KVH® 1725 Inertial Measurement Unit (IMU)

Technical Manual

1725 IMU

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This manual supports KVH Industries' 1725 Inertial Measurement Unit (IMU). The 1725 IMU is an ultra-compact, extremely precise, commercial strap-down inertial sensor system using KVH's advanced proprietary DSP-1750 fiber optic gyros combined with very low-noise MEMS accelerometers. The 1725 IMU is small, lightweight, low power, and rugged, offering accurate performance in extreme environments. Its flexible digital data and power interface is designed for ease of integration in new applications and upgrades to existing systems.

Technical and performance specifications, interface data, mounting guidelines, and a brief troubleshooting guide are included. For a more complete system overview, refer to "Appendix C: Electrical Signaling ICD" on page 31.

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QUALITY CERTIFIED SYSTEM ISO 9001

KVH Part # 54-1054 Rev. C

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Product Specifications

NOTE: *Performance specifications are based on a 1000 Hz data rate and 921.6 kbaud baud rate.*

Figure 1: 1725 IMU Specifications

Attribute	Value
Performance - Gyros	
Input Rate	±490°/s (max.)
Bias Instability (constant temp.)	0.05°/hr-1σ (typical) 0.1°/hr-1σ (max.)
Bias Offset (room temp.)	±5°/hr (max.)
Bias Temperature Sensitivity (1°C/minute ramp)	≤4°/hr-1σ
Scale Factor Non-Linearity	≤200 ppm-1σ (full rate)
Scale Factor Temperature Sensitivity	≤300 ppm-1σ
Angle Random Walk (ARW) (room temp.)	≤0.017°/√hr ≤1.0°/hr/√Hz
Input Axis Misalignment	±0.5 mrad
Bandwidth (-3 dB)	≥440 Hz
Performance - Accelerometers	
Input Range	±10 g
Bias Instability (1 year, full environment)	7.5 mg (typical) 25 mg (max.)
Bias Instability (room temp.)	≤0.1 mg-1σ
Bias Offset (room temp.)	±5 mg (max.)
Bias Temperature Sensitivity	≤2 mg-1σ (1°C/minute ramp)
Scale Factor Non-Linearity	<0.9% of full scale
Scale Factor Temperature Sensitivity	≤300 ppm/°C (max.)
Velocity Random Walk (room temp.)	≤0.23 ft/s/√hr ≤0.12 mg/√Hz
Input Axis Misalignment	±1 mrad
Bandwidth (-3dB)	≥200 Hz

Attribute	Value
Environment	
Temperature (operating)	-40°F to +167°F (-40°C to +75°C)
Temperature (storage)	-58°F to +185°F (-50°C to +85°C)
Vibration (operating)	8 g rms (20-2000 Hz, random) *Peak acceleration level limited to 10 g*
Vibration (non-operating)	12 g rms (20-2000 Hz, random)
Shock (operating)	9 g (11 ms, sawtooth)
Shock (non-operating)	40 g (11 ms, sawtooth)
Digital Data Output	
Format	RS422
Data Rate	1 to 1000 Hz, user-selectable
Baud Rate	9.6 to 921.6 kbaud, user-selectable
Turn-On Time (room temp.)	≤3.0 s (valid data)
Full Performance Time (room temp.)	≤60 s (typical)
Power Supply	
Input Voltage	9-36 VDC
Input Power	5 W (typical), 8 W (max.)
Package	
Weight	<1.45 lbs (0.7 kg)
Dimensions	Ø3.5" x 2.9" h (88.9 mm x 73.7 mm)

