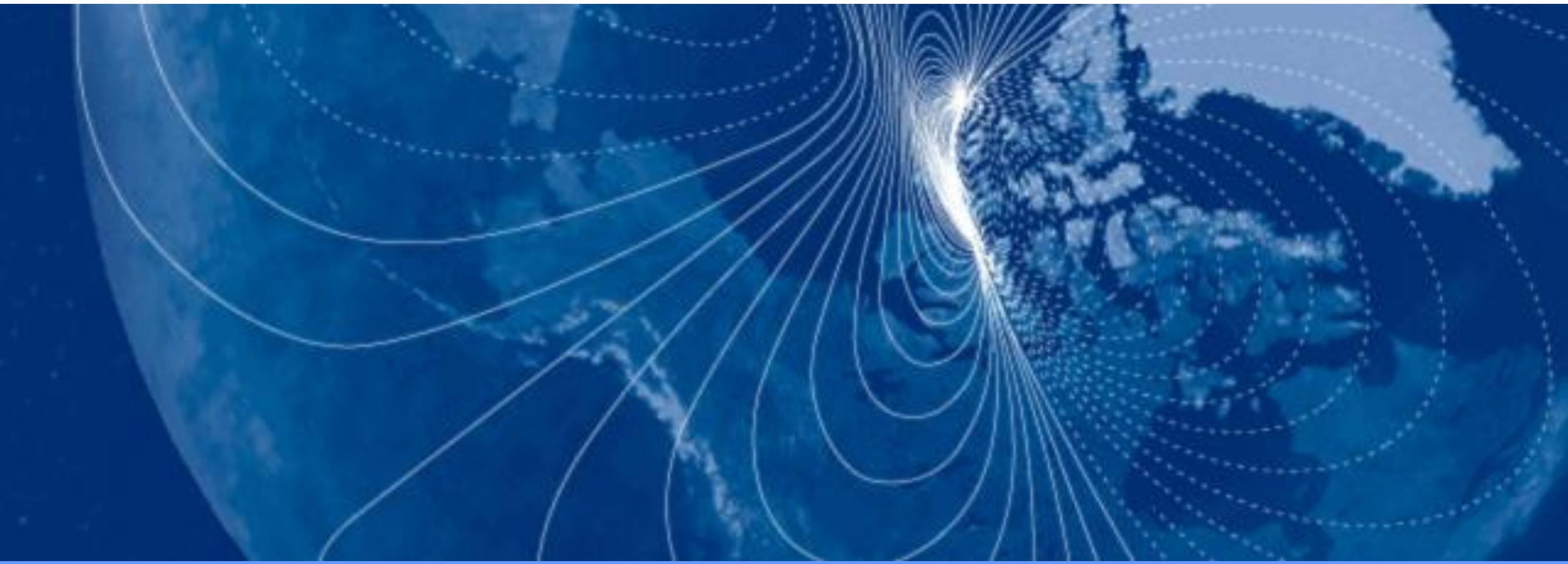


User Manual

RM3000 & RM2000

Reference Magnetic Sensor Suite

SENSOR CORPORATION

Table of Contents

List of Figures

List of Tables

1 Copyright & Warranty Information

Revised April 2011: for the most recent version visit our website at www.pnicorp.com

PNI Sensor Corporation
133 Aviation Blvd, Suite 101
Santa Rosa, CA 95403, USA
Tel: (707) 566-2260
Fax: (707) 566-2261

Warranty and Limitation of Liability. PNI Sensor Corporation ("PNI") manufactures its Products from parts and components that are new or equivalent to new in performance. PNI warrants that each Product to be delivered hereunder, if properly used, will, for ninety (90) days following the date of shipment unless a different warranty time period for such Product is specified: (i) in PNI's Price List in effect at time of order acceptance; or (ii) on PNI's web site (www.pnicorp.com) at time of order acceptance, be free from defects in material and workmanship and will operate in accordance with PNI's published specifications and documentation for the Product in effect at time of order. PNI will make no changes to the specifications or manufacturing processes that affect form, fit, or function of the Product without written notice to the Customer, however, PNI may at any time, without such notice, make minor changes to specifications or manufacturing processes that do not affect the form, fit, or function of the Product. This warranty will be void if the Products' serial number, or other identification marks have been defaced, damaged, or removed. This warranty does not cover wear and tear due to normal use, or damage to the Product as the result of improper usage, neglect of care, alteration, accident, or unauthorized repair. THE ABOVE WARRANTY IS IN LIEU OF ANY OTHER WARRANTY, WHETHER EXPRESS, IMPLIED, OR STATUTORY, INCLUDING, BUT NOT LIMITED TO, ANY WARRANTY OF MERCHANTABILITY, FITNESS FOR ANY PARTICULAR PURPOSE, OR ANY WARRANTY OTHERWISE ARISING OUT OF ANY PROPOSAL, SPECIFICATION, OR SAMPLE. PNI NEITHER ASSUMES NOR AUTHORIZES ANY PERSON TO ASSUME FOR IT ANY OTHER LIABILITY.

If any Product furnished hereunder fails to conform to the above warranty, Customer's sole and exclusive remedy and PNI's sole and exclusive liability will be, at PNI's option, to repair, replace, or credit Customer's account with an amount equal to the price paid for any such Product which fails during the applicable warranty period provided that (i) Customer promptly notifies PNI in writing that such Product is defective and furnishes an explanation of the deficiency; (ii) such Product is returned to PNI's service facility at Customer's risk and expense; and (iii) PNI is satisfied that claimed deficiencies exist and were not caused by accident, misuse, neglect, alteration, repair, improper installation, or improper testing. If a Product is defective, transportation charges for the return of the Product to Customer within the United States and Canada will be paid by PNI. For all other locations, the warranty excludes all costs of shipping, customs clearance, and other related charges. PNI will have a reasonable time to make repairs or to replace the Product or to credit Customer's account. PNI warrants any such repaired or replacement Product to be free from defects in material and workmanship on the same terms as the Product originally purchased.

Except for the breach of warranty remedies set forth herein, or for personal injury, PNI shall have no liability for any indirect or speculative damages (including, but not limited to, consequential, incidental, punitive and special damages) relating to the use of or inability to use this Product, whether arising out of contract, negligence, tort, or under any warranty theory, or for infringement of any other party's intellectual property rights, irrespective of whether PNI had advance notice of the possibility of any such damages, including, but not limited to, loss of use, revenue or profit. In no event shall PNI's total liability for all claims regarding a Product exceed the price paid for the Product. PNI neither assumes nor authorizes any person to assume for it any other liabilities.

Some states and provinces do not allow limitations on how long an implied warranty lasts or the exclusion or limitation of incidental or consequential damages, so the above limitations or exclusions may not apply to you. This warranty gives you specific legal rights and you may have other rights that vary by state or province.

2 Introduction

Thank you for purchasing PNI Sensor Corporation's RM2000 or RM3000 Reference Magnetic Sensor Suite (pn 90042 and pn 90043, respectively). The RM2000 is comprised of two Sen-XY Reference Magnetic Sensors (pn 12683) and a 3D MagIC ASIC MLF controller (pn 12927), and this forms the basis for a 2-axis (horizontal) digital compass. The RM3000 is the same as the RM2000 but adds a Sen-Z Reference Magnetic Sensor (pn 12779), such that compassing measurements are not constricted to the horizontal plane.

When implementing an RM3000 or RM2000 Reference Magnetic Sensor Suite, each Reference Magnetic Sensor serves as the inductive element in a simple LR relaxation oscillation circuit, with the sensor's effective inductance proportional to the magnetic field parallel to the sensor axis. The LR circuit is driven by the 3D MagIC ASIC. Since the LR circuit's oscillation frequency varies with the strength of the magnetic field parallel to the sensor, the 3D MagIC's internal clock is used to measure the circuit's oscillation frequency (cycle counts) and hence the magnetic field. The 3D MagIC also contains an interface circuitry to communicate with a host microprocessor on an SPI bus. The 3D MagIC can control and measure up to three PNI Reference Magnetic Sensors, with each sensor individually selected for measurement and individually configured for measurement gain (resolution).

Since the Reference Magnetic Sensor Suite works in the frequency domain, resolution and noise are established cleanly by the number of cycle counts. In comparison, fluxgate and MR technologies require expensive and complex signal processing to obtain similar resolution and noise, and in many respects the Reference Magnetic Sensor Suite's performance simply cannot be matched. Also, the output from the 3D MagIC is inherently digital and can be fed directly into a microprocessor, eliminating the need for signal conditioning or an analog/digital interface between the sensor and a microprocessor. The simplicity of the Reference Magnetic Sensor Suite combined with the lack of signal conditioning makes it easier and less expensive to implement than alternative fluxgate or magneto-resistive (MR) technologies.

For more information on PNI's magneto-inductive sensor technology, see PNI's whitepaper "Magneto-Inductive Technology Overview" at http://www.pnicorp.com/technology/papers.

Note: PNI's Sen-Z Shield is available as an option to provide mechanical protection to the Sen-Z sensor since the solder joint that attaches the Sen-Z to the user's PCB may break if the Sen-Z is impacted. The Sen-Z shield generally should not be required in a well-controlled, high-volume production environment, but may be advisable for product development and testing or in less-controlled production environments.

3 Specifications

3.1 RM Sensor Suite Characteristics

Table 3-1: RM Sensor Suite Performance[1]

Parameter		Min	Typical	Max	Units
Field measurement range[2]		-1100		+1100	µT
Gain @ 200 Cycle Counts[3]			45		counts/µT
Noise @ 200 Cycle Counts[3]			35		nT
Maximum Sample Rate, Single Axis @ 200 Cycle Counts[4]			450		Hz
Linearity - best fit over ±200 µT			0.6	1.0	% of ±200 µT
Average Current per Axis @ 35 Hz and @ 200 Cycle Counts[5]			0.3		mA
Bias Resistance (R_B)	2.6 V to 3.3 V		68		Ω
	1.6 V to 2.6V		33 + (V-1.6)*35		Ω
External Timing Resistor for Clock (R_{EXT})			33		kΩ
Circuit Oscillation Frequency			185		kHz
High Speed Clock Frequency			45		MHz
Operating Temperature		-40		+85	C

Footnotes:

1. Specifications subject to change. Unless otherwise noted, performance characteristics assume the user implements the recommended bias resistors and external timing resistor for the high-speed clock (as indicated in Figure 4-1), the DC supply voltage is 3.3 V, and the 3D MagIC is operated in Standard Mode. Other bias resistors, external timing resistors and operating voltages may be used, but performance may differ from the values listed.
2. Field measurement range is defined as the monotonic region of the output characteristic curve.
3. Gain and noise are related to useable resolution. Below ~200 cycle counts the gain setting dominates the usable resolution (resolution = 1/gain) while above ~200 cycle counts the system noise dominates. The user establishes the gain value by setting the Cycle Count Register value. See Figure 3-4 for the typical relationship between cycle counts, gain, and resolution. Above ~200 cycle counts noise is relatively constant and there are diminishing returns in usable resolution as the cycle count value increases. Also, performance will vary from sensor to sensor: ~50% of the sensors will have performance greater than "Typical" and ~50% less than "Typical".
4. The maximum sample rate and gain/resolution are inversely related, so higher sample rates can be obtained by reducing the number of cycle counts, but this also results in reduced gain and resolution. Also see Figure 3-4 and Figure 3-5.
5. Operating at reduced cycle counts reduces current consumption, but also reduces resolution. Operating at greater cycle counts increases current consumption but, due to system noise, does not significantly increase useable resolution. Also see Figure 3-6.

3.2 Sen-XY and Sen-Z Characteristics

Table 3-2: Sen-XY and Sen-Z Absolute Maximum Ratings

Parameter	Minimum	Maximum	Units
Input Pin Current @ 25 C		50	mA
Storage Temperature	-40	+85	C

CAUTION:

Stresses beyond those listed above may cause permanent damage to the device. These are stress ratings only. Assuming operation with the 3D MagIC per the guidelines in this manual, these maximum ratings will not be violated.

Table 3-3: Sen-XY and Sen-Z Characteristics[1]

Parameter		Min	Typical	Max	Units
Inductance[1]			400-600		μH
DC resistance @ 25C ±15C		30		45	Ω
Resistance versus temperature			0.4		%/C
Weight	Sen-XY		0.06 [0.002]		gm [oz]
	Sen-Z		0.09 [0.003]		gm [oz]
Operating Temperature		-40		+85	C

Footnote:

1. 1 V peak-to-peak across the coil @ 100 kHz (sinewave). No DC bias resistance. Measured orthogonal to Earth's magnetic field.

