**Final Project**
**MECH 3050 – Measurement & Instrumentation**
**Spring 2025. Auburn University**

# PROGRAMMABLE AIR-TO-LAND CRUISE MISSILE SENSOR SYSTEM

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## ABSTRACT

Since the development of modern warfare systems, missile guidance has become a critical component in ensuring accuracy and mission success. The ability to guide a missile to its intended target is essential, especially as targets become faster, more maneuverable, and more difficult to detect. Effective guidance also ensures that only intended targets are engaged, reducing collateral damage. Missile guidance presents a complex engineering problem because it requires guidance, navigation, and control systems to operate in real time under tight performance constraints. Factors such as target motion, aerodynamic disturbances, sensor inaccuracies, and time delays all influence the missile trajectory. Small errors in measurement, such as position, velocity, or orientation, can compound over time, leading to significant deviations from the desired path. In this project, we address the missile guidance problem using a combination of onboard sensors to estimate the missile state. The ADIS16470 MEMS internal measurement unit provides triaxial gyroscope data to determine orientation, and a triaxial accelerometer which provides acceleration data used to estimate velocity and position through integration. The Garmin GRA 5500 digital radar altimeter measures altitude above terrain, improving vertical position estimation and low-altitude performance. Additionally, the OmniPreSense OPS243-A Doppler radar velocity sensor measures velocity relative to the ground using Doppler shift, providing a direct and reliable velocity reference that helps correct drift from inertial measurements. Together, these sensors enable accurate state estimation, which is essential for reliable guidance and control of the missile toward its target. This report covers the theory of operation, technical specifications, implementation, signal conditioning, and system integration for each sensor, along with a cost analysis of the complete system.

## NOMENCLATURE

$\omega$ Angular velocity (deg/s or rad/s)
$a$ Linear acceleration (m/s² or g)
$h$ Altitude above ground level (ft or m)
$V$ Ground speed (m/s)
$f_d$ Doppler frequency shift (Hz)
$f_t$ Transmitted frequency (Hz)
$c$ Speed of light (m/s)
IMU Inertial Measurement Unit
GNC Guidance, Navigation, and Control
SPI Serial Peripheral Interface
ADC Analog-to-Digital Converter
AGL Above Ground Level
INS Inertial Navigation System

## INTRODUCTION AND BACKGROUND

Modern cruise missiles rely on a suite of sensors integrated into a guidance, navigation, and control (GNC) system to navigate from a launch platform to a designated target. The fundamental challenge in missile guidance is maintaining accurate knowledge of the vehicle's position, velocity, and attitude throughout flight while accounting for unknown disturbances such as wind gusts, temperature/pressure gradients, and terrain variations. This project focuses on selecting and integrating four key sensors into a programmable air-to-land cruise missile system, demonstrating how each sensor's data contributes to the overall mission objective.

The missile is designed to fly to a preprogrammed target at a low altitude to avoid radar detection, maintaining stable flight through active feedback control. The four measurands critical to this operation are: angular velocity and orientation (gyroscope) as seen in Figure 1, linear acceleration (accelerometer), altitude above terrain (radar altimeter), and ground speed (Doppler radar velocity sensor). These measurands provide the data necessary for the inertial navigation system (INS) to continuously update the missile's estimated state, enabling the flight control system to make corrective adjustments in real time, and guide the missile towards the intended target.

