Calibration Procedures and Techniques

August 22, 2025

Empowering your Vision

AHRS-M1 & AHRS-M2 Orientation Sensors

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- Contains Suite of Tri-axial Sensors:
  - Tri-axial Magnetometers
  - Tri-axial Accelerometers
  - Tri-axial Gyros
- Fully temperature compensated from -40 to +70C
- Utilizes Sparton's AdaptNav III™ sensor fusion algorithm
- Small form factor; M2 = 12.3g, M1-OEM = 1.4g
- Includes NorthTek™ on-board programming environment
- Two Adaptive In-Field Magnetic Calibration Methods:
  - Manual calibration provides precision calibration using up to 32 measurements
  - AdaptCal™ provides simplified in-field calibration
- Note that these products are not appropriate for air-borne applications due to their dependence on gravity.

AHRS-M2

Applications

Platforms with motors, vibrations or electrical noise

UAV's

Optical Targeting

GPS Augmentation

Autonomous Vehicle Navigation

Conquering Complexity™

Sparton AdaptNav™ Sensor Fusion

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- What is Sensor Fusion?

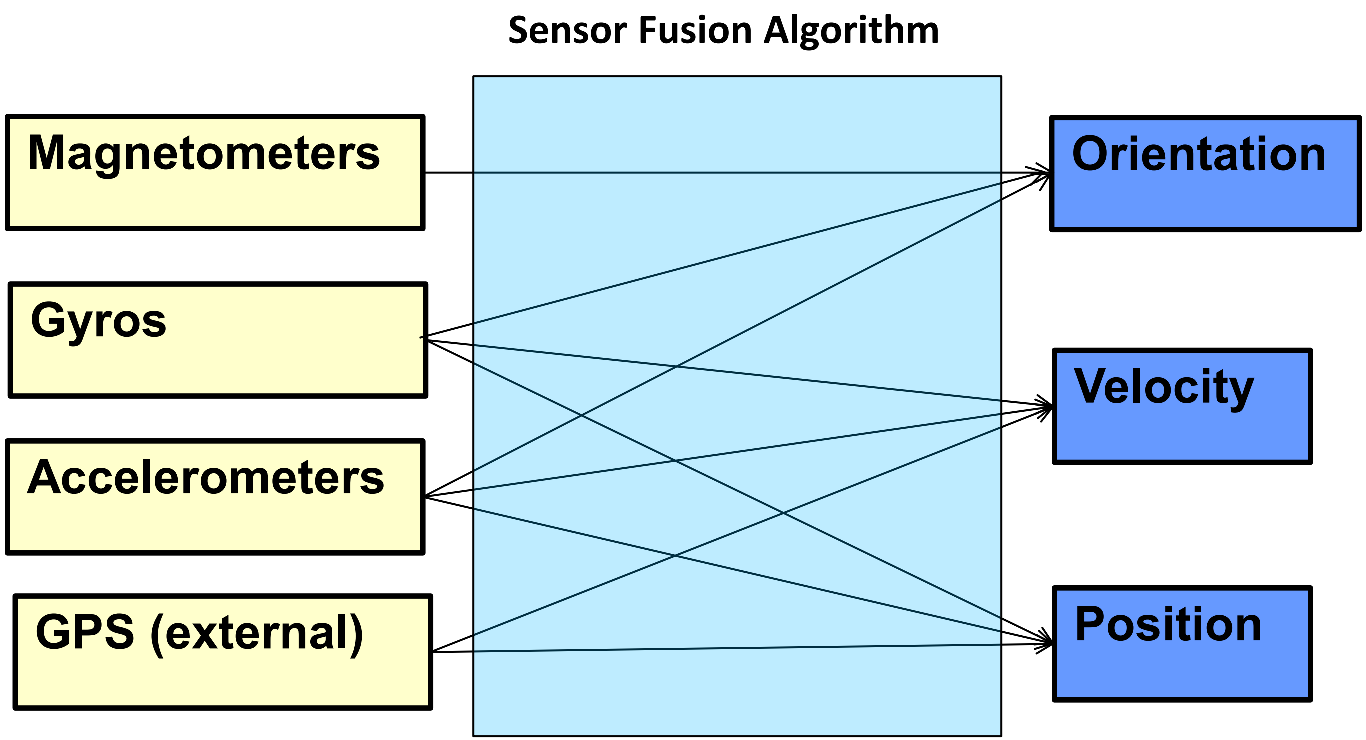
  - Navigation Modules use Multiple Sensor Technologies
    - Accelerometers – Measure acceleration & Earth's gravity
    - Gyros – Measure rotational velocity
    - Magnetometers – Measure orientation relative to magnetic North
    - GPS – Measure position and velocity (not in M1/M2)

  - For navigation, we need to know Position, Velocity, and Orientation of the navigation module based on these sensor measurements

  - For the M1 & M2 specifically, only Orientation is important since GPS is not integrated into the system

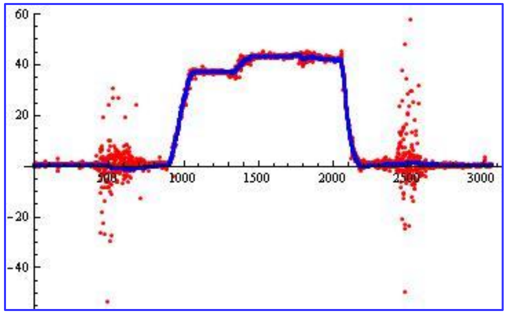
Sparton AdaptNav™ Sensor Fusion

What is Sensor Fusion?