3.3 3D MagIC Characteristics

Table 3-4: 3D MagIC Absolute Maximum Ratings

Parameter	Minimum	Maximum	Units
Analog/Digital DC Supply Voltage (AV_{DD} & DV_{DD})	-0.3	+3.7	VDC
Input Pin Voltage	-0.3	AV_{DD} or DV_{DD}	VDC
Input Pin Current @ 25C	-10.0	+10.0	mA
Storage Temperature	-40°	+125°	C

CAUTION:

Stresses beyond those listed above may cause permanent damage to the device. These are stress ratings only. Operation of the device at these or other conditions beyond those indicated in the operational sections of the specifications is not implied.

Table 3-5: 3D MagIC Recommended Operating Conditions

Parameter		Symbol	Min	Typ	Max	Units
Analog/Digital DC Supply Voltage		AV_{DD}, DV_{DD}	1.6	3.3	3.6	VDC
Supply Voltage Difference (DV_{DD}-AV_{DD})	During Operation	ΔV_{DD_OP}	-0.1	0	+0.1	VDC
	Analog Unpowered	ΔV_{DD_OFF}	DV_{DD}-0.1	DV_{DD}	DV_{DD}+0.1	VDC
Supply Voltage Ripple on AV_{DD} or DV_{DD}		V_{DD_ripple}			0.05	V_{PP}
High level input voltage		V_{IH}	0.7*DV_{DD}		DV_{DD}	VDC
Low level input voltage		V_{IL}	0		0.3*DV_{DD}	VDC
High level output current		I_{OH}			-1	mA
Low level output current		I_{OL}	1			mA
Idle Mode Current					1	µA
Leakage Current @ DV_{DD} pin (AV_{DD}=AV_{SS}=DV_{SS}=0V, DV_{DD}=3.6V)					100	nA
Operating Temperature		T_{OP}	-40		+85	C

3.4 Typical Sensor Suite Operating Performance

Figure 3-1 plots typical gain-determined resolution as a function of the single axis sample rate. The plot starts at 300 Hz since the usable resolution is limited by best-case system noise of ~15 nT. The plot stops at 2400 Hz because this represents a cycle count of ~30, and operating at cycle counts much lower than this introduces significant quantization error. (The number of cycle counts is determined by the user, as explained in Sections 5.1 and 6.2.)

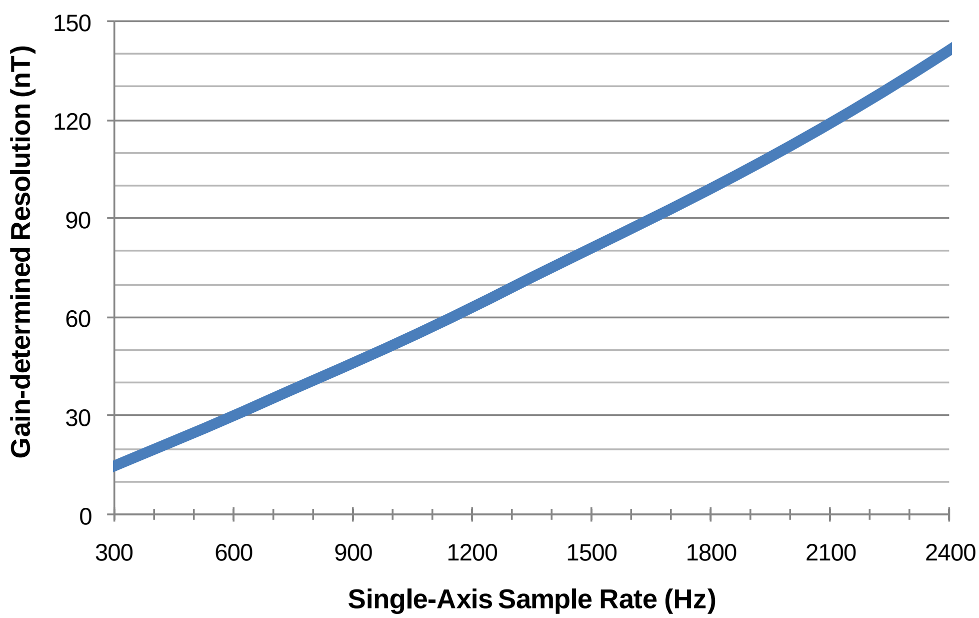


Figure 3-1: Sample Rate vs. Resolution – Standard Mode
(Usable resolution will be limited by system noise at lower sample rates)

The plots below are representative of performance as a function of the number of cycle counts, which is a parameter directly controlled by the user. The first two plots show performance for operation in both Standard Mode and the default Legacy Mode out to 10,000 cycle counts. The maximum number of cycle counts in Legacy Mode is 4096. In Standard Mode the maximum cycle counts is 65.5k, but there's rarely a reason to operate in Standard Mode much beyond 200 cycle counts, as discussed in the following paragraph.

Figure 3-4, Figure 3-5, and Figure 3-6 show performance when operating in Standard Mode out to 200 cycle counts. Operation in Standard Mode at more than 200 cycle counts usually is inefficient since more time and power is consumed per measurement, with diminishing returns in usable (noise-limited) resolution.

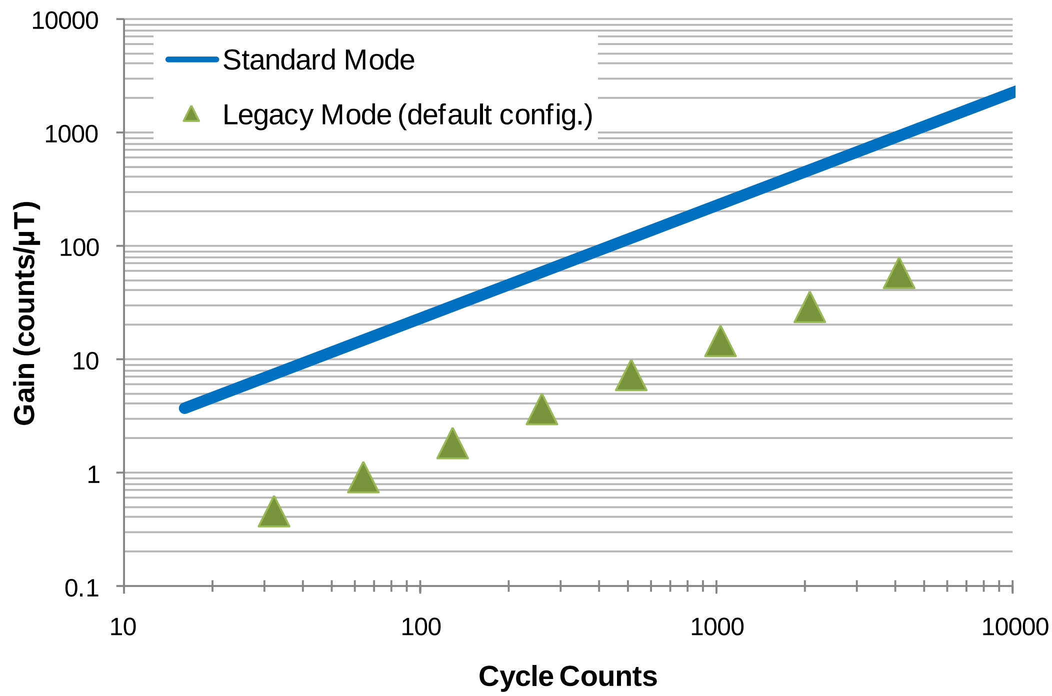


Figure 3-2: Gain vs. Cycle Counts – Standard & Legacy Modes
(Resolution = 1/Gain, to the system's noise limit)

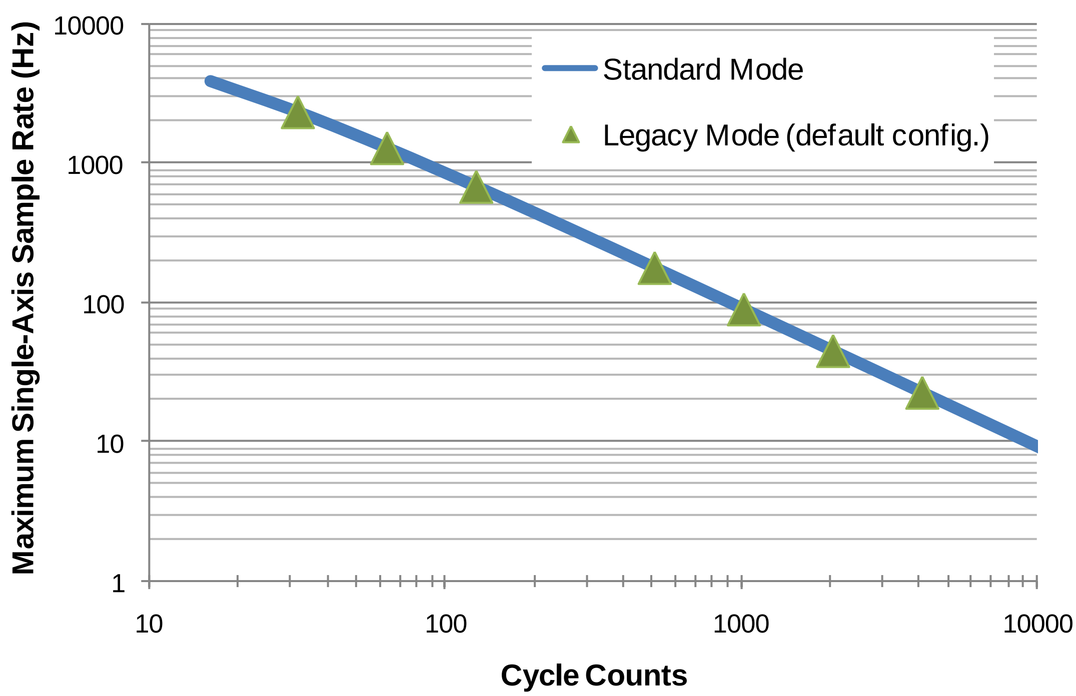


Figure 3-3: Single-Axis Sample Rate vs. Cycle Counts – Standard & Legacy Modes

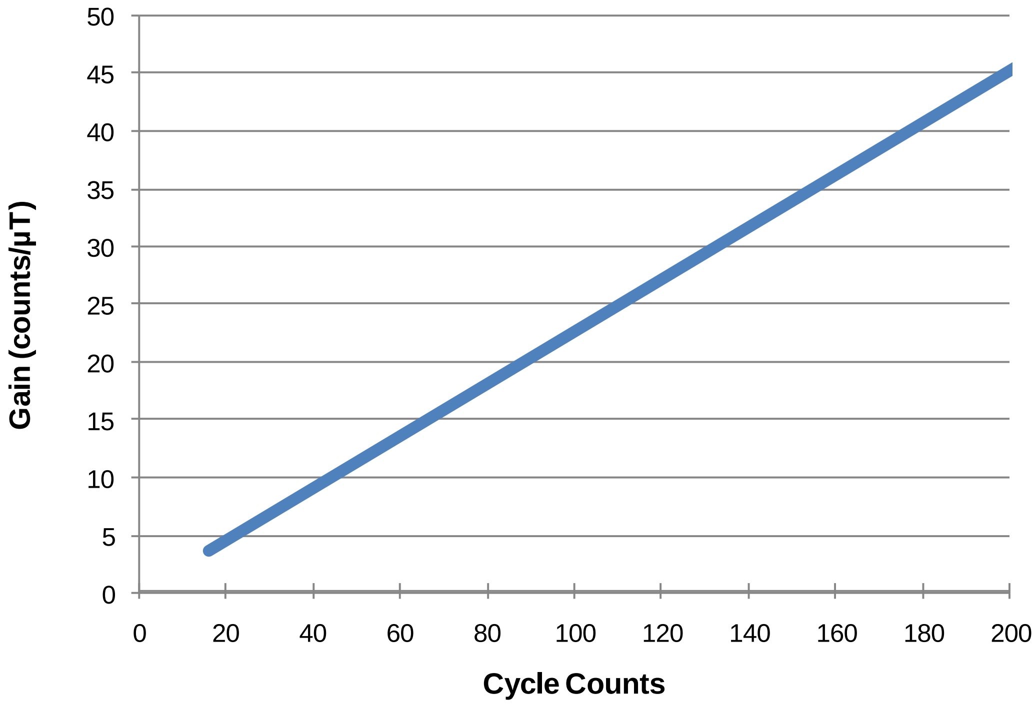


Figure 3-4: Gain vs. Cycle Counts – Standard Mode
(Resolution = 1/Gain, to the system's noise limit)