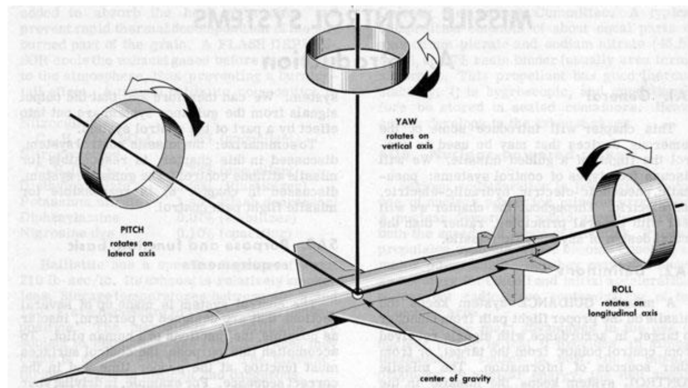


Figure 1: Missile Gyroscope Axis

Historically, tactical missile systems have employed fiber-optic gyroscopes (FOGs) and ring laser gyroscopes (RLGs) for attitude determination due to their high precision and low drift rates. However, these systems are expensive, heavy, and bulky. With advances in technology, modern IMUs such as our selected ADIS16470 offer comparable performance in a smaller package at a fraction of the cost. Similarly, traditional barometric altimeters have been supplemented or replaced with radar altimeters, like our selected Gramin GRA 5500, that provide terrain-relative measurements unaffected by atmospheric pressure variations. For velocity measurement, pitot-static systems have traditionally been used due to their simplicity, but they are vulnerable to icing and blockage in inclement weather conditions. Our selected doppler radar velocity sensor (OmniPreSense OPS243-A) offers a non-contact alternative that measures ground speed directly by detecting the frequency shift of microwave signals reflected from the terrain, eliminating the need for a pitot tube exposed to the atmosphere.

The conditions that may affect measurement accuracy in this application include extreme vibration and shock during launch and flight, rapid temperature changes at varying altitudes, electromagnetic interference from onboard electronics and adversarial jamming systems, and aerodynamic turbulence at high speeds. Each sensor selected for this project has been evaluated for its ability to perform reliably under these conditions. The following sections detail the theory of operation, specifications, implementation, signal conditioning, and system integration for each of the four sensors.

## SENSORS

The sensor suite for this missile system consists of three physical sensor units providing four measurands: the ADIS16470 IMU (gyroscope and accelerometer), the Garmin GRA 5500 radar altimeter, and the OmniPreSense OPS243-A Doppler radar velocity sensor.

### Gyroscope (ADIS16470 IMU)

The triaxial gyroscope within the ADIS16470 IMU measures the angular velocity of the missile about the roll, pitch, and yaw axes. This data is essential for determining and updating the vehicle's attitude and orientation within the inertial navigation system.

**Theory of Operation.** The ADIS16470 gyroscope is a vibratory MEMS device that uses the Coriolis effect to measure angular rate. Inside the sensor, a mass is driven into oscillation at its resonant frequency. When the sensor experiences rotation, the Coriolis force acts perpendicular to both the direction of vibration and the axis of rotation, causing a secondary displacement of the mass. This displacement is detected by sensors and is proportional to the angular velocity. The raw analog signal is then digitized by an internal ADC and passed through factory calibration equations that correct for sensitivity errors, bias offsets, and misalignment. The corrected digital output is made available through the SPI interface. The angular displacement can be obtained by integrating the angular velocity over time, as shown in Eq. (1).

$$\theta(t) = \int \omega(t)\, dt \tag{1}$$

**Technical Specifications.** The ADIS16470 gyroscope has a range of ±2000°/sec across all three axes. The digital resolution in 16-bit mode is 10 LSB/°/sec, and in 32-bit mode it is 655,360 LSB/°/sec. The in-run bias stability is 8°/hr (1σ), and the angular random walk is 0.34°/√Hr (1σ). The rate noise density is 0.008°/sec/√Hz rms, and the 3 dB bandwidth is 550 Hz. The sensitivity error over the compensated temperature range (−10°C to +75°C) is ±0.25%. Axis-to-axis misalignment is ±0.1°. The sensor operates on a single 3.3 V supply and communicates via SPI. The operating temperature range is −25°C to +85°C, and the device can survive mechanical shocks up to 2000 g. The complete manufacturer's datasheet is included in Appendix 1 [1].

**Implementation.** The gyroscope within the ADIS16470 will be mounted at or near the missile's center of gravity to minimize the effects of vibration and to provide the most accurate angular rate measurements for the flight control system. The device will be rigidly attached to the airframe using vibration-absorbing mounts to reduce the high-frequency noise that could come from the propulsion system or aerodynamic loads. The factory calibration equations correct for bias and sensitivity drift due to varying operating temperatures. The programmable digital filters within the module will be configured to minimize sensor noise above the control system's bandwidth.