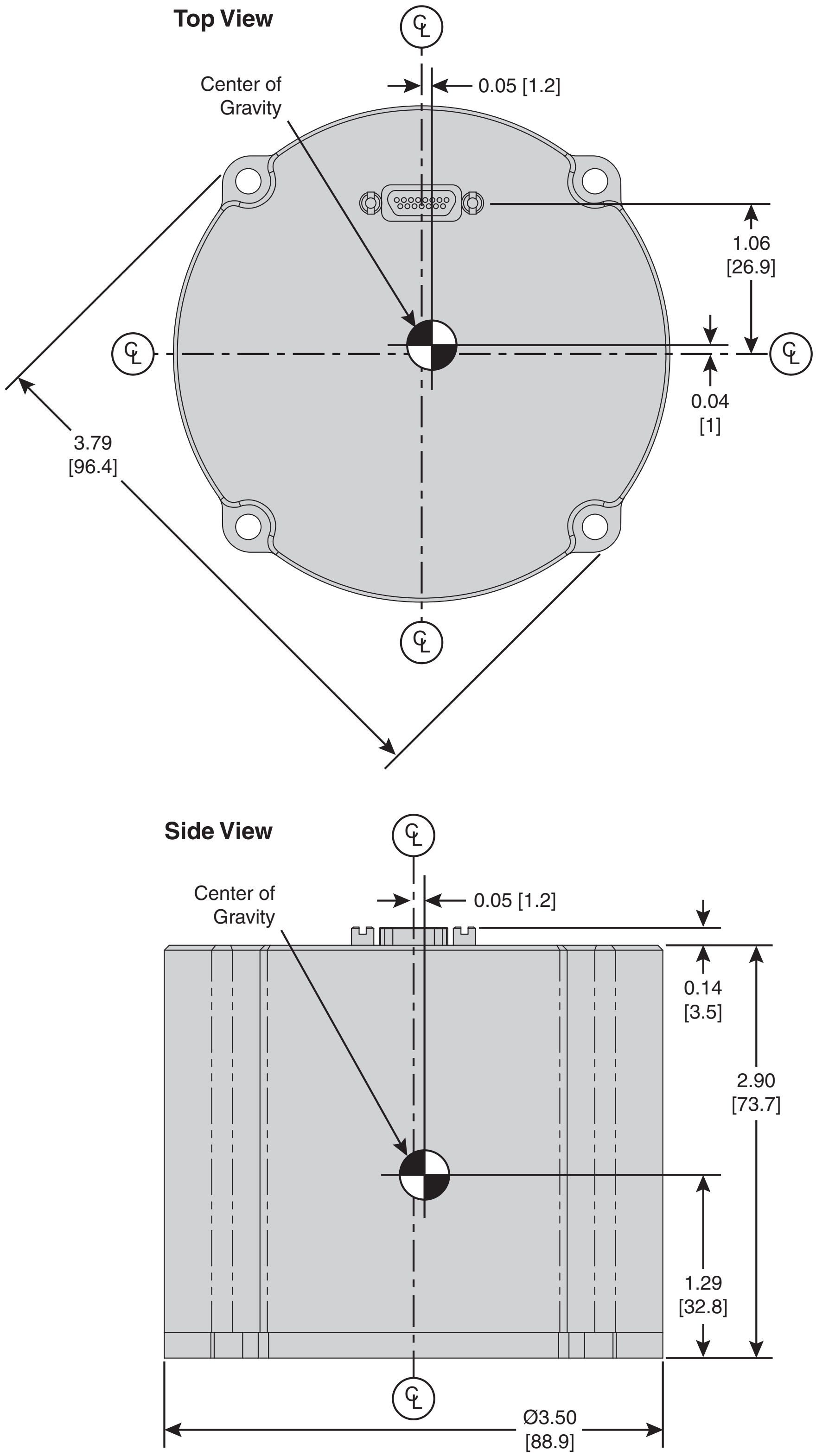
IMPORTANT!

The 1725 IMU is a precision instrument. Handle the unit with care and avoid exposing it to severe mechanical shock.

General dimensions are provided below.

NOTE: *All dimensions are shown in inches [millimeters] format.*

Figure 2: General Dimensions



Storage and Handling

The 1725 IMU may be stored in a location with an environmental temperature between -58°F to +185°F (-50°C to +85°C). Ideally, the unit should be stored at a room temperature of approximately 70°F (21°C).

IMPORTANT!

The 1725 IMU is a precision instrument. Handle the unit with care and avoid exposing it to severe mechanical shock.

The 1725 IMU is a sensitive measuring device. Take normal safety precautions when handling to ensure the integrity of the device. During unpacking and installation, proper ESD handling procedures should be enforced, per MIL-STD-1686C (Electrostatic Discharge Control Program for Protection of Electrical and Electronics Parts, Assemblies, and Equipment). The 1725 IMU has been tested to EN 61000-4-2, ESD Immunity for EMI/EMC.

