Jewell

Instruments

ECV eCompass
Technical Manual

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1 Introduction

This document provides a technical description of the ECV eCompass and its companion PC software. The bare compass is an electronic, strap-down circuit board with no moving parts. It combines a 3-axis magnetometer, a 3-axis accelerometer, 2-axis electrolytic tilt sensor, and 3 MEMS rate gyros to provide accurate heading and tilt measurements over a wide range of environmental conditions. The compass sends heading, pitch, and roll information to a host computer using an NMEA 0183 compatible protocol via an RS232 or RS485 serial port.

The ECV is an enhanced version of the ECS eCompass that is designed to operate accurately in dynamic environments. It accomplishes this by stabilizing pitch, roll, and yaw inertial measurements. Information from the MEMS rate gyros is blended with accelerometer or electrolytic tilt sensor signals to produce accurate pitch and roll over a wide bandwidth of frequencies.

Like all eCompass compasses, the ECV features on-board non-volatile storage of operating parameters and calibration coefficients. Contents include serial communication parameters; the extent of filtering or smoothing; alarm tuning; and coefficients to compensate for any local permanent and induced magnetic fields. These settings are typically changed only once, when the compass is initially installed.
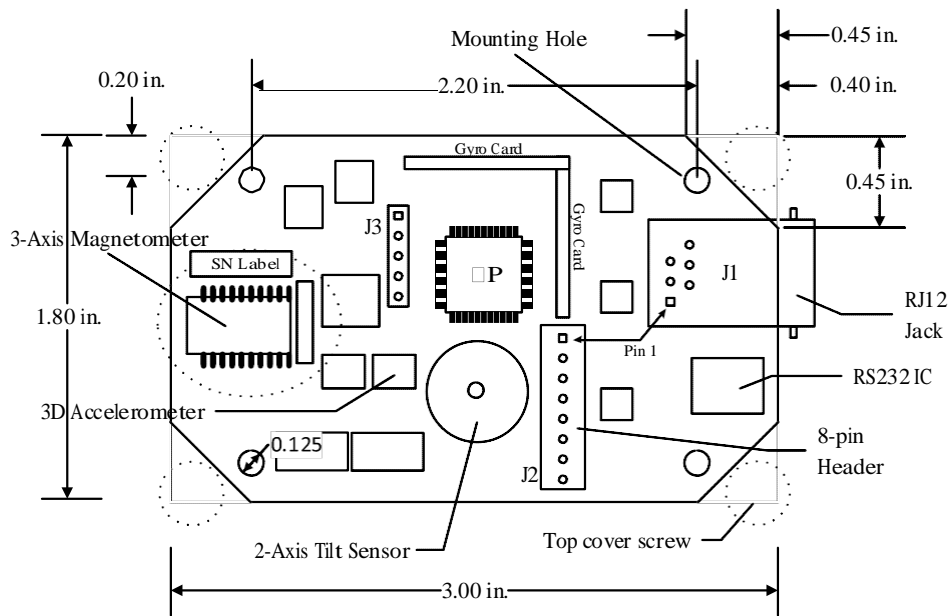
Figure 1 – Top View of ECV Compass Card

The diagram in Figure 1 shows the top of the compass card. The board is 3.0" long by 1.8" wide and requires 0.75" clearance in height. The four mounting holes are on 1.4" by 2.2" centers. They accept #4 size screws. The corners of the card are cut to allow clearance for screws that fasten the top cover.

1.1 Background

Electronic and mechanical compasses typically rely on gravity to determine the component of the earth's magnetic field that lies in the horizontal plane. For a 2-axis magnetometer mounted on a two-degree-of-freedom gimbal, gravity keeps the plane of measurement horizontal. When a 3-axis magnetometer is used, accelerometers and/or liquid level detectors measure the gravity vector. Its direction relative to the magnetometer axes is used to calculate magnetic field components that lie in the horizontal plane.

Accelerations other than gravity acting on the compass can produce large errors, depending on the direction of the acceleration vector and the direction the compass card is pointed. For example, when the axis of the compass card is pointed north, acceleration along this axis causes no error in heading. However, acceleration in the transverse, or east-west, direction produces a large error. In the northern continental USA, a leisurely 4 ft/sec^2 transverse acceleration (0-60 mph in 22 sec) results in more than 15° azimuth error.

The negative effect of short term accelerations can be significantly reduced by using rate gyros to measure changes in pitch, roll, and yaw. A rate gyro is sensitive to rate of rotation (degrees per second) about a single axis and is not sensitive to linear accelerations. By integrating the rate gyro measurements, absolute pitch and roll can be calculated.

A significant problem with integration is that, over time, small errors in offset or gain of the rate measurement become large errors in absolute tilt. To avoid this, the rate measurement cannot simply be integrated; it must be blended with the output of the acceleration sensor to produce an optimum estimation of tilt. How the signals are blended depends on the characteristics of the gyro and acceleration sensors as well as the mechanical characteristics of the operating environment.

The eCompass ECV uses complementary filters to blend signals from the rate gyros and accelerometers or liquid tilt sensor. High frequency components of the rate gyro signal are added to low frequency components of the acceleration sensor to calculate an estimate of absolute tilt. A single time constant sets the center-point frequency and can be adjusted per the application requirements. The diagram in Figure 7 and the text on page 16 explain the math in detail.

1.2 Definitions

Azimuth   The horizontal angular distance measured clockwise from a reference direction, usually magnetic or geographic north.

Heading   Horizontal direction in which an object points or moves, measured from 0° at a reference direction (generally true north or magnetic north) clockwise through 359.9°.

Deviation   Angle between the magnetic meridian and the axis of the compass card, expressed in degrees east (E) or west (W) to indicate direction in which the northern end of the compass card is offset from magnetic north. Add easterly deviation to compass heading to obtain magnetic heading. When sending deviation values to the eCompass, westerly values are positive.

Variation   Angle between magnetic and geographic meridians expressed in degrees east (E) or west (W) to indicate the direction of local magnetic north from true north. Add easterly variation to magnetic heading to obtain true heading. Send positive numbers for westerly variation.

Declination   same as variation

Dip angle   Angle that the earth's magnetic field makes with the horizontal plane in a specific geographic location. Positive in the northern hemisphere.

Inclination   same as dip angle

Hard Iron   A local source of permanent magnetism that moves with the body of the compass. By rotating both the compass and this source together in a uniform external field, i.e. the earth's magnetic field, both the magnitude and direction of the locally generated field can be determined.

Soft Iron   A local source of induced magnetism that moves with the compass. Ferrous material gains and loses magnetization depending on its orientation to the earth's magnetic field. As it rotates with the compass, the effect is to warp an otherwise circular locus of points into an elliptical shape.

Pitch   Angular displacement of the compass card about its lateral axis, measured vertically from the horizontal plane.

Roll   Angular displacement of the compass card about its lengthwise axis, measured vertically from the horizontal plane.

Yaw   Angular displacement of the compass card about an axis perpendicular to the surface of the card.

1.3 Features and Limitations

The compass delivers high accuracy for its small size, low cost, and low power consumption. It provides two independent serial communication channels. Both can be RS-232, or one can be RS-232 and the other RS-485. For battery operation, a low-power standby mode is incorporated to reduce required current to 5mA. Start up from standby requires less than 1 millisecond.

Additional features of the compass include:

- Current consumption only 40 mA at full bandwidth
- Measurement rate of 28 samples per second
- Single supply operation: 7 to 45V
- Magnetic field measurement range: ±1.6 Gauss (gain 100)
- Magnetic field measurement sensitivity: 0.3 milliGauss (gain 500)
- Pitch and roll range of ± 43° with liquid sensor, ± 90° with accelerometer
- Pitch and roll rates to ± 250°/sec
- Accelerometer bias correction using liquid sensor data near level
- Accepts GPS RMC input for magnetic variation and ground speed (to correct acceleration error when circling)
- Hard and soft iron compensation
- Non-volatile storage for calibration coefficients and setup parameters
- Angles in degrees (0.0 to 359.9°), mils (0 to 6399), milliradians (0 to
    - 6282), or 16-bit integer (0 – 65535)
- NMEA 0183 output data format with the following available sentences:
    - HDT (True heading)
    - HDG (Heading, deviation, and variation)
    - XDR (Transducer data: pitch, roll, magX, magY, and magZ)
    - HTM (Heading, tilt, and magnetic field)
    - NCD (Normalized compass data)
    - CCD (Conditioned compass data)
    - BNR (Binary data in NMEA envelope)
- Output data available:
    - Heading, pitch, and roll
    - Magnetometer X, Y, Z, and calculated total field
    - N, E, H, and V – normalized magnetic field components
    - Magnetic inclination (dip angle)
    - Ambient temperature in °C (binary data only – see BNR data)
    - Input voltage level in mV (binary data only – see BNR data)
- Separate magnetic and tilt IIR single-pole filters (RUN mode)
- Selectable time constants for complementary filters

The PC software provides functions for verification, calibration, tuning, and data capture. These functions can be performed without disconnecting system wiring, and without affecting the host computer. Features include:

- A separate Dynamic-Link Library (Compass.DLL) that implements the compass serial interface, calibration functions, and data conversion routines. This DLL can be used separately to simplify the task of integrating the compass into an end-user system.
- Capture and storage of an ASCII communication log that shows all serial
  - I/O with the compass
- Enhanced graphical displays for magnetometer calibration routines and cockpit attitude data
- Magnetic calibration routine

While there are many more features than limitations, the eCompass will not work in all environments and may not perform adequately under some conditions. It cannot operate reliably if any of the following conditions exist:

- Local permanent magnetic field greater than 1 gauss
- Ambient temperature less than -40°C or greater than 125°C
- Input voltage less than 7V (unless operating without gyros)

  Accuracy may be compromised under the following

  circumstances:

- Changes in the local permanent or induced magnetic field. This could be caused by repositioning ferrous material relative to the compass, or by turning DC currents on or off in nearby wires. In such cases, the magnetometer calibration is no longer valid.

1.4 eCompass Sensors

The compass determines azimuth by measuring two fundamental fields: the earth's magnetic field and its gravitational force field. A magnetometer is used to measure the magnitude and direction of the earth's magnetic field. An inclinometer measures the orientation of the compass card relative to the vertical gravity vector.

Current Source

X-Y Sensor

Z Sensor

X

Y

Z

3-Axis Magneto-resistive Bridge Circuit

X signal

Y signal

Z signal
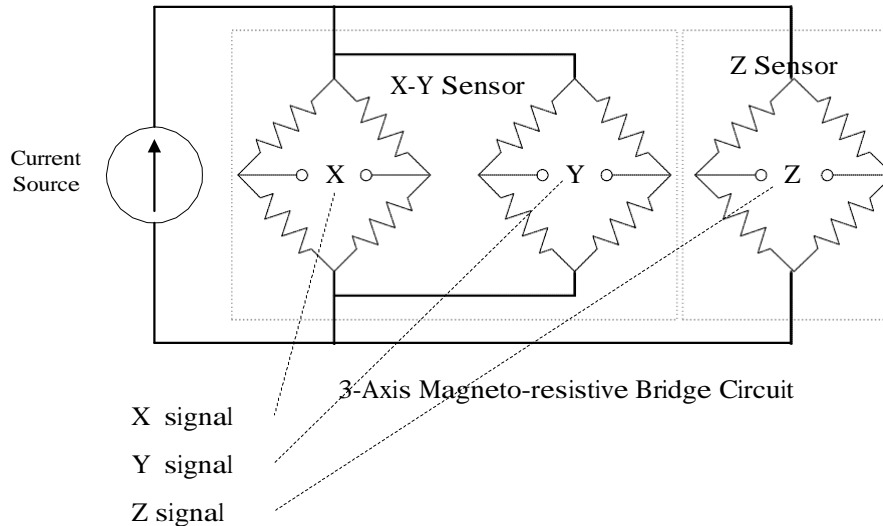
Figure 2 – Three Axis Magnetometer Schematic View

The magnetometer is composed of three anisotropic magneto-resistance (AMR) sensors arranged so that their sensitive axes are mutually orthogonal. The electrical resistance of each sensor changes in direct proportion to the strength of the magnetic field along its sensitive axis. Both the magnitude and direction of the earth's magnetic field are determined by calculating the vector sum of the three signals. The measured direction is relative to the orientation of the magnetometer on the compass card, so it must be rotated to a terrestrial frame of reference to determine azimuth.

The AMR sensors have a linear range of ± 2 Gauss and produce an output signal of 15 mV per Gauss along the sensitive axis. A gain of 300 is required to amplify the earth's nominal 0.5 G field to the full-scale range of the A/D converter. The gain can be adjusted from 100 to 500. A lower gain is needed when there is a large local permanent magnetic field (hard iron) that cannot be eliminated.

One of the gravity sensors used is a dual-axis electrolytic tilt sensor (electrolytic tilt sensor). The diagram in Figure 3 shows one axis of the sensor tipped at approximately 15°. The sensor is partially filled with an electrically conductive fluid, the electrolyte, whose surface remains level as the sensor body tilts. Pitch and roll angles are determined by measuring conductivity between orthogonal pairs of electrodes immersed in the fluid. Note that these angles are measured in the tilted frame of reference of the sensor and are not the angles needed to perform a coordinate transformation, say θ and ρ, which are independent rotations about orthogonal

axes of the compass card. If we arbitrarily perform the roll rotation first (i.e. $\rho =$ R), then θ can be determined using the following trigonometric relation:

$$\sin\theta = \frac{\tan P}{\sqrt{1+\tan^2 P + \tan^2 R}} \, ,$$

where P and R are the measured pitch and roll angles.
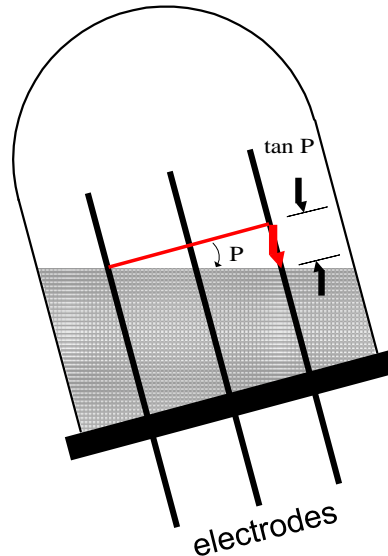
Figure 3 – electrolytic tilt Sensor, Single Axis View

The electrolyte is an alcohol-based fluid that has an operating temperature range of -40°C to 125°C and a storage range of -55°C to 135°C. Ionic salts dissolved in the fluid give it its electrical conductivity. The sensor is excited with alternating current to keep the salts from plating onto the electrodes. Excitation with direct current would initially change conductivity and ultimately destroy the sensor.

The other gravity sensor is a 3-axis MEMS device packaged in a single integrated circuit. Acceleration is sensed by measuring capacitance changes in 3 orthogonal micro machined sense elements. Range is ±2g in each direction. There is significant zero-g offset variation compared to the electrolytic tilt sensor. A
correction algorithm in the compass firmware can be set up to use electrolytic tilt sensor data near level to correct the MEMS offset variation.

MEMS rate gyros are used to augment the inertial tilt sensor, which cannot distinguish between gravity and other sources of linear acceleration. The rate gyros are sensitive only to rotational motion in the plane of the sensor. Pitch and roll gyros are mounted on daughter cards that are plugged into the main compass board, while the azimuth gyro is mounted on the main board. Gyro axes are electronically aligned with the corresponding axes of the acceleration sensors.

1.5 ECV eCompass Serial Interface

The ECV eCompass serial interface is an extension of the standard eCompass

interface. The ECV has two independent serial channels: one for the RJ12 and one for the internal 8-pin header. When a command is received, the ECV sends its response only on the same channel. The response does not interfere with communication on the other channel. The two channels can have separate baud rates, and unsolicited RUN mode NMEA sentences (data that has been setup to be sent automatically) can be directed to either or both channels. Refer to the Serial tab of the Settings dialog in the PC eCompass software for more details.

There are three physical data links: RS-232 on the RJ12 jack and both RS-232 and RS-485 on the 8-pin header. A special plug with the outer pins shorted can be used in the RJ12 jack to signal that a device is connected. This lets the ECV know when an external device puts the compass in calibrate mode. The RJ12 is continuously monitored to determine when the external device is disconnected so that the normal operating mode can be restored in the event that calibration is not completed.

Figure 4 shows the basic serial interface and connector pin outs. Note that pin 1 is near the center of the board for both connectors.
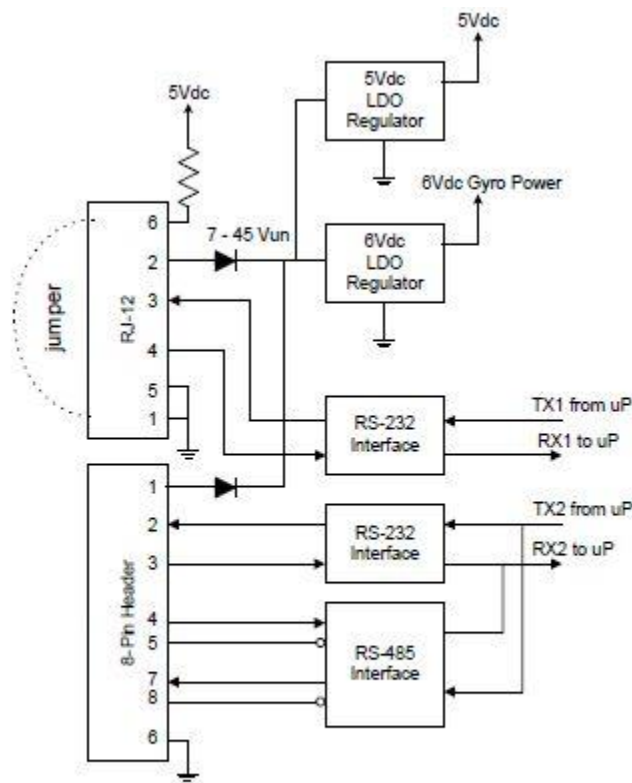
Figure 4 – AV Interface Block Diagram

2 Description of Operation

A block diagram of the compass is shown in Figure 5. The central component is an 8-bit microcontroller operating at 20 MHz (5 MHz crystal). It incorporates:

- 128K bytes program memory, and 3.5K bytes RAM
- 12-bit A/D converter
- 2 independent UARTS for serial I/O
- SPI serial interface for on-board communication

The two serial interface connectors are shown on the left-hand side of Figure 4. The RJ12 is a 6-position modular jack that provides RS-232 and power connections. A PC can be temporarily connected here for tuning and calibration. The 8 pin header is the internal system wiring connector that provides both RS-232 and RS-485 ports as well as power connections.

Protection diodes are provided to allow the compass to be powered from either connector. If power sources are connected to both, the source with the highest voltage will supply current. The diode in line with the lower voltage source will block current that would otherwise attempt to charge the source. Schottky diodes with a typical forward drop of less than 0.4 volts are used.