**Accelerometer (ADIS16470 IMU)**

The triaxial accelerometer within the same ADIS16470 IMU measures linear acceleration along the missile's body axes (longitudinal, lateral, and vertical). These measurements support the inertial navigation system in estimating the missile's velocity and position through double integration, from Eqs. (2) and (3).

**Theory of Operation.** The MEMS accelerometer operates on the principle of inertial force detection. A mass is suspended within the sensor structure. When the sensor experiences linear acceleration, the mass deflects relative to the fixed frame due to its inertia. This deflection is measured by sensors arranged symmetrically around the mass. A simplified version of the accelerometer (only 1 axis) can be seen in Fig. (2). The capacitance change from the sensors is proportional to the displacement and the applied acceleration. An internal ASIC converts this analog capacitance signal to a digital output, applying a factory calibration equation for sensitivity, bias, and cross-axis alignment. Velocity and position can be estimated by integrating the acceleration from the sensor, as shown in Eqs. (2) and (3).

$$v(t) = \int a(t)\, dt \tag{2}$$

$$x(t) = \int v(t)\, dt = \iint a(t)\, dt^2 \tag{3}$$

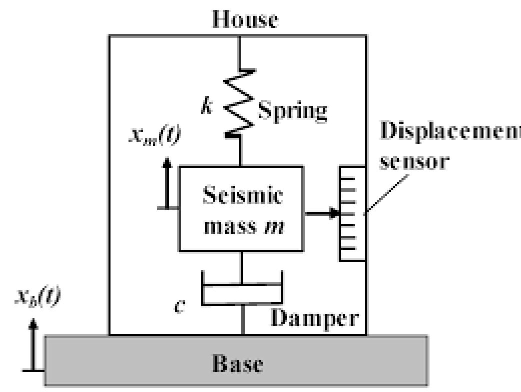


Figure 2: Basic Accelerometer Diagram

**Technical Specifications.** The ADIS16470 accelerometer provides a dynamic range of ±40g on each axis. In 16-bit mode, the sensitivity is 800 LSB/g, and in 32-bit mode it is 52,428,800 LSB/g. The in-run bias stability is 13μg (1σ), which is critical for minimizing position drift during long flights. The sensitivity error over the compensated temperature range is specified by the manufacturer's calibration data. The sensor also provides delta velocity outputs, which can be used directly by the navigation algorithm to reduce integration errors. The ±40 g range is acceptable for capturing the high accelerations expected during missile launch and terminal maneuvers, while the 13 μg bias stability provides sufficient accuracy for mid-course cruise navigation. The operating temperature range and supply voltage are the same as the gyroscope, since both sensors are integrated in the same physical package [1].

**Implementation.** Since the accelerometer is part of the ADIS16470 IMU package, no additional mounting or wiring is required beyond what is described in the gyroscope implementation section. The main concern for accelerometer implementation is the effect of vibration. Structural vibrations from the turbofan or turbojet engine can introduce broadband noise into the acceleration measurement. The ADIS16470 specifies a vibration rectification error of 0.0005°/sec/$g^2$ for the gyroscope; for the accelerometer, the programmable Bartlett-window FIR filter can be configured to reduce vibration frequencies above the navigation system's bandwidth. Bias calibration can be performed before launches by recording the accelerometer output while the missile is stationary and subtracting any measured offset from future readings.

**Radar Altimeter (Garmin GRA 5500)**

The Garmin GRA 5500 digital radar altimeter measures the missile's altitude above ground level. This measurement is critical to ensure the missile remains at the proper height above the terrain, so that it can follow flight plans that allow it to fly under radar detection.

**Theory of Operation.** The GRA 5500 operates on the principle of frequency-modulated continuous-wave radar. The unit transmits a continuous radio frequency signal directed downward toward the terrain. When the signal reflects off the ground and returns to the receiver antenna, there is a time delay proportional to twice the altitude of the missile above the terrain. Because the transmit frequency is continuously changing, the frequency difference between the currently transmitted signal and the received echo is directly proportional to the time delay, and therefore to the altitude. The frequency is then measured by the digital signal processor to compute the altitude.