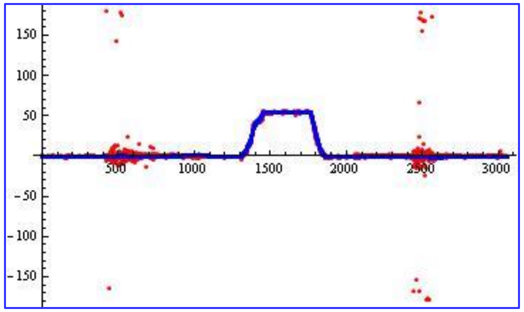


Sparton AdaptNav™ Sensor Fusion

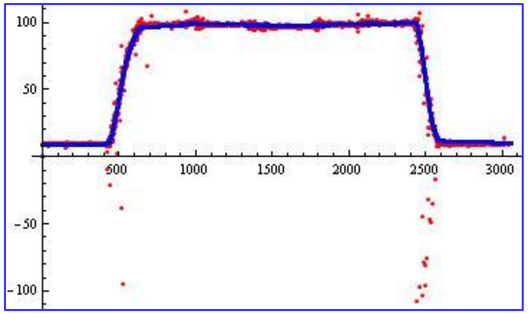
- **Sensor Fusion Challenges?**
  - **Sensors corrupted by noise**
  - **Sensor characteristics can vary over time & temperature**
  - **Sensors can be highly non-linear**
  - **Motion dynamics can be highly non-linear**
  - **Operating Environment may be unpredictable**
- **Fusion Algorithm Must Adjust Sensor Weights In Real-Time To Compensate**
- **Fusion Algorithm Must Be Intelligent**
- **For Sensor Fusion to be successful, it must use high quality, calibrated sensor measurements**



Pitch



Roll



Yaw

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Calibration Considerations

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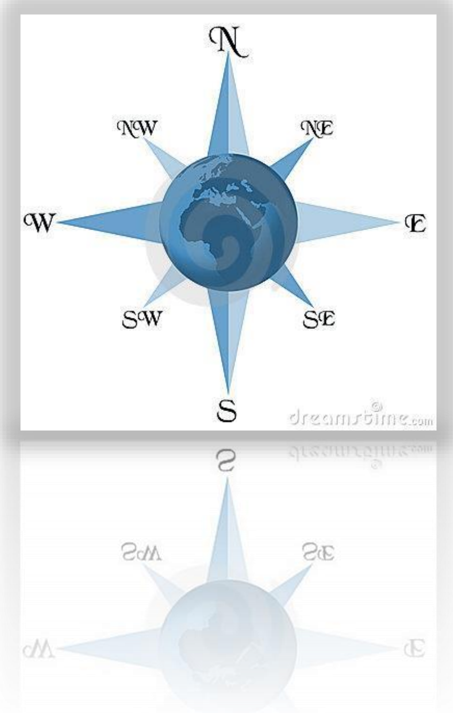

- Accurate sensor calibration is necessary for high performance orientation and navigation
- Sensors are affected by both internal and external error sources
- Consideration of physical limits during design phase
- Performing post-installation calibration can dramatically improve overall system performance and accuracy
- Periodic post-installation calibrations will help to maintain performance

Calibration Considerations

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- Don't fight the laws of physics!
  - Sensors have upper and lower physical limits
  - Saturating sensors inhibit their ability to make precision measurements
  - Excessive external noise raises the sensor noise floor masking low level signals.

- Position sensors to be as far as possible from any offending sources like motors and batteries
- Electrical shielding of spurious EMI
- Adequate noise suppression on power supply
- Vibration dampening

Calibration Considerations

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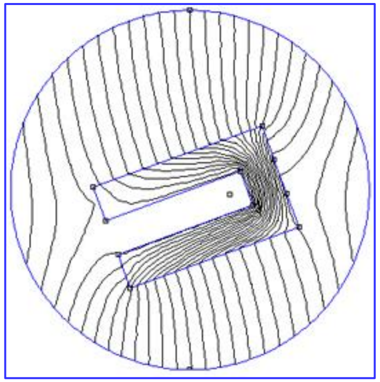
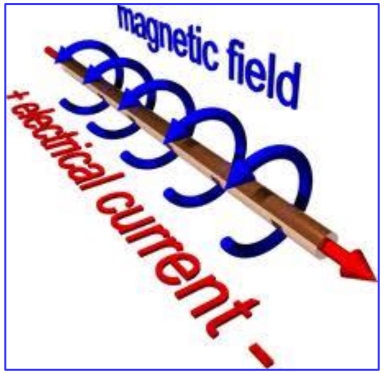
- Successful User Calibrations
  - Magnetically Clean Environment
    - Away from buildings, vehicles, and other magnetic material
    - Be aware of potential buried magnetic material
    - Stay away from fluctuating noise sources like power lines
  - Good diversity of sampled points for calibration
    - Sampled points should be a representation of magnetic field distortions from ALL directions and orientations – even inverted
  - Operate unit in intended configuration during calibration
    - All normal systems active and drawing typical current from power source
  - Minimize movement of magnetic material relative to navigation sensor during the calibration process

Magnetic Errors in Navigation Applications

- Internal Sensor Error Sources
  - Orthogonality
  - Scaling
  - Linearity
  - Bias Offsets
  - Thermal Stability

- External Sensor Error Sources
  - External Magnetic Material That Adds to or Distorts the Earth's Magnetic Field
    - Hard Magnetic Material
    - Soft Magnetic Material
  - Non-Uniform (Gradient) Magnetic Fields
  - Interfering Magnetic Field due to Currents in Wires