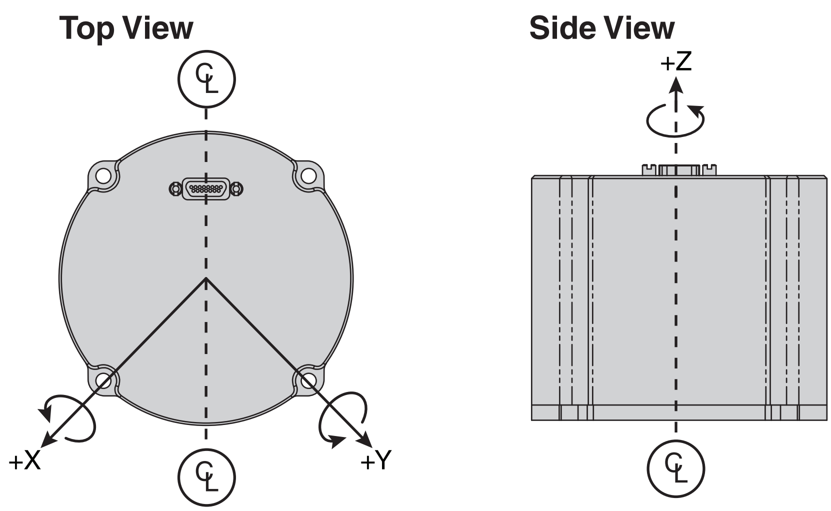
Maintenance

The 1725 IMU is supplied as a sealed unit; there are no field maintainable components. Opening the enclosure will void the warranty and may violate the contract under which the unit was supplied.

Output Orientation

The 1725 IMU senses acceleration and angular velocity on three physical axes, as shown in Figure 3. You may configure a rotation matrix to set the output axes relative to the physical orientation of these measurement axes, allowing the IMU to measure motion in three arbitrarily orthogonal axes (see “Configuration Options” on page 13). These settings are saved and reapplied on restart. You may revert to the factory default settings at any time (see “Resetting Parameters to Factory Defaults” on page 15).

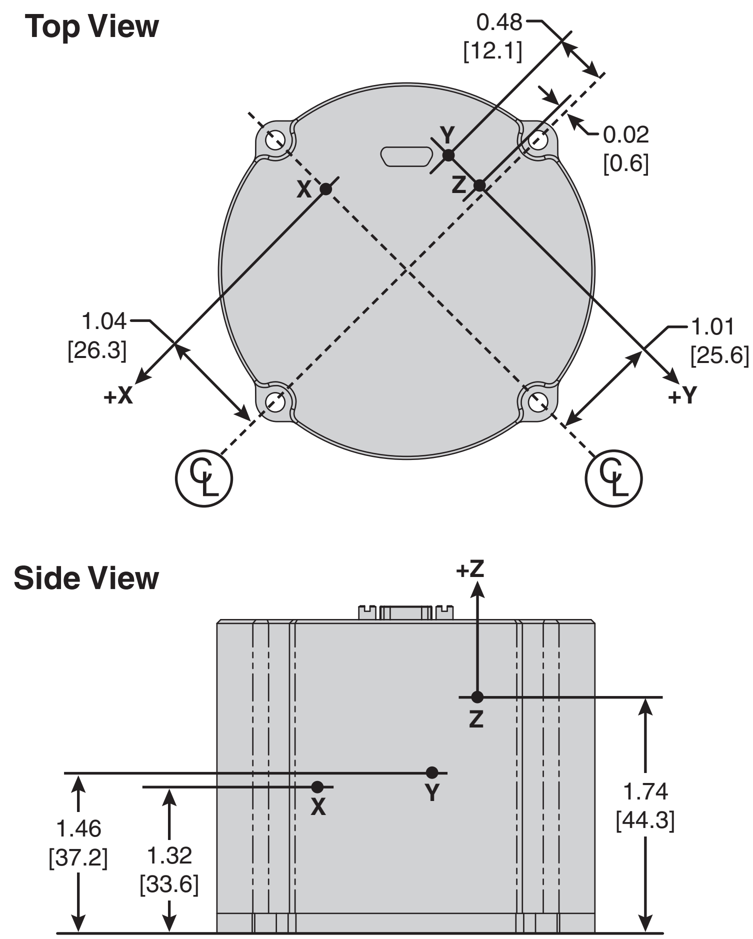
Figure 3: Gyro Measurement Axes Orientation



__NOTE:__ The three axes of rotation are coincident with the linear acceleration axes. Positive rotation is a counterclockwise rotation about an axis, following the right-hand rule. Linear acceleration polarity is such that the IMU will report +1 G due to Earth gravity when its + axis is up.