**Technical Specifications.** The GRA 5500 is a digital radar altimeter capable of processing hundreds of altitude readings per second. It operates on a 14/28 VDC supply. The unit maintains altitude accuracy within a roll angle of ±20°, and operates with relaxed (±20%)

accuracy limits between ±20° and ±30° of roll. The physical unit measures approximately 3.99 inches in height, 3.02 inches in width, and 11.62 inches in depth (with mounting rack and connector), and weighs 3.5 lbs with the mounting rack. The digital signal processing technology provides smooth altitude tracking by filtering unknown noise. The unit requires two antennas (one transmitter, one receiver) for operation. [2].

**Implementation.** The GRA 5500 will be mounted inside the missile's avionics bay with the two antennas (transmit and receive) flush-mounted on the bottom surface of the missile, oriented directly downward toward the ground. The antenna placement must ensure an unobstructed field of view to the ground. The radar altimeter's digital output will be interfaced with the flight computer, which will compare the measured altitude above ground level to the planned flight path. If the measured altitude is different than the desired altitude, the flight control system will generate corrective pitch commands to bring the missile back to the desired altitude. The primary concern for this sensor is the effect of rough or highly reflective terrain, which can cause inaccurate readings. The GRA 5500's digital signal processing is designed filter such anomalies, which should help. At very low altitudes (below ~50 feet), the signal-to-noise ratio may decrease due to the proximity of the ground return, so the flight computer can be programmed to apply additional filtering at lower altitudes.

**Doppler Radar Velocity Sensor (OmniPreSense OPS243-A)**

The OmniPreSense OPS243-A is a 24 GHz continuous-wave Doppler radar sensor that measures the ground speed of the missile by detecting the Doppler frequency shift of microwave signals reflected from the terrain below. This measurement provides a direct, non-contact determination of the missile's velocity relative to the ground, which is critical for navigation accuracy and aerodynamic control surface manipulation.

**Theory of Operation.** The OPS243-A operates on the Doppler effect principle applied to continuous-wave radar. The sensor transmits a continuous microwave signal at a center frequency of 24.125 GHz (ISM K-band) toward the ground with a patch antenna. As the missile moves over the terrain, the reflected signal returns to the receiver antenna with a frequency shift proportional to the relative velocity between the missile and the ground, similar to how the radar altimeter works. This frequency shift, known as the Doppler shift, is given by Eq. (5), where f_d is the Doppler frequency shift, f_t is the transmitted frequency, V is the velocity of the missile relative to the ground, c is the speed of light, and θ is the angle between the radar beam and the velocity vector.

$$f\_d = (2 \cdot f\_t \cdot V \cdot \cos\theta) / c \tag{5}$$

Solving for velocity yields Eq. (6):

$$V = (f\_d \cdot c) / (2 \cdot f\_t \cdot \cos\theta) \tag{6}$$

The sensor's onboard digital signal processor performs a Fast Fourier Transform (FFT) on the mixed baseband signal to extract the Doppler frequency with high resolution. The FFT output identifies the dominant frequency, which corresponds to the ground-speed. Because all signal processing is performed internally on the sensor's microcontroller, the OPS243-A outputs a processed speed value directly, eliminating the need for external signal processing hardware.

**Technical Specifications.** The OPS243-A operates at 24.0–24.25 GHz in the ISM K-band. The detection range extends from 1 to 100 meters, with speed reporting capability in excess of 62 m/s (138 mph or 222 km/h). The speed measurement accuracy is within ±0.5% of the measured value. The sensor has a narrow 20° beam width at the −3 dB point, which concentrates the radar energy into a well-defined cone directed at the terrain. The operating temperature range is −40°C to +85°C, which exceeds the requirements for most tactical missile flights. The sensor dimensions are 75 × 90 × 12 mm with a mass of only 15 grams, making it extremely compact and lightweight for integration into a missile airframe. Power consumption is 1.5 W in active mode and 0.7 W in idle mode, with a supply voltage of 5 VDC [3].