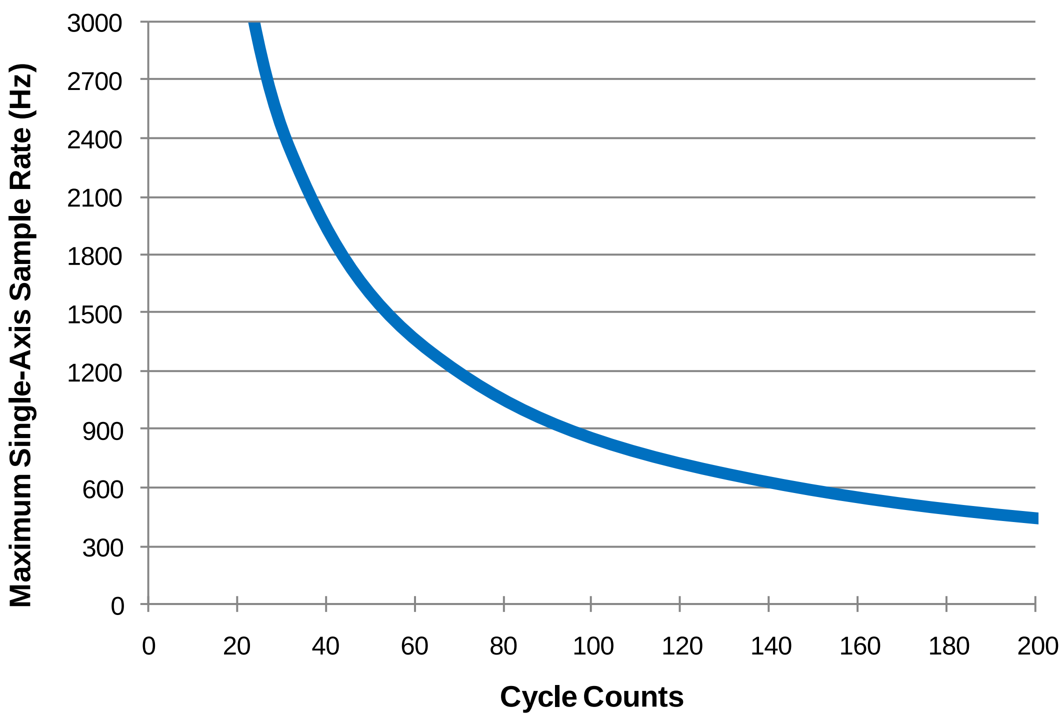


Figure 3-5: Single-Axis Sample Rate vs. Cycle Counts – Standard Mode

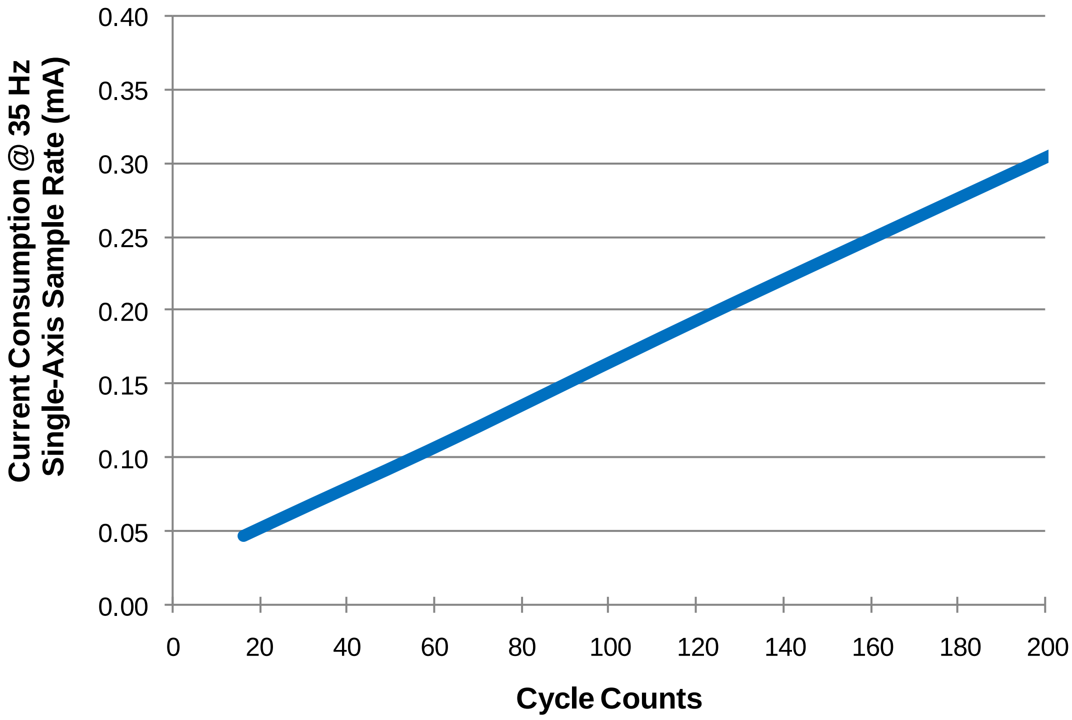


Figure 3-6: Current Consumption vs. Cycle Counts – Standard Mode

3.5 Dimensions and Packaging

3.5.1 Sen-XY Dimensions & Packaging

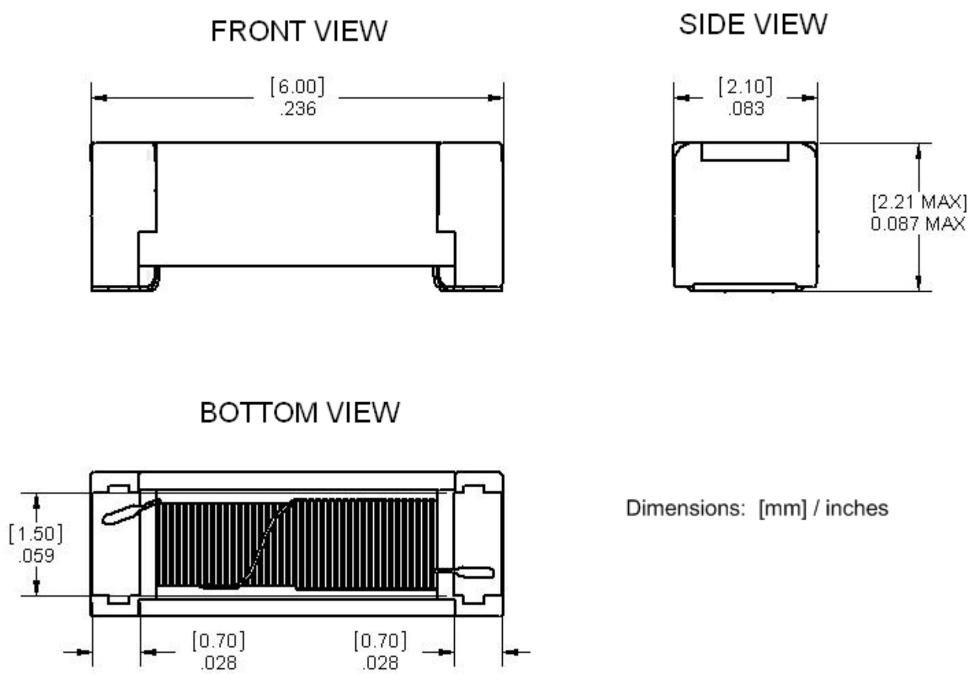


Figure 3-7: Sen-XY Sensor Dimensions

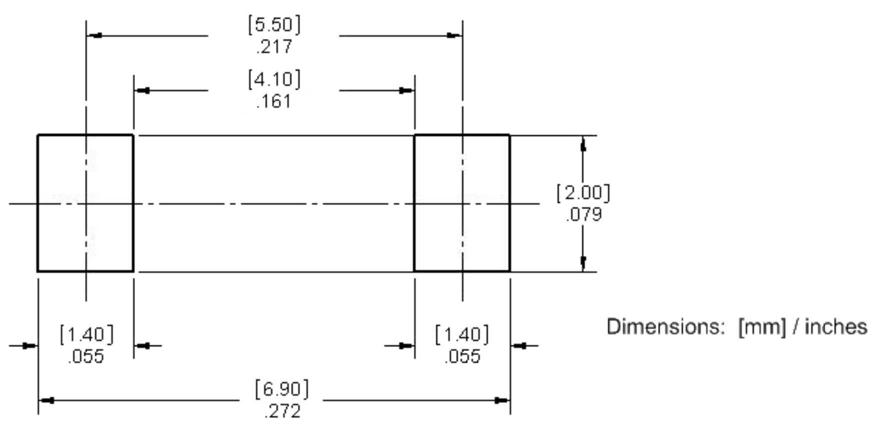
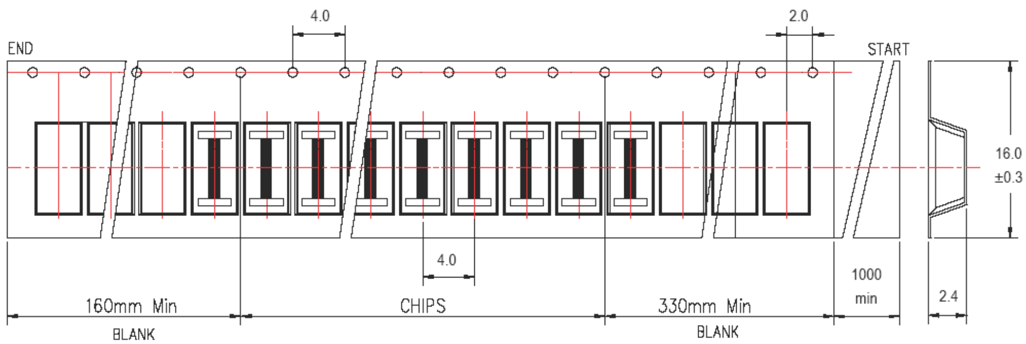


Figure 3-8: Sen-XY Solder Pad Layout



Dimensions: mm
Full reel is 5,000 pcs. Smaller quantities on cut-tape.
Tape & Reel meets ANSI/EIA standard EIA-418-B

Figure 3-9: Sen-XY Tape and Reel Dimensions

3.5.2 Sen-Z Dimensions & Packaging

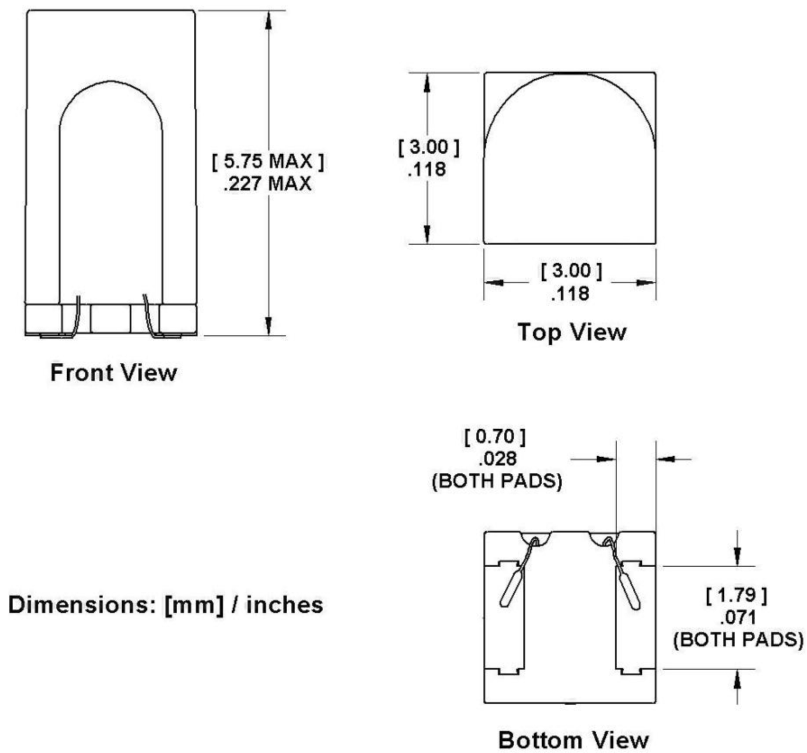


Figure 3-10: Sen-Z Sensor Dimensions

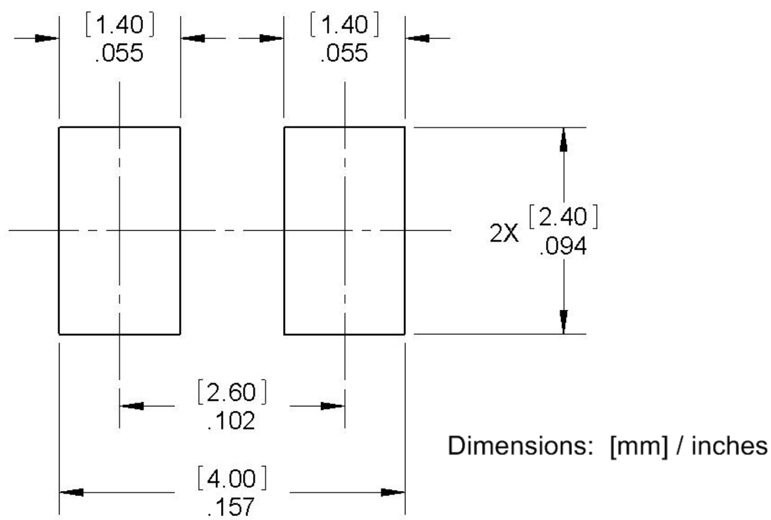
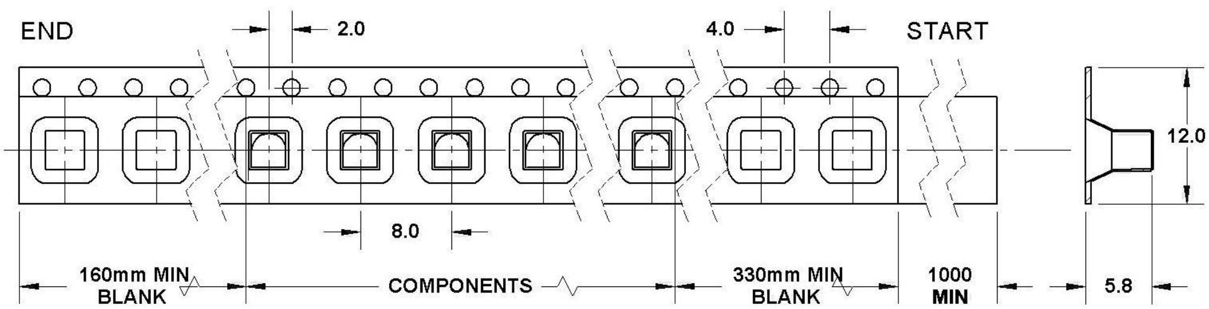