Three low drop out (LDO) linear regulators isolate the 5V digital, 5V analog (not shown), and 6V gyro power rails from external fluctuation. Loss of regulation occurs when the LDO input drops below 6.3 volts. Thus, if voltage at the connector is less than 6.7 volts, it should be from a regulated source greater than 6.4V. The input voltage level is measured on board and is available in the BNR data sentence (page 43).

The magnetometer consists of two Honeywell integrated circuits: the HMC1002, an X-Y sensor that incorporates two bridge circuits oriented perpendicular to each other; and the HMC1001, a separate Z sensor. The sensors are powered by a constant current source that is only turned on while making a measurement. The box labeled "Set-Reset Control" includes a charge pump converter that generates 20V for the required flipping pulses.

Either a liquid inclinometer or a 3D accelerometer, or both, can be used to measure pitch and roll. The inclinometer is based on a Spectron SP-5003, dual-axis, electrolytic tilt sensor, labeled "X-Y Tilt Sensor" in the diagram. The drive control excites one axis at a time, alternating between pitch and roll at a 55 Hz rate. The duration of a single pulse is roughly 0.5 milliseconds. Pulses of opposite polarity occur back to back on the same axis. Pitch and roll measurements are each updated at a 27.5 Hz rate.

The 3D accelerometer is a Kionix KXR94 ±2g tri-axis part. It is a MEMS device that consists of a sense element packaged with a separate ASIC that performs signal conditioning and self-test. It is calibrated to compensate for bias drift over the full ECV operating temperature range of -40°C to 125°C.
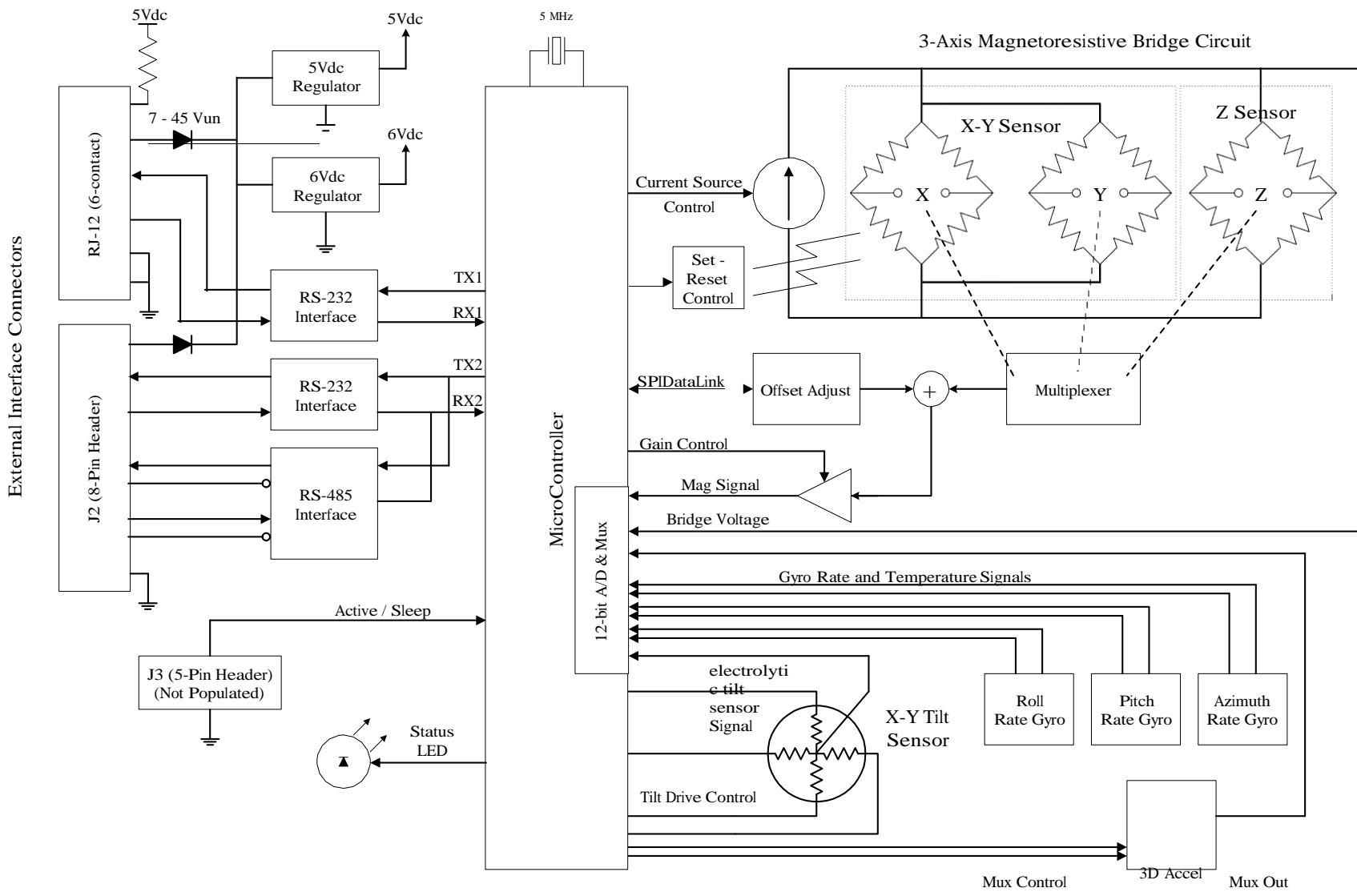
Figure 5 – eCompass ECV Block Diagram

Pitch, roll, and azimuth rate gyros are Analog Devices ADXRS646 devices. These parts require a 6V power supply. They have excellent vibration rejection and exhibit reasonable bias stability and low angle random walk. They have an internal temperature sensor that is sampled along with rate data to normalize bias over the operating temperature range.

The microcontroller powers and drives signals to the magnetometer, liquid tilt sensor, MEMS accelerometer, and gyros, sequencing the sensors in a precise, repeatable manner to collect eleven raw data values: X, Y, and Z magnetic readings; X, Y, and Z accelerometer readings; X and Y electrolytic tilt sensor readings; and pitch, roll and azimuth rate signals. Rate gyro signals are aligned to the same X, Y, and Z axes so that integrated rate data can be blended with acceleration readings.

Magnetometer readings are the orthogonal components of the earth's magnetic field vector plus any local disturbance vector. Tilt readings are used to determine the gravity vector. The processor performs trigonometric computations required to determine compass heading from the two measured vectors (magnetic field and gravity). Pitch and roll measurements are angles derived directly from the P and R liquid tilt measurements.

The processor controls analog gain and offset so that magnetometer and tilt readings are scaled within range of 12-bit A/D converters. While the earth's magnetic field varies from approximately 0.4 to 0.6 G (gauss or Oersted), magnetometer outputs are scaled so that the A/D range is approximately □1.0 G. Stray magnetic fields in excess of 0.4 G may cause the input to saturate and prevent the calculation of heading. For situations where hard iron is excessive, the range can be increased to approximately ±2.0 G.

Unit-to-unit variations in tilt and magnetic sensors make it essential to calibrate each device individually to achieve good accuracy. Alignment of the tilt and gyro sensors relative to the magnetometer and orientation of the magnetometer axes are corrected electronically prior to shipment. This operation is performed in a clean magnetic environment free of mechanical vibration.

The microcontroller performs the matrix operations required for both hard and soft-iron calibration using coefficients stored in its EEPROM. It also provides a calibration mode of operation that automatically sends the low-level data required to calculate new coefficients. A separate processor capable of performing double precision floating point calculations and supporting more memory is used to calculate new coefficients.

In RUN mode, an alarm on the calculated horizontal magnetic field strength can be setup to prevent sending heading data when either of two disturbances is present:

1. Horizontal components of acceleration affecting the tilt measurement, or

2. Stray magnetic fields affecting the magnetometer.

While the rate gyros should eliminate the effect of most short-term accelerations on tilt, there are situations where a persistent acceleration will not be

compensated. One example is continuous rotation in a horizontal plane. Eventually, rotating at 1 rpm at a diameter of 100 feet results in a 1° tilt error.

2.1   Initial Power On

When power is applied, the eCompass first initializes the I/O ports and clears all RAM memory. Next, EEPROM and FLASH parameter data is read. This is the only time that the EEPROM is read. Its contents are copied into volatile RAM, and are accessed there to control operation of the compass. Note that the address mapping from EEPROM to RAM is not one-to-one.

If an error occurs reading the EEPROM or if the contents are corrupted, then operation proceeds using factory defaults stored in microcontroller program memory (Flash). When this happens, the "EEPROM read error" serial status bit is set, and the compass unit ID is hexadecimal DEFA (57082 or -8454 decimal). The compass operates in RUN mode at 19,200 baud with no hard or soft iron calibration and no tilt calibration.

When the EEPROM is read successfully, the desired serial baud rates (stored in the EEPROM) are determined. The stored values are indices into a table of possible rates. If an index is out-of-range, 2400 baud is selected. Otherwise, the indexed value is used.

The baud rate can be overridden by external signals applied during startup. If the signal on J3.4 is low, then the serial receive data line (RX input) is tested for a continuous low signal (RS232 space, start bit state). If it is low for one second, then the baud rate is set to 2400 baud and the operating mode is forced to SAMPLE.

J3 is a 5-pin unpopulated connector that can only be accessed by removing the cover. J3.4 is driven low by connecting it to J3.3. The RX input is driven low by asserting a break condition on the RJ12 RS-232 input (J1.4).

2.2   Normal Operation

After configuring the serial ports with the selected baud rates, the microcontroller starts a 220 Hz timer and enables interrupts. The timer triggers a sequence of 8 states that direct the progress of the measurement cycle. At the beginning of each state, a chain of interrupt events is initiated and culminates in a new set of raw data.

What the processor does next depends on the settings in EEPROM and the state of the ACTIVE input on J3.4. If J3.4 is pulled low, the microcontroller enters a low-power, standby mode of operation. The main oscillator is stopped and the compass remains dormant until J3.4 is pulled high or disconnected.

When J3.4 signals the active state, continuing operation depends on the mode bit in EEPROM. In RUN mode, the processor automatically starts a measurement cycle and updates all measurements every 36 milliseconds. In SAMPLE mode, the processor waits to receive an NMEA query sentence or a setup command before starting a measurement cycle.

When measurements are in progress, the Set-Reset flipping circuit generates an audible 27.5 Hz buzz. Set-Reset flipping is used on each measurement to reduce cross-axis error (see Honeywell AN-205 for a detailed technical explanation). The sound is due to short duration, high-current pulses (10 μsec, 4 Amp) that realign magnetic domains in the Permalloy film of the AMR sensors.

The magnetic field sensors require offset adjustment so that their small differential signals can be amplified without saturating the output. A typical sensor produces 16 mV per Gauss signal strength, while the sensor offset can be as large as 40 mV. The ±8 mV signal due to the earth's magnetic field may be swamped by the offset.

The adjustment procedure is based on a half-interval search algorithm that requires 8 measurement cycles to complete. During this time, the magnetometer measurements should not be used. The heading field is null in HDT, HDG, HTM, CCD, and NCD sentences; and the magnetic status field in HTM is set to C. (For details, refer to the section describing the HTM sentence in Serial Communication Reference).

The procedure begins with the first measurement cycle after power on, and is only invoked thereafter when one of the three offsets changes by 1 mV. Since the offset temperature coefficient is nominally 10 ppm / °C with Set-Reset flipping, an offset should change by no more than 0.04 mV over a 100°C temperature span. Thus, the offset adjustment procedure is invoked only once.

2.2.1 RUN Mode

In RUN mode, the compass takes measurements and calculates heading 27.5 times per second. It also iterates filters and trigonometric functions in the signal path at this same rate. This mode consumes the most power, but it also provides the fastest response to changes in direction and inclination.

The diagram in Figure 6 shows the signal processing functions performed in RUN mode. Starting at the left of the diagram, hard iron offsets are first subtracted from individual components in the magnetic field vector. Next, the vector is multiplied by a 3x3 gain matrix to compensate for any soft iron effect. Then each component signal is smoothed using low-pass filters.

Filtered outputs are orthogonal components of the earth's magnetic field measured in a body-reference coordinate system attached to the compass card. The resulting vector is rotated to a terrestrial frame of reference (North-East-Down) using measurements of absolute pitch and roll from the inclinometer. The magnitudes of components in the horizontal plane are then used to determine heading.
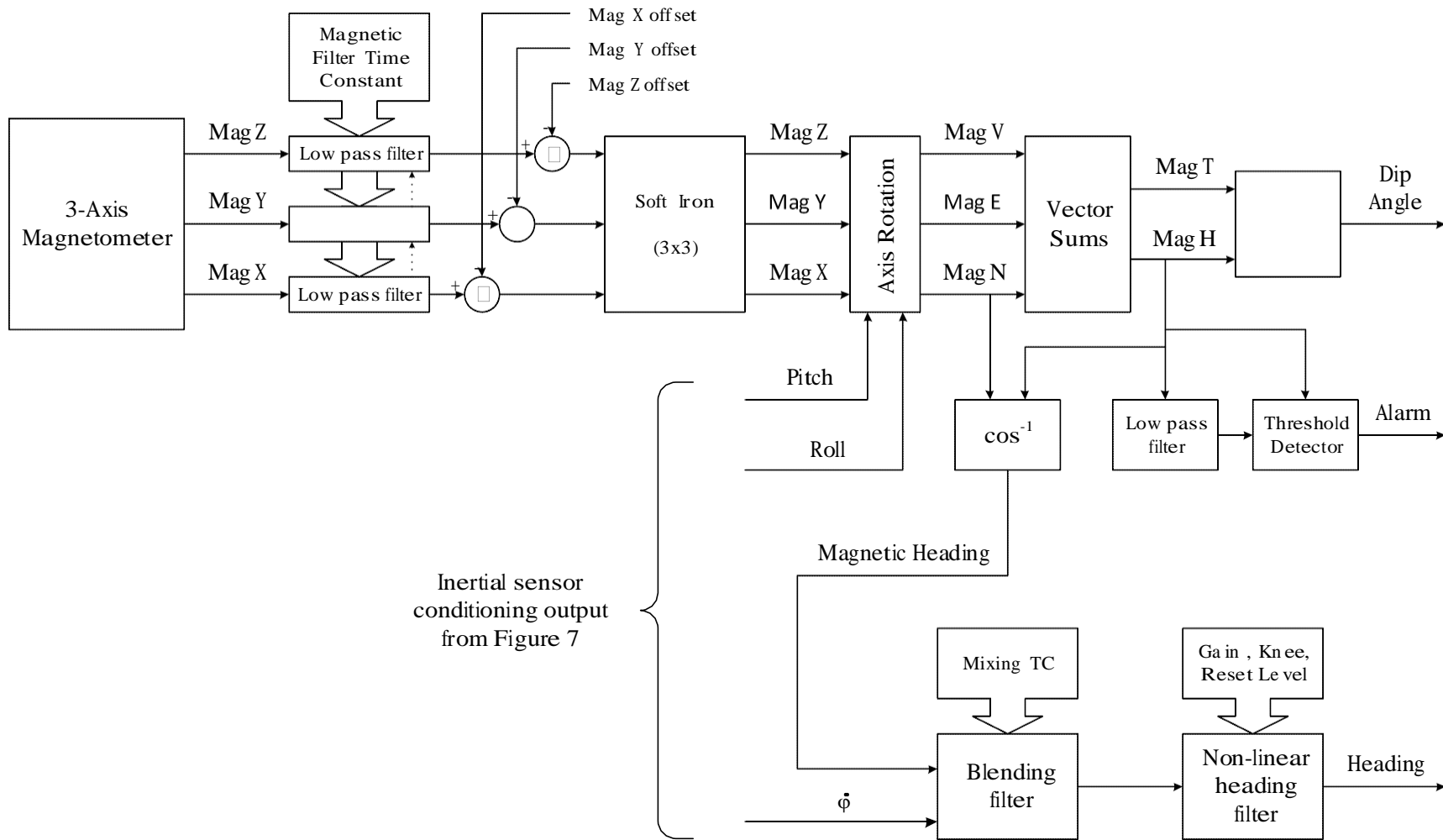
Figure 6 – RUN Mode Signal Processing

Signals from the accelerometer and electrolytic sensor are first gain and offset adjusted for temperature, then decoupled and aligned to the measurement axes of the magnetometer. Calibration curves stored in non-volatile memory are used to generate linear pitch and roll signals. These signals are then blended with the corresponding calibrated gyro signal in a complementary filter. The signal processing is shown in Figure 7.