Figure 4 below shows the physical locations of the accelerometer axes and the location of the sensing point on each axis.

Figure 4: Accelerometer Axes and Sensing Points



Interface Connector

The 1725 IMU is equipped with a 15-pin (male) Micro-D interface connector of the following type: MIL-DTL-83513. Figure 5 shows the connector location. Figure 6 describes the function of each pin. For more information, refer to "Appendix C: Electrical Signaling ICD" on page 31.

Figure 5: Interface Connector Location

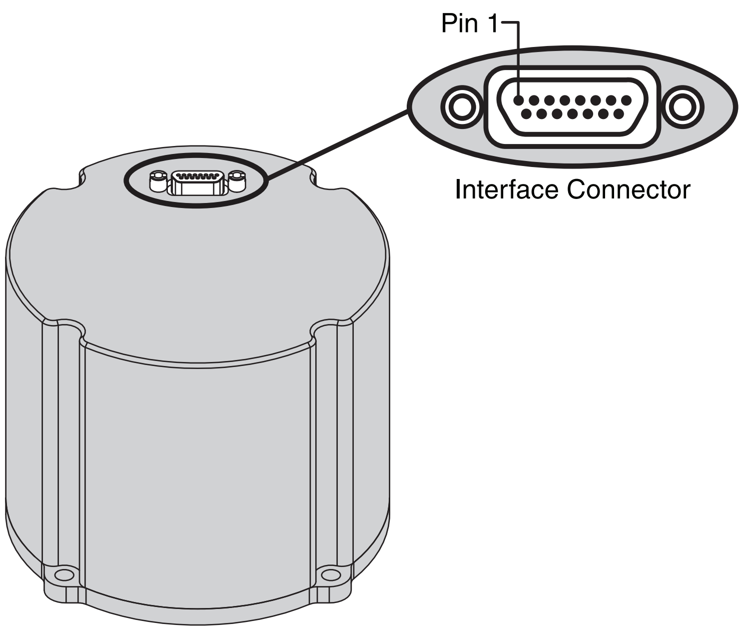


Figure 6: Interface Connector Pins

Pin	Type	Description
1	RS422-TX (+)	IMU RS422 Transmit High
2	RS422-TX (–)	IMU RS422 Transmit Low
3	RS422-RX (–)	IMU RS422 Receive Low
4	RS422-RX (+)	IMU RS422 Receive High
5	EXT-RST (–)	IMU Reset Low (Optional)
6	Config-RST-In (–)	IMU Configuration Reset Low (Optional)
7	MSync (–)	Master Sync Low (External Clock) (Optional)
8	TOV-Out (–)	Time of Validity Signal Low (Optional)
9	Power (–)	Power Return

Pin	Type	Description
10	Power (+)	9-36 VDC Power
11	MSync (+)	Master Sync High (External Clock) (Optional)
12	TOV-Out (+)	Time of Validity Signal High (Optional)
13	Config-RST-In (+)	IMU Configuration Reset High (Optional)
14	EXT-RST (+)	IMU Reset High (Optional)
15	Signal-GND	Do Not Connect

Interface Cable

The power and data interface cable must be fitted with a 15-socket (female) Micro-D connector per MIL-DTL-83513 with a Flourosilicone interfacial seal. You can purchase a 24" (60 cm) shielded interface cable with this connector from KVH (KVH part no. 32-1293-02).

If your application requires a serial cable or interface adapter (such as an RS422-USB serial adapter), make sure it is compatible with the IMU and supports speeds of at least 1 Mbps baud (KVH recommends USB converter Startech ICUSB422 or equivalent set at RS-422, no echo, no term). Also be sure to use shielded cables to prevent signal loss and noise interference.

Data Communications Equipment

A computer or other data communications device is necessary to communicate with the IMU. This equipment's serial port communications must match the IMU’s serial port settings for proper operation.