Figure 3-11: Sen-Z Solder Pad Layout



Dimensions: mm
Full reel is 1200 pcs. Smaller quantities on cut-tape.
Tape & Reel meets ANSI/EIA standard EIA-418-B

Figure 3-12: Sen-Z Tape and Reel Dimensions

3.5.1 Sen-Z Shield Dimensions & Packaging

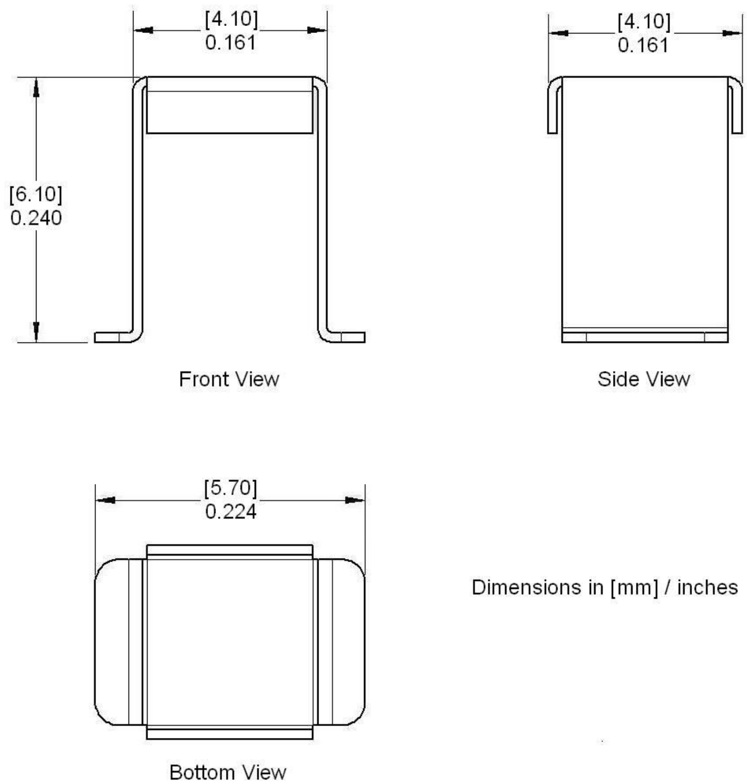


Figure 3-13: Sen-Z Shield Sensor Dimensions

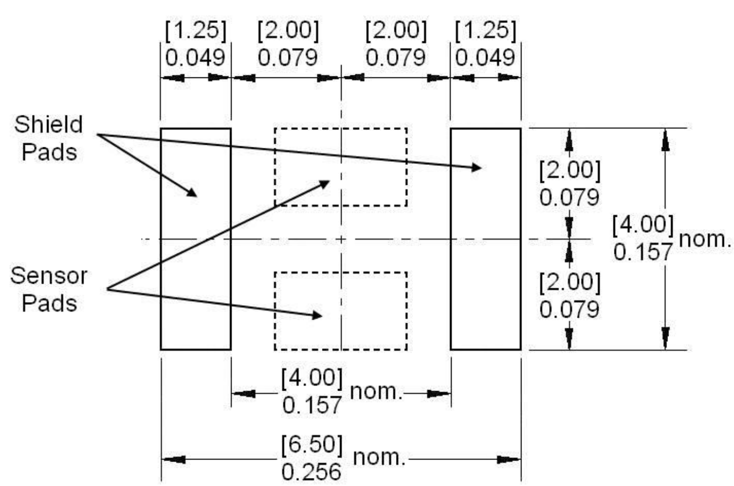
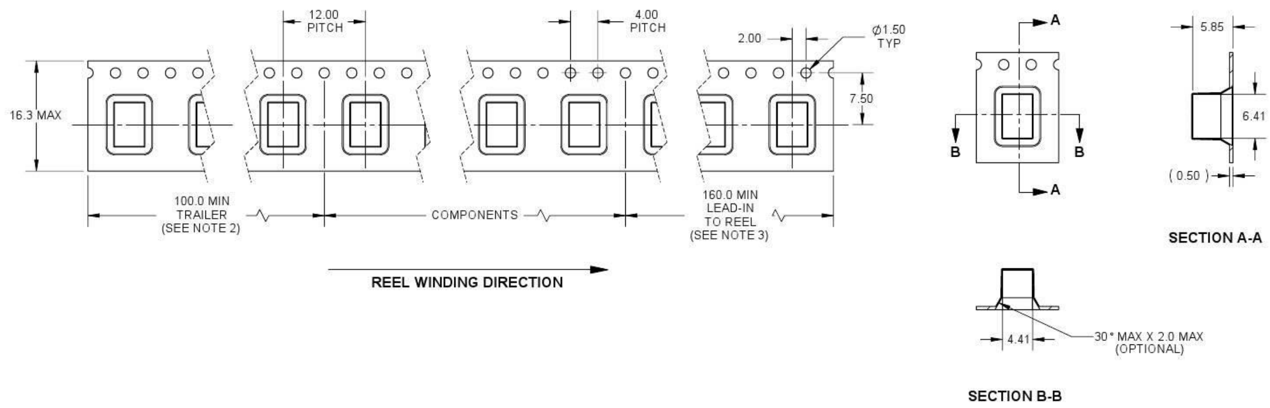


Figure 3-14: Sen-Z Shield Solder Pad Layout



Dimensions: mm
Full reel is 600 pcs. Smaller quantities on cut-tape.
Tape & Reel meets ANSI/EIA standard EIA-418

Figure 3-15: Sen-Z Shield Tape and Reel Dimensions

3.5.2 3D MagIC Dimensions and Packaging

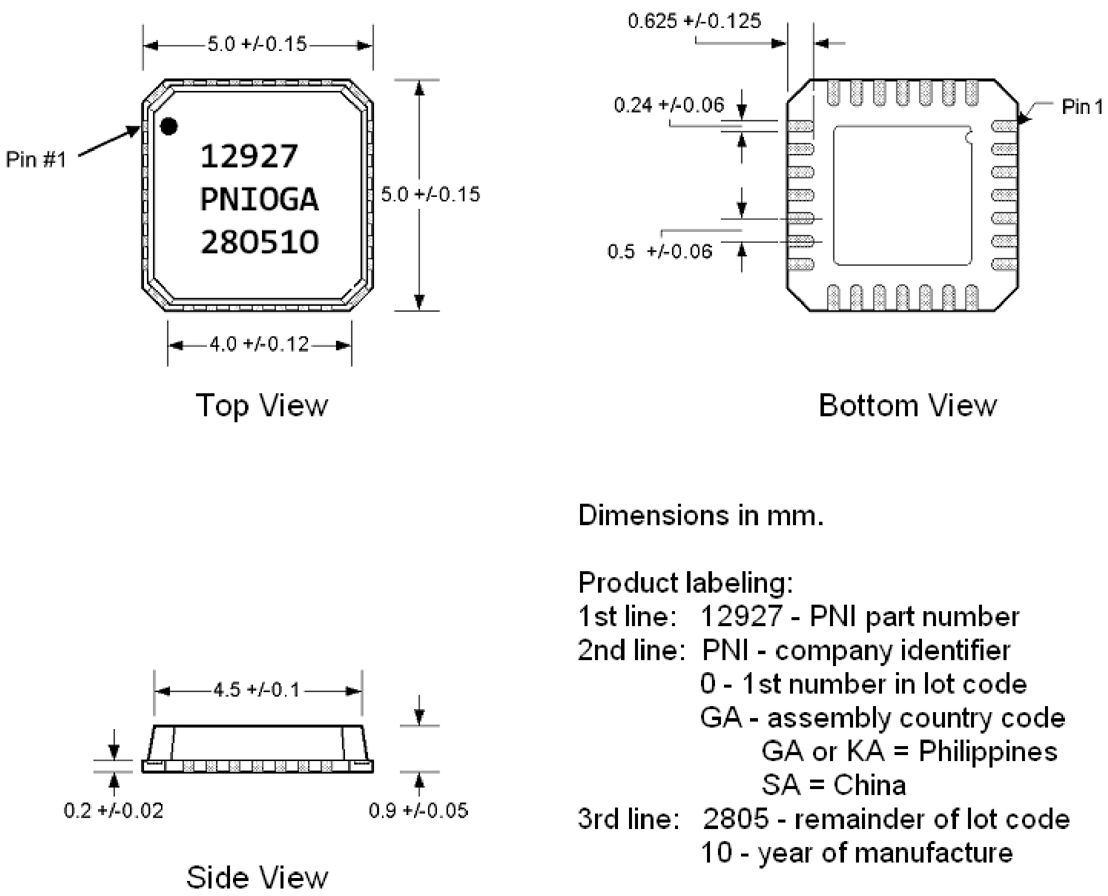


Figure 3-16: 3D MagIC MLF Mechanical Drawing

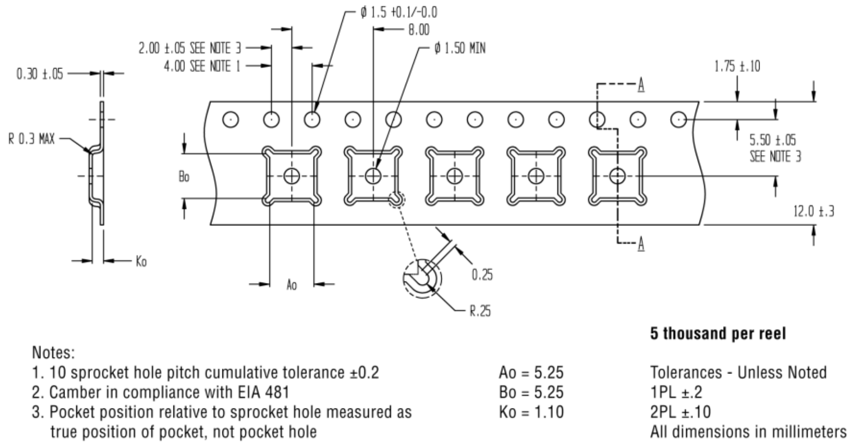
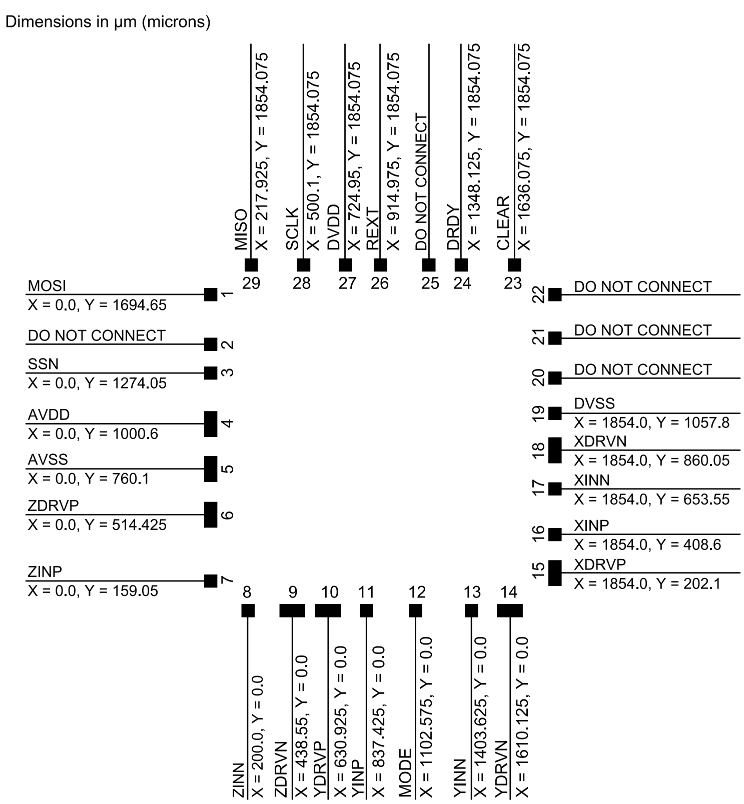


Figure 3-17: 3D MagIC MLF Tape Dimensions



NOTES:
The origin (0, 0) is the lower left coordinate of the center pads.
The chip size (2080.0 μm x 2080.0 μm) is calculated using pad to scribe distance.
Bond pad coordinates are to the center of the bond pad.
Bond pad openings are 68 um x 68 um, except for AVDD, AVSS, ZDRVP, ZDRVN, YDRVP, YDRVN, XDRVP and XDRVN which are 68 um x 136 um.