Notes:
1. Pitch blending filter same as roll, separate t
2. Magnetic azimuth blended with azimuth rate φ̇
3. Optional circling correction (compass aligned to body forward motion)
4. Requires optional 2-axis electrolytic sensor
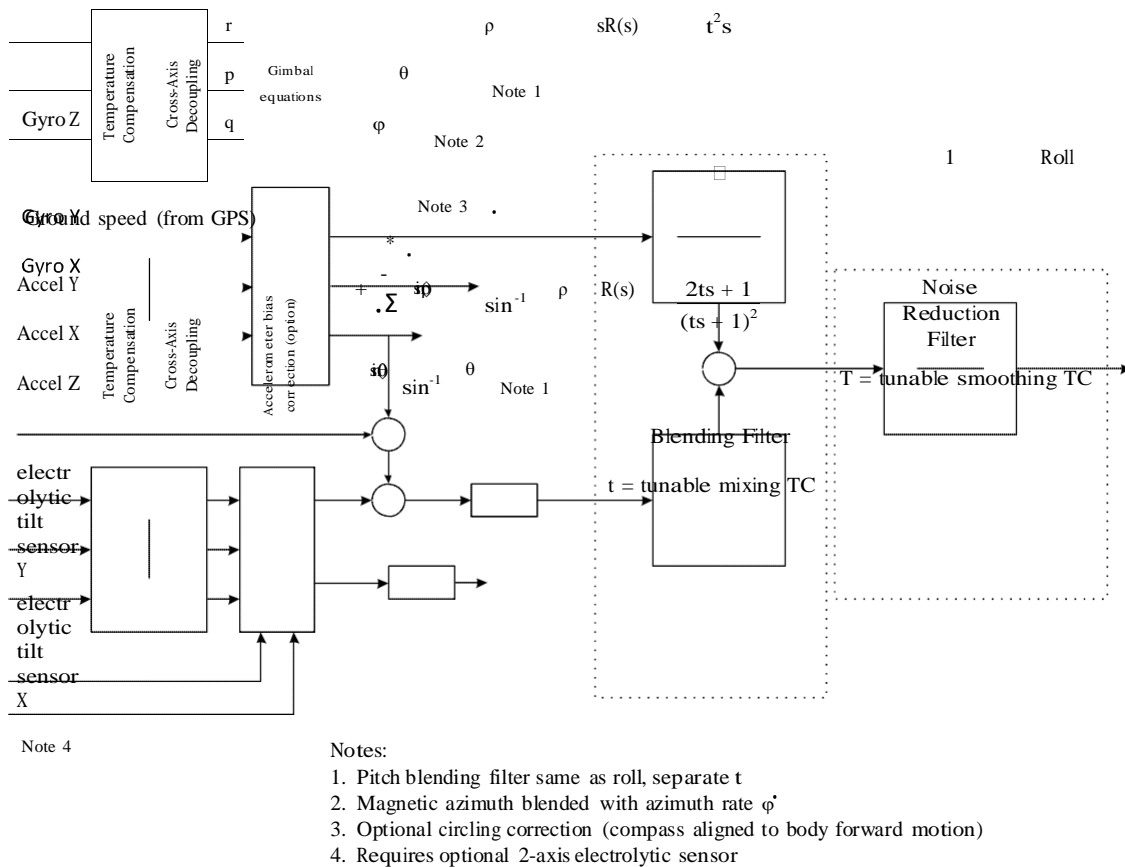
Figure 7 – RUN Mode Inertial Sensor Signal Processing

In the figure, the gimbal equations transform rotations measured in the body axis of the compass to the earth-fixed axis of the accelerometer measurements. If we assign r, p, and q as roll, pitch, and yaw body rotation rates; and ρ, θ, and φ as earth-fixed roll, pitch, and yaw angles, then the corresponding earth-fixed rotation rates are given by:

$$\begin{bmatrix} \dot{\rho} \\ \dot{\theta} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} 1 & \sin(\rho) \cdot \tan(\theta) & \cos(\rho) \cdot \tan(\theta) \\ 0 & \cos(\rho) & -\sin(\rho) \\ 0 & \sin(\rho) \div \cos(\theta) & \cos(\rho) \div \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} r \\ p \\ q \end{bmatrix}$$

Since *r*, *p*, and *q* measurements can be affected by accelerations other than gravity, these quantities are only approximations of the true attitude values. Better estimates are the outputs of the corresponding complementary filters. In

the compass firmware Roll, Pitch, and Heading values from Figure 6 are substituted in the above matrix for ρ, θ, and φ respectively.

The blending filter transfer functions shown in Figure 7 are based on the initial approach described in the 1997 article "A Low-cost and Low-weight Attitude Estimation System for an Autonomous Helicopter" by Baerveldt and Klang[1]. Although this filter was not used in their application, it works well here because the accelerometer has a fast response that makes it approximate an ideal sensor.

In the compass firmware, the 2nd order low-pass filters are implemented in two stages. First, both the accelerometer and gyro signals are passed through 1st order low-pass filters to reduce noise. Next, a lead filter in the accelerometer branch boosts frequencies between 1/2t and 1/t. In the rate gyro branch, the derivative in the second stage helps to attenuate gyro bias drift. Note that the sum of the separate transfer functions yields a flat frequency response:

$$\frac{2\tau s+1}{(\tau s+1)^2}P(s) + \frac{\tau^2 s}{(\tau s+1)^2}sP(s) = \frac{\tau^2 s^2 + 2\tau s + 1}{(\tau s+1)^2}P(s) = P(s).$$

The signals shown as Mag N, Mag E, and Mag V in the diagram of Figure 6 correspond to components of the earth's magnetic field in the $\underline{N}$orth, $\underline{E}$ast, and $\underline{V}$ertical (down) direction. When a component value is negative, it is oriented South, West, or up. The positive direction for the vertical component is selected to be down so that the coordinate system is right-handed. When the compass card is level, Mag N = Mag X, Mag E = Mag Y, and Mag V = Mag Z.

Measured pitch and roll angles are not independent rotations about the lengthwise and lateral axes of the compass card. For the electrolytic tilt sensor, they are angles measured from the tilted plane of the compass card to the horizontal plane (surface of the liquid) along the pins of the liquid tilt sensor (which are normal to the compass card). To rotate measurements from the compass card's tilted frame of reference to the earth's horizontal frame of reference, the transformation is:

$$\begin{bmatrix} N \\ E \\ V \end{bmatrix} = \begin{bmatrix} \dfrac{1+r^2}{\sqrt{1+r^2}\sqrt{1+p^2+r^2}} & \dfrac{p\cdot r}{\sqrt{1+r^2}\sqrt{1+p^2+r^2}} & \dfrac{p}{\sqrt{1+r^2}\sqrt{1+p^2+r^2}} \\ 0 & \dfrac{1}{\sqrt{1+r^2}} & \dfrac{-r}{\sqrt{1+r^2}} \\ \dfrac{-p}{\sqrt{1+p^2+r^2}} & \dfrac{r}{\sqrt{1+p^2+r^2}} & \dfrac{1}{\sqrt{1+p^2+r^2}} \end{bmatrix} \bullet \begin{bmatrix} X \\ Y \\ Z \end{bmatrix},$$

where N, E, V, X, Y, and Z are magnetic field components; and p and r are tangents of the pitch and roll angles. For small angles, or when either pitch or roll is zero, this transformation is the same as a three dimensional coordinate rotation.

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[1] Proc. of the IEEE Int. Conf. on Intelligent Engineering Systems (INES), 1997, pp. 391–395

For the 3D accelerometer, the transformation is easier to show using vector math. Let $\overline{A} = \begin{bmatrix} a \\ b \\ c \end{bmatrix}$ represent the vector of acceleration measurements with $\sqrt{a^2 + b^2 + c^2} = 1$, and let $\overline{X} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$ be the compass X direction vector, then

$\overline{E} = \overline{A} \times \overline{X} = \begin{bmatrix} 0 \\ c \\ -b \end{bmatrix}$ and $\overline{N} = \overline{E} \times \overline{A} = \begin{bmatrix} b^2 + c^2 \\ -ab \\ -ac \end{bmatrix}$. So the transformation matrix is:

$$\begin{bmatrix} N \\ E \\ V \end{bmatrix} = \begin{bmatrix} \dfrac{b^2+c^2}{\sqrt{b^2+c^2}} & \dfrac{-ab}{\sqrt{b^2+c^2}} & \dfrac{-ac}{\sqrt{b^2+c^2}} \\ 0 & \dfrac{c}{\sqrt{b^2+c^2}} & \dfrac{-b}{\sqrt{b^2+c^2}} \\ a & b & c \end{bmatrix} \bullet \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}.$$

The diagram in Figure 6 shows two additional features only available in RUN mode. They are

1. A non-linear heading filter, and

2. alarm on horizontal magnitude deviation.

The non-linear heading filter provides more smoothing for small changes in heading and no smoothing for large changes. As the difference between the filter input and output increases, the amount of smoothing decreases according to a 2nd order function. An example transfer function is shown in Figure 8. Both the transition region (Knee) of the curve and its slope near zero (Gain) can be tuned.
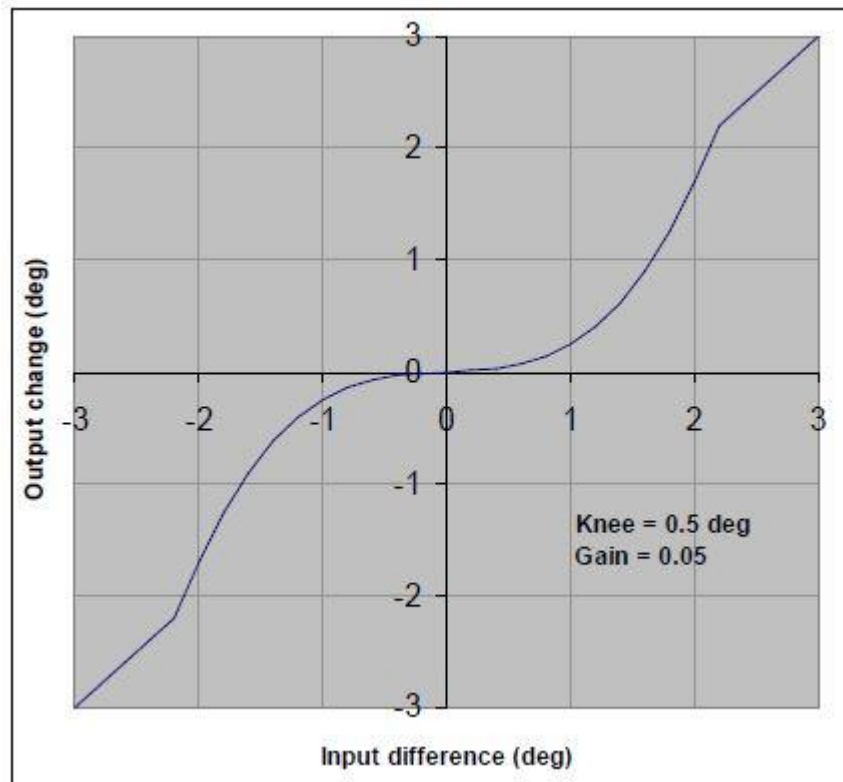
Figure 8 – Non Linear Heading Filter Transfer Function

The algorithm for this filter is shown in the following. Calculations are iterated at the 27.5 Hz measurement rate.

Parameters	K = transition knee	(angle units, 0 = disable)
	G = gain	$(0 < G < 1, 0 = \text{disable}, \text{max} = 0.999985)$
Variables	I = current heading input	
	O = smoothed heading output	
	D = input difference	
Calculate	$D = I - O_{i-1}$	(input difference)
	$P = G + G * (D/K)^{**}2$	(saturate P as D/K gets large, $G <= P <= 1$)
	$O_i = O_{i-1} + D * P$	(note that O = I for P = 1)

The third feature available only in RUN mode is the ability to alarm on an excessive deviation in the calculated horizontal component of the earth's magnetic field. For a properly calibrated compass, the calculated horizontal magnetic field strength, MagH, should remain constant in a restricted geographic area. Deviations can be caused by spurious magnetic anomalies, like passing under a steel bridge; by hard or soft iron errors; by tilt measurement errors; and by errors induced by horizontal acceleration.

2.2.2 SAMPLE Mode

In SAMPLE mode, the compass waits for one of the NMEA query sentences to be received before making any measurements. This mode consumes less power than RUN mode because the magnetometer and inclinometer are normally turned off. When a request for data is received, the compass temporarily enters the RUN mode state and accumulates measurements until it responds with the requested average data. Once the requested data is sent, the magnetometer and inclinometer are turned off and the compass resumes waiting for the next data request. The gyros are not used in this mode and can be turned off.

The diagram in Figure 9 shows the signal processing chain in this mode. Following a request for data, measurement cycles are performed in a manner identical to those in RUN mode. One or more of the first measurement cycles may be ignored depending on the setting of the parameter stored in EEPROM named "Sample Ignore Count." The measurement cycle rate is 27.5 Hz, as in RUN mode. Measurements are accumulated until the number saved in EEPROM, "Sample Mode Count," has been taken. The accumulated results are averaged and plugged into the requested NMEA sentence, which is then sent via the serial port.

Both tilt and magnetic data are accumulated and averaged for the same amount of time. This is different from RUN mode, where separate time constants are used to smooth tilt and magnetic data. In addition, only one sentence that contains the final averaged data is sent in SAMPLE mode. In RUN mode, sentences can be sent continuously.
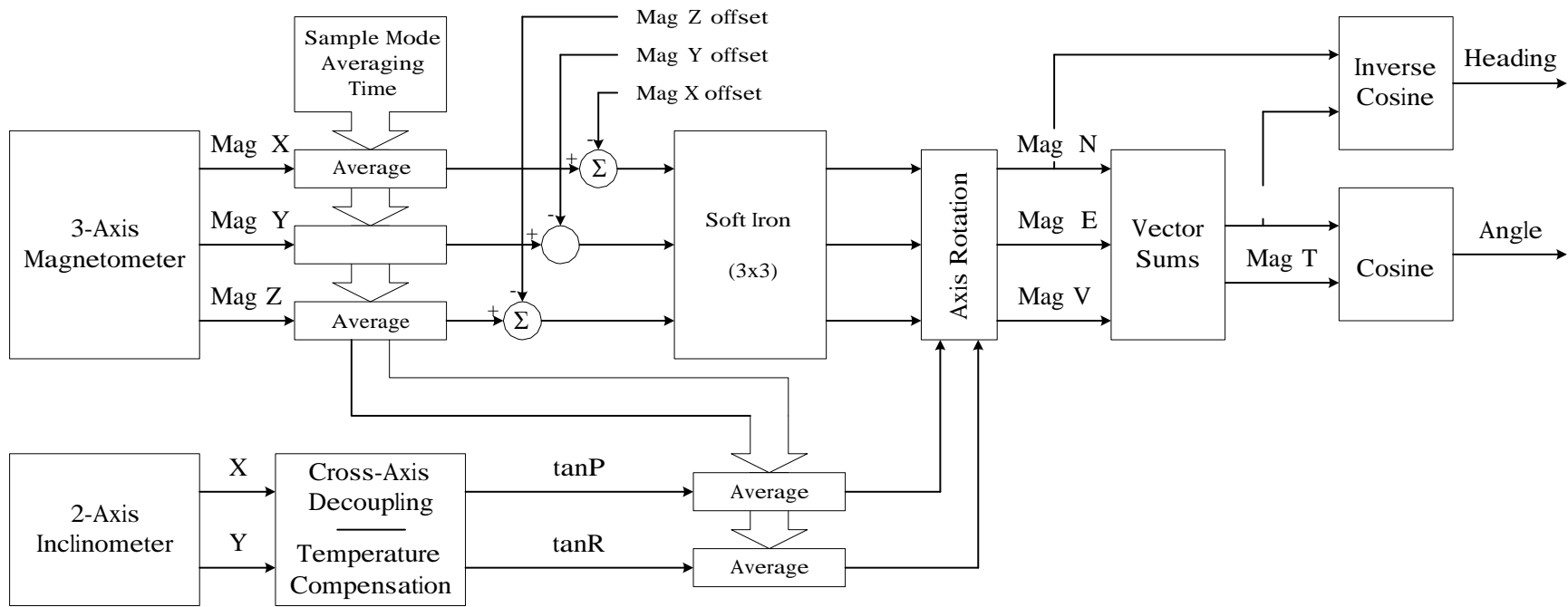
Figure 9 – SAMPLE Mode Signal Processing

2.3   Standby Operation

Power consumption is reduced to an absolute minimum when the compass operates in standby mode. Analog components are turned off, and the microcontroller's main oscillator is stopped. Serial communication is disabled, and the RS-485 and RS-232 drivers are dormant.

Standby operation can be invoked in either of two ways: by connecting the logic-level input on J3.4 (see Figure 4) to ground; or by disconnecting RS-232 signals while plugged into the external RJ12 jack. The first method is intended for embedded applications where a logic-level connection can be made to the compass. The second method is designed for situations where a connected device can remove power from its RS-232 driver.

The eCompass's RS-232 IC can detect when a valid RS-232 signal is present at either the RJ12 or J2 input. When both input signals are greater than-3V and less than 3V for more than a microsecond (i.e., disconnected), then the IC indicates that no valid RS-232 signal is present. In this case, the microcontroller enables the RS-485 signal input and can optionally be set up to switch to standby operation.

When a valid RS-232 input is not detected, operation depends on the setting of a volatile flag in the microcontroller's RAM. When power is first applied, the flag is reset and the compass will not enter standby mode. Once the control flag has been set, the compass will automatically enter and exit low-power standby mode depending on the states of both input signals. Allow at least 1 millisecond after setting the RS-232 signal to a valid marking level before sending the first character.

The flag is called SleepWithout232 and it must be set to TRUE to allow standby mode to take effect when no RS-232 signal is present. This is a volatile control flag (not stored in EEPROM) that is initially cleared to FALSE when the microcontroller is reset. The command string to set this flag is: @F29.4=1*5B<cr><lf>. Refer to the Setup Protocol section for an explanation of the fields in this string.

To exit standby operation, allow J3.4 to float high or apply a valid RS-232 signal to one of the input channels. Wait at least 1 millisecond before starting a serial transmission. This allows the microcontroller time to start up its oscillator and begin executing instructions.

3 Optimizing Performance

The performance of the eCompass depends on how well its parameters are adjusted for the operating environment. Accuracy, repeatability, speed of response, rejection of anomalous measurements, and power consumption can be optimized by careful tuning of coefficients that adapt the compass to different conditions. For example, in a hand-held surveying application, low power consumption and high accuracy are important for intermittent samples. Operating in SAMPLE mode would be appropriate, and automatically entering sleep mode between samples would minimize power consumption. Parameters used only in RUN mode can be ignored. These include settings for magnetic and tilt filters; settings for the magnetic alarm; and settings for the non-linear heading filter.

In contrast, automatic antenna positioning requires continuous measurements in the presence of mechanical noise and magnetic anomalies. The RUN mode of operation is required, and settings for filters and alarms must be adjusted to account for operating conditions. If fast, large-angle movements are to be ignored, the non-linear heading filter can be enabled. If vibration from engine noise, ocean waves, or nearby heavy equipment causes liquid tilt sensor oscillation, the rate gyros should be enabled and the complementary filter time constant is set to optimize tilt angle estimation.

For all applications, the compass accuracy should be verified in-situ by performing a magnetic calibration. This entails first capturing a vertical reference in a nearby location free of magnetic interference, then taking measurements about a circle with the compass mounted in place. The vertical reference can be skipped if you are convinced that there is no vertical component of hard iron.

3.1 Factors Affecting Accuracy

As mentioned in the section on Features and Limitations, there are a number of factors that can potentially affect the accuracy and repeatability of the compass. The following list explains the mechanism of each factor and presents an order of magnitude of its effect on accuracy.

3.1.1 Static Permanent Magnetism (Hard Iron)

The source of a local permanent magnetic field can be a piece of hard iron (hence the common name), a constant DC current, or some other type of magnet. This source of error can be significantly reduced by calibration. The curve in Figure 10 shows that a residual error of 0.1% of the earth's magnetic field on both X and Y axes produces a peak accuracy error of 0.20° at 66° inclination (middle US).