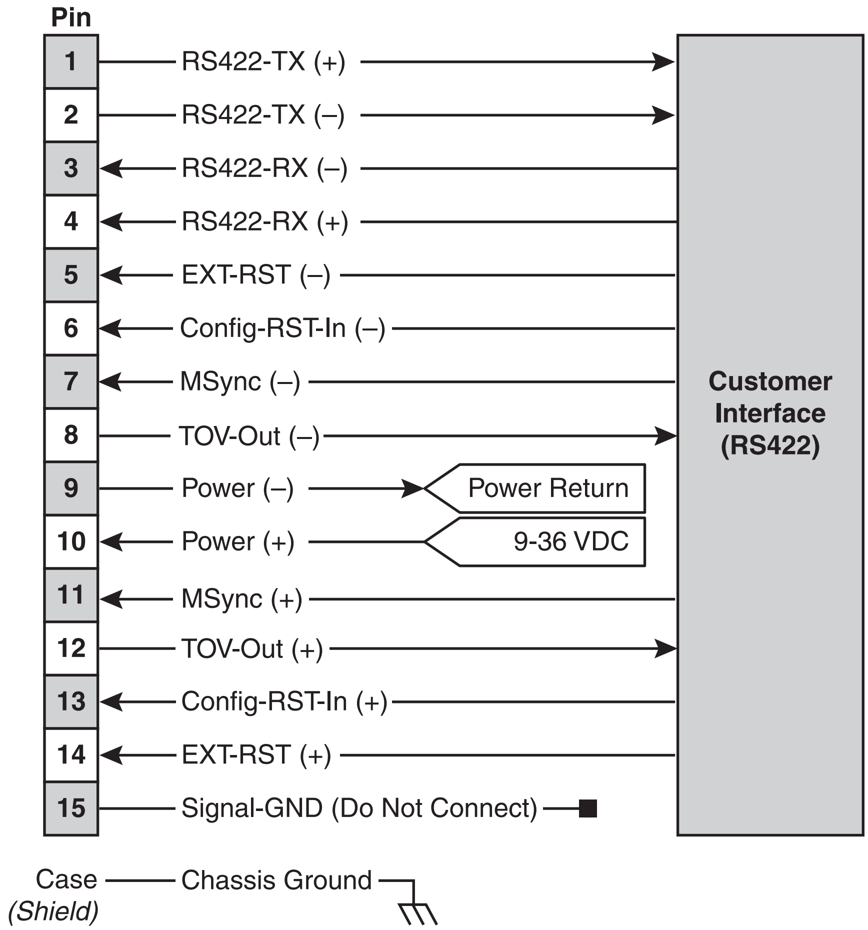
When connected to the IMU, you can enter commands directly from the terminal or through a terminal emulation application.

Use RS-422 differential signaling methods for all 1725 IMU digital control signals (KVH preferred). Alternatively, RS-422 single-ended signaling may be used if cabling susceptibility and other environmental interferences are proven acceptable. For more information, refer to “Appendix C: Electrical Signaling ICD” on page 31.

Wiring the IMU

Use Figure 7 as a guide to connect the IMU to your application. For more information, refer to "Appendix C: Electrical Signaling ICD" on page 31.

Figure 7: Wiring Diagram



Digital Data Output

The IMU provides a digital interface with the following characteristics:

Figure 8: Interface Characteristics

Parameter	Value
Type	RS422
Baud Rate	Selectable: 9600, 19200, 38400, 57600, 115200, 460800, 576000, 921600 (default)
Parity	None
Start Bits	1 (space, binary 0)
Data Bits	8 (1 message byte, starting with LSB)
Stop Bits	1 (mark, binary 1)
Flow Control	None

An idle line is always marking (in a binary 1 state). Thirty-six (36) characters in sequence constitute a basic message with default settings. For more information, refer to "Appendix C: Electrical Signaling ICD" on page 31.

NOTE: *The IMU's RS422 RX signals are internally terminated to a nominal impedance of 100Ω.*

Data Output Signal Processing

For information about data output signal processing, refer to "Appendix C: Electrical Signaling ICD" on page 31.

Message Structure

Figure 9 and Figure 10 provide an example of the output format and data. For more information, refer to "Appendix C: Electrical Signaling ICD" on page 31.