Figure 3-18: 3D MagIC Die Pad Layout

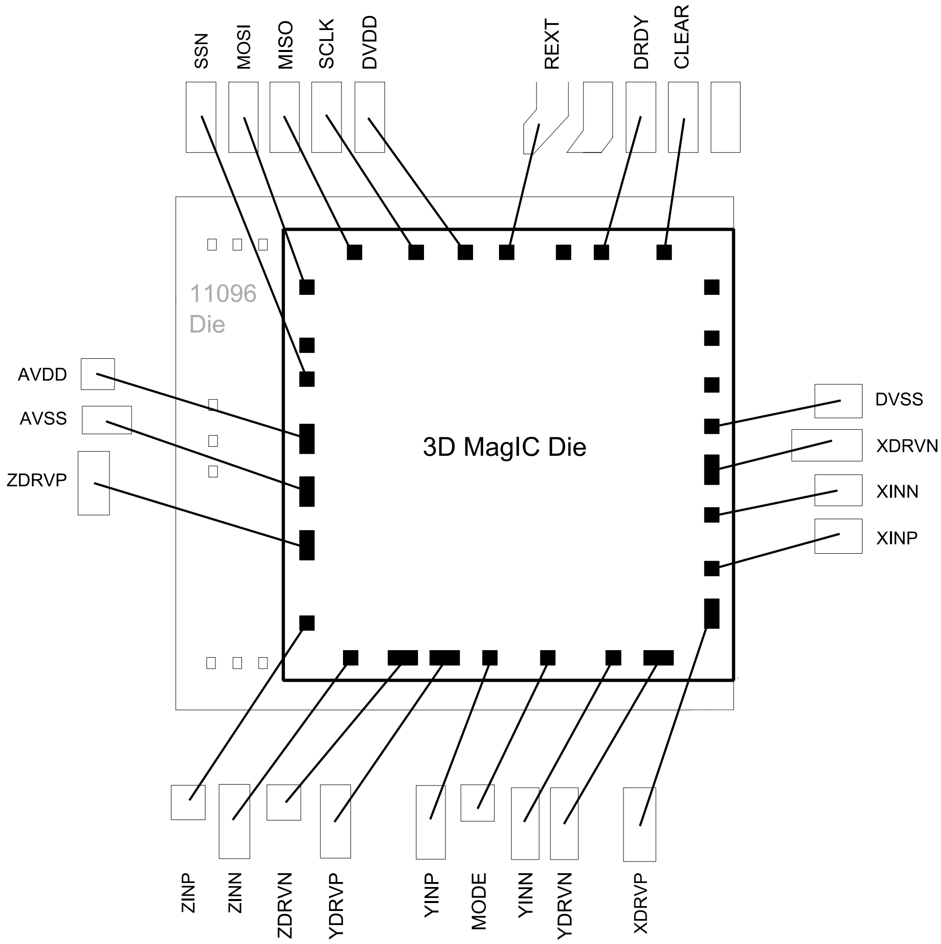


Figure 3-19: Example Wire Bonding Layout for Legacy 11096 ASIC Applications

Note that Figure 3-19 is for illustrative purposes only. The sample bond pad layout was taken from a PNI product that incorporates the 3D MagIC die. The customer's bond pad layout will vary, as will the best layout for the customer's application.

3.6 Soldering

Figure 3-20 and Table 3-6 provide the recommended solder reflow profile and processing parameters for RM3000 components. After soldering PNI components to a board, it is possible to wave solder the opposite side of the PCB.

IMPORTANT: PNI sensors require the use of halide-free solder pastes and processes for reflow and cleaning. Please contact PNI if you would like recommendations.

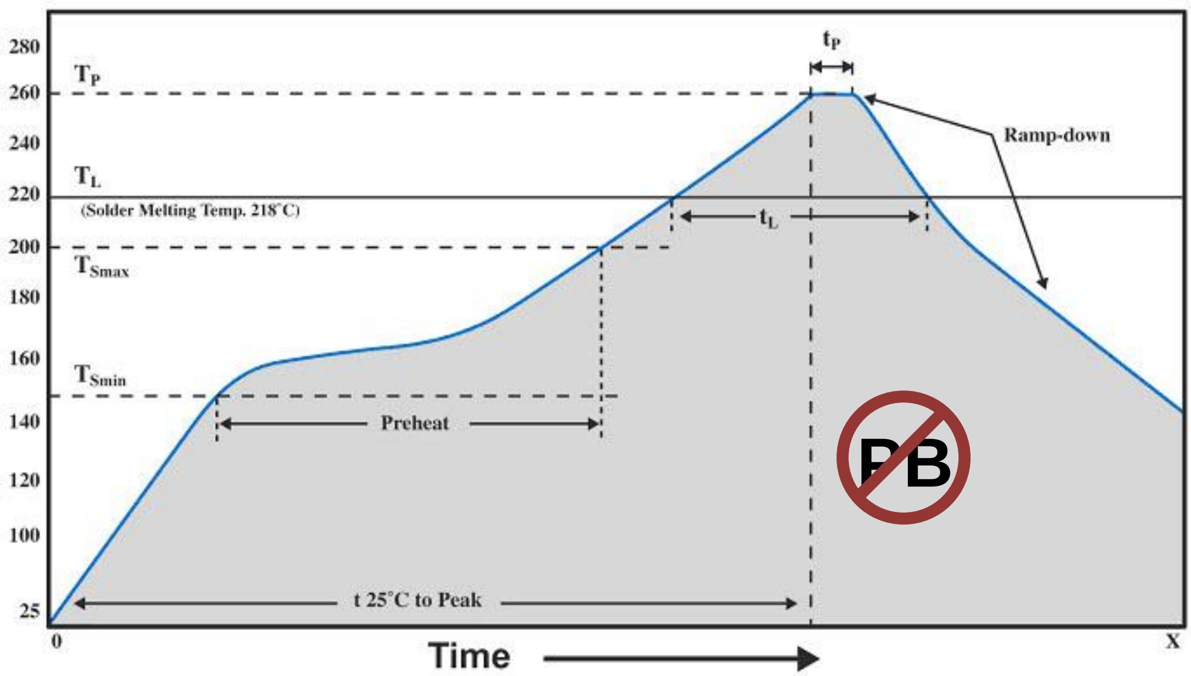


Figure 3-20: Recommended Solder Reflow Profile

Table 3-6: Recommended Solder Processing Parameters[1]

Parameter	Symbol	Value
Preheat Temperature, Minimum	T_{Smin}	150°C
Preheat Temperature, Maximum	T_{Smax}	200°C
Preheat Time (T_{Smin} to T_{Smax})		60 – 180 seconds
Solder Melt Temperature	T_L	>218°C
Ramp-Up Rate (T_{Smax} to T_L)		3°C/second maximum
Peak Temperature	T_P	<260°C
Time from 25°C to Peak (T_P)		6 minutes maximum
Time above T_L	t_L	60 – 120 seconds
Soak Time (within 5°C of T_P)	t_P	10 – 20 seconds
Rampdown Rate		4°C/second maximum

Footnote:

1. Meets IPC/JEDEC J-STD-020 profile recommendations. Sen-XY and Sen-Z classified as moisture sensitivity level 1. 3D MagIC MLF classified as moisture sensitivity level 3.

4 RM Sensor Suite Overview & Set-Up

4.1 Overview

Figure 4-1 provides a basic schematic for implementing the RM3000 Sensor Suite in Standard Mode. The 3D MagIC is at the center of the schematic, as it ties the user's host controller (on the left) to the three Reference Magnetic Sensors (on the right). To implement the RM2000, simply do not connect the Sen-Z sensor. The 3D MagIC also can operate only one sensor if desired. Unused sensor connections should remain floating. To implement either Reference Magnetic Sensor Suite in Legacy Mode, the Mode pin (pin #12) should be connected to DVDD, rather than tied to ground.

Note: RM3000 and RM2000 Reference Magnetic Sensor Suites typically are used in compassing applications, where each channel represents a Cartesian coordinate axis (x, y, or z). For this reason, the term "axis" generally is used instead of "channel".

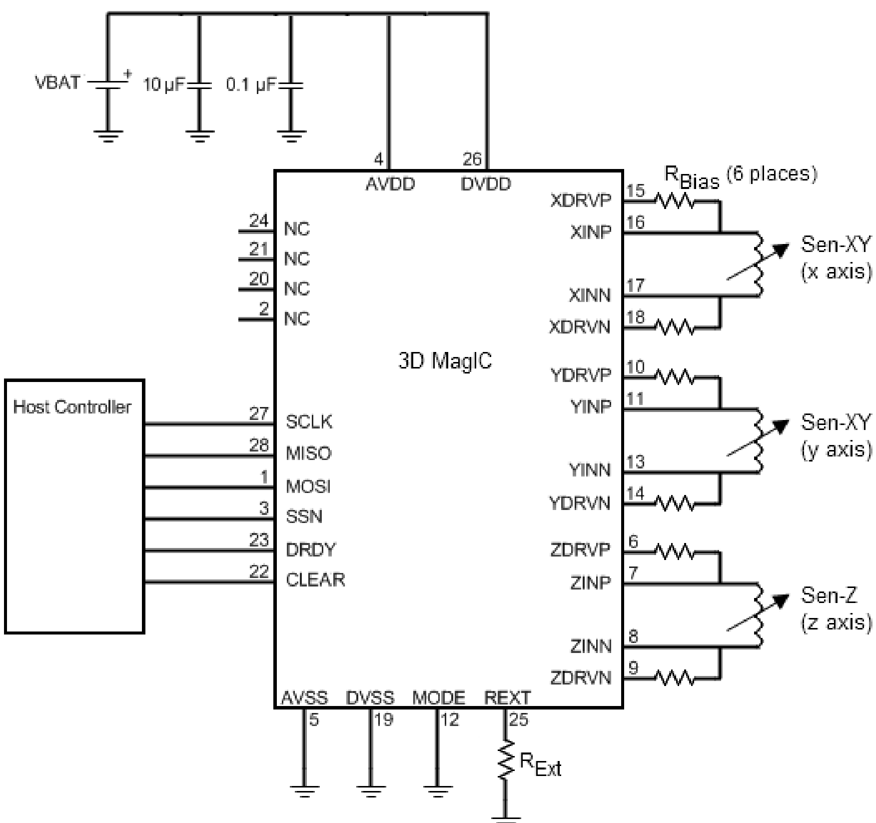


Figure 4-1: RM3000 reference schematic – Standard Mode

The Sen-XY and/or Sen-Z sensors serve as the inductive element in a simple LR relaxation oscillation circuit which is composed of an external bias resistor along with digital gates and a comparator internal to the 3D MagIC. The sensor's inductance varies with respect to the magnetic field. As such, the frequency of oscillation of the circuit varies with the strength of the total magnetic field parallel to the sensor. To make a measurement, one side of the sensor is grounded while the other side is alternately driven with positive and negative current through the oscillator. The circuit is driven for a user-specified number of circuit oscillations (the cycle counts), and the time to complete the specified number of cycle counts is measured using the 3D MagIC's internal high-speed clock. The 3D MagIC next switches the bias connection to the sensor and makes another measurement. The side that was previously grounded is now charged and discharged while the other is now grounded. Since the total magnetic field represents the sum of the external magnetic field and the circuit-induced magnetic field, and since the circuit-induced magnetic field has the same magnitude but opposite direction for the two bias polarities, the external magnetic field is proportional to the difference in the time to complete the user-defined number of cycle counts (i.e. the difference in the total measured magnetic field). The difference in the number of high-speed clock oscillations between the forward and reverse bias directions is output from the 3D MagIC, and this number is directly proportional to the strength of the local magnetic field in the direction of the sensor. Note that only one sensor can be measured at a time and the number of cycle counts is individually set for each sensor. Also, the greater the number of cycle counts, the higher the resolution of the measurement (to the noise limit) and the longer the sample time. Figure 4-2, below, provides a detail of the biasing circuit. For additional information on PNI's magneto-inductive sensor technology, please refer to the "Magneto-Inductive Technology Overview" white paper found on PNI's website.