The error varies sinusoidally with direction and produces a single cycle for each rotation of the compass. Phase depends on the signs and magnitudes of errors on each axis. The magnitude of the error depends on inclination because the residual hard iron error is expressed as a fraction of the total field strength.
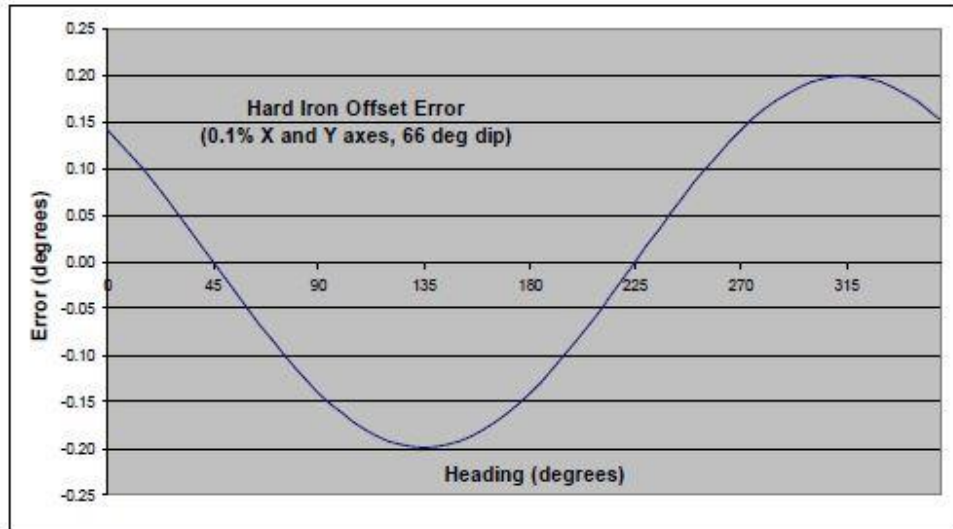
Figure 10 – Hard Iron Heading Error

Fortunately, a residual Z-axis error is less critical. This error comes into play only when the compass card is tilted from level. At 30° tilt, a Z-axis error of 0.3% would be required to produce the same 0.2° peak accuracy error at 66° dip. The accuracy error decreases with decreasing tilt.

This is fortunate because it can be difficult to determine the Z-axis hard iron coefficient. When the compass is mounted in a large vehicle, it may be impossible to turn the vehicle over in order to get good calibration data. An estimate of the Z coefficient can be made so long as some tilted data is collected, but a reasonable estimate may still require tilt angles that can't be achieved.

To eliminate this problem, the eCompass allow an optional two-step Z-axis calibration. Reference data is first collected outside the vehicle, in an area free of magnetic interference. When the compass is mounted in the vehicle, the measured vertical component is compared to the reference data to calculate the coefficient. So long as the compass is within a few degrees of level during both measurements, the calculated result is accurate.

3.1.2 Static Induced Magnetism (Soft Iron)

Bring a magnet in contact with a metal paper clip and the paper clip becomes magnetized. When the magnet and paper clip are separated, the paper clip retains none of its temporary, or induced, magnetism. Soft iron, alloys of iron and nickel, common steel, and some types of stainless steel can all be easily magnetized, even in a weak field.

When these materials are in the vicinity of the compass and rotate with the compass, they become magnetized and demagnetized depending on their orientation with respect to the earth's magnetic field. Instead of seeing a constant field that would produce a perfect circle as the compass turns, the compass sees a field of varying magnitude that maps an elliptical shape. This induced magnetism gives rise to a heading accuracy error as shown in the example of Figure 11.
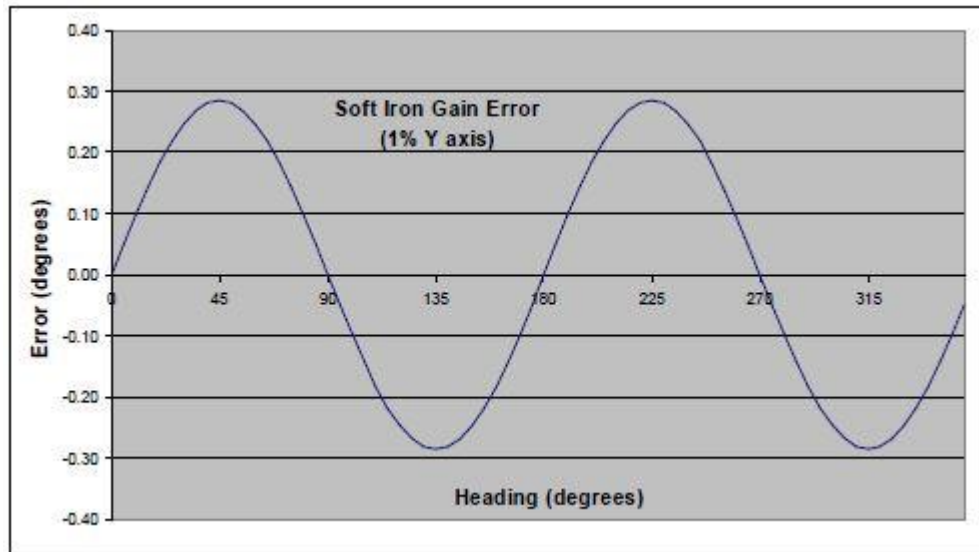
Figure 11 – Soft Iron Heading Error

When the compass is rotated in a level plane, the error varies sinusoidally and produces two cycles per eCompass of the compass. In the figure, peaks are located at 45°, 135°, 225°, and 315° because the gain error is aligned with the Y axis, which would be the major axis of the ellipse. In practice, the major axis could be aligned at any angle.

In three dimensions, the locus of points would map to an ellipsoid instead of a perfect sphere. In this case, a 3x3 matrix of gain coefficients is needed to compensate. A minimum of 12 independent measurements is needed to determine 9 soft-iron gains and 3 hard-iron offsets.

If the compass is only being used near level, then a simpler, two-dimensional compensation may be adequate. The eCompass PC software includes an algorithm to estimate 2D soft-iron coefficients based on the approach set forth in "Direct Least Squares Fitting of Ellipses," by Fitzgibbon et al. in IEEE TransactionsonPatternAnalysisand MachineIntelligence, Vol. 21, No. 5, May, 1999. The software reports the ellipticity, in percent, of the ellipse that best fits the collected data. This metric can be used to decide if soft-iron compensation is needed.

In situations where soft-iron is significant, it may be better to relocate the compass. First, a two-dimensional compensation is only approximate, and small variations in tilt may produce dramatic changes in the soft-iron ellipse. Proper compensation may require that three-dimensional data be collected and analyzed to produce the full 3x3 gain matrix.

Secondly, soft magnetic materials that give rise to induced magnetism also exhibit varying degrees of remanence, the tendency to remain magnetized after a magnetizing force is removed. The magnetization of the material may change over time due to exposure to vibration, temperature changes, and varying electrical and magnetic fields. This results in hard-iron errors that must be periodically compensated to maintain accuracy.

If there is no alternative and 3D soft iron must be compensated, the eCompass PC program provides an option to collect 3D data and calculate the optimum 12 compensation coefficients. The iterative algorithm works to find the ellipsoid that best fits the collected data by minimizing the sum of the squared geometric distances between the collected data and the parametric ellipsoid.

3.1.3 Time Varying Magnetic Fields

A time varying magnetic field in the vicinity of the compass cannot be compensated. Either its frequency must be above the pass band of the compass (i.e. greater than 30 Hz), or it must be eliminated. The eCompass's measurement cycle rate of 27.5 Hz is chosen to maximize attenuation of 50 Hz to 60 Hz signals associated with AC power systems.

To estimate the order of magnitude effect of a DC current near the compass magnetometer, use Ampere's law to calculate the magnetic field near a long wire: $B \cong \dfrac{\mu_0 i}{2 \pi r}$, where $\mu_0 = 4\pi \times 10^{-3}$ Gauss-meter / amp. A long wire carrying 25 mA of current located 50 mm from the magnetometer produces a 1 mG (100 nT) magnetic disturbance at the sensor. In the middle US, where inclination is roughly 66° and the earth's magnetic field strength is about 500 mG, this can result in almost 0.3° heading error.

3.1.4 Tilt Measurement Errors

Errors in pitch and roll measurements give rise to single-cycle heading errors that cannot be differentiated from heading error caused by residual hard-iron. The plot in Figure 12 shows how an error as small as 0.1° on both X and Y axes affects heading accuracy at 66° magnetic inclination. The phase of this curve

depends on the relative signs and magnitudes of the separate X-axis and Y-axis errors.
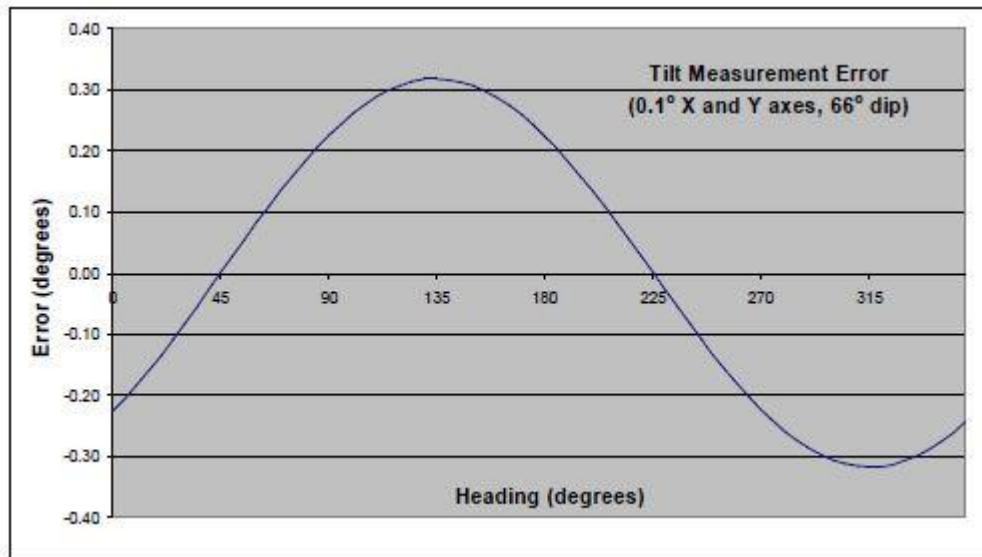
Figure 12 – Effect of Tilt Error on Heading Accuracy

Compare the shape and phase of the curve in Figure 12 to the hard-iron error curve in Figure 10. In this case, the curves are not in phase, and the two sources of error tend to cancel each other. The resulting peak error is reduced by a factor of three as shown in the curve labeled "Errors Cancel" in Figure 13. But change the signs on both pitch and roll errors, and the two curves align in phase, producing the result also shown in Figure 13.

Tilt measurement errors can be caused by one or more of the following:

1. sensor offset and/or gain errors
2. sensor cross-axis coupling
3. misalignment of tilt and magnetic sensor axes
4. uncompensated horizontal acceleration

In applications where the compass cannot be held perfectly steady, the error due to horizontal acceleration can be pronounced. Although the rate gyros will initially compensate, if the acceleration persists, it will eventually affect the measurement. For a modest constant horizontal acceleration of 0.05g (roughly 1 mile per hour per second), the tilt measurement error is 2.9° (obtained by calculating $\tan^{-1}0.05$). For the example 66° inclination used above, this results in a sinusoidal heading error of 6.5° peak magnitude.
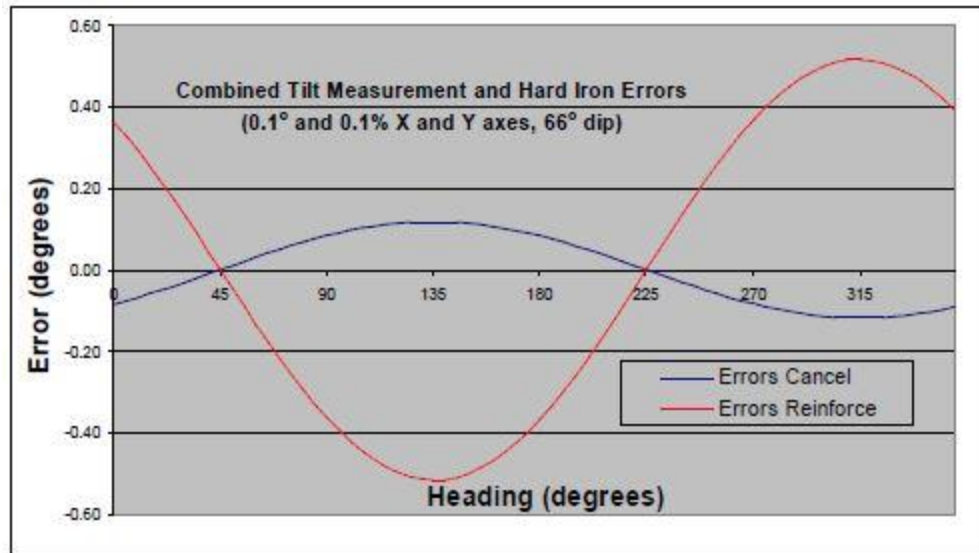
Figure 13 – Combined Effect of Hard Iron and Tilt Errors

3.1.5 Magnetic Inclination (Dip Angle)

Near its magnetic poles, the overall strength of the earth's magnetic field increases. But the horizontal component decreases substantially, making navigation by magnetic compass nearly impossible. For mechanical compasses, the needle dips excessively, trying to align with almost vertical lines of force. For an electronic compass, accuracy decreases because the horizontal field is smaller, and because the effect of tilt errors is more pronounced.
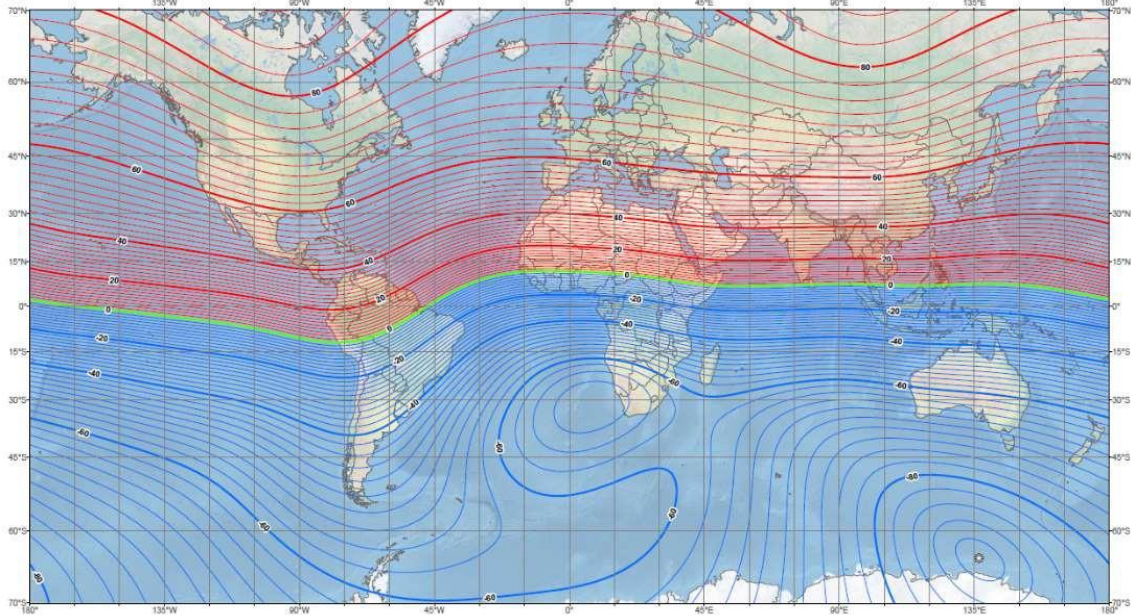
Figure 14 – Magnetic Inclination Contour Lines (in degrees)

The map in Figure 14 shows lines of constant dip angle around the globe. Each of the narrow lines is separated by 2°. The map is based on the US/UK world magnetic model for the year 2015.

Near the magnetic equator, tilt measurement errors have very little influence on compass heading. Between ±5° dip, a 1° error in tilt produces no greater than 0.09° heading error. In northern Alaska (80° dip), the same 1° tilt error results in as much as 6° heading error.

3.2 Calibrating the Compass

The compass EEPROM stores 12 coefficients used to correct for local magnetic fields, both permanent and induced, that remain in a fixed orientation relative to the magnetometer. There are 3 offsets and 9 gains that transform the measured magnetic components - X, Y, and Z - as follows:

$$
\begin{bmatrix} MagX \\ MagY \\ MagZ \end{bmatrix} = \begin{bmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{bmatrix} \bullet \begin{bmatrix} (X - Xoffset) \\ (Y - Yoffset) \\ (Z - Zoffset) \end{bmatrix}.
$$

The purpose of a calibration procedure is to determine values for these 12 coefficients when the compass is operating in its installed position. For a perfectly calibrated magnetometer, the locus of points (MagX, MagY, MagZ) maps to a sphere centered at the origin. A local permanent magnetic field moves the center of the sphere from the origin, affecting one or more of the 3 offsets. An induced local field distorts the shape of the sphere into a three dimensional ellipsoid. The ellipsoid's 3 orthogonal semi-axes are, in general, rotated relative to the magnetometer X, Y, and Z axes. The gain matrix in the transformation above is determined by finding the relative lengths of the semi-axes and then rotating the resulting vector to the magnetometer X-Y-Z frame of reference.

Successful calibration requires that the magnetometer and the local magnetic effects be pointed in at least 12 different orientations in a fixed external field. Best results are obtained when the points are equally spaced about the 3D spheroid. With measurement noise, more than 12 points is generally needed to produce acceptable results. The extra data can be used to algorithmically determine the ellipsoid that is a best fit based on a least-square error criterion.

3.2.1 External Hard and Soft-Iron Calibration

In many applications, it can be difficult or impossible to collect sufficient 3D calibration data. When the compass is mounted in a boat, truck, tractor, or RV, turning everything upside down is unreasonable. In these cases, a compromise that results in acceptable accuracy for normal operating conditions is needed.

The eCompass calibration procedures result in such a compromise. These procedures are based on the following key assumptions:

1. the compass is operated and calibrated in a nearly horizontal position,
2. the Z-axis offset can be estimated using the vertical component of the earth's magnetic field, and
3. where the soft-iron effect is significant, the shape of the ellipsoid in the plane of the compass card does not vary radically with small pitch and roll angles.

If the compass is oriented horizontally during calibration, then the Z-axis is nearly vertical. The Z-axis offset can be estimated by first saving a vertical field reference in a magnetically clean area (i.e., out of doors, away from steel structures) and then calculating the vertical field strength during calibration. The Z-axis offset is the difference between these two values. The error in the estimate is proportional to $(1 - \cos\theta)$, where θ is the inclination. This is less than 1% when compass card inclination is less than 8°.

The X and Y axis offsets are determined by a similar estimation procedure. Measurements are captured at multiple points about a circle while the compass card remains within a few degrees of horizontal. Inclinometer readings are then used to project the measurements into the horizontal plane. Like the Z-offset, if inclinometer readings are accurate, then the error in the estimates will be small.

A problem is that the inclinometer or accelerometer is affected by horizontal components of acceleration, which may be substantial for circular motion, even when moving at a constant speed. A vehicle moving at 5 mph on a circle of radius 70 ft. will traverse the circle in the recommended 1 minute. The centripetal acceleration is 0.77 ft/sec^2, or 24 mg. This results in a 1.3° error in inclination, which at 66° dip angle gives rise to a peak heading error of 3° after calibration.