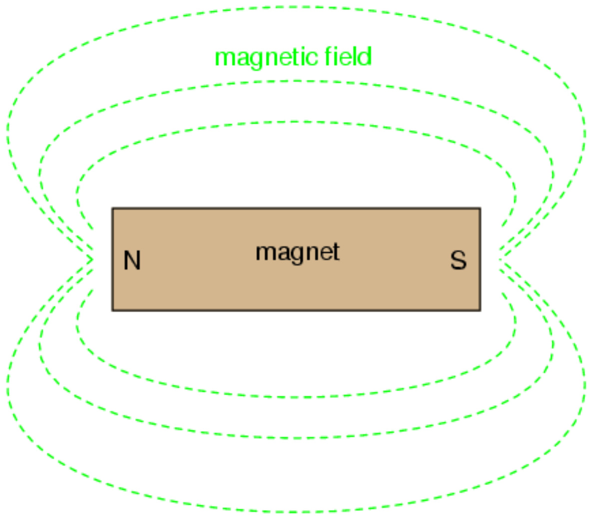




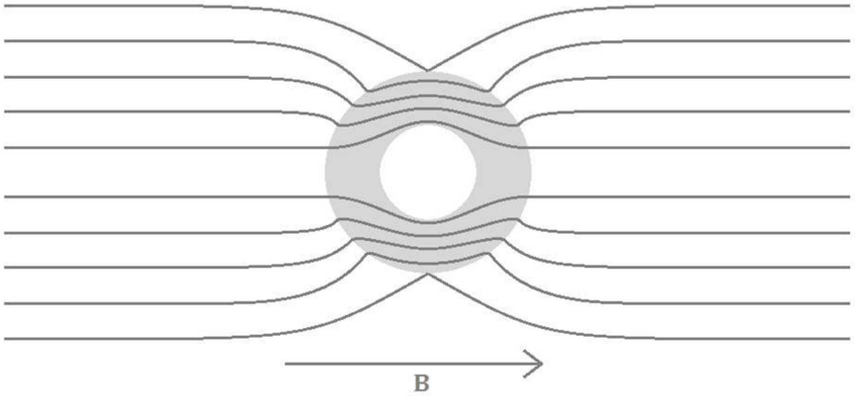
Magnetic Distortions

- The Earth's magnetic field measured by magnetometers within an inertial system can be altered by two main types of magnetic material; hard and soft

Hard Magnetic Materials



Soft Magnetic Materials



Sources of Magnetic Distortions

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Common ferrous materials that will be found in a typical system are:

- iron
- steel
- nickel
- cobalt
- Some grades of stainless steel

Materials that do not affect surrounding magnetic fields are:

- copper
- brass
- gold
- aluminum
- silver
- tin
- silicon

Sources of Magnetic Distortions

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- A permanent magnet can produce strong magnetic fields if placed close to the inertial system
- The magnetometer in an inertial device could become saturated and calibration would not be possible
- Strong magnetic fields, such as those over 20 gauss, accidently placed in the proximity of the inertial system may cause the magnetometers to become magnetized.

Acceleration Errors in Navigation Applications

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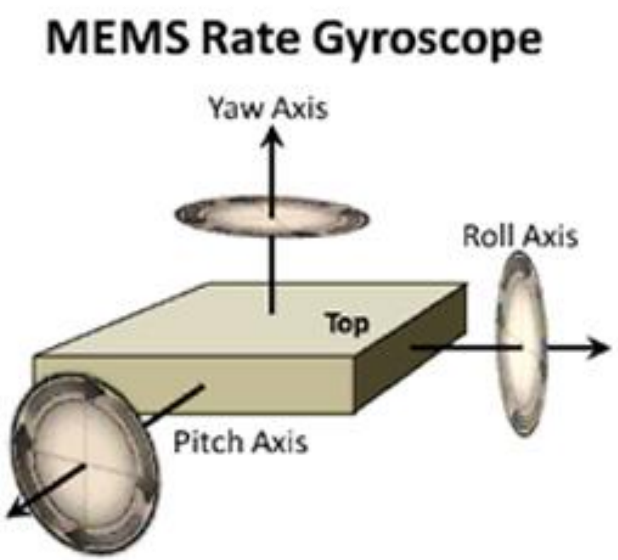
- Internal Error Sources
  - Orthogonality
  - Scaling
  - Linearity
  - Bias Offsets
  - Thermal Stability

- External Error Sources
  - Vibration
  - Acceleration due to movement

Gyro Errors in Navigation Applications

- Has same internal errors as magnetometers and accelerometers
- Gyro bias errors can cause orientation estimates to drift
- Linear acceleration effects on gyro bias (g^2 sensitivity)
- Noise in gyros gets integrated over time causing Angular Random Walk (ARW) in the orientation estimates
- Use of the gyros helps to mitigate transient changes in the magnetic field



Factory Calibration

Mitigation of Navigation Errors

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- Mitigation of Internal Errors
  - Factory Calibration of Sensors
  - Design for Temperature Stability
- Mitigation of External Errors
  - Incorporate In-Field Calibration
  - Filter Sensor Data to reduce transient noise
  - Augment Inertial System with additional sensors
    - Gyroscopes (Angular Rate Sensors)
    - GPS
  - Increase Sample Rate of Sensors

Factory Calibration

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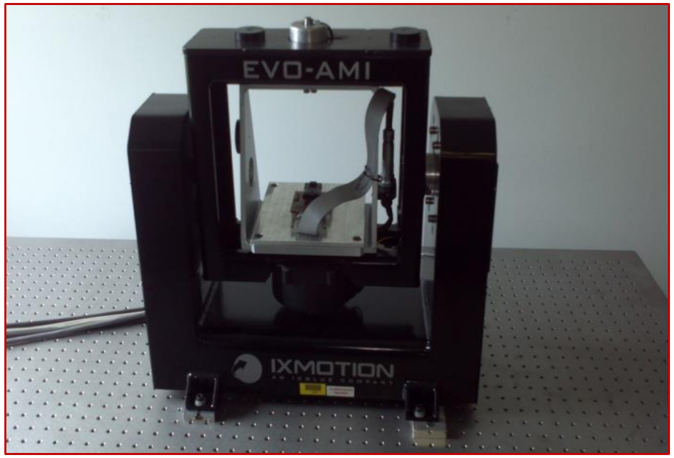
Computer-Controlled Precision Factory Calibration Corrects:

- Sensor Bias Offsets
- Sensitivity or Scale Factor
- Linearity
- Axial Misalignment or Cross-Axis Errors
- Errors due to temperature



Magnetic Compensation Procedures

- All high accuracy inertial systems will have an onboard magnetic compensation procedure
- The compensation procedure must correct for hard and soft magnetic disturbances
- This procedure is usually a device specific 2D or 3D calibration involving measurement sampling at various azimuth and elevations positions by rotating the device 360 degrees

Conventional 12 Point Manual Magnetic Calibration

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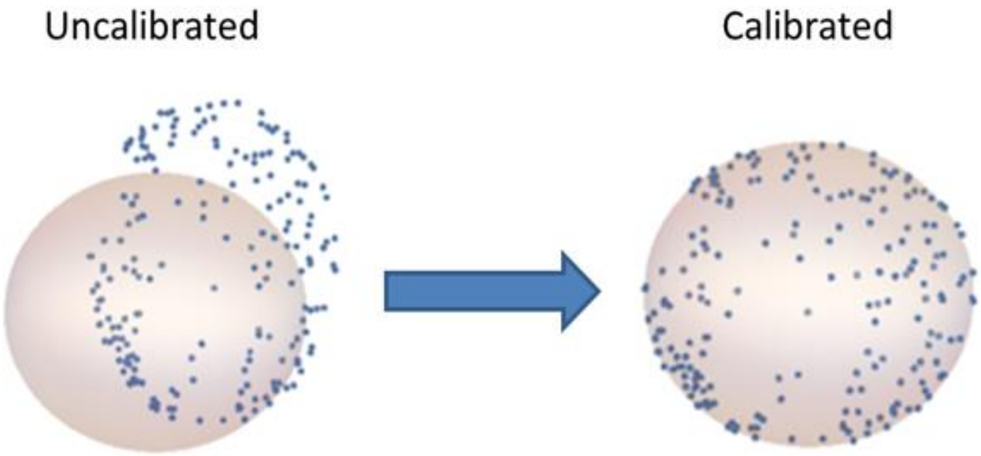
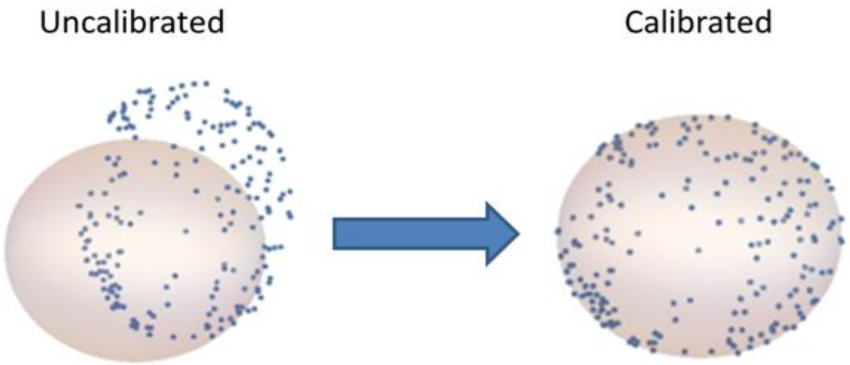
Typical calibration process for industry:

- **Step 1**:
  Collect points from 12 diverse orientations
- **Step 2**:
  Initiate calibration algorithm
- **Step 3**:
  Wait for solution
- **Step 4**:
  Calibration complete



M1 & M2 Calibration Methods

- **M1 & M2 offers two types of infield magnetic calibration methods: Manual and AdaptCal**
- **Manual Calibration is the most accurate calibration due to unit stationary during measurement collection**
  - **Adaptive process starts when number of points >= *minCalPoints* (*default=4)***
  - **Calibration is refined as additional measurements are collected**
  - **Measurements are averaged at each orientation. Number of points averaged set by *magAverageWindow***
  - **Selectable to turn off after convergence or transition to AdaptCal mode (*pointCalTermination*)**
- **AdaptCal is less accurate than manual calibration but doesn't require the unit to be stationary**
  - **Measurements are not averaged at each orientation**
  - **Handles measurement collection and screening automatically in real-time**
  - **Calibration is refined as additional measurements are collected**
  - **Adaptive process starts when number of points >= *minCalPoints* (*default=4)***
- **Handles up to 32 points for extremely distorted environments**



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Manual Calibration Procedure

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- Manual Calibration Procedure
  - Orient unit to first position. No need to know location of magnetic north
  - Send '*manualCalibratonPoint 1 set drop*' to take a measurement
    - No need to set *pointFieldCalActive* as this will turn on automatically
    - Make sure the unit is not moved during measurement
    - Can issue 'manualCalibrationPoint di.' to see if measurement complete
  - Orient system to other positions. Include as much pitch and roll as allowed by the system
  - Send '*manualCalibratonPoint 1 set drop*' at each position to collect measurements
  - Try to collect a minimum of 12 diverse measurement. More measurements are even better.
    - The compass is solving for 12 unknowns (9 Cross Axis and 3 Bias Terms)
    - Adaptive calibration starts when calNumPoints >= minCalPoints (default 4)
  - When complete, send 'pointFieldCalActive 0 set drop' to turn off the manual calibration
  - *pointCalTermination* can be configured ahead of time if desired
    - 0 = Turn off calibration when convergence complete
    - 1 (Default) = Stay in point cal mode until user turns it off
    - 2 = Transition to AdaptCal mode when convergence complete
  - *magAverageWindow can be used to reduce measurement noise. Default set to 20 samples*