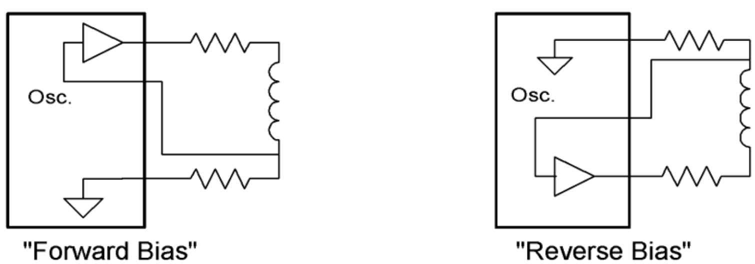


Figure 4-2: LR Oscillator Circuit Biasing Diagram

Since the Reference Magnetic Sensor Suite works in the frequency domain, resolution is cleanly established by the number of cycle counts. Also, the output from the 3D MagIC is inherently digital and can be fed directly into a microprocessor, which eliminates the need for signal conditioning or an analog/digital interface between the sensor and host processor.

4.2 Layout

4.2.1 Sensor Orientation

Figure 4-3 indicates how the three Reference Magnetic Sensors in a RM3000 Suite should be oriented for a system referenced as north-east-down (NED). The arrow represents the direction of travel or pointing. Positioning of the sensors is not critical, other than ensuring they are not positioned close to a magnetic component, such as a speaker.

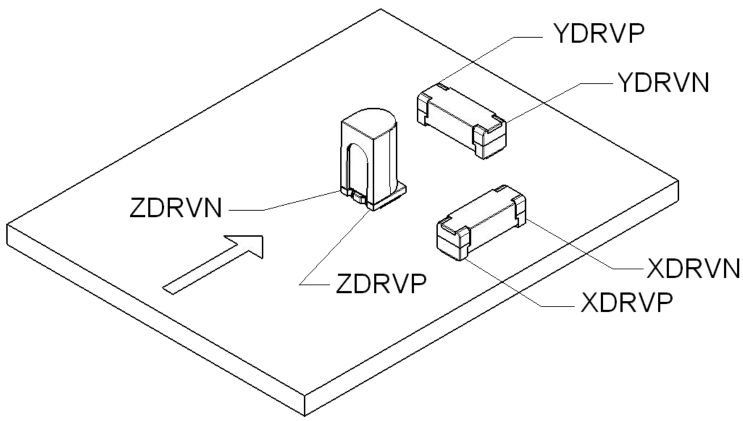


Figure 4-3: RM3000 North-East-Down (NED) Sensor Layout

If the Sen-Z sensor is flipped to the bottom of the board such that the curved portion of the sensor still points forward, then to retain NED the Sen-Z's ZDRVN and ZDRVP pads should be as shown above, except on the bottom of the board. Since the pads on the Sen-Z have switched positions, the connections to the Sen-Z sensor will be reversed.

4.2.2 Local Magnetic Field Considerations

Since the sensors measure magnetic field, it is important to consider what items in the vicinity of the sensors can affect the sensor readings. Specifically:

- The sensors have a linear regime of ±200 µT. (Earth's field is ~50 µT.) To ensure the sensors operate in their linear regime, do not place the sensors close to large electric currents, large masses of ferrous material, or devices incorporating permanent magnets, such as speakers and electric motors.
- Locate the sensors away from changing magnetic fields. While it is possible to calibrate the sensors to accommodate local magnetic distortion that is fixed

relative to the sensors, changing local magnetic fields generally cannot be accommodated. When the local magnetic field will change, try to take readings only when the field is in a known state. For instance, if a motor will be running part of the time, take readings only when the motor is in a known state (e.g. off).

- If you are uncertain about the effect a specific component may have on the system, the RM3000 Evaluation Board can be used to help ascertain this. Place the RM3000 Evaluation Board on a firm surface and gradually bring the component in question close to the board, then note when the magnetic field starts to change. If the component cannot be moved, then gradually move the RM3000 Evaluation Board towards the component; however it is necessary to ensure the orientation of the board remains constant while doing this. If an RM3000 Evaluation Board is not available, gradually bring the component in question closer to one of the Reference Magnetic Sensors and observe when the sensor reading starts to change. Note that the affect of a local magnetic distortion drops off as $1/\text{distance}^{3}$.

4.2.3 Other Layout Considerations

Other design considerations include:

- To minimize the effect of gradients in the magnetic field, position the sensors as close to each other as possible.
- To reduce coupling to and from other signals, keep the two traces from the 3D MagIC to each sensor as close as possible to each other. (The 3D MagIC can be located up to 0.5 m away from the sensors.)
- Keep capacitors (especially tantalum capacitors) far away from the sensors.

4.3 3D MagIC Pin-Out

The 3D MagIC's pin-out is summarized in Table 4-1. Pin numbers run counterclockwise (when looking from the top), starting at the Pin 1 designator as shown in Figure 3-16.

Table 4-1: 3D MagIC Pin Assignments

MLF Pin#	Die Pad#	Pin Name	Description
1	1	MOSI	SPI interface – Master Output, Slave Input Serial Data
2	2	NC	Do not connect
3	3	SSN	SPI interface – Active low to select port
4	4	AV_{DD}	Supply voltage for analog section of ASIC
5	5	AV_{SS}	Ground pin for analog section of ASIC
6	6	Z_{DRVP}	Z sensor drive output
7	7	Z_{INP}	Z sensor measurement input
8	8	Z_{INN}	Z sensor measurement input
9	9	Z_{DRVN}	Z sensor drive output
10	10	Y_{DRVP}	Y sensor drive output
11	11	Y_{INP}	Y sensor measurement input
12	12	MODE	Mode Select: tie to DV_{SS} for Standard, DV_{DD} for Legacy
13	13	Y_{INN}	Y sensor measurement input
14	14	Y_{DRVN}	Y sensor drive output
15	15	X_{DRVP}	X sensor drive output
16	16	X_{INP}	X sensor measurement input
17	17	X_{INN}	X sensor measurement input
18	18	X_{DRVN}	X sensor drive output
19	19	DV_{SS}	Ground pin for digital section of ASIC
--	20	NC	Do not connect
20	21	NC	Do not connect
21	22	NC	Do not connect
22	23	CLEAR	Clear Command Register
23	24	DRDY	Data ready command
24	25	NC	Do not connect
25	26	R_{EXT}	External timing resistor for high speed clock.
26	27	DV_{DD}	Supply voltage for digital section of ASIC.
27	28	SCLK	SPI interface - Serial clock input
28	29	MISO	SPI interface – Master Input, Slave Output

MODE

The MODE pin establishes whether communication with the 3D MagIC will comply with Standard Mode protocol (see Section 5) or Legacy Mode protocol (see Section 6). The MODE pin should be grounded (connected to DVSS) to operate in Standard Mode, and set HIGH (connected to DVDD) to operate in Legacy Mode.

SCLK (SPI Serial Clock Input)

SCLK is a SPI input used to synchronize the data sent in and out through the MISO and MOSI pins. SCLK is generated by the customer-supplied master device and should be 1 MHz or less. One byte of data is exchanged over eight clock cycles. Data is captured by the master device on the rising edge of SCLK. Data is shifted out and presented to the 3D MagIC on the MOSI pin on the falling edge of SCLK, except for the first bit (MSB) which must be present before the first rising edge of SCLK.

SSN (SPI Slave Select)

This signal sets the 3D MagIC as the operating slave device on the SPI bus. The SSN pin must be LOW prior to data transfer in either direction, and must stay LOW during the entire transfer.

The SSN pin must transition from HIGH to LOW prior to initiating a multi-axis measurement (MAM) command and prior to reading or writing to the Cycle Count Register or Clock Divide Register. It must stay LOW for the remainder of the operation.

After communication between the 3D MagIC and master device is finished, the SPI bus can be freed up (SSN pin set HIGH) to communicate with other slave devices while the 3D MagIC takes a measurement or is idle.

MISO (SPI Serial Out)

MISO is a SPI output that sends data from the 3D MagIC to the master device. Data is transferred most significant bit first and is captured by the master device on the rising edge of SCLK. The MISO pin is placed in a high impedance state if the 3D MagIC is not selected (i.e. if SSN=1).

MOSI (SPI Serial In)

MOSI is a SPI input that provides data from the master device to the 3D MagIC. Data is transferred most significant bit first. Data must be presented at least 50 ns before the rising edge of SCLK, and remain valid for 50 ns after the edge. New data typically is presented to the MOSI pin on the falling edge of SCLK.

DRDY (Data Ready)

DRDY is used to ensure data is read from the 3D MagIC only when it is available. After initiating a sensor measurement, DRDY will go HIGH when the measurement is complete. This signals the host that data is ready to be read. The DRDY pin should be set LOW prior to initiating a measurement. This is done automatically in Standard Mode and by toggling the CLEAR pin in Legacy Mode.

Note: If a new command sequence is started before the previous measurement has completed (before DRDY goes HIGH), the previous command will be overwritten. This will also stop the measurement cycle. If you try to send a new command during the readout phase, after DRDY goes HIGH, the command will be ignored until all 16 bits have been clocked our or the CLEAR pin is set HIGH (then LOW again).

CLEAR (Clear Command Register)

To initiate a clear command in Legacy Mode, the CLEAR pin must be toggled LOW-HIGH-LOW. CLEAR is usually LOW. CLEAR will reset the DRDY pin to LOW. CLEAR can be used to stop any sensor measurement in progress. CLEAR has no effect on the SPI register state.

Note: The CLEAR pin is similar to the RESET pin on PNI's legacy ASIC. However in Standard Mode the 3D MagIC automatically resets the DRDY line, so it is not necessary to use the CLEAR pin when operating in Standard Mode.

AVDD and DVDD (Supply Voltages)

AVDD and DVDD should be tied to the analog and digital supply voltages, respectively. The recommend voltages are defined in Table 3-5, and the maximum voltages are given in Table 3-4. DVDD must be on whenever AVDD is on, so DVDD should either be brought up first or at precisely the same time as AVDD. AVDD can be turned off when not making a measurement to conserve power, since all other operations are supported with DVDD. Under this condition, register values, such as those in the Cycle Count Register, will be retained as long as DVDD is powered. Also, AVDD must be within 0.1 V DVDD when AVDD is on.

AVSS and DVSS (Ground Pins)

AVSS and DVSS should be tied to the analog and digital ground, respectively. Assuming the ground plane is clean, they may share a common ground. They may have their own ground planes if this is more convenient from the standpoint of the user's circuit layout. DVSS and AVSS should be within 0.1 V of each other.

R_{EXT} (External Timing Resistor)

R_{EXT} ties to the external timing resistor for the high-speed clock. The recommended value for the resistor and associated clock speed are defined in Table 3-1.

Sensor Drive and Measurement Pins

The various sensor drive and measurement pins should be connected to the Reference Magnetic Sensors. For a north-east-down (NED) reference frame, the connections should be as defined in Figure 4-3.

4.4 SPI Timing Requirements

When implementing a SPI port, whether a dedicated hardware peripheral port or a software-implemented port using general purpose I/O (also known as *Bit-Banging*), the timing parameters (defined below in Figure 4-4 and specified in Table 4-2) must be met to ensure reliable communication. Note that Standard Mode and Legacy Mode timing requirements are identical with the exception of Legacy Mode utilizing the CLEAR line. The SPI clock (SCLK) should run at 1 MHz or less. Generally data is considered valid while SCLK is HIGH, and data is in transition when SCLK is LOW. The clock polarity used with the 3D MagIC is zero (exclusively CPOL=0). Data is present on MISO or should be presented on MOSI before the first low to high clock transition (exclusively CPHA = 0).