To avoid this problem, the preferred method of collecting calibration data is to first stop at a measurement point and then average a number of readings to produce a value. This eliminates horizontal components of acceleration. Care must be exercised to ensure that the vehicle is completely stopped before acquiring data.

The calibration procedure cannot be performed in some conditions such as within, above, or below a steel structure like a parking garage or office building. In these locations, the earth's magnetic field may not remain constant over the area required for calibration. To determine if a site is appropriate, perform a survey with a hand-held compass to map variations in the horizontal and vertical components of the field.

When the eCompass calibration procedures are not appropriate, there are two additional options for hard and soft-iron calibration. First, you can capture data separately and determine appropriate coefficients using a method of your choosing. Refer to the Command Reference section of this document for instructions on tuning new coefficients.

An independent technique based on the maritime procedure for magnetic compass adjustment can also be used. The resulting deviation tables are stored in the compass EEPROM and are used to automatically correct for compass error. See the PC software help for instructions on using the tables.

3.2.2 Onboard Hard-Iron Calibration

Embedded in the firmware of the eCompass ECV are routines to collect and analyze magnetic calibration data. A least-squares algorithm is implemented to compute hard-iron offsets that optimize accuracy. There are a number of options that can be preset using the PC eCompass software:

- Sample data geometry options
  a   3D (sample points not coplanar)
  b   2D (sample points in approximate horizontal plane)
  c   2D with vertical reference (V_{ref} used to estimate Z offset)

- Sample data collection options
  a   Continuous by time
  b   Continuous by traversed angle (sample every 3 degrees of rotation)
  c   Multi-step samples triggered manually

- Progress notification options
  a   Send CAL sentence for sample points and completion
  b   Send CAL sentence for completion only

- Completion options
  a   Apply results automatically (store new offsets if better than old)
  b   Send results with indicator to keep old offsets or apply new values

The selected options are stored in EEPROM and can be preset at Jewell Instruments if desired. In addition, the EEPROM stores whether external or internal calibration is enabled. Since external is set by default, the onboard calibration must be enabled before entering calibration mode. See Onboard Magnetic Calibration for additional details.

After specifying the calibration options and selecting onboard calibration, data collection is started by setting Enter Magnetic Calibration Mode = 1. If Onboard No CAL Progress Sentence

DLL Parameter Index: 160
Access Type Character: F
Hex Address: 19.4
Read Example: @F19.4?*6B
Write Example: @F19.4=1*58

Set this flag to 1 to disable calibration progress sentences during data collection. See Onboard Hard-Iron Calibration for contents of the CAL sentence.

3.2.2.1 Onboard Short CAL Progress Sentence

DLL Parameter Index: 196
Access Type Character: F
Hex Address: 19.7
Read Example: @F19.7?*68
Write Example: @F19.7=1*5B

Set this flag to 1 to reduce the number of characters sent in the calibration progress sentences. No data is transferred for tanP, tanR, magX, magY, magZ, or heading during the capture phase. Following is an example sentence:

$PTNTCAL,,,,,,,C,1*22

The series of commas represent the null fields. Only the status and capture count are transmitted, keeping the sentence length less than 25 characters.

When the capture and calculation phases are completed, the results sentence is as follows:

$PTNTCAL,7,9,,,,,O,8*29

Data for the first two fields, old and new variation, is included along with the status character and capture count at the end. See section 3.2.2 for additional CAL sentence details.

 = 0, a CAL progress sentence is sent whenever a sample point is saved or rejected. The sentence adheres to the NMEA 0183 standard (see section 4.1) and is formatted as follows:

$PTNTCAL,x.x,x.x,x.x,x.x,x.x,x.x,a,x.x*hh<cr><lf>

During the data capture phase, the sentence includes the magnetic measurements along with other diagnostic data. The fields are, in order:

tanP   32768 times tangent of angle between compass board lengthwise axis and a level plane. The angle is measured from the tilted plane of the compass card to the horizontal plane (surface of the liquid) along the pins of the tilt sensor. It represents a rotation about the lateral axis of the card (pitch).

tanR   same as tanP but for the compass board lateral axis (roll)

magX   normalized and filtered magnetic field strength measured along the lengthwise axis of the compass board (5 nT per count)

magY   same as magX but along the compass board lateral axis

magZ   same as magX and magY but along an axis perpendicular to the plane of the board

heading   calculated heading based on the magnetometer and inclinometer data in this sentence. This field will be null if the heading cannot be calculated.

status   text character that indicates calibration status

count   number of saved calibration samples

The status character will be one of the following while collecting calibration data:

1. C = data captured and saved
2. M = magnetic field strength out of range, data not saved
3. T = tilt out of range, data not saved
4. R = rotation reversed, restarting capture
5. D = done with capture phase

The D status is sent at the end of data collection when either 120 vectors have been saved or when Onboard Finish Calibration is set to 1. The calculation phase proceeds immediately and is completed when the final CAL sentence is sent. In this case, the status character will be one of the following:

1. S = new offsets saved
2. N = use new offsets
3. O = keep old offsets
4. F = too few captured points, offsets not calculated
5. L = low range of magnetic field component, offsets not calculated

For status characters S, N, and O, the first five data fields are, in order: oldVar

                ten times total field variation in % using old hard-iron offsets

newVar   ten times total field variation in % using new hard-iron offsets

offsetX   calculated change in X offset

offsetY   calculated change in Y offset

offsetZ   calculated change in Z offset

The oldVar and newVar values provide quantitative measures of how well the new and old offsets compensate for hard-iron. Accuracy is improved as variation decreases. Values shown are calculated as 3000 times the standard deviation of the total field magnitudes divided by the average total field. For each captured data point, the total field magnitudes are calculated as follows:

$$\text{magT}_{old} = \text{Sqrt}(\text{magX}^2 + \text{magY}^2 + \text{magZ}^2)$$

$$\text{magT}_{new} = \text{Sqrt}((\text{magX–offsetX})^2 + (\text{magY–offsetY})^2 + (\text{magZ–offsetZ})^2)$$

The S or N status is sent when old variation is greater than new variation by 0.5% or more. Otherwise the O status is sent.

Status character F is sent if there are fewer than 6 calibration samples when Onboard Finish Calibration=1 is detected. In this case, new offsets are not calculated and the other data fields in the sentence can be ignored.

For status character L, the first five data fields are, in order:

magHmax   maximum calculated horizontal field strength

magHmin   minimum calculated horizontal field strength

magXrange   range (max − min) of X field component

magYrange   range (max − min) of Y field component

magZrange   range (max − min) of Z field component

New offsets are not calculated because it appears that the captured data does not span enough range to ensure correct results. Both X and Y components must vary enough so that their range is at least as large as the minimum horizontal magnitude, magHmin. If the range of the Z component is insufficient when a 3D calibration is selected, the Z offset is not calculated.

Following is an example communication log for a successful calibration. Options are for a 2D calibration with vertical reference; capturing data every 3 degrees of rotation.

```
Send: @F28.5=1*5B
Recv: @!0000*21
Send: @F3C.6=1*22
Recv: @!0000*21
Recv: $PTNTCAL,197,-66,3026,-127,9803,357.6,C,1*05
Recv: $PTNTCAL,166,-69,3049,46,9803,0.9,C,2*1B
Recv: $PTNTCAL,140,-93,3064,222,9797,4.1,C,3*2A
Recv: $PTNTCAL,167,-76,3031,386,9802,7.3,C,4*2E
Recv: $PTNTCAL,171,-71,3020,550,9802,10.3,C,5*14
…
Recv: $PTNTCAL,191,-95,3050,-94,9804,358.2,C,116*3C
Recv: $PTNTCAL,203,-90,3040,66,9808,1.2,C,117*12
Recv: $PTNTCAL,202,-75,3038,231,9804,4.4,C,118*27
Recv: $PTNTCAL,204,-94,3018,391,9807,7.4,C,119*26
Recv: $PTNTCAL,147,-48,3016,555,9795,10.4,D,120*1C
Recv: $PTNTCAL,42,3,-603,32,838,10.8,N,120*25
```

Old variation is 4.2%. New variation is 0.3%. Calculated offset deviations are x = -603, y = 32, and z = 838. Status N indicates that stored offsets have not been updated, but they should be adjusted to improve accuracy. Status would be S if Onboard Apply Results Automatically = 1. In this case, offsets are adjusted and saved in EEPROM automatically.

3.3 Accelerometer Bias Correction

With the eCompass ECV you can choose one of two gravity sensors to measure inclination: a 2-axis liquid-filled electrolytic sensor (electrolytic tilt sensor), or a 3D MEMS accelerometer. Each sensor has inherent strengths and weaknesses.

The electrolytic tilt sensor has very stable offsets. There is virtually no change with time or temperature because gravity keeps the surface of the liquid level. However, the sensor gain varies with temperature and the degree of liquid agitation. Its range is limited by the sensor height and liquid fill level.

MEMS accelerometer offsets are typically much less stable than the electrolytic tilt sensor. They can suffer from thermal hysteresis and drift over time and temperature. But MEMS are superior when operating at higher inclination and when mechanical

vibration is present. The electrolytic tilt sensor gain varies with temperature and the degree of liquid agitation (repeated from prior paragraph). In unfortunate situations near resonance, the undulating liquid can produce measurement spikes that greatly exceed the actual motion.

Improved inclination accuracy is achieved by using the difference between electrolytic tilt sensor and MEMS measurements near level to calculate corrected MEMS offsets. Corrections are then applied over the full range of MEMS measurements. The algorithm can be tuned by the user for their specific application.

Parameter settings direct the software to capture only appropriate electrolytic tilt sensor data to be used for MEMS offset corrections. An updated version of the eCompass Test program provides a special settings dialog to adjust parameters and view the calculated bias corrections. A screen shot of the settings dialog follows.
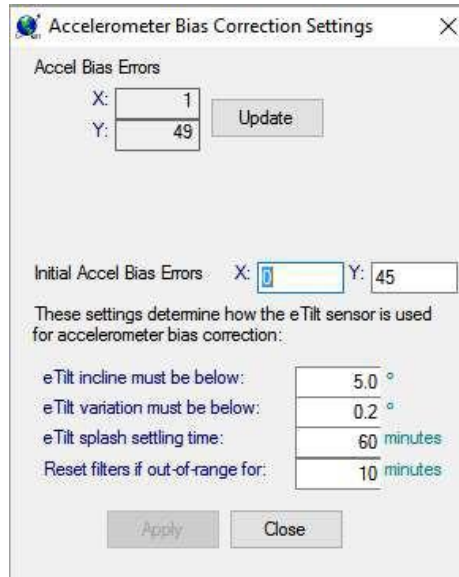
The "Accel Bias Errors" section shows the current differences (accel–electrolytic tilt sensor) in counts, with 16384 counts equal to 1G (gravity). The "Initial Accel Bias Errors" are parameters unconditionally applied when the compass is reset. These initial corrections remain in force until acceptable electrolytic tilt sensor readings are captured.

3.4 Roll Circling Correction using Ground Speed

When an aircraft is circling for a long time, the roll blending filter cannot compensate for the constant effect of centripetal acceleration. Although the aircraft is banking, the roll measurement from the accelerometer or electrolytic tilt sensor will indicate zero. This is because the component of gravity sensed along the lateral axis is canceled by centripetal acceleration. In this situation, a calculated value can be added back to the sensor measurement to correct the roll angle. Centripetal acceleration is equal to ground speed times rotation rate around the vertical axis (see Note 3 in Figure 7).

To obtain ground speed, one option is that the compass will accept and parse the GPS $GPRMC sentence. Following is an example sentence:

$GPRMC,123519,A,4807.038,N,01131.000,E,022.4,084.4,230394,003.1,W*6A

Where:

RMC	Recommended Minimum sentence C
123519	Fix taken at 12:35:19 UTC
A	Status A=active or V=Void.
4807.038,N	Latitude 48° 07.038' N
01131.000,E	Longitude 11° 31.000' E
022.4	Ground speed in knots
084.4	Track angle in degrees True
230394	Date - 23rd of March 1994
003.1,W	Magnetic variation
*6A	Optional hexadecimal checksum, always begins with *

Data from both ground speed and magnetic variation fields will be accepted when the Status field value is A. Magnetic variation is used in the calculation of true heading. The value from RMC is reported in the HDG sentence (see section 4.1.4.1) and is subtracted from magnetic heading to report true heading in HDT and HTM. If either field is null, no update will be applied to the corresponding value.

Ground speed can also be updated by writing to a designated register (hex address 218) in the compass. The value to write is 10 times the ground speed in knots. The following example sets the ground speed to 106.3 knots. (See section 4.2 for protocol details.)

    Send: @W218=1063*65<cr><lf>
    Recv: @!0000*21<cr><lf>

When ground speed is updated, a watchdog timer is activated to reset the value to zero in the event that another valid update is not received. The default setting for the WDT is 250 measurement cycles, which is 9 seconds. The value can be set to zero to disable the circling correction function.

To change the WDT value, use the eCompassTest program as follows:

- Select "Modify Extended Settings" from the Tools menu
  (If the menu item cannot be selected, exit the program and edit the eCompassTest.INI file to set AllowSpecialSettings=1)

- In the Category section click on the "All" radio button

- In the Value box, change the number to any value between 0 and 32767

- Click [Apply]

Ground speed and Y-axis correction are available in the Mix Data string of the ECV Binary data (section 4.1.4.8). In the eCompassTest program, click on the View menu and select ECV Binary Sentences, then select Mix Data. (If the Mix Data section is not visible, exit the program and edit the eCompassTest.INI file to set AllowSpecialSettings=1)
Ground speed is shown in knots times ten. The circling correction is scaled the same as total acceleration with 16384 counts equal to one gravity unit.

3.5 Configuring RUN Mode Filters

With the compass operating in RUN mode, there are three sets of functions that control the stability and speed of response of heading output:

1. low-pass filters for tilt and magnetic measurements,

2. the non-linear heading filter, and

3. the complementary filters that blend gyro, tilt, and heading signals.

These functions are shown in Figure 6 and described briefly in the section on RUN Mode Operation. This section focuses on adjusting tuning parameters to optimize performance.

There are three single-pole low-pass filters for magnetic signals - MagX, MagY, and MagZ - and five for tilt: tanP and tanR (tangents of pitch and roll) for the electrolytic tilt sensor sensor signals; and X, Y, Z accelerometer signals . One time constant sets the
3 dB point for the three magnetic signal filters, and a separate parameter controls filtering for the five tilt signals. For fastest response but least stability, set both time constants to zero. This disables both filters.

Some amount of filtering, or smoothing, is generally advisable to reduce noise in the measurement. But even a small time constant can dramatically affect speed of response. For example, in a tracking application with the compass rotating at 1 rpm (6°/sec), the factory-set magnetic time constant of 0.2 sec results in a 1.2° tracking error ($1.2° = \tan^{-1}[0.2*2\pi/60]$). With a time constant of zero, there is no tracking error.

Another consideration for choosing an appropriate time constant is output settling time. For a step change in the input, filter output changes exponentially and is within 1% of its final value after 5 time constants ($1 - e^{-5} = 0.99$). For the factory-set time constant of 0.2 sec allow 1 second for the magnetic signals to settle after a quick rotational change.

When a time constant is changed while operating in RUN mode, the compass should be reset so the new value takes effect immediately.

In applications where there is a fast large-scale change followed by a period of stopped motion to acquire a reading, the best response may be achieved by enabling the non-linear heading filter. Set the reset level to be 2 or 3 degrees and the knee and gain as desired. Also use larger time constants on the tilt and magnetic signal filters. The fast movement will cause the low-pass fitters and the non-linear heading filter to be reset. This circumvents the lag time that would normally be required for the exponential filter output to stabilize.

3.6 Enabling and Configuring Alarms

When operating in RUN mode, the compass can generate an alarm on deviations of the calculated horizontal component of the measured magnetic field. If the compass is properly calibrated and there is no horizontal acceleration
and no magnetic disturbance, then the horizontal magnetic field strength remains

constant within a particular geographical area. As the compass rotates and tilts, the stability of the horizontal field strength is a measure of the accuracy of the heading output.

Configuring the alarm requires that the following three parameters be set:

1. The low-pass filter time constant that produces a smoothed reference from horizontal field strength measurements. The setting may be as high as 10 to 15 seconds or more, depending on the application.

2. The reference acquisition time that is the minimum amount of time required to determine a reference value after an alarm is triggered.

3. The alarm threshold in percent of the calculated smoothed reference. If the current field strength is outside the reference value plus or minus this percentage, then an alarm is triggered.

After an alarm is triggered or the magnetic signal filters are reset, the compass remains in alarm while the acquisition time expires. The horizontal field is averaged, and the current field strength is tested against the average for excessive deviation. The acquisition time counter and the average are reset if a deviation exceeds the alarm threshold. The alarm is not cleared until deviations remain within the threshold for the entire duration.

The alarm is only annunciated in the HTM sentence and does not cause the heading to be blanked. The magnetometer status character will be M if the deviation was below the reference or O if above. The only way to determine the state of this alarm is to test the value of this character.

As a rough guide, set the threshold to 2% to have confidence that the heading error is less than 1°. Where horizontal acceleration affects the tilt sensor, increase the acquisition time so that the alarm remains while braking or speeding up. Keep the acquisition time short when the compass is held steady after fast transients.

4 Serial Communication Reference

eCompass serial communications are governed by a simple, asynchronous, ASCII protocol modeled after the NMEA 0183 standard. Either an RS-232 or an RS-485 electrical interface can be used. ASCII characters are transmitted and received using 1 start bit, 8 data bits (LSB first), no parity (MSB always 0), and 1 stop bit; 10 bits total per character. Baud rate can be 2400, 4800, 9600, 19200, 38,400, or 57,600.

The communication link is full duplex (separate transmit and receive circuits), and the protocol requires two-way simultaneous operation. This means that the eCompass will always accept input, even while transmitting unsolicited output. The response to an input may be delayed until an unsolicited output string is completed.

There are two types of serial transactions with the compass: data and setup. Data requests and responses begin with $ and adhere closely to the NMEA standard. Setup commands and responses begin with @ and use a similar sentence format. The setup protocol is more involved than the data transactions and is usually not needed for normal operation.

The compass is intended to be an embedded component of a navigation system. The companion PC software is provided to assist with one-time setup and calibration procedures. Once the compass is set up to operate as needed, the user's host computer need only deal with NMEA 0183 format data.

A helpful resource for examples is the communication log maintained by the PC software. The log shows all strings that are transmitted to and received from the compass. Following is an example from the start of a communication session. The PC output is marked as "Send." The beginning of the string is a time stamp with resolution that depends on the PC timer capability.

```
=== 8/17/2006 ===
09:08:26.029 *** Start of Session ***
09:08:26.185 Send:   @X?*67
09:08:26.232 Recv:   @ TNT1600 Rev 5.47 - PCB 1610 Rev B - 04/21/06 !0000*44
09:08:26.232 Send:   @W2F4?*28
09:08:26.263 Recv:   @21103*31
```

The first Send command requests the firmware ID and device status. The second Send command is used to read the device ID, which is 21103 in this case.