AdaptCal Procedure

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- AdaptCal provides easier calibration method for end-user
  - Typically not as accurate as the manual calibration method due to constant movement
  - magAverageWindow is NOT used for this method
  - Orient unit to first position. No need to know location of magnetic north
  - Send '*autoFieldCalActive 1 set drop*' to start data collection process
  - Move system through other positions. Include as much pitch and roll as allowed by the system
  - Rotational speed must be <45deg/sec for measurements to be taken
  - Try to collect a minimum of 12 diverse measurement. More measurements are even better.
    - The compass is solving for 12 unknowns (9 Cross Axis and 3 Bias Terms)
    - Adaptive calibration starts when calNumPoints >= minCalPoints (default 4)
  - When complete, send 'autoFieldCalActive 0 set drop' to turn off the calibration
  - Compass will decide when to take measurements based on the orientation of unit
    - 3D sphere divided into 32 equally spaced regions as defined by *sphericalPoints*
    - Direction of magnetic vector points to region of sphere where measurement will be taken
    - Measurements may be overwritten if it reduces the overall Mean-Squared-Error (MSE)

Spherical Coverage During Calibration

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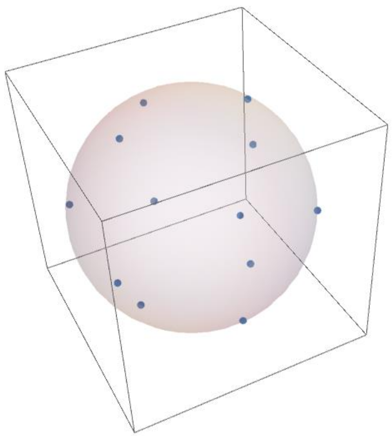
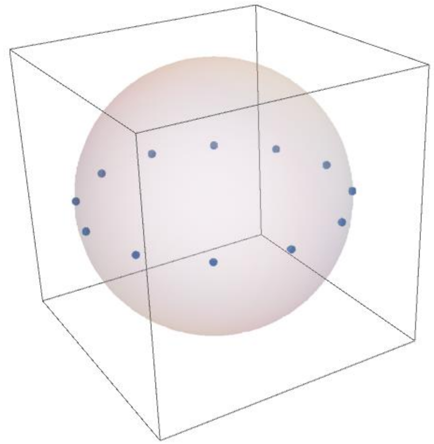
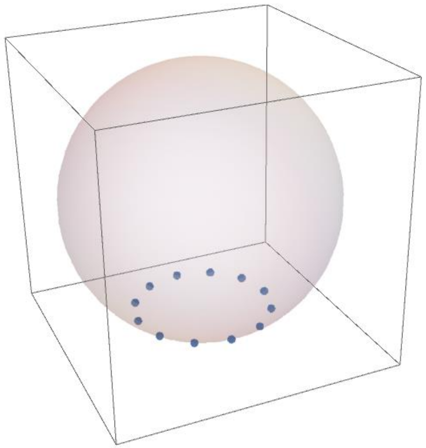
(1) 12-Point Ideal 3D Distribution

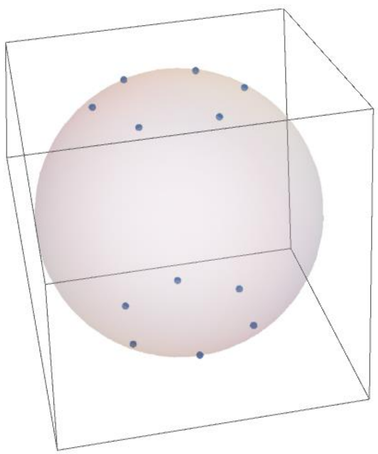


(2) 2D Rotation (0 Dip Angle)

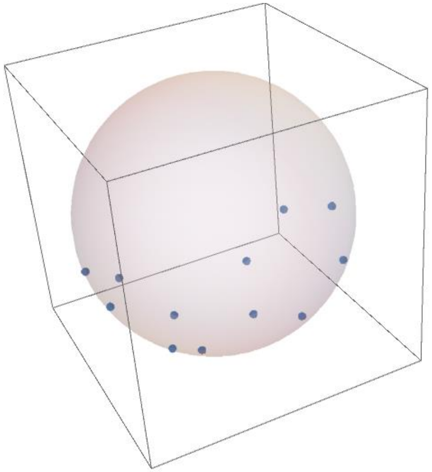


(3) 2D Rotation (-45Deg Dip Angle)





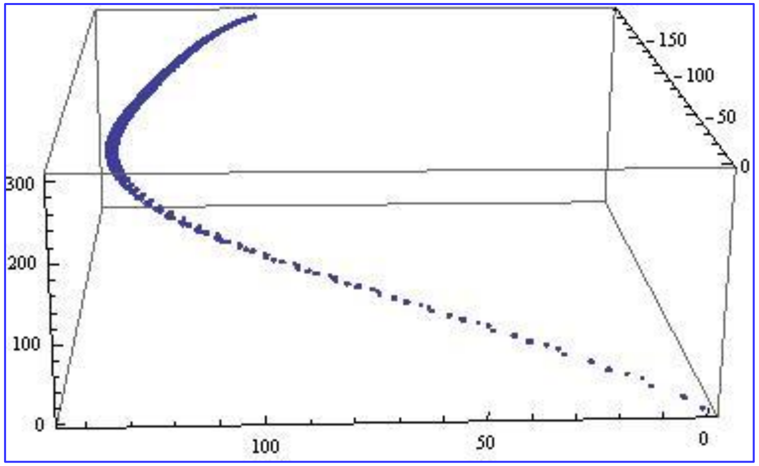
(4) 0 & 180 Roll (-45 Dip Angle)