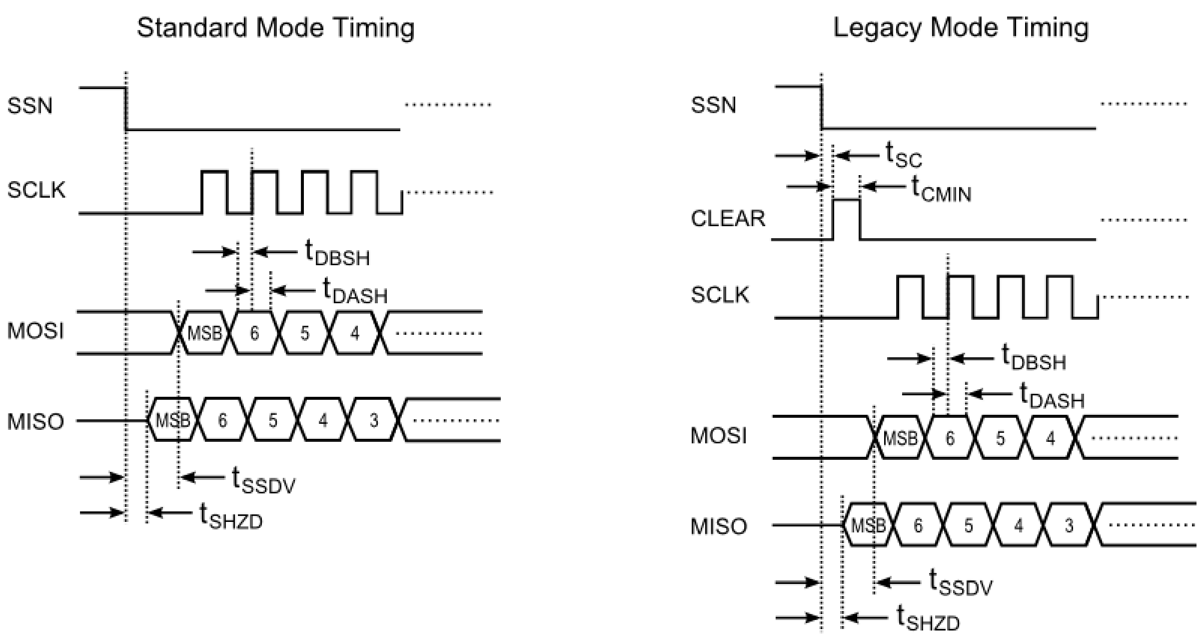


Figure 4-4: SPI Timing Diagram

Table 4-2: SPI Timing Specifications

Symbol	Description	Min	Max	Units
t_{SC}	Time from SSN to CLEAR	10		ns
t_{CMIN}	CLEAR duration	100		ns
t_{SSDV}	Time from SSN to Command Byte on MOSI	1		us
t_{DBSH}	Time to setup data before active edge	50		ns
t_{DASH}	Time to setup data after active edge	50		ns
t_{SHDZ}	Time from SSN to data tri-state time		100	ns

4.5 Idle Mode

The 3D MagIC incorporates an Idle Mode to reduce power consumption, in which the circuit automatically idles when it is not exchanging data or taking a measurement. The 3D MagIC starts in the Idle Mode at power-up and remains in Idle Mode until a measurement is needed.

Note: The 3D MagIC starts in Idle Mode when powered on. This is different from the legacy 11096 ASIC, which required cycling through one measurement request operation to put it into Idle Mode.

5 3D MagIC Operation – Standard Mode

Note: This section discusses how to operate the 3D MagIC in Standard Mode. For a description of operation in Legacy Mode, see Section 6. The 3D MagIC operates in Standard Mode when pin #12 is held LOW (grounded to DVSS).

The basic functions to be performed when operating the 3D MagIC are:

- Setting the values in the Cycle Count Registers, and
- Taking sensor measurements.

The user should first establish the number of cycle counts to be measured for each sensor by writing to the Cycle Count Registers. This is followed by sending a command or series of commands to make the sensor measurements. Assuming the user will use the same number of cycle counts for subsequent measurements, it is not necessary to rewrite to the Cycle Count Registers for subsequent sensor measurements.

In Standard Mode, the 3D MagIC provides two methods to take sensor measurements, which are discussed later in this section:

- Single-axis measurement (SAM), and
- Multi-axis measurement (MAM).

The SAM Command Byte initiates a measurement for one sensor and sets up the 3D MagIC to write the measured values out on the MISO line. The MAM Command Byte initiates a sensor measurement for up to 3 sensors, and a later Command Byte sets up the 3D MagIC to write the measured values out on the MISO line for up to 3 sensors. For two or three axis systems, normally it is more efficient to operate using the MAM Command Byte.

5.1 Cycle Count Registers

Prior to sending a command to take a sensor measurement, it is necessary to write values to the Cycle Count Registers. (The default value for the Cycle Count Registers is 512D, but this was chosen for legacy reasons and is an inefficient value otherwise.) The Cycle Count Registers establish the number of sensor oscillation cycles that will be counted for each sensor in both the forward and reverse bias directions during a measurement sequence. Increasing the cycle count value increases measurement resolution, but system noise limits the useable resolution such that the maximum efficient cycle count value generally is around 200-300 cycle counts. Lowering the cycle count value reduces acquisition time, which increases maximum achievable sample rate or, with a fixed sample rate, decreases power consumption. See Figure 3-4, Figure 3-5, and Figure 3-6 to estimate the appropriate cycle count value for your application. Once the Cycle Count Registers are set, they do not need to be repopulated unless the user wants to change the values or the system is powered down (in which case the default values would populate the register fields when powered up again).

To initiate a read to or write from the Cycle Count Register, the command byte is defined as:

Bit #	7	6	5	4	3	2	1	0
Value	1	R/W	0	0	ADR3	ADR2	ADR1	ADR0

R/W: Read/Write

HIGH signifies a Read operation from the addressed register. LOW signifies a Write operation to the addressed register.

ADR0 – ADR3: Register Address Bits

Establishes which register will be written to or read from. Each sensor is represented by two registers, with addresses defined as follows:

Table 5-1: Cycle Count Register Commands

Register Description	Read Command Byte	Write Command Byte
X Axis Cycle Count Value - MSB	$C3_H$	83_H
X Axis Cycle Count Value - LSB	$C4_H$	84_H
Y Axis Cycle Count Value - MSB	$C5_H$	85_H
Y Axis Cycle Count Value - LSB	$C6_H$	86_H
Z Axis Cycle Count Value - MSB	$C7_H$	87_H
Z Axis Cycle Count Value - LSB	$C8_H$	88_H

Since the registers are adjacent, it is not necessary to send multiple Command Bytes, as the 3D MagIC automatically will read/write to the next adjacent register.

A sample command sequence is provided below which sets the cycle count value to 100_D (64_H) for all 3 axes. This is purely for illustrative purposes and the value could be different and/or the number of axes to be addressed could be different.

- Start with SSN set HIGH, then set SSN to LOW.
- Send 83_H (this is the Write Command Byte to address the MSB for the X axis)

- Send 0 (value for the MSB for the X axis)
- Send 64_H (value for the LSB for the X axis - pointer automatically increments)
- Send 0 (value for the MSB for the Y axis - pointer automatically increments)
- Send 64_H (value for the LSB for the Y axis - pointer automatically increments)
- Send 0 (value for the MSB for the Z axis - pointer automatically increments)
- Send 64_H (value for the LSB for the Z axis - pointer automatically increments)
- Set SSN to HIGH

5.2 Single-Axis Measurement (SAM) Operation

The SAM Command Byte initiates a sensor measurement on a single sensor, and sets up the 3D MagIC to output the measured values on the MISO line. Generally SAM operation is not as efficient as MAM operation, except when only one sensor (in total) is to be measured.

5.2.1 SAM SPI Activity Sequence

The SPI activity sequence for SAM operation is given below. SPI timing is discussed in Section 4.4. The Return Byte is $9A_H$. Three (3) data bytes will be clocked out for a single-axis measurement. The Command Byte is discussed below.

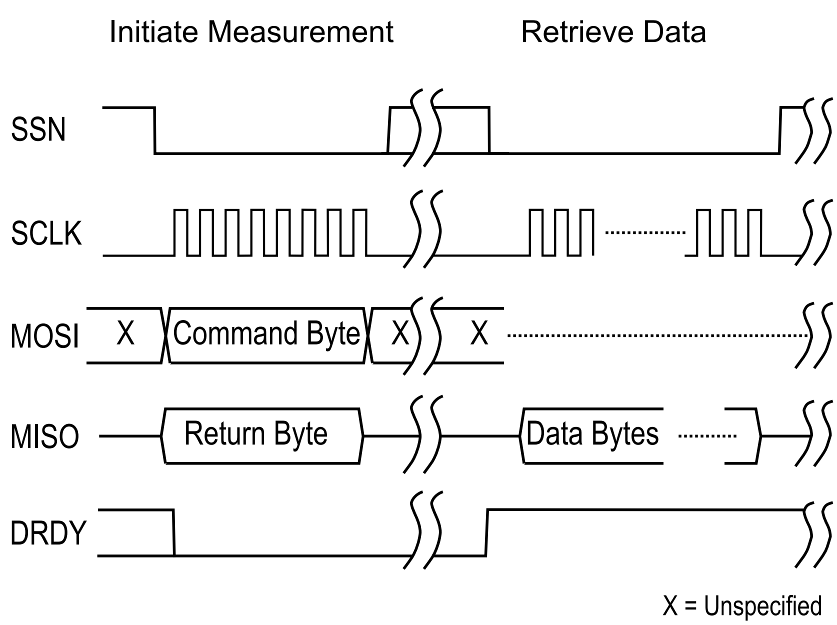


Figure 5-1: SPI Activity Sequence Diagram for SAM Operation

5.2.2 SAM Command Byte

The SAM Command Byte is defined as follows:

Bit #	7	6	5	4	3	2	1	0
Value	0	0	0	0	0	0	AS1	AS0

Table 5-2: SAM Axis Select Bits

Axis Measured	AS1	AS0
No axis measured	0	0
X axis	0	1
Y axis	1	0
Z axis	1	1

5.2.3 Making a Single-Axis Measurement

The steps to make a single-axis sensor measurement are given below. The 3D MagIC will return the result of a complete forward- reverse measurement of the sensor in a 24 bit 2's complement format (range: -8388608 to 8388607).

- SSN pin is set LOW. This enables communication with the master device.
- The SAM Command Byte is clocked into the 3D MagIC on the MOSI pin. Simultaneously, the 3D MagIC will present a fixed $9A_H$ on the MISO pin. Once the 8 bits have clocked in, the 3D MagIC will execute the command (i.e. take a measurement).
- The SSN input may be returned HIGH at this point to free up host communication with another device if desired. This will not affect the measurement process.
- A measurement is taken.
- At the end of the measurement, the DRDY pin is set HIGH, indicating data is ready, and the 3D MagIC is placed in Idle Mode.
- The SSN input should be set LOW, if it is not already, to read the data.
- The data is clocked out on the MISO pin with the next 24 clock cycles.

If another measurement is immediately made, SSN can remain LOW and the process repeated. Otherwise it is recommended that SSN is set HIGH to release the SPI bus.

5.3 Multi-Axis Measurement (MAM) Operation

An initial MAM Command Byte initiates a sensor measurement for up to 3 sensors. After the measurements are made and the DRDY line goes HIGH, another MAM Command Byte sets up the 3D MagIC to output the measured values on the MISO line.

5.3.1 MAM SPI Activity Sequence

The SPI timing sequence is given below for MAM operation. SPI timing is discussed in Section 4.4. The Return Byte is $9A_H$. The number of data bytes will be determined by the number of axes that are to be measured. Each axis is comprised of 3 bytes of data, so for a 3 axis measurement 9 total bytes would be clocked out to receive all the data. The Command Byte and Axes Select Byte are discussed below.

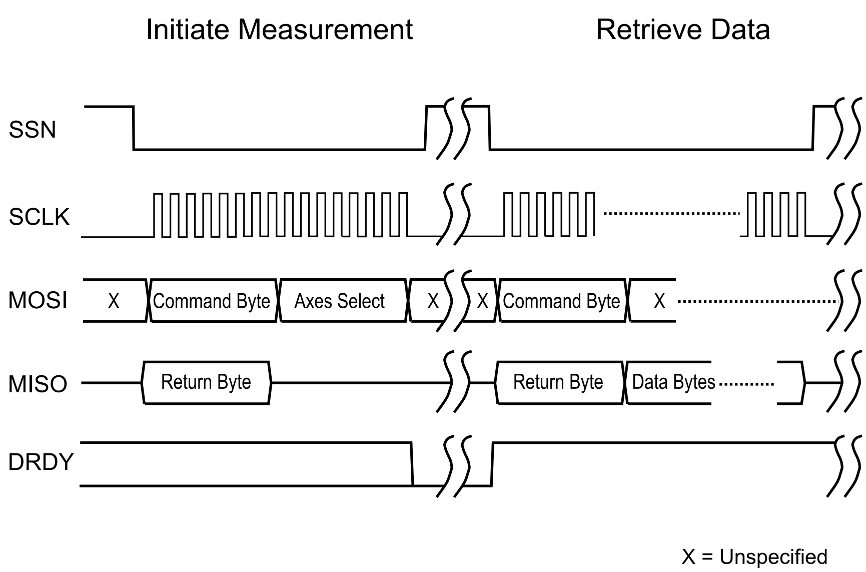


Figure 5-2: SPI Activity Sequence Diagram for MAM Operation

5.3.2 MAM Command Byte

The MAM Command Byte either initiates a sensor measurement or initiates placing the measurement results on the MISO line for the host to read. The MAM Command Byte is 82_H to initiate a sensor measurement and is $C9_H$ to retrieve the data.