4.1 NMEA 0183 Format Data

An NMEA sentence has the following general form:

$aaaaa,x.x,x.x,....*hh<cr><lf>

All sentences start with a "$" followed by a 4 to 7 character identification field and then one or more data fields (x.x) delimited by commas. The sentence ends with carriage return and line feed, <cr><lf>. An optional checksum field, hh, appears at the end and is preceded by an asterisk ("*").

If the contents of a data field cannot be determined, then that field can be null. In this case, there would be two successive commas with no intervening space. A null heading field is transmitted when heading cannot be calculated due to a problem with either the inclinometer or magnetometer.

The number radix for data fields is decimal. Angle data - heading, pitch, roll, and dip - will include a decimal point if the unit of measurement is set to degrees (default). Angles can also be transmitted in mils (0 – 6399), milliradians (0 – 6283), or 16-bit integer (0 – 65535).

There are three types of sentences: standard, query, and proprietary. The length of the identification field depends on the sentence type. The eCompass ECV can send three standard sentences and five proprietary sentences:

4.1.1 Standard Sentences

1. Heading, True: $HCHDT,x.x,T*hh<cr><lf>
2. Heading, Deviation, & Variation: $HCHDG,x.x,x.x,a,x.x,a*hh<cr><lf>
3. Transducer measurements: $HCXDR,A,x.x,D,PITCH,...*hh<cr><lf>

4.1.2 Proprietary Sentences

1. Heading, Tilt, & Magnetic Field: $PTNTHTM,x.x,a,x.x,a,...*hh<cr><lf>
2. Normalized Compass Data: $PTNTNCD,x.x,x.x,x.x,...*hh<cr><lf>
3. Conditioned Compass Data: $PTNTCCD,x.x,x.x,x.x,...*hh<cr><lf>
4. Raw Compass Data: $PTNTRCD,x.x,x.x,x.x,...*hh<cr><lf>
5. Binary Compass Data: $PTNTBNRfnbbbbbbbbbbbb...*hh<cr><lf>
6. Magnetic Calibration Data: $PTNTCAL,x.x,x.x,x.x,...*hh<cr><lf>

The proprietary HTM sentence is the workhorse of the eCompass compass. It provides the entire set of measurements normally required by an application:

- Heading, pitch, and roll angles (attitude data)
- Dip angle (magnetic inclination)
- Relative magnitude of horizontal component of magnetic field
- Magnetic field and tilt alarm status

Generally, the heading, pitch, and roll angles are the measurements of interest. The dip angle and horizontal component are diagnostic measurements that can be used to assess the reliability of the primary data. Both values should remain constant in a particular geographic area, provided that the compass is properly calibrated and is not being accelerated.

When the compass operates in RUN mode, it can be programmed to send one or more data sentences automatically. Each sentence has a separate rate that can be set from 0 to 1650 sentences per minute. The rates are stored in EEPROM.

In both SAMPLE and RUN modes, the compass sends the requested data sentence in response to one of the following queries:

4.1.3 Query Sentences

1. Send HDT: $TNHCQ␣HDT*34<cr><lf>
2. Send HDG: $TNHCQ␣HDG*27<cr><lf>
3. Send XDR: $TNHCQ␣XDR*22<cr><lf>
4. Send HTM: $PTNT␣HTM*63<cr><lf>
5. Send NCD: $PTNT␣NCD*7B<cr><lf>
6. Send CCD: $PTNT␣CCD*76<cr><lf>
7. Send RCD: $PTNT␣RCD*67<cr><lf>
8. Send BNR: $PTNT␣BNR*6C<cr><lf>

For the first three queries, any 2-character talker ID is accepted in place of TN provided that the checksum characters are correct (if transmitted). The checksum characters are generated by accumulating the bitwise exclusive OR (XOR) of the binary numeric values corresponding to the characters between $ and *. For example, the checksum for the HDT query is calculated as follows ("^" denotes XOR and the radix for numeric values is hexadecimal):

T		N		H		C		Q		␣		H		D		T		
54	^	4E	^	48	^	43	^	51	^	2C	^	48	^	44	^	54	=	34

4.1.4 Data Field Contents

4.1.4.1 HDG   Heading, Deviation, & Variation

$HCHDG␣x.x␣x.x␣a␣x.x␣a*hh<cr><lf>

Field contents, in order:

1. measured compass heading (e.g. 259.3),
2. magnitude of programmed or calculated deviation angle (e.g. 6.3),
3. deviation direction, the single character E or W,
4. magnitude of programmed variation (e.g. 10.7),
5. variation direction, E or W.

The magnetic heading field may be null. If either deviation or variation has not been programmed, the corresponding field will contain a value of zero[2]. Add easterly (E) deviation to compass heading to get magnetic heading. Add easterly variation to magnetic heading to get true heading.

---

[2] Variation is automatically set when it is available in a received GPS RMC sentence.

4.1.4.2 HDT   Heading, True

$HCHDT,x.x,T*hh<cr><lf>

True heading is calculated by adding deviation and variation (see HDG) to magnetic heading. The heading field may be null.

4.1.4.3 XDR   Transducer Measurements

$HCXDR,A,x.x,D,PITCH,A,x.x,D,ROLL,G,x.x,,MAGX,
G,x.x,,MAGY,G,x.x,,MAGZ *hh<cr><lf>

Each of the five sensor measurements - pitch, roll, and magnetic x, y, and z - can be individually included in or excluded from the message (see "XDR has ..." parameters). There are four subfields for each of the included measurements: Type, Data, Units, and ID. See NMEA 0183 for a detailed description of the "Type-Data-Units-ID" field encoding. The data field of an included measurement will be null if its contents cannot be determined.

MAGX aligns with the lengthwise axis of the compass board, which is also the axis about which ROLL is measured. MAGY is in the direction of the lateral axis, which is the axis about which PITCH is measured. MAGZ is perpendicular to the plane of the compass board.

4.1.4.4 HTM   Heading, Tilt, & Magnetic Field

$PTNTHTM,x.x,a,x.x,a,x.x,a,x.x,x.x*hh<cr><lf>

This sentence combines the primary measurement and diagnostic data required by most applications. Heading, pitch, and roll measurements are included as well as status and diagnostic data.

HTM data fields represent, in order:

1. true heading (compass measurement + deviation + variation)
2. magnetometer status character – C, L, M, N, O, P, or H (see below)
3. pitch angle
4. pitch status character – N, O, P (see below)
5. roll angle
6. roll status character – N, O, P (see below)
7. dip angle
8. relative magnitude horizontal component of earth's magnetic field

Status field characters have the following meanings:

1. C = magnetometer offset calibration alarm
2. L = low alarm
3. M = low warning
4. N = normal
5. O = high warning
6. P = high alarm
7. H = magnetometer voltage level alarm

If any of the three status fields indicates alarm, then the heading field will be null as well as the corresponding measurement field. Thresholds for alarm and warning levels can be changed in the EEPROM.

4.1.4.5 NCD   Normalized Compass Data

$PTNTNCD,x.x,x.x,x.x,x.x,x.x,x.x,x.x*hh<**cr**><**lf**>

This sentence provides conditioned tilt and normalized magnetic measurements for diagnostic use. The fields are, in order:

tanP   same as tanP in CCD sentence: 32768 times tangent of angle between compass board lengthwise axis and a level plane. The angle is measured from the tilted plane of the compass card to the horizontal plane (surface of the liquid) along the pins of the tilt sensor. It represents a rotation about the lateral axis of the card (pitch).

tanR   same as tanP but for the compass board lateral axis (roll) same as tanR in CCD sentence

magN   normalized and filtered magnetic field strength calculated in the direction of magnetic north

magE   same as magN but calculated in the direction of magnetic east

magH   calculated horizontal component of earth's magnetic field magV

calculated vertical component of earth's magnetic field

heading   calculated heading based on the magnetometer and inclinometer data in this sentence. This field will be null if the heading cannot be calculated.

4.1.4.6 CCD   Conditioned Compass Data

$PTNTCCD,x.x,x.x,x.x,x.x,x.x,x.x,x.x*hh<**cr**><**lf**>

This sentence provides conditioned tilt and magnetic measurements for diagnostic use. The fields are, in order:

tanP   same as tanP in NCD sentence: 32768 times tangent of angle between compass board lengthwise axis and a level plane. The

angle is measured from the tilted plane of the compass card to the horizontal plane (surface of the liquid) along the pins of the tilt sensor. It is a rotation about the lateral axis of the card.

tanR   same as tanP but for the compass board lateral axis (roll) same as tanR in NCD sentence

magX   normalized and filtered magnetic field strength measured along the lengthwise axis of the compass board.

magY   same as magX but along the compass board lateral axis.

magZ   same as magX and magY but along an axis perpendicular to the plane of the board.

magT   same as MagT field in XDR sentence

heading   calculated heading based on the magnetometer and inclinometer data in this sentence. This field will be null if the heading cannot be calculated.

4.1.4.7 RCD   Raw Compass Data

$PTNTRCD,x.x,x.x,x.x,x.x,x.x,x.x,x.x,x.x,x.x,x.x*hh<cr><lf>

This sentence provides raw tilt and magnetic measurements for diagnostic use. Contents of each field represent A/D readings for, in order: tiltAp, tiltAm, tiltBp, tiltBm, magA, magB, magC, magAsr, magBsr, magCsr. All values represent the A/D readings from the most recent conversions. Mag_sr values represent the sum of the most recent Set and Reset pulse measurements for each magnetometer sensor. The A direction lies along the lengthwise axis of the board; B is along the lateral axis, and C is perpendicular to the board. There are never any null fields in this sentence.

4.1.4.8 BNR   Binary Compass Data

$PTNTBNRfnbbbbbbbbbb...*hh<cr><lf>

The binary data sentence is unique to the eCompass ECV. It is designed to provide a large amount of data at high data rates. It can also be used to eliminate the need for ASCII-to-binary conversions.

The first binary byte f following $PTNTBNR is a flag byte whose individual bits indicate which sub-fields are present in the data bytes that follow.

Bit Weight	Data
128 (0x80)	Compass
64 (0x40)	IMU
32 (0x20)	Normalized Magnetic
16 (0x10)	Normalized Tilt

8 (0x08)	Magnetometer
4 (0x04)	Gravity Sense
2 (0x02)	Rate Gyros
1 (0x01)	Mix Data

Any combination of sub-fields can be present, provided that the total number of bytes in the sentence does not exceed 100. For example, a value of 148 (0x94) would indicate that Compass (16 bytes), Rate Gyroscope (12 bytes), and Raw Magnetic data (14 bytes) are in the sentence. A total of 42 binary data bytes would be transmitted.

The next binary byte   n is the number of binary data bytes b that follow. This is the sum of the number of bytes in each of the included sub-fields. Sub-field data values are transmitted LSB first in the order listed in the following descriptions:

Compass Data   13 values, 26 bytes

1. heading   16-bit magnetic heading (65536 = 360□)
2. pitch   16-bit pitch angle (±16384 = ±90□)
3. roll   16-bit roll angle (±16384 = ±90□)
4. inclination   16-bit inclination angle (±16384 = ±90□)
5. dip angle   16-bit dip angle (±16384 = ±90□)
6. magH   horizontal field intensity (5 nT per count)
7. magT   total magnetic field intensity (5 nT per count)
8. accelT   total acceleration (±16384 = ±1G)
9. input mV   voltage input in mV (0 – 45,000 mV)
10. ambient temp   ambient temperature in 0.1 ℃ (234 = 23.4 □C)
11. gyroP   filtered pitch rate[3] (NED, ±32768 = ±300□/sec)
12. gyroR   filtered roll rate (NED, ±32768 = ±300□/sec)
13. gyroH   filtered azimuth rate (NED, ±32768 = ±300□/sec)

---

[3] Values are counts in North-East-Down reference frame, ±32768 counts = ±300□/sec
  Pitch rate is rotation about East axis. Roll rate is rotation about North axis.

IMU Data   11 values, 22 bytes

1. accelX   unfiltered card X-axis acceleration ($\pm16384 = \pm1G$)
2. accelY   unfiltered card Y-axis acceleration
3. accelZ   unfiltered card Z-axis acceleration
4. magX   unfiltered card X-axis magnetic field (5nT per count)
5. magY   unfiltered card Y-axis acceleration
6. magZ   unfiltered card Z-axis acceleration
7. gyroX   unfiltered card X-axis[4] rate ($\pm32768 = \pm300°/sec$)
8. gyroY   unfiltered card Y-axis rate
9. gyroZ   unfiltered card Z-axis rate
10. TiltX   unfiltered Tilt X-axis angle ($\pm16384 = \pm90°$)
11. TiltY   unfiltered Tilt Y-axis angle

Normalized Mag   9 values, 18 bytes

1. magX   card X-axis magnetic field (5nT per count)
2. magY   card Y-axis magnetic field (5nT per count)
3. magZ   card Z-axis magnetic field (5nT per count)
4. magN   navigation North axis field strength
5. magE   navigation East axis field strength
6. magV   navigation Vertical axis field strength
7. angleP   filtered pitch angle ($\pm16384 = \pm90°$)
8. angleR   filtered roll angle
9. heading   16-bit magnetic heading ($65536 = 360°$)

Normalized Tilt   11 values, 22 bytes

1. accelX   card X-axis acceleration ($\pm16384 = \pm1G$)
2. accelY   card Y-axis acceleration
3. accelZ   card Z-axis acceleration
4. gyroX   card X-axis rotation rate ($\pm32768 = \pm300°/sec$)
5. gyroY   card Y-axis rotation rate
6. gyroZ   card Z-axis rotation rate
7. angleP   pitch angle ($\pm16384 = \pm90°$)
8. angleR   roll angle
9. heading   16-bit magnetic heading ($65536 = 360°$)
10. TiltX   Tilt X-axis angle ($\pm16384 = \pm90°$)
11. TiltY   Tilt Y-axis angle

---

[4] When card is level at 0° heading, X aligns with North axis, Y is East and Z is down.

Magnetometer	7 values, 14 bytes
1. magA	unaligned X-axis magnetometer (after Set)
2. magB	unaligned Y-axis magnetometer
3. magC	unaligned Z-axis magnetometer
4. magSumA	X magnetometer S/R sum signal
5. magSumB	Y magnetometer S/R sum signal
6. magSumC	Z magnetometer S/R sum signal
7. bridgeVolts	magnetometer bridge voltage (16384 = 5V)

Gravity Sense	14 values, 28 bytes
1. accelA	X-axis accelerometer measurement
2. accelB	Y-axis accelerometer measurement
3. accelC	Z-axis accelerometer measurement
4. accelTemp	ambient temperature signal
5. TiltAp	X-axis positive drive tilt signal
6. TiltAm	X-axis negative drive tilt signal
7. TiltBp	Y-axis positive drive tilt signal
8. TiltBm	Y-axis negative drive tilt signal
9. TiltRefAp	X side positive drive reference
10. TiltRefAm	X side negative drive reference
11. TiltRefBp	Y side positive drive reference
12. TiltRefBm	Y side negative drive reference
13. bridgeVolts	magnetometer bridge voltage (16384 = 5V)
14. tempGain	temperature compensation gain (16384 = 1.0)

Rate Gyros	10 values, 20 bytes
1. gyroA	unaligned X-axis gyro signal
2. gyroB	unaligned Y-axis gyro signal
3. gyroC	unaligned Z-axis gyro signal
4. gyroAtemp	X gyro temperature signal
5. gyroBtemp	Y gyro temperature signal
6. gyroCtemp	Z gyro temperature signal
7. gyroAnow	calibrated X-axis gyro signal
8. gyroBnow	calibrated Y-axis gyro signal
9. gyroCnow	calibrated Z-axis gyro signal
10. bridgeVolts	magnetometer bridge voltage (16384 = 5V)

Mix Data   15 values + 1 byte, 31 bytes

   1. TiltX   card Tilt X-axis angle (±16384 = ±90°)

   2. accelX   card accelerometer X-axis angle (±16384 = ±90°)

   3. gyroX   card X-axis rotation rate (±32768 = ±300°/sec)

   4. gyroP   pitch change rate (N-axis)

   5. angleP   pitch angle (N-axis)

   6. TiltY   card Tilt Y-axis angle (±16384 = ±90°)

   7. accelY   card accelerometer Y-axis angle (±16384 = ±90°)

   8. gyroY   card Y-axis rotation rate (±32768 = ±300°/sec)

   9. gyroR   roll change rate (E-axis)

  10. angleR   roll angle (E-axis)

  11. groundSpeed 10 times ground speed in knots (from GPS input)

  12. accelT   total acceleration (16384 = 1G)

  13. circlingAdjust centripetal acceleration correction (±16384 = ±1G)

  14. gyroH   heading rate of change

  15. heading   16-bit heading (65536 = 360°)

  16. statusFlags

When a receiver recognizes $PTNTBNR the next two binary bytes f and n are read verbatim, without checking for NMEA ASCII delimiters that could be coded in the data. Then the number of binary bytes given in n is also collected without checking. The byte following the n binary values is the * character that delineates the NMEA checksum characters. All n+2 of the preceding binary values are accumulated in the checksum, along with the PTNTBNR characters.

In the eCompass PC software, binary data in BNR sentences is converted to 16-bit hexadecimal characters and printed with commas separating the values. For example, when only compass data is requested, the following is logged:

```
Send:   $PTNT,BNR*6C
Recv:   PTNTBNR,80,1A,83AB,009E,FF48,00F3,314D,09E1,1BFC,4002,24EE,0122,FFFD,000A,0003*FB
```

The flag byte f=80 indicates that only compass data is present. There are n=1A data bytes, or 26 bytes in 13 values. Data values are decoded in the following table:

Measurement	Hex Value	Decimal Value	Engineering Units
Heading	83AB	33707	185.16°
Pitch	009E	158	0.87°
Roll	FF88	-120	-0.66°
Inclination	00F3	243	1.33°
Dip angle	314D	12621	69.33°

Horizontal field	09E1	2529	12645 nT
Total Field	1BFC	7164	35820 nT
Total Acceleration	4002	16386	1000.1 mg
Input mV	24EE	9454	9454 mV
Ambient Temp	0122	290	29.0°C
Pitch Rate	FFFD	-3	-0.03°/sec
Roll Rate	000A	10	0.09°/sec
Azimuth Rate	0003	3	0.03°/sec

The flag byte f can be changed using the setup protocol described in the next section.