Figure 9: Example Message Format

Function	Total # Bytes	Description
Header	4	Always 0xFE81FF55; this value will never occur anywhere else
Message data	28	Refer to "Appendix C: Electrical Signaling ICD" on page 31.
CRC	4	See Figure 12 on page 12

Figure 10: Example Message Data Format

Datum	Byte Number(s)	Data Type*	Units	Notes
X rotational data	5,6,7,8	SPFP	Radians or degrees, selectable	MSB (Byte 5) is output first; delta-angle, rate of rotation, selectable
Y rotational data	9,10,11,12	SPFP	Radians or degrees, selectable	MSB (Byte 9) is output first; delta-angle, rate of rotation, selectable
Z rotational data	13,14,15,16	SPFP	Radians or degrees, selectable	MSB (Byte 13) is output first; delta-angle, rate of rotation, selectable
X acceleration	17,18,19,20	SPFP	g	MSB (Byte 17) is output first
Y acceleration	21,22,23,24	SPFP	g	MSB (Byte 21) is output first
Z acceleration	25,26,27,28	SPFP	g	MSB (Byte 25) is output first
Status	29	DISC	1 = valid data 0 = invalid data	See Figure 11 on page 12
Sequence number	30	UINT8	0-127	Increments for each message and resets to 0 after 127
Temperature	31,32	INT16	°C, 1/100 °C, °F, 1/100 °F, selectable	MSB (Byte 31) is output first

* *SPFP = Single Precision Floating Point (IEEE-754); DISC = Discrete Data; UINT8 = Unsigned 8-bit integer; INT16 = Signed 16-bit integer*

Figure 11: Status Byte Format

Function	Bit #	Notes
Gyro X status	0 (LSB)	1 = Valid data, 0 = Invalid data
Gyro Y status	1	1 = Valid data, 0 = Invalid data
Gyro Z status	2	1 = Valid data, 0 = Invalid data
Reserved	3	Always 0
Accelerometer X status	4	1 = Valid data, 0 = Invalid data
Accelerometer Y status	5	1 = Valid data, 0 = Invalid data
Accelerometer Z status	6	1 = Valid data, 0 = Invalid data
Reserved	7	Always 0

NOTE: *In addition to this general status information, an extended built-in test (BIT) may be initiated by entering the "**?bit**" or "**?bit,2**" command. (Extended BIT data is also output whenever the IMU is first powered on.) The extended BIT provides six bytes of diagnostic data. The 1725 IMU records and reports stored BIT history as an optional diagnostic aid. For more information, refer to* *"Appendix C: Electrical Signaling ICD" on page 31*.

Figure 12: CRC Format

Parameter	Value
Width	32
Poly	0x04C11DB7
Reflect In	False
XOR In	0xFFFFFFFF
Reflect Out	False
XOR Out	0

NOTE: *The 32-bit CRC used for message data verification ensures the data received (or transmitted) is valid.*

Configuration Options

The 1725 IMU offers many user configurable parameters. These parameters can optimize the 1725 IMU performance for specific application needs (e.g., faster update rates for higher dynamic conditions, very low latency sensing and time synchronization, digital signal processing filters, and options for ease of platform installation and interfacing to control systems). In addition to the default and standard user options available, customized digital filters are also supported. Figure 13 lists the User-Configuration options. For more information, refer to "Appendix C: Electrical Signaling ICD" on page 31.

Figure 13: User-Configurable Parameters

Parameter	Command	Options		Default
Baud Rate	=BAUD,<*x*>	9600 19200 38400 57600	115200 460800 576000 921600	921600
Data Rate (Hz)	=DR,<*x*>	1 5 10 25 50	100 250 500 750 1000	1000
Temperature Units	=TEMPUNITS,<*x*>	C F C_100 *(1/100 expanded resolution)* F_100 *(1/100 expanded resolution)*		C
Angular Units	=ROTUNITS,<*x*>	DEG RAD RESET		RAD
Angular (Gyro) Data Format	=ROTFMT,<*x*>	DELTA *(radians or degrees -- refer to the footnote on page 14 for a definition)* RATE *(radians or degrees per second)* RESET		DELTA