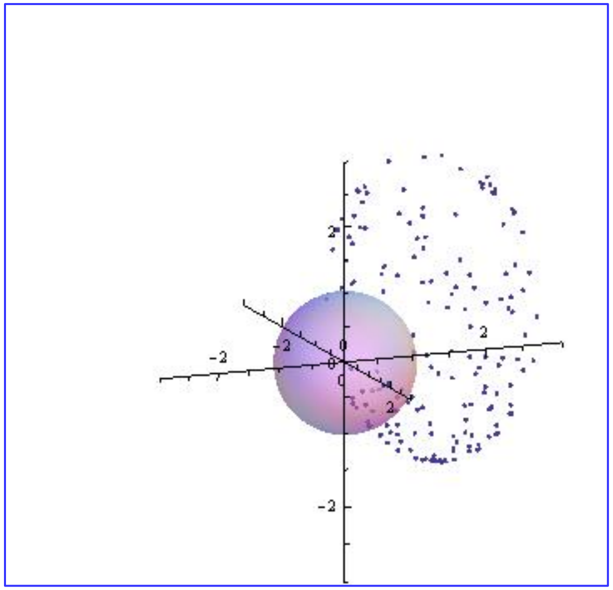
(5) +/-45deg Pitch (-45 Dip Angle)

Adaptive Calibrations

- Compensates for the presence of any hard and soft iron magnetic effects in the application platform that may affect sensor performance
- Sparton uses innovative adaptive algorithm to optimize magnetometer sensitivity, bias offset, and cross-axis distortions in full 3-Dimensions

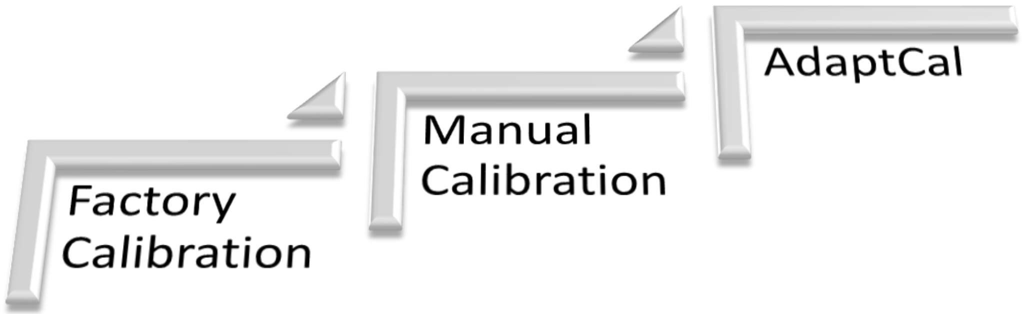


Adaptive Time Sequence



Full 3D In-Field Calibration

Layers of Calibration



- Factory calibration is applied to the raw sensor data (*magr, accelr, gyror*)→ Processed Data (*magp, accelp, gyrop*)
- Manual calibration is applied to factory processed data →
  - *pointMagBias* → *magBias*
  - *pointMagCrossAxisCorrection* → *magCrossAxisCorrection*
  - Compass always uses *magBias* and *magCrossAxisCorrection* to mitigate magnetic errors
- AdaptCal starts by using current *magBias* and *magCrossAxisCorrection*
  - *magBias* is updated with new values
  - *magCrossAxisCorrection* is updated with new values
- *revertFieldCal* will restore the bias and cross-axis correction values to the last manual calibration
  - *pointMagBias* → *magBias*, *pointMagCrossAxisCorrection* → *magCrossAxisCorrection*
- *clearPointCal* will restore the factory calibration
  - {0,0,0} -> *magBias* & *pointMagBias*
  - Identity Matrix[3] -> *magCrossAxisCorrection* & *pointMagCrossAxisCorrection*

Buffered Measurements for Calibration

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```
calPointBufferOccupied =
00-- 0
01-- 0
02-- 1
03-- 1
04-- 1
05-- 1
06-- 1
07-- 1
08-- 0
09-- 1
10-- 0
11-- 1
12-- 0
13-- 0
14-- 0
15-- 0
16-- 1
17-- 0
18-- 1
19-- 0
20-- 1
21-- 1
22-- 1
23-- 1
24-- 0
25-- 0
26-- 0
27-- 1
28-- 0
29-- 0
30-- 0
31-- 0
```

```
calPointBufferMag =
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 182.681610 182.992157 -341.915649
 104.735085 413.130371 47.138283
 66.356476 -259.367981 -332.126495
 159.091736 -12.061237 -393.932343
 170.091766 171.822937 355.225769
 -337.061462 44.444321 278.654572
 0.000000e+00 0.000000e+00 0.000000e+00
 -230.686508 -242.278030 282.392883
 0.000000e+00 0.000000e+00 0.000000e+00
 146.090912 261.771942 305.104523
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 -351.366333 27.042910 -253.685730
 0.000000e+00 0.000000e+00 0.000000e+00
 -11.087143 -261.764893 -337.485626
 0.000000e+00 0.000000e+00 0.000000e+00
 -202.771240 251.185608 -290.184998
 -314.658661 117.948929 -275.600311
 38.589397 -227.968033 365.811554
 128.197174 -9.382504 405.387848
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 -152.028336 -290.009796 289.026947
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
```

