems lie in critical performance parameters such as higher angle random walk/noise, which is an extremely important performance criterion in stabilization and positioning systems. In addition, MEMS gyros have higher bias instability, which results in a degraded navigation or stabilization/pointing solution. Thermal sensitivity of MEMS gyros and inertial systems also impacts their bias and scale factor performance; these attributes are critical in both stabilization and navigation applications.

## Traditional and Trending Applications for MEMS and MEMS-based IMUs

MEMS deliver the small size, low cost, and level of performance ideal for consumer grade applications such as digital cameras, smartphones, video game controllers, and automotive applications such as airbag deployments and electronic stability control systems. MEMS-based IMUs are commonly used for industrial-grade applications including miniaturized AHRS, and low/moderate pointing and positioning systems. Emerging applications in which MEMS are likely to lead include consumer entertainment applications such as full body motion capture for movie special effects and game developers. Movement science turns to MEMS for motion capture for sports applications and medical/health applications such as rehabilitation and clinical diagnosis. In the field of GPS/sensor-aided autonomous platforms requiring small size over other performance parameters, MEMS are being tested for short-term mission duration, stabilization, control, and navigation.

## Conclusion

Engineers designing systems for various applications requiring gyro-stabilization or inertial navigation need to define and prioritize the performance factors that are most important to the success of their design. By taking into consideration the five most compelling performance factors as outlined in this paper, engineers can select the appropriate gyro and technology. A comparison of FOG or MEMS gyros and IMUs based on their specific technologies and performance strengths and weaknesses enables a choice that is most likely to result in an effective and successful design.

KVH FOGs and IMUs are the choice of engineers designing higher performance systems for a wide variety of challenging applications including robotics, remote weapons systems, inertial navigation in GNSS-denied environments, unmanned land, air, and ground vehicles, and driverless car technology. KVH's high performing commercially available IMU, the 1750 IMU, and the DSP-1750 FOG, the world's smallest highest performing fiber optic gyro, are providing solutions for the most difficult navigation and stabilization challenges. KVH's new 1725 IMU provides excellent performance at a lower cost to be more competitive in consumer and industrial applications; allowing customers to obtain FOG performance at MEMS prices. KVH gyros and IMUs are chosen by industry leaders including Boston Dynamics, NovAtel, Inc., Daifuku Webb, Raytheon, Lockheed Martin, General Dynamics, Subsea Tech, Inc., Fugro, BAE Systems, Inc., Boeing, and iRobot.

## About KVH Industries

KVH Industries, Inc., is a premier manufacturer of high performance sensors and integrated inertial systems for defense and commercial guidance and stabilization applications. KVH is also a leading manufacturer of solutions that provide global high-speed Internet, television and voice services via satellite to mobile users at sea, on land, and in the air. An ISO 9001-certified company, KVH is based in Middletown, Rhode Island, U.S.A., with facilities in Illinois, U.S.A., Denmark, Norway, the U.K., Singapore, the Philippines, Cyprus, and Japan. For more information, contact:

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