Parameter	Command	Options	Default
Output Filter	=FILTEN,<*x*>	0 *(disabled)* 1 *(enabled)*	1
	=FILTTYPE,A,<*x*> *(accel)* or =FILTTYPE,G,<*x*> *(gyro)*	CHEBY *(Chebyshev type II low-pass)* BUTTER *(Butterworth low-pass)* AVE *(Uniform Averager)*	CHEBY
	=FC,A,<*x*> (*accel*) or =FC,G,<*x*> (*gyro*)	Custom (*accelerometer or gyro filter coefficients*)	CHEBY
X, Y, Z Axis Definitions	=AXES, [X0], [X1], [X2], [Y0], [Y1], [Y2], [Z0], [Z1], [Z2]	Floating point values defining a 3x3 rotation matrix sets the output axes relative to the physical orientation of measurement axes (see page 5)	1 0 0 0 1 0 0 0 1
Output Synchronization	=MSYNC,<x>	EXT *(external)* IMU	IMU
Linear (Accelerometer) Data Format	=LINFMT,<x>	ACCEL DELTA *(refer to the footnote below)* RESET	ACCEL
Linear (Accelerometer) Data Units *(only applies if data output is set to delta)*	=LINUNITS,<x>	METERS *(mps)* FEET *(fps)* RESET	METERS

NOTE: *Delta units for acceleration (delta-velocity) and rotation (delta-angle) are computed based on the final output data and the data output rate. They represent the increment of motion for the output time period.*

For more information, refer to "Appendix C: Electrical Signaling ICD" on page 31. Settings are saved and reapplied on restart. You may revert to the factory default settings at any time (see "Resetting Parameters to Factory Defaults" on page 15).

NOTE: *Changing parameters from their default values may impact performance.*

You can query the current value of any parameter by entering the corresponding “**?**” command (e.g., to view the current data rate, you would enter the “**?dr**” command).

To enter any configuration command, the IMU must first be set to Configuration mode. In Configuration mode, the IMU stops sending data and listens for user commands (a terminal prompt indicates the IMU is ready to accept commands). To put the IMU in Configuration mode, enter the “**=config,1**” command. When you are done configuring the unit, enter the “**=config,0**” command to exit Configuration mode and return to the Normal mode of operation.

Resetting Parameters to Factory Defaults

There are two options for resetting all of the user-configurable parameters to their factory default values (see Figure 14).

Option 1: Enter the “**=rstcfg**” command in Configuration mode.

Option 2: Apply a positive RS-422-compliant voltage from pin 6 (Config-RST-In (-)) to pin 13 (Config-RST-In (+)) before applying power, and hold it at that level until the unit starts outputting data. The pins may be left disconnected until you need to perform a reset.

Figure 14: Default Values

User-Configurable Parameters	Default Value
Linear Format	Acceleration
Linear Units	Meters per second
Angular Units	Radians
Angular Format	Delta angle
Temperature Units	°C
Temperature Data Resolution	1°
Baud Rate	921600 baud
Data Rate	1000 Hz
Filter Type	Chebyshev Type II
Clock Source	IMU

NOTE: *The baud rate will default for Config-RST-In; baud rate will* not *change for =rstcfg command (Rev. C or later software).*

User Commands

In addition to the configuration commands described in "Configuration Options" on page 13, the following commands are also available to the user. For more information, refer to "Appendix C: Electrical Signaling ICD" on page 31.

Figure 15: User Commands

Command	Description
?bit	Initiates a built-in test in Normal mode
?bit,2	Initiates a built-in test in Normal mode with extended diagnostic information
=config	Forces the unit into or out of Configuration mode
?config	Reports whether or not the IMU is currently running in Configuration mode
=echo *(or ?echo)*	Reports how many times the echo command has been called; useful for verifying communications to the unit
=help *(or ?help)*	Displays a list of available commands
?is	Reports the system serial number
=restart	Restarts the IMU
=rstcfg	Resets all user-configurable parameters to their factory default values
?temp	Reports the internal temperature of the IMU; detected by the controller board
=TestFilt *(or ?TestFilt)*	Tests the configured output filter response to a unit impulse
?volt	Reports all available voltages on the controller board
?ws	Reports the software versions of IMU components
?logs	Reports stored BIT diagnostic history

All commands must be entered while the IMU is in Configuration mode except "?bit", "?bit,2", *(entered in Normal mode)* and "=config" *(entered in Configuration or Normal mode)*.