```
calPointBufferAccel =
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 2.596089e-02 2.058184e-01 -9.782457e-01
 -1.350521e-01 9.164775e-01 3.766031e-01
 -4.472486e-03 -2.294786e-01 -9.733034e-01
 -2.400759e-02 2.094125e-01 -9.775326e-01
 1.455035e-01 5.288435e-02 9.879434e-01
 -4.147092e-01 7.493395e-02 9.068634e-01
 0.000000e+00 0.000000e+00 0.000000e+00
 -3.066966e-01 -2.428666e-01 9.203005e-01
 0.000000e+00 0.000000e+00 0.000000e+00
 -1.485185e-02 3.902442e-01 9.205916e-01
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 -5.216458e-01 -2.167119e-01 -8.251797e-01
 0.000000e+00 0.000000e+00 0.000000e+00
 -8.177983e-02 -2.087654e-01 -9.745404e-01
 0.000000e+00 0.000000e+00 0.000000e+00
 -4.421330e-01 1.429399e-01 -8.854866e-01
 -5.151752e-01 -9.450357e-02 -8.518589e-01
 -1.807618e-01 -1.351615e-01 9.741954e-01
 -1.842120e-01 5.899430e-02 9.811145e-01
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 -2.701921e-01 -2.723797e-01 9.234747e-01
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
 0.000000e+00 0.000000e+00 0.000000e+00
```

The data above was collected during an AdaptCal. For this type of calibration, measurements are stored based on the their location on a unit sphere. Measurements are compared against reference points defined by *sphericalPoints.*

If a manual calibration was performed instead, all the measurements would have been stored sequentially, taking up indices 00 through 14. The vector *calPointBufferOccupied* highlights which indices hold valid measurements.

Buffered Measurements for Calibration

- Calibration buffer can hold up to 32 measurements for use in infield magnetic calibration
- ***calPointBufferMag*** **– [32 x 3] array of factory-calibrated magnetic measurements (no field cal applied)**
- ***calPointBufferAccel*** **– [32 x 3] array of normalized factory-calibrated accel measurements**
- ***calPointBufferOccupied*** **– [32 x 1] vector, 1 = Measurement Active, 0 = No Measurement**
- ***calNumPoints*** **– scalar value providing the number of measurements currently stored in calibration buffer**

$$magpCorrected = \begin{pmatrix} mCAC11 & mCAC12 & mCAC13 \\ mCAC21 & mCAC22 & mCAC23 \\ mCAC31 & mCAC32 & mCAC33 \end{pmatrix} \begin{pmatrix} magX \\ magY \\ magZ \end{pmatrix} - \begin{pmatrix} mBiasX \\ mBiasY \\ mBiasZ \end{pmatrix}$$

Where: mCAC = Elements of 3x3 cross-axis correction → *magCrossAxisCorrection*

mBias = Magnetic Bias (X, Y, Z) → *magBias*

mag = Magnetic vector measurements (X,Y,Z)

Sensor Limitations

- Magnetometers
  - Calibrated to up to +/- 900mgauss in computer controlled Helmholtz coil set
  - Impractical to put Helmholtz coil set in a thermal chamber
  - Uses a family temperature correction derived from pre-production engineering tests

- Accelerometers
  - Calibrated while unit is stationary using Earth's gravity of +/- 1000 milli-g
  - Thermal effects characterized over a temperature range of -40 to +70C
  - Sensor absolute maximum is user selectable (2g, 4g, 8g, 16g). Default is 4g.
  - Factory calibration only performed using 4g range.

- Gyros
  - Calibrated while unit is rotating at constant rate from -300 to +300 deg/sec
  - Thermal effects characterized over a temperature range of -40 to +70C
  - Sensor absolute maximum is +/-500 deg/sec

Bounding the Adaptive Calibration Errors

- Bad measurements taken during calibration can produce undesirable effects
  - Excessive magnetic biases > 1000mgauss
  - Excessive cross-axis and scaling terms

- Mitigation
  - AdaptCal incorporates a screening process at the time of data collection where measurements are compared to previous measurements. If the current measurement produces a lower Minimum Mean Squared Error (MMSE) for the adaptive algorithm, it will be buffered and overwrite a past measurement collected in that region of the sphere