**Implementation.** The OPS243-A will be mounted inside the bottom surface of the, with the patch antenna pointed downward at the terrain. The mounting angle (θ) between the radar beam centerline and the missile's velocity vector must be known and fixed, as it directly enters the velocity calculation (Eq. 6). A typical installation angle of 30-45° from the axis is a good balance between ground return signal strength and velocity sensitivity. The output from the OPS243-A will be connected to the flight computer, which will then apply the cosine correction equation based on the known beam angle and the current pitch attitude (obtained from the IMU) to obtain the true ground speed. The primary environmental concerns for this sensor are the effects of terrain type and altitude on signal return strength. Over water or other smooth terrain, there might be less backscatter, which may degrade the signal-to-noise ratio. Over rough or complex terrain, strong returns are expected. At the low altitudes typical of cruise missile flight (50–300 feet AGL), the ground return signal will be strong and the measurement will be accurate. Vibration damping is less important for this sensor compared to the IMU, as the Doppler measurement is based on frequency rather than amplitude, making it unaffected by mechanical vibration.

## SIGNAL CONDITIONING AND INSTRUMENTATION

Each of the sensors used in this system already includes built-in signal conditioning. This makes the overall design simpler and reduces the need for extra external components.

The ADIS16470 IMU comes pre-calibrated to correct for sensitivity, bias, and alignment errors. Inside the unit, the raw signals from the gyroscope and accelerometer are amplified, filtered, and converted into digital data. It also includes a programmable filter that reduces noise above a selected frequency. For this system, the filter will be set to limit the bandwidth to about 100 Hz, which matches the control system's update rate. The data is sent digitally using SPI communication at speeds up to 2 MHz. The only external requirement is a stable 3.3 V power supply, along with small bypass capacitors (100 nF and 10 μF recommended by the manufacturer) placed near the device.

The Garmin GRA 5500 radar altimeter is a fully self-contained unit that handles all the signal processing internally. It generates the radar signal, receives the reflected signal, and processes it using an internal processor. This includes filtering noise, smoothing the data, and checking for accuracy before outputting the final altitude above ground level. It requires a 14 or 28 VDC power supply, which will be provided. No additional external processing is needed.

The OPS243-A Doppler radar velocity sensor also performs all signal conditioning internally. It transmits a continuous-wave signal at 24.125 GHz and measures the frequency shift of the returned signal to determine ground speed. An onboard processor uses a Fast Fourier Transform (FFT) to calculate this frequency accurately, then converts it to speed. The result is sent as text. The sensor only needs a 5 V power supply. The flight computer will adjust the measured speed based on the sensor's mounting angle and the missile's pitch from the IMU to determine the true ground speed along the flight path.

The central flight computer serves as the hub for the entire system. It communicates with the ADIS16470 via SPI, with the OPS243-A via UART, and receives altitude data from the GRA 5500 through its digital interface. The flight computer runs the navigation and control algorithms at a fixed update rate (typically 50–200 Hz), continuously reading sensor data and calculating control outputs. The system is powered by the missile's onboard power source.

## SYSTEM SUMMARY AND COST

The proposed sensor system combines four key measurements from three sensors into one integrated guidance, navigation, and control system for a programmable air-to-land cruise missile. The ADIS16470 IMU provides both gyroscope and accelerometer data for the inertial navigation system, the GRA 5500 radar altimeter provides altitude relative to the ground for terrain-following flight, and the OPS243-A Doppler radar sensor provides ground-speed data for navigation and motion control.

The performance of these sensors fits well with what a tactical cruise missile needs. The IMU's 550 Hz gyroscope bandwidth and quick accelerometer update rate easily support a control system that runs at 100-200 Hz. The radar altimeter's ability to process many readings per second allows for smooth and accurate altitude control over changing terrain. The Doppler velocity sensor's ±0.5% speed accuracy works well in low altitude, high vibration conditions since it does not require physical contact.

The main limitation of the system is drift in the internal navigation system. Over extended flight times, small errors in the gyroscope and accelerometer stack up, which causes the estimated position and orientation to become less accurate. In real world systems, this is usually corrected using external references like GPS, terrain-contour matching, or digital scene-matching area correlation. These methods are not included in this project but are important for longer duration missions. Another limitation is the OPS243-A's maximum speed of about 62 m/s (138 mph), which means the system is best suited for slower, subsonic cruise missiles. Faster systems would need more advanced radar sensors, which add additional cost.