Note: Measurement results are stored in registers within the 3D MagIC. If SCLK continues to run after the appropriate number of data bytes for the defined number of axes to be measured, then the information on the MISO line will have little meaning. SCLK should be stopped once the measurements are clocked out.

5.3.3 MAM Axes Select Byte

The MAM Axes Select Byte establishes which axes are to be measured and is defined as follows:

Bit #	7	6	5	4	3	2	1	0
Value	0	0	0	AAX1	AAX0	0	0	1

Table 5-3: MAM Axes Select Bits

Axes Measured	AAX1	AAX0
X, Y, and Z	0	0
X and Y	0	1
X only	1	0
No axis measured	1	1

5.3.4 Making a Multi-Axis Measurement

The steps to make a multi-axis sensor measurement are given below. The 3D MagIC will return the result of a complete forward- reverse measurement of each sensor in a 24 bit 2's complement format (range: -8388608 to 8388607).

- Start with SSN set HIGH, then set SSN to LOW.
- Initiate a sensor measurement by sending 82_H (MAM Command Byte to write to the Mode Register) followed by 01_H (Mode Register Word to initiate measurement) on the MOSI pin. The 3D MagIC will now take the prescribed measurements.
- Return SSN to HIGH. This will not affect the measurement process, but will free up the host to communicate with other devices and ensure the next Command Byte sent to the 3D MagIC is interpreted properly.
- A measurement is taken.
- At the end of the measurement, the DRDY pin is set HIGH, indicating data is ready, and the 3D MagIC is placed in Idle Mode.
- When the host is ready to read the measured values, set SSN to LOW. If SSN already is LOW, then toggle SSN from LOW to HIGH to LOW.

- Send $C9_H$ (MAM Command Byte to read from the) on the MOSI pin to initiate reading the measurement values. Data is clocked out on the MISO pin. Each sensor reading consists of 3 bytes of data, clocked out MSB first. X-axis data is presented first, then y-axis data, then z-axis data. The first nine (9) bytes represent a complete 3-axis measurement.
- Return SSN to HIGH to free up the host to communicate with other devices and to ensure the next Command Byte sent to the 3D MagIC is interpreted properly.

6 3D MagIC Operation – Legacy Mode

Note: This section discusses how to operate the 3D MagIC in Legacy Mode. For a description of operation in Standard Mode, see Section 5. The 3D MagIC will operate in Legacy Mode when pin #12 is held HIGH (connected to DVDD).

The intent of Legacy Mode is to enable the user to easily substitute PNI's 3D MagIC for PNI's legacy 11096 ASIC (p/n 12576).

If the user wishes to simply duplicate the performance of the 11096 ASIC (Legacy Operation), then a measurement is made by sending the Legacy Command Byte. This command byte is the same as for the 11096 ASIC. The Legacy Command Byte initiates a sensor measurement on a single sensor, and sets up the 3D MagIC to output the measured values on the MISO line. Legacy Operation is covered in Section 6.1

If the user wishes to derive the lower power consumption advantages of the 3D MagIC and is willing to make some code changes but cannot make hardware changes, then Enhanced Legacy Operation allows for this. (If the user can make both code and hardware changes, then operation in Standard Mode is recommended.) For Enhanced Legacy Operation, the user first will write to the Clock Divide Register and after this follow the same process as for Legacy Operation. Please review both Sections 6.1 and 6.2, as Section 6.1 still applies and Section 6.2 covers the additional steps required for Enhanced Legacy Operation.

6.1 Legacy Operation

In Legacy Mode a sensor measurement is initiated with the Legacy Command Byte, and this command also sets up the 3D MagIC to output measurement data on the MISO line once this data becomes available.

Note the 3D MagIC's high-speed clock runs at nominally 45 MHz, but the 11096 ASIC runs at nominally 2 MHz. Consequently, when the 3D MagIC is in default Legacy Mode, the clock speed is divided by 16 thus reducing the clock speed to 2.8 MHz. At an effective clock speed of 2.8 MHz the gain of the 3D MagIC circuit will closely match the gain of the 11096 ASIC circuit operating at 2 MHz. (The effective clock speed of the 3D MagIC is not 2 MHz for gain matching because of differences in the circuit oscillation frequency between the 3D MagIC and the 11096 ASIC circuits.) As such, the performance of the 3D MagIC closely matchs that of the 11096 ASIC circuit with no software coding or hardware changes on the user's part. But performance is sub-optimized, and specifically power consumption can be reduced by up to 90% with software changes on the user's part, as discussed in Section 6.2.

6.1.1 Legacy Operation SPI Activity Sequence

The SPI activity sequence is given below for Legacy operation. SPI timing is discussed in Section 4.4. The Return Byte is $9B_H$. Two (2) data bytes will be clocked out for a Legacy measurement. The Command Byte is discussed below.

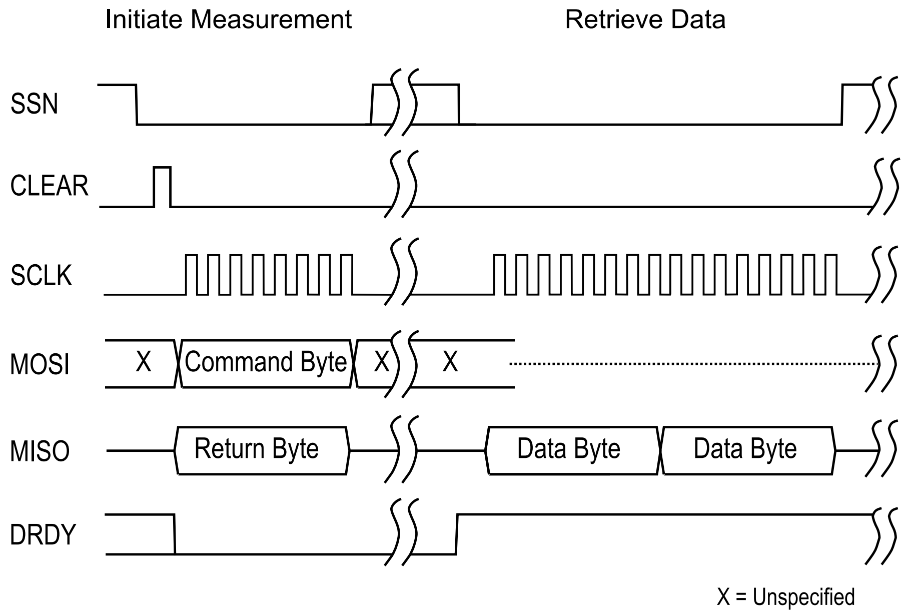


Figure 6-1: SPI Activity Sequence Diagram for Legacy Operation

6.1.2 Legacy Command Byte

The command byte to initiate a sensor measurement is defined as follows:

Bit #	7	6	5	4	3	2	1	0
Value	0	PS2	PS1	PS0	0	0	AS1	AS0

PS0-PS2: Period Select

Selects the number of sensor circuit oscillation cycles (cycle counts) to be counted while simultaneously using the internal fixed reference clock to measure the time to obtain this count.

Table 6-1: Legacy Period Select Bits

Period Select Value	Cycle Counts	PS2	PS1	PS0
0	32	0	0	0
1	64	0	0	1
2	128	0	1	0
3	256	0	1	1
4	512	1	0	0
5	1024	1	0	1
6	2048	1	1	0
7	4096	1	1	1

AS0-AS1: Axis Select

Determines the sensor to be measured.

Table 6-2: Legacy Axis Select Bits

Axis Measured	AS1	AS0
No axis measured	0	0
X axis	0	1
Y axis	1	0
Z axis	1	1

6.1.3 Making a Legacy Measurement

The steps to make a sensor measurement are given below. In Legacy Mode, the 3D MagIC returns the result of a complete forward- reverse measurement of the sensor in a 16 bit 2's complement format (range: -32768 to 32767). Note this is different from Standard Mode, where a 24 bit value is returned.

- SSN pin is set LOW. (This enables communication with the master device.)
- CLEAR pin is set HIGH, then LOW. This is not required, but is optional to maintain compatibility with the legacy 11096 ASIC.
- A command byte is clocked into the 3D MagIC on the MOSI pin. Simultaneously, the 3D MagIC will present a fixed $9B_H$ on the MISO pin. Once the 8 bits have clocked in, the 3D MagIC will execute the command (i.e. take a measurement).

- The SSN input may be returned HIGH at this point to free up host communication with another device if desired. This will not affect the measurement process.
- A measurement is taken, which consists of forward biasing the sensor and making a period count; then reverse biasing the sensor and counting again; and then taking the difference between the two directions and presenting this value.
- At the end of the measurement, the DRDY pin is set HIGH, indicating data is ready, and the 3D MagIC is placed in Idle Mode.
- The SSN input should be set LOW, if it is not already, to read the data.
- The data is clocked out on the MISO pin with the next 16 clock cycles.

If another measurement is to be made immediately, the SSN pin can remain low and the process repeated. Otherwise, it generally is recommended to set the SSN pin HIGH to release the SPI serial bus.

6.2 Enhanced Legacy Operation

Note: Enhanced Legacy Operation involves improving performance of a legacy system by implementing only software changes. If the user can make both software and hardware changes, then operation in Standard Mode is recommended as it allows for multi-axis measurement operation and finer granularity in establishing the number of cycle counts.

The 3D MagIC incorporates a Clock Divide Register that effectively divides the 3D MagIC's high-speed internal clock by some integer value (Clock Divide Value). In Legacy Mode the default is 16 as this results in performance matching that of the 11096 ASIC at similar Period Select values. But for the most efficient operation, the value should be 1 since this gives the greatest time-based resolution. If a legacy user cannot set pin #12 to DVSS to operate in Standard Mode, but can make code changes, it is possible to significantly reduce power consumption (see Table 6-4) by over-writing the Legacy Mode default Clock Divide Value and using a smaller Period Select value. In this case, the user first will write to the Clock Divide Register and after this follow the same process as for Legacy Operation, except with a different Period Select value.

For example, if a user operates in default Legacy Mode and sets the Period Select value to 5, the cycle count will be 1024 and the effective clock speed with be ~2.8 MHz. By changing the Clock Divide value from 16 (Legacy Mode default) to 1, the effective clock speed increases to ~45 MHz. With this significantly higher clock speed, the Period Select value can be reduced to 1 (64 cycle counts) such that the gain remains unchanged but the time to take the measurement, and hence power consumption, is dramatically reduced.

6.2.1 Clock Divide Command Byte

The Command Byte to initiate reading or writing to the Clock Divide Register is defined as follows:

Bit #	7	6	5	4	3	2	1	0
Value	1	R/W	0	0	0	0	0	0

R/W: Read/Write

When HIGH signifies a Read operation from the Clock Divide Register. When LOW signifies a Write operation to the Clock Divide Register.

6.2.2 Clock Divide Register

The Clock Divide Register is defined as follows:

Bit #	7	6	5	4	3	2	1	0
Value	0	0	0	0	0	CD2	CD1	CD0

Table 6-3: Clock Divide Bits

Clock Divide Value	CD2	CD1	CD0
1 (Standard Mode default)	0	0	0
2	0	0	1
4	0	1	0
8	0	1	1
16 (Legacy Mode default)	1	0	0
16	1	0	1
16	1	1	0
16	1	1	1

6.2.3 Command Sequence for Setting Clock Divide Value

A sample command sequence is given below which sets the Clock Divide Value to "1".

- Set SSN to LOW.
- Send 80_H (this is the Command Byte to write to the Clock Divide Register)
- Send 0 (this sets the Clock Divide Value to "1")
- Set SSN to HIGH

6.2.4 Changes to the Period Select Value

Since the high-speed clock is running faster, the time resolution of the measurement is increased. Consequently, the number of cycle counts required to achieve a desired magnetic field resolution is substantially reduced, and the Period Select value in the Legacy Command Byte should be altered. Generally speaking, the best performance will be obtained with the Clock Divide Value set to 1.

Table 6-4: Enhanced Legacy Mode with CD = 1

Default Legacy		Enhanced Legacy with CD = 1			
Period Select	Cycle Counts	Equivalent[1] Period Select	Cycle Counts	Power Consumption	Gain
0	32	0	32	same	16x greater
1	64	0	32	~40% reduction	8x greater
2	128	0	32	~65% reduction	4x greater
3	256	0	32	~80% reduction	2x greater
4	512	1	64	~90% reduction	Same
5	1024	2	128	~90% reduction	Same
6	2048	3	256	~90% reduction	Same
7	4096	4	512	~90% reduction	Same

Footnote:

1. Equivalent Period Select is defined as the Period Select Value that provides equivalent gain to the default Legacy Mode. If the Equivalent Period Select Value cannot be reduced (i.e. is at 0), then the improvement in Gain is shown.