  - When the adaptive algorithm runs, it monitors the computed biases and cross-axis terms. If the biases or cross-axis terms become excessive, the calibration is reset, the calibration buffer is flushed, and the AdaptCal process start over.
  - When performing manual calibration, the biases and/or cross-axis corrections are reset but the calibration buffer is not flushed. It is left to the user to insure that the environment is magnetically clean and adequate for precision calibrations.

Noise Mitigation through Pre-Filtering

- M1 & M2 incorporate user-adjustable pre-filtering of the raw sensor data to mitigate input noise (Version 3.5.1 or higher)
- Pre-Filtering is applied to all sensors (mags, accels, gyros) and all axes (X, Y, Z)
- Implements a 3rd-order Savitzky-Golay filter with up to 15 coefficients (factory default is 11)
- Filter computes best fit curve through N-points and selects the central point
- Filter adds a fixed sample delay to the sensor data dependent on the length of the filter
    - Slow system dynamics → Use higher order filtering
    - Fast system dynamics → Use lower order filtering
- Variables that control the filtering are *preFilterSize* and *preFilterCoeffs*

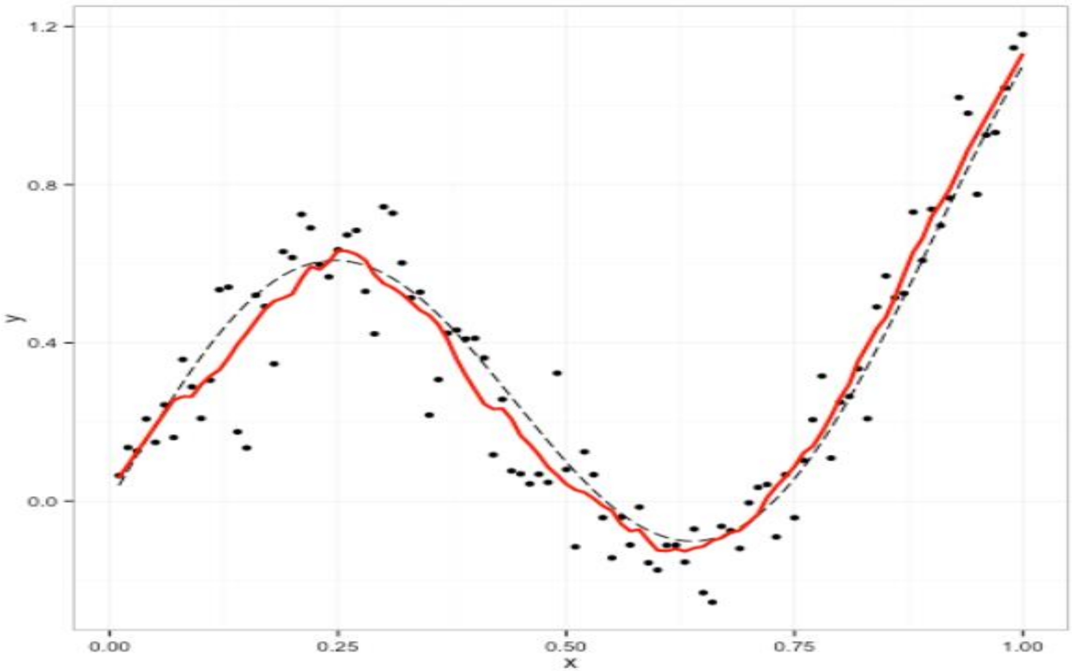

Figure-Of-Merit (FOM)

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- **A number of Figure-Of Merit (FOM) variables exist in the M1 & M2**
- **Provides estimates based on data collected during the in-field magnetic calibration and real-time data**
- **Estimates are only valid AFTER the in-field calibration has been performed**
  - **On power-up, estimates are not valid yet**
  - **Compass hasn't had a chance to analyze the current magnetic environment**

- **Useful FOM variables for M1 & M2. Based on buffered calibration measurements.**
  - ***aEqAveraged* (*magErr*) : Adaptive Convergence Error**
  - ***magFieldCalErr* : Measure of residual magnetic variability after calibration, expressed in mgauss**
  - ***EstimatedPk2PkYawError* : Estimated Peak-to-Peak yaw error expressed in degrees**
  - ***EstimatedRMSYawError* : Estimated RMS yaw error expressed in degrees**
  - ***yawErrEst* : *magFieldCalErr* + AdaptNav error estimates based on noise in system**
  - ***absoluteYawErr* : Error between actual magnetic vector and estimated magnetic vector**
  - ***sphericalCalCoverage* : Measure of calibration point diversity expressed as %coverage of 3D sphere**

Boresight Matrix

- Boresight matrix is applied at the very end of the AdaptNav processing
- Boresight allows the compass to be mathematically rotated so that the roll, pitch, and yaw can be translated into a different frame of reference
- Has no effect on X,Y,Z axis when looking at mags, accels, and gyros. These vectors are always represented in the body-frame of the compass.

$$\begin{pmatrix} newX \\ newY \\ newZ \end{pmatrix} = \begin{pmatrix} bm11 & bm12 & bm13 \\ bm21 & bm22 & bm23 \\ bm31 & bm32 & bm33 \end{pmatrix} \begin{pmatrix} oldX \\ oldY \\ oldZ \end{pmatrix}$$

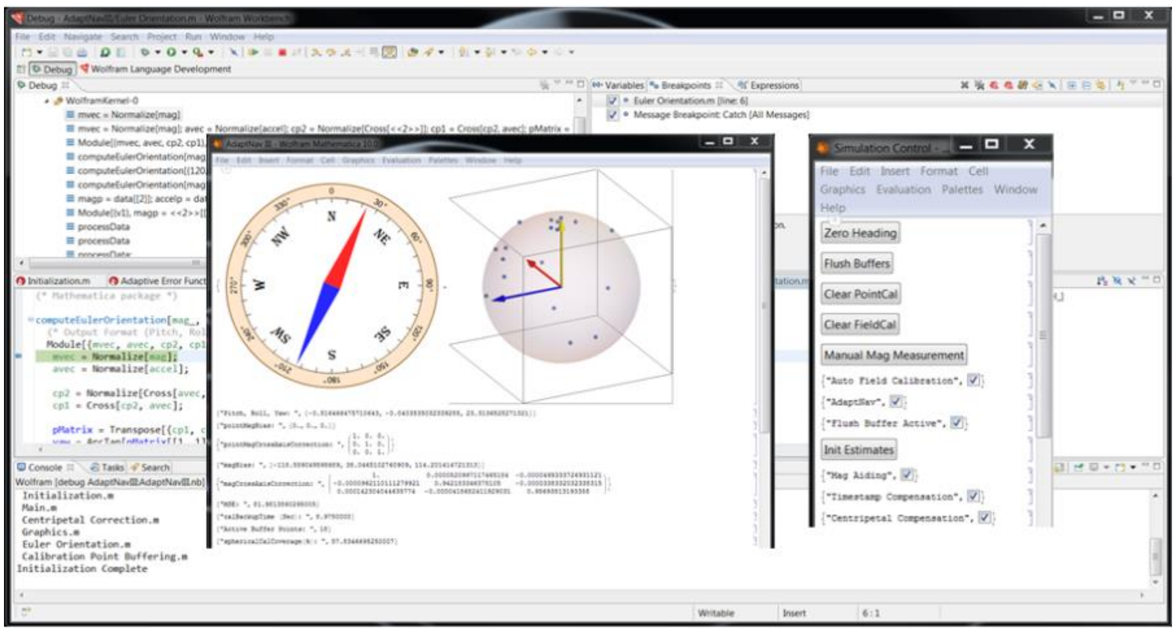
Where: bm = Elements of 3x3 boresight matrix→ ***boresightMatrix***

old = Original body-frame vector measurements (X,Y,Z)

new = Rotated vector (X, Y, Z) expressed in new reference frame

Sparton's Adaptive Calibration

- **Manual and AdaptCal modes were modeled in Mathematica and tested in real-time**
- **Algorithms coded in firmware and run completely on the compass**



Summary

- Sparton is committed to advancing this technology and has invested significant resources for product development
- Flexible and motivated to work with end users to modify product to suit their needs
- Working with many prime contractors on current and future programs
- Encourage collaboration with the Military user community and Industry to align product roadmaps and cooperate on development & testing

AHRS-M1

AHRS-M1 OEM

AHRS-M2

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