4.2 Setup Protocol

Instead of using pseudo-English mnemonics for parameter names and operating commands, the setup protocol allows parameter and data memory to be read or written using byte addresses and generic data types. Memory can be accessed in 1, 8, or 16-bit increments. Access to some areas of memory is either prohibited or restricted, depending on the contents.

To start a setup transaction, the host sends a command string and waits for a response from the compass. Only one command can be issued at a time. The host must wait for a response before sending the next command string. The response may be delayed by an unsolicited output string that is being sent when the command is received.

4.2.1 Command Input Syntax

A command to the compass has the following general form:

> @<type><adr><r/w>x.x,x.x,...*hh<cr><lf>

Command sentences start with a "@" followed by an access type character; then the address, a read or write indicator, and data. The sentence ends with carriage return and line feed, <cr><lf>. The checksum field, hh, at the end is preceded by an asterisk ("*") and, as with NMEA sentences, is the XOR of characters between @ and *.

A graphical representation of this syntax is shown in Figure 15. Traverse the diagram from left to right, taking branches allowed for by gradual turns. Optional branches are shown on top of one another. Only one such branch is selected per command string. The indicated characters should be transmitted as they are encountered in the diagram. Note that no character is sent when traversing a blank branch.

Lower case letters in the diagrams denote the following:

   a = alphanumeric character in the range A-Z or 0-9.
   n = numeric digit in decimal or hexadecimal notation (0-9, A-F)
   h = hexadecimal digit (0-9, A-F)
   b = bit position (0-7)
   cr = carriage return (ASCII decimal code 13)
   lf = line feed (ASCII decimal code 10)
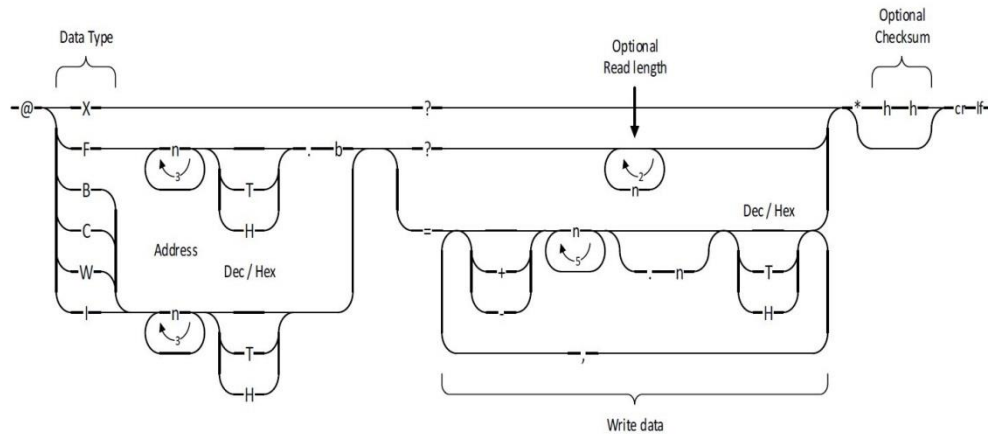
Figure 15 – Command Syntax Diagram

There are several places in the diagram where a feedback loop is encountered. The number inside the loop designates the maximum number of times the loop can be traversed. Note that three of the feedback loops require at least one digit be transmitted, while one allows for zero to two digits.

The access type character can be one of the following:

   F   is used to read or write individual flag bits. A bit designator, 0-7, must follow the byte address of the flag. A flag's value can be either 0 or 1.

   B   designates an unsigned byte value (0 to 255)

   C   means a character, or signed byte value (-128 to 127)

   W   indicates a word, or unsigned 2-byte value (0 to 65535)

   I   means an integer, or signed 2-byte value (-32768 to 32767)

   X   is a special type used to query for an identification string. The returned string includes:

   • Hardware and firmware identifiers (from program memory)
   • Firmware revision level and date code (from program memory)
   • Unit status (e.g. power-on, EEPROM error, time-out reset, etc.)

A byte address of one to three digits follows the access type. By default, address digits are interpreted as hexadecimal if neither T (decimal) nor H (hex) follows the digits. Upper case T is used to indicate the decimal radix to avoid confusion with the valid hexadecimal numeral D.

Following the address, the host sends either '?' for read, or '=' for write. A read operation can specify that a sequence of data be returned, and a write operation can specify multiple sequential values in a single message. For read requests, the number of requested sequential data values must be such that the maximum output string length of 110 characters is not exceeded. If the requested read length is too long, only as many values as can fit in the maximum string length are returned. The read length digits are interpreted as hexadecimal if an explicit radix indicator (T or H) is not sent.

For write requests, the maximum input buffer length of 110 characters cannot be exceeded. If the input message is too long, an error response is generated and none of the data is written. In addition, if the format for any one data value is corrupted, then an error response is generated and none of the data is written. Multiple values must be separated by a comma with no additional white space. Data value digits are interpreted according to the default radix in EEPROM if an explicit digit type (T or H) is not sent. Multiple values are written to sequential addresses starting from the address supplied. For bit data, only a single bit can be read or written with each command.

4.2.2 Response Output Syntax

The syntax for the compass response to a command is shown in Figure 16. The response begins with @ and is followed by the requested data or a status string. The checksum characters at the end are the XOR of characters between @ and *.
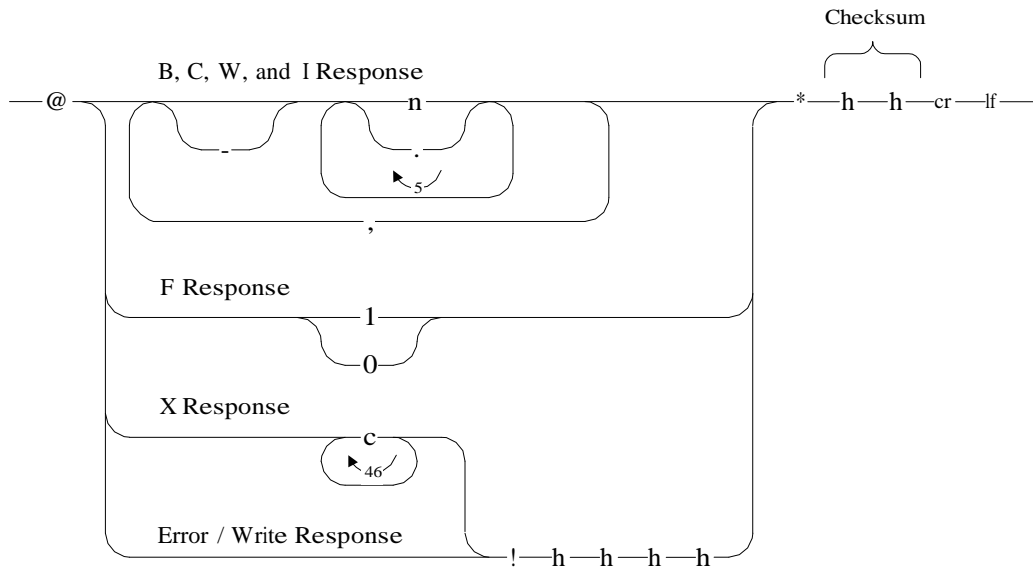
Figure 16 – Response Syntax Diagram

The top branch shows the eCompass's response to an 8 or 16-bit read request. When more than one value is requested, sequential values are separated by a comma. Each value is presented in decimal or hexadecimal notation according to the setting in EEPROM. If any byte location in the requested sequence is prohibited from being accessed, then an error message is returned.

Remaining branches show semantically simpler responses for special conditions. The second branch shows that values for the F data type can only be 0 or 1. In the third branch, the diagram depicts eCompass's response to the X command as a string of characters. The bottom branch shows the response to a write command and the error response. The first 2 hex digits following the exclamation point contain an error code that indicates one of the following:

- 00H = OK
- F1H = Error in contents of access type field
- F2H = Syntax error in input string
- F3H = Address not allowed
- F4H = Flag number out of range 0 - 7
- F5H = Error in data length field
- F6H = Write protect error

- F7H = Error in contents of data field
- E8H = Error writing EEPROM
- 80H = Badly formed input sentence
- 81H = Missed LF at end of sentence
- 82H = Missed @ or $ start of sentence

The last two hex digits contain flag bits that are cleared after they are sent. Individual bits have the following meanings:

- 01H = Receive data overrun
- 02H = Receive character framing error
- 04H = 110 character receive buffer overrun
- 08H = Receive sentence checksum error
- 10H = Received unknown sentence
- 20H = EEPROM read error
- 40H = Power on reset occurred
- 80H = Time out reset occurred

4.2.3 Command Reference

This section presents the details of commands to change compass operating parameters. Related sets of parameters are described in a single section.

4.2.3.1 Operating Mode: RUN = 1, SAMPLE = 0

DLL Parameter Index: 1
Access Type Character: F
Hex Address: 0.3
Read Example: @F0.3?*54
Write Example: @F0.3=0*66

This stored flag specifies the compass operating mode.

4.2.3.2 Angle Units: Degrees, MilliRadians, Mils, or 16-bit Integer

DLL Parameter Index: 12, 13, 14
Access Type Character: F
Hex Address: 2.2, 2.3, 2.4
Read Example: @F2.2?*57
Write Example: @F2.2=0*65

Set one of these three stored flags to specify the desired angle units. If none of the flags is set, angles are presented as 16-bit integers, i.e. the range 0 to 65535 or -32768 to 32767 represents one complete revolution. If more than one flag is set, then degrees takes precedence over mils, and mils takes precedence over milliradians. One revolution is 6400 mils, 6283 milliradians, or 360.0 degrees.

4.2.3.3   Reset Compass

DLL Parameter Index: 43
Access Type Character: F
Hex Address: 28.6
Write Example: @F28.6=1*58

Set this flag to 1 to reset the compass.

4.2.3.4   RJ12 Baud Rate Index

DLL Parameter Index: 19
Access Type Character: B
Hex Address: 6
Read Example: @B6?*4B
Write Example: @B6=3*7A

This stored byte value is a selector that specifies the serial communication rate used on the RJ12 channel. The value 1 selects 2400 baud, 2 is 4800, 3 is 9600, 4 is 19200 baud, 5 is 38400 baud, and 6 is 57600. Any other value results in 2400 baud operation. The new value does not take effect until the compass is reset (see Reset Compass command).

4.2.3.5   Enable Automatic Data to RJ12

DLL Parameter Index: 150
Access Type Character: F
Hex Address: 13.1
Read Example: @F13.1?*64
Write Example: @F13.1=1*57

Automatic data can be enabled to the RJ12 or J2 serial channel, or it can be sent to both. If baud rates are different, it may be necessary to disable automatic data to the slower channel so that the sentence update rate is not throttled by the slower serial channel capacity.

4.2.3.6   J2 Baud Rate Index

DLL Parameter Index: 123
Access Type Character: B
Hex Address: 16
Read Example: @B16?*7A
Write Example: @B16=6*4E

This stored byte value is a selector that specifies the serial communication rate used on the 8-pin connector (J2). See RJ12 Baud Rate Index command for association of index to baud rate.

4.2.3.7 Enable Automatic Data to J2

DLL Parameter Index: 149
Access Type Character: B
Hex Address: 13.0
Read Example: @F13.0?*65
Write Example: @F13.0=0*57

Automatic data can be enabled to the RJ12 or J2 serial channel, or it can be sent to both. If baud rates are different, it may be necessary to disable automatic data to the slower channel so that the sentence update rate is not throttled by the slower serial channel capacity.

4.2.3.8 Output Rate Indices: HDG, HDT, XDR, HTM, RCD, CCD, NCD, BNR

DLL Parameter Index: 20, 21, 22, 23, 24, 25, 26, 168
Access Type Character: B
Hex Address: 7, 8, 9, A, B, C, D, 17
Read Example (for HTM rate): @BA?*3C
Write Example (for HTM rate): @BA=0*0E

These are byte values that specify the automatic output rate for NMEA sentences in RUN mode. Each value is an index into a table of available output rates. Index 0 turns off the automatic updates. There are 26 additional rates, in sentences per minute, shown in Table 1.

Index	Rate	Index	Rate	Index	Rate
1	1	10	180	19	31
2	2	11	275	20	15
3	3	12	413	21	8
4	6	13	550	22	4
5	12	14	825	23	2
6	20	15	825	24	1
7	30	16	206	25	1650
8	60	17	118	26	1650
9	120	18	60	27	Unknown

Table 1 - Automatic NMEA Sentence Rates (sentences/minute)

Values from 27 to 255 will be accepted by the compass, but they will index beyond the table and produce unknown results. When changing from a slow rate to a faster rate, the remaining time interval must expire before the new rate takes effect. This is most noticeable when switching from 1 to 1650 sentences per minute. In this case, it is faster to first set 0 and then 1650. Wait at least one measurement cycle (36 msec) between commands.

These parameters are ignored in SAMPLE mode.

4.2.3.9 BNR Sentence Contents: Compass, IMU, Normalized Magnetic, Normalized Tilt, Magnetometer, Gravity Sense, Gyro, Mix

DLL Parameter Index: 169, 170-177
Access Type Character: B, F
Hex Address: 25, 25.7, 25.6, 25.5, 25.4, 25.3, 25.2, 25.1, 25.0
Read Example: @B25?*7A
Write Example: @F25.2=1*51

These flags specify the contents of the proprietary BNR sentence. The 8 flags are contained in a single byte that resides in the protected memory space. To change the contents of this byte, first set the flag at address 28.5 to enable writes to protected memory.

4.2.3.10 XDR Sentence Contents: Pitch, Roll, MagX, MagY, MagZ

DLL Parameter Index: 5, 6, 7, 8, 9
Access Type Character: F
Hex Address: 1.0, 1.1, 1.2, 1.3, 1.4
Read Example (for MagZ): @F1.4?*52
Write Example (for MagZ): @F1.4=0*60

These are stored flags that specify the contents of the XDR sentence. When a flag value is 1, the corresponding sensor data is included in the sentence.

4.2.3.11 Time Constants: Tilt, Magnetic, Alarm; Gyro H, P, R

DLL Parameter Index: 16, 17, 18, 187, 185, 192
Access Type Character: B
Hex Address: 3, 4, 5, 10, 18, 11
Read Example: @B3?*4E
Write Example: @B3=55*4C

These are stored values that specify the normalized time constant for tilt, magnetic, and alarm IIR filters (single pole); and for the complementary filters that combine tilt and gyro signals. Each value can range from 0 to 255. A value of zero disables the filter. Divide the value entered by 13.75 to get the equivalent time constant in seconds. For example, set the value 55 to specify a 4.0 second time constant.

These settings are ignored in SAMPLE mode.

4.2.3.12   Magnetic Alarm Acquire Time

DLL Parameter Index: 95
Access Type Character: B
Hex Address: 15
Read Example: @B15?*79
Write Example: @B15=69*74

This stored value specifies the number of cycles at 13.75 Hz to acquire a MagH
reference for the magnetic deviation alarm function. Specify a value in the range
of 1 to 255. Divide the value set by 13.75 to get the acquisition time in seconds.

During the acquisition time, the magnetometer status character in the HTM
sentence will be either M (low) or O (high), depending on whether the last
detected excursion was above or below the nominal reference.

This setting is ignored in SAMPLE mode.

4.2.3.13   Magnetic Alarm Deviation Limit

DLL Parameter Index: 57
Access Type Character: W
Hex Address: 2A4
Read Example: @W2A4?*2F
Write Example: @ W2A4=3277*2C

This stored value specifies the allowed deviation of the current calculated magH
about the smoothed magH reference. If the deviation is above this limit, the
magnetometer status character in the HTM sentence will be O (high). If it is
below the negative limit, the status character will be M (low). Set a value from 0
to 65555 that designates the range from 0 to 99.998% of the reference value. In
other words, to allow deviation within ± 1% of the reference, set the value 655.
Set the value 0 to disable this alarm.

This setting is ignored in SAMPLE mode.

4.2.3.14 Sample Time, Samples to Ignore

DLL Parameter Index: 27, 28
Access Type Character: B
Hex Address: E, F
Read Example: @BE?*38
Write Example: @ BE=42*2C

These stored values specify the number of measurement cycles that occur in
SAMPLE mode following receipt of an NMEA query message. The sample time
sets the number of samples to average. Set a value from 1 to 255. Divide this
number by 13.75 to get the sample time in seconds.

Before averaging begins, the compass discards the number of samples to ignore.
Generally one or two samples are sufficient. If a delay is required between the
NMEA query and the average measurement, set this value to a maximum of 255.

These settings are ignored in RUN mode.

4.2.3.15 Magnetometer Gain

DLL Parameter Index: 33
Access Type Character: B
Hex Address: 14
Read Example: @B14?*78
Write Example: @B14=251*4C

This stored value is an index for a 256 tap digital potentiometer that sets the magnetometer signal gain. Set a value from 0 to 255 to adjust gain from 100 to 500. The equation that relates tap index, N, to signal gain, G, is:

$$G = 100 + \frac{25600}{2624 - 10 * N}.$$

Perform a magnetic calibration after changing this gain.

4.2.3.16 Enter Magnetic Calibration Mode

DLL Parameter Index: 125
Access Type Character: F
Hex Address: 3C.6
Read Example: @F3C.6?*11
Write Example: @F3C.6=1*22

Set this flag to 1 to enter calibration mode. Once in calibration mode, set this flag to zero to abort data collection and return to normal operating mode. The flag is reset automatically when calibration finishes normally. This flag is in a protected data space requiring that flag Allow Protected Writes=1.

4.2.3.17 Allow Protected Writes

DLL Parameter Index: 42
Access Type Character: F
Hex Address: 28.5
Read Example: @F28.5?*68
Write Example: @F28.5=1*5B

Set this flag to 1 to allow writes into protected data space. This flag is automatically cleared when the microcontroller is reset.

4.2.3.18 Onboard Magnetic Calibration

DLL Parameter Index: 156
Access Type Character: F
Hex Address: 19.0
Read Example: @F19.0?*6F
Write Example: @F19.0=1*5C

Set this flag to 1 to use the calibration routines embedded in the compass firmware. Clear the flag to use external calibration software.

4.2.3.19 Onboard 3D Calibration

DLL Parameter Index: 157
Access Type Character: F
Hex Address: 19.1
Read Example: @F19.1?*6E
Write Example: @F19.1=1*5D

Set this flag to 1 to specify that three-dimensional data will be collected and used to determine X, Y, and Z offsets. Clear the flag when data is collected by rotating in a roughly horizontal plane. When the flag is clear, determination of a Z offset is controlled by the Onboard Use Vertical Reference flag.

4.2.3.20 Onboard Use Vertical Reference

DLL Parameter Index: 159
Access Type Character: F
Hex Address: 19.3
Read Example: @F19.3?*6C
Write Example: @F19.3=1*5F

Set this flag to 1 to use the stored vertical reference (see Magnetic Field Vertical Reference) to estimate the magnetometer Z axis offset when performing a 2D calibration (Onboard 3D Calibration = 0). The value stored in Magnetic Field Vertical Reference must not equal 32767. A vertical reference can either be measured directly in a magnetically clean environment or it can be estimated using geomagnetic model data for the geographic location where the calibration is performed.