The system is designed for a single use application, as the missile is destroyed on impact, so long term operation is not a concern. However, each sensor is built to be durable: the ADIS16470 can withstand 2000 g mechanical shock and a wide temperature range (−25°C to +85°C), the GRA 5500 meets strict reliability standards, and the OPS243-A is a solid device with no moving parts rated for a wide temperature range (−40°C to +85°C). A potential flaw is the radar altimeter, as it depends on signals reflecting off the ground, which are less reliable in open areas, like water or a desert.

**Table 1.** System Component Cost Breakdown

| Component | Est. Cost |
|---|---|
| ADIS16470 IMU (Gyro + Accel) | $345 |
| Garmin GRA 5500 Radar Altimeter | $7,765 |
| OmniPreSense OPS243-A Doppler Sensor | $224 |
| Flight Computer (embedded SBC) | $350 |
| Power Supply / DC-DC Converters | $150 |
| Wiring Harnesses & Connectors | $75 |
| Vibration Isolation Mounts | $50 |
| Installation & Integration | $500 |
| **Total System Cost** | **$9,459** |

The total estimated system cost of $9,459 is largely due to the Garmin GRA 5500 radar altimeters. In a real production missile, a simpler military-specific radar altimeter would likely be used which could lower the overall cost. The ADIS16470 IMU provides great value at $495 since it combines both gyroscope and accelerometer functions in one unit. The OPS243-A Doppler velocity sensor at $224 offers a compact, reliable way to measure ground speed without the need for external tubes or probes, making it more dependable than traditional pitot static systems. Overall, this navigation system is much lower cost than those of competitors, as missiles commonly cost hundreds of thousands to millions per shot.

In summary, this sensor system provides a complete measurement suite for missile guidance, navigation, and control. The gyroscope and accelerometer tell the inertial navigation information about the missile's attitude and velocity. The radar altimeter enables low-altitude terrain-following flight to minimize the probability of detection by radar and air defense systems. The Doppler radar velocity sensor provides ground-speed measurement for navigation and aerodynamic control. Together, these four measurands provide the flight computer with sufficient information to guide the missile along its programmed trajectory from launch to target impact.

## REFERENCES

[1] Analog Devices, 2023. "ADIS16470 Wide Dynamic Range, Miniature MEMS IMU Data Sheet," Rev. C. Analog Devices, Inc., Norwood, MA. See also URL https://www.analog.com/en/products/adis16470.html.

[2] Garmin International, 2023. "GRA 5500 Digital Radar Altimeter." Garmin Ltd., Olathe, KS. See also URL https://www.garmin.com/en-US/p/135561/.

[3] OmniPreSense, 2024. "OPS243-A Doppler Radar Sensor Product Brief," OPS-PB-004-C. OmniPreSense Corporation, San Jose, CA. See also URL https://omnipresense.com/product/ops243-doppler-radar-sensor/.

[4] Skolnik, M. I., 2008. Radar Handbook, 3rd ed. McGraw-Hill, New York.

[5] Titterton, D. H., and Weston, J. L., 2004. Strapdown Inertial Navigation Technology, 2nd ed. The Institution of Electrical Engineers, London.

[6] Siouris, G. M., 2004. Missile Guidance and Control Systems. Springer-Verlag, New York.

[7] Figliola, R. S., and Beasley, D. E., 2015. Theory and Design for Mechanical Measurements, 6th ed. John Wiley & Sons, Hoboken, NJ.

[8] "Principles of Guided Missiles and Nuclear Weapons." Maritime.org, maritime.org/doc/missile/part1.php.

[9] "Optical Accelerometers." Encyclopedia.pub, encyclopedia.pub/entry/24101.

 

**APPENDIX 1**

## Technical Specification Sheets

1. Analog Devices ADIS16470 Data Sheet (Rev. C) – Gyroscope and Accelerometer: https://www.analog.com/media/en/technical-documentation/data-sheets/adis16470.pdf
2. Garmin GRA 5500 Radar Altimeter Specifications: https://www.garmin.com/en-US/p/135561/#specs
3. OmniPreSense OPS243-A Doppler Radar Sensor: https://omnipresense.com/wp-content/uploads/2024/01/OPS243-Product-Brief_004-F.pdf