4.2.3.21 Onboard Timed Capture

DLL Parameter Index: 158
Access Type Character: F
Hex Address: 19.2
Read Example: @F19.2?*6D
Write Example: @F19.2=0*5F

For a 2D calibration (Onboard 3D Calibration = 0), this flag controls whether data is collected by time or rotation angle. Set this flag to 1 to capture calibration data by time. The value stored in Onboard Sample Count controls the time

between stored samples. Clear the flag to capture calibration data every 3 degrees of rotation. The flag is not used when Onboard 3D Calibration = 1.

4.2.3.22 Onboard Multi-Step Sample Collection

DLL Parameter Index: 162
Access Type Character: F
Hex Address: 19.6
Read Example: @F19.6?*69
Write Example: @F19.6=1*5A

To manually trigger the collection of calibration data, set this flag to 1. After positioning the vehicle at a desired orientation, set Onboard Trigger Sample = 1 to capture a calibration sample. The number of readings specified in Onboard Sample Count are accumulated and averaged to compute the data. The flag is automatically cleared when the average is computed. When a representative set of data has been captured, set flag Onboard Finish Calibration = 1 to compute new hard-iron offsets.

4.2.3.23 Onboard Sample Count

DLL Parameter Index: 163
Access Type Character: B
Hex Address: 1A
Read Example: @B1A?*0D
Write Example: @B1A=14*0A

Number of samples to average in multi-step mode, or to skip in timed continuous mode. The range is from 1 to 255. Measurements are updated 27.5 times per second. For 3D or timed 2D capture mode, the data capture rate is 27.5 divided by this value.

4.2.3.24 Onboard Trigger Sample

DLL Parameter Index: 164
Access Type Character: F
Hex Address: B00.4
Read Example: @FB00.4?*21
Write Example: @FB00.4=1*12

Set this flag to 1 to capture a calibration sample when Onboard Multi-Step Sample Collection = 1. The flag is automatically cleared. It is ignored in continuous capture mode.

4.2.3.25 Onboard Finish Calibration

DLL Parameter Index: 165
Access Type Character: F
Hex Address: B00.5
Read Example: @FB00.5?*20
Write Example: @FB00.5=1*13

Set this flag to 1 to calculate new hard-iron offsets using the captured data. When completed, the microcontroller automatically resets and resumes operation in normal mode.

4.2.3.26 Onboard Apply Results Automatically

DLL Parameter Index: 161
Access Type Character: F
Hex Address: 19.5
Read Example: @F19.5?*6A
Write Example: @F19.5=1*59

Set this flag to 1 to automatically save new offsets in EEPROM when the calculated field variation using the new offsets is less than the old variation.

4.2.3.27 Onboard No CAL Progress Sentence

DLL Parameter Index: 160
Access Type Character: F
Hex Address: 19.4
Read Example: @F19.4?*6B
Write Example: @F19.4=1*58

Set this flag to 1 to disable calibration progress sentences during data collection. See Onboard Hard-Iron Calibration for contents of the CAL sentence.

4.2.3.28 Onboard Short CAL Progress Sentence

DLL Parameter Index: 196
Access Type Character: F
Hex Address: 19.7
Read Example: @F19.7?*68
Write Example: @F19.7=1*5B

Set this flag to 1 to reduce the number of characters sent in the calibration progress sentences. No data is transferred for tanP, tanR, magX, magY, magZ, or heading during the capture phase. Following is an example sentence:

    $PTNTCAL,,,,,,,C,1*22

The series of commas represent the null fields. Only the status and capture count are transmitted, keeping the sentence length less than 25 characters.

When the capture and calculation phases are completed, the results sentence is as follows:

    $PTNTCAL,7,9,,,,,O,8*29

Data for the first two fields, old and new variation, is included along with the status character and capture count at the end. See section 3.2.2 for additional CAL sentence details.

4.2.3.29 Magnetic Field Vertical Reference

DLL Parameter Index: 62
Access Type Character: I
Hex Address: 2AE
Read Example: @I2AE?*40
Write Example: @I2AE=32767*75

This stored value is used in the magnetic calibration procedure to determine an estimate of the magnetometer Z-axis offset. It is set automatically at the end of the vertical reference determination procedure. The value 32767 is used to designate that no vertical reference has been saved.

4.2.3.30 Hard Iron Offsets: MagXoffset, MagYoffset, MagZoffset

DLL Parameter Index: 58, 59, 61
Access Type Character: I
Hex Address: 2A6, 2A8, 2AC
Read Example: @I2A6?*33
Write Example: @I2A6=42*37

These stored values are compensation coefficients for hard iron. They are set automatically at the end of the magnetic calibration procedure. There is also an internal Z offset at target address 2AA that should not be changed.

4.2.3.31 Soft Iron Gains: Gxx, Gxy, Gxz, Gyx, Gyy, Gyz, Gzx, Gzy, Gzz

DLL Parameter Index: 64, 65, 66, 67, 68, 69, 70, 71, 72
Access Type Character: I
Hex Address: 2B2, 2B4, 2B6, 2B8, 2BA, 2BC, 2BE, 2C0, 2C2
Read Example: @I2B2?*34
Write Example: @I2B2=16384*0E

These stored values are compensation coefficients for soft iron. When the eCompass is delivered new, the nine values comprise an identity matrix (i.e., $Gxx = Gyy = Gzz = 1.0$ and other elements are zero). Set a value from -32768 to 32767 to designate a gain in the range from -2.0000 to 1.9999. Use 16384 for a gain of 1.0000.

4.2.3.32 Do Soft Iron and Apply Soft Iron to CCD

DLL Parameter Index: 0, 89
Access Type Character: F
Hex Address: 0.1, 0.2
Read Example: @F0.1?*56
Write Example: @F0.1=1*65

These stored flags tell the compass whether to apply soft-iron gains to the data, and if so, whether to apply the gains to tilted (CCD) or rotated (NCD) data. The Do Soft Iron flag enables and disables gain compensation. It can be set at any time but has no effect if the gain matrix is the identity matrix.

Set Apply Soft Iron To CCD true to multiply magnetic field X, Y, and Z components (values in the CCD and XDR sentences) by the gain matrix. If the flag is set to zero, then N, E, and V components in the NCD sentence are multiplied by the gains. This puts the matrix multiply block after the axis rotation block in the diagrams of Figure 6 and Figure 9.

4.2.3.33 Deviation and Variation

DLL Parameter Index: 48, 49
Access Type Character: I
Hex Address: 290, 292
Read Example: @I290?*4D
Write Example: @I290=-12.6*79

These stored values specify the corrections used to determine magnetic bearing and true bearing from compass reading. The deviation value is used only when the Single Deviation flag is set true. Otherwise deviation is calculated automatically from corrections supplied in the deviation table.

Data is read and written in the angle units currently specified.

4.2.3.34 Single Deviation and Use Degauss-On Table

DLL Parameter Index: 91, 92
Access Type Character: F
Hex Address: 2.6, 2.7
Read Example: @F2.6?*53
Write Example: @F2.6=1*60

These stored flags specify how compass deviation is determined. Set the Single Deviation flag true to use the value stored in Deviation. To use the electronic compass card, or deviation table, set Single Deviation to zero. One of the two saved deviation tables, degauss on and degauss off, is specified by the Use Degauss-On Table flag.

4.2.3.35 Pitch and Roll Offsets

DLL Parameter Index: 52, 53
Access Type Character: I
Hex Address: 298, 29A
Read Example: @I298?*45
Write Example: @I298=2.4*6F

These stored values are subtracted from pitch and roll measurements to output adjusted angles. They do not affect pitch and roll used to compute heading.

Data is read and written in the angle units currently specified.

4.2.3.36 Tilt Alarm and Warning Levels

DLL Parameter Index: 50, 51
Access Type Character: W
Hex Address: 294, 296
Read Example: @I294?*57
Write Example: @I294=30*48

These stored values are the thresholds above which pitch and roll measurements are too high. Measurements are blanked along with heading above the alarm level. Status characters in the HTM sentence indicate when the warning level is exceeded.

Data is read and written in the angle units currently specified.

4.2.3.37 No Data to J2 and Sleep Without RS232

DLL Parameter Index: 44, 45
Access Type Character: F
Hex Address: 29.2, 29.4
Read Example: @F29.4?*68
Write Example: @F29.2=1*5D

These volatile flags are only used when the RJ12 port is connected. NMEA sentences are only sent to the RJ12 port when No Data to J2 is set. This is intended to prevent confusion during maintenance, so the host computer does not receive data requested by a plug-in device.

When Sleep Without RS232 is set, the compass will enter its low-power standby mode when both RS-232 input signals become invalid. This is intended to automatically conserve battery power when a plug-in PDA turns its RS-232 driver off.

Both flags are initialized to zero when the compass powers up or is reset. Both flags are ignored when the RJ12 plug is removed. The Sleep Without RS232 flag is ignored when the compass is operating in calibration mode.

4.2.3.38 Non-Linear Heading Filter: Knee, Reset Level, and Gain

DLL Parameter Index: 54, 31, 55
Access Type Character: W
Hex Address: 29C, 29E, 2A0
Read Example: @W29C?*20
Write Example: @W29C=2.0*0E

These stored parameters specify the operation of the non-linear heading filter described on page 18 in the section describing RUN Mode. The knee and reset level are angles that are read and written in the units currently specified. Set the gain from 1 to 65535 to specify maximum to minimum smoothing.

Both the knee and gain values must be non-zero to enable the filter.

4.2.3.39 Ground Speed Update Timeout

DLL Parameter Index: 193
Access Type Character: W
Hex Address: 2CA
Read Example: @W2CA?*20
Write Example: @W2CA=275*0E

When ground speed is received, either from an active RMC sentence or via a write to hexadecimal register 218, a count-down timer is started. If the count reaches zero before another update is received, the ground speed is set to zero. The timer decrements at the 27.5 Hz measurement cycle rate of the compass. Thus, writing a count of 275 specifies a timeout of 10 seconds. Write a value from 0 to 65535 counts. The value zero disables the circling correction function by forcing ground speed to remain zero no matter what value is received in an RMC sentence or written to register 218. The maximum value of 65535 counts represents 39 minutes and 43 seconds.

AMP 640621-8, 0.1" MTA connector

Pin	Wire		Signal
1	OR	OR	Power (5V to 30V)
2	OR / WT	OR / WT	RS232 TX Out
3	BR	BR	RS232 RX In
4	BL	BL	A RS485 RX+
5	BL / WT	BL / WT	B RS485 RX-
6	BR / WT	BR / WT	Ground
7	GR	GR	Y RS485 TX+
8	GR / WT	GR / WT	Z RS485 TX-

P2 8-Pin Receptacle

Inside compass cover

Outside

Signal directions

Gromet inserts into hole in compass cover

Cable length (8' or per order)

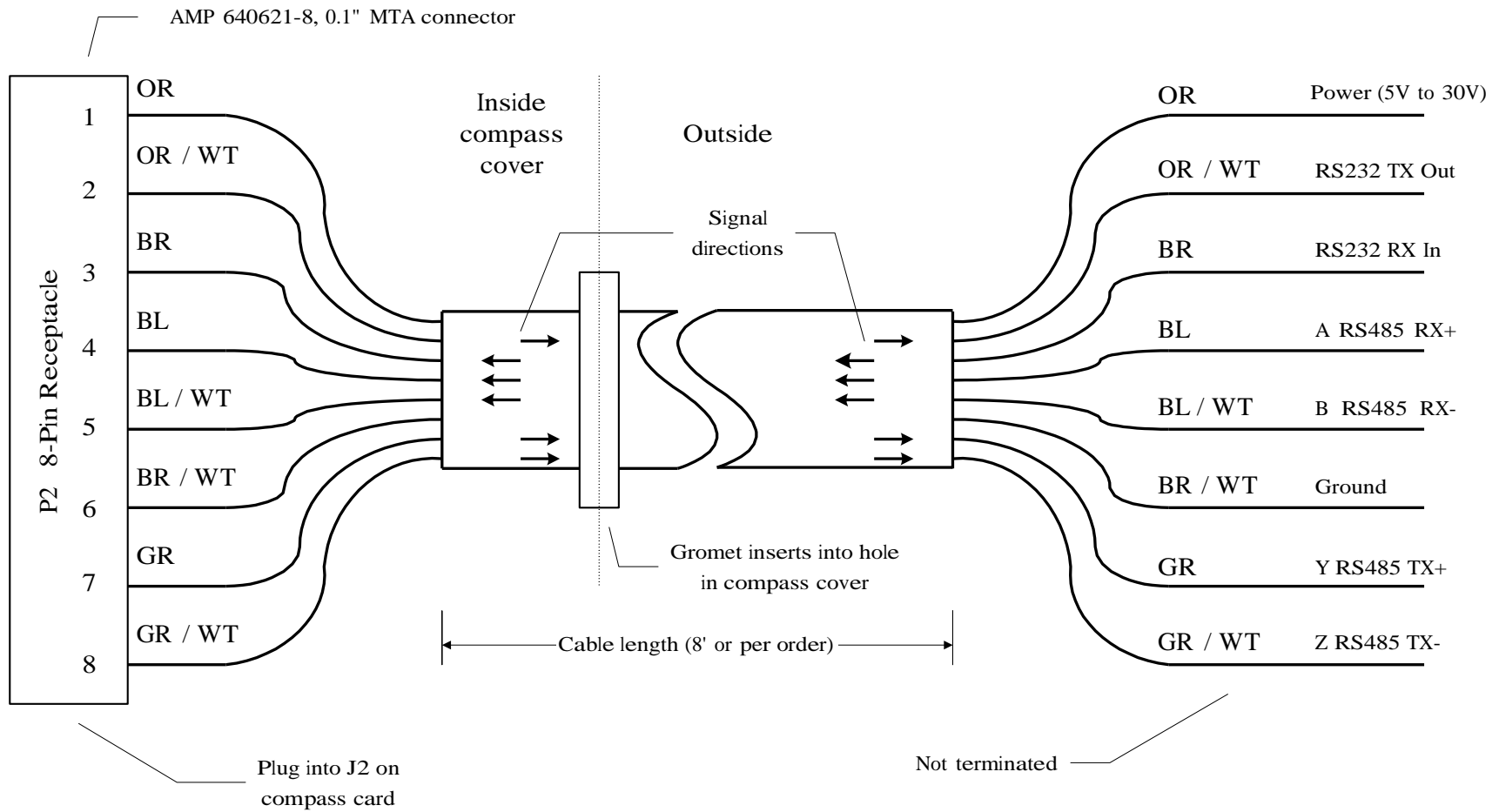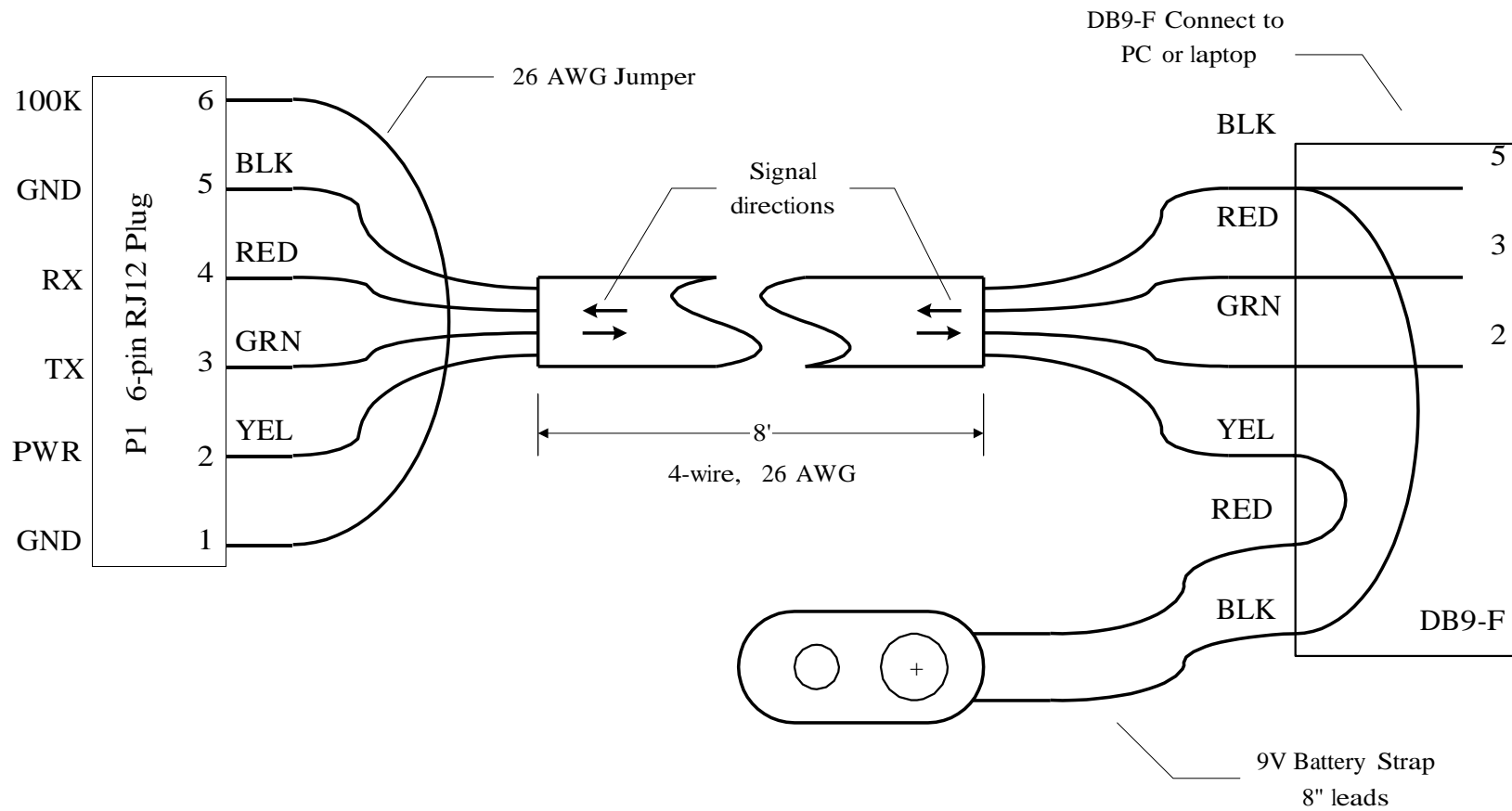Plug into J2 on compass card

Not terminated

Figure 17 – eCompass System Wiring Cable (TNT 1580)

Figure 18 – eCompass PC Interface Cable (TNT 1540)