Time of Validity (TOV) Output

The 1725 IMU provides an optional RS-422 differential output on the external connector (named TOV-OUT+/TOV-OUT-) to indicate the time at which the data being output on the serial port can be considered to be valid. TOV should not be used or considered valid when operating the IMU in modes other than Normal Mode (e.g., in Configuration mode). TOV signaling is based on the IMU's internal clock and shown in Figure 16. For more information, refer to "Appendix C: Electrical Signaling ICD" on page 31.

Figure 16: TOV Output Timing Relative to Serial Port Activity

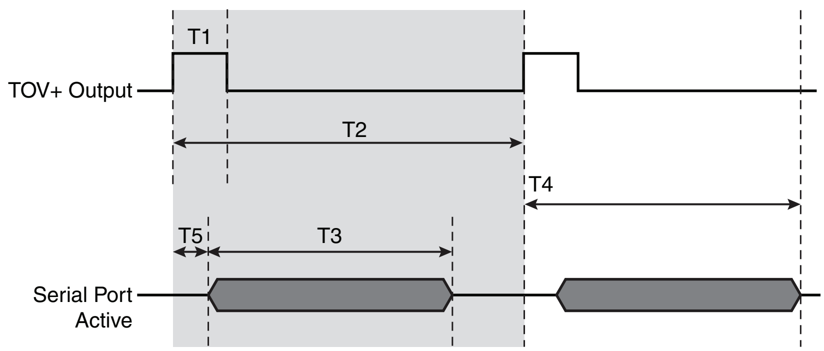


Figure 17: User-Configurable Parameters

Parameter	Description	Value
T1	TOV high	Depends on MSYNC configuration; MSYNC,IMU: high time is 10% of the TOV period (e.g., at default rate of 1,000 Hz, the T1 high time will be 100 μs for internal clock mode) MSYNC,EXT: high time is approximately the same as the external MSYNC signal active time
T2	TOV period	Depends on MSYNC configuration; MSYNC,IMU: Period is determined by the output data rate (e.g., at default data rate of 1,000 Hz, T2 = 1000 μs) MSYNC,EXT: period reflects the external MSYNC signal

Parameter	Description	Value
T3	Duration of serial port output	Depends on output format and baud rate; approximately equal to the number of characters output multiplied by the number of bits per character (10) divided by the baud rate (e.g., at default baud rate of 921600 Bd, T3 is approx 390 μs)
T4	Time between rising edge of TOV-Out and the end of data transmission	<500 μs (at default baud rate of 921600 Bd)
T5	Time between start of TOV and the start of T3	30 to 100 μs (typical)

Master Sync (External Data Request)

MSYNC is an optional 1725 IMU timing synchronization method used for external control systems. An external (master synchronization) differential signal input will trigger the IMU output at its rising edge. The 1725 IMU can accept an optional user-supplied RS-422 differential master sync input signal on pin 7 (MSync (-)) and pin 11 (MSync (+)). The IMU's output will be triggered on the rising edge of this master sync signal. *The 1725 IMU master sync signal input supports both isosynchronous and non-isosynchronous signaling methods of transmission synchronization.* Use of the external MSYNC option can affect, or be affected by other configuration settings. For more information, refer to "Appendix C: Electrical Signaling ICD" on page 31.

Figure 18: Master Sync

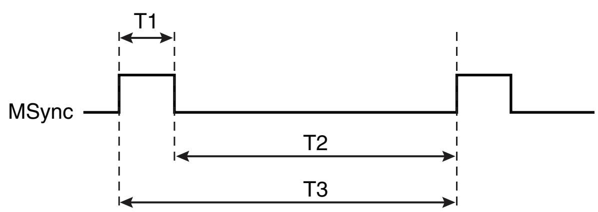


Figure 19: MSync Timing Parameters

Parameter	Description	Value
T1	MSync high	≥30 μs
T2	MSync low	≥30 μs
T3	Period between rising edges	1.0-2000 ms

To synchronize the IMU's output with an external signal on pin 7 and pin 11, enter the "**=MSYNC,ext**" command in Configuration mode. Upon initiating the "**=MSYNC,ext**" command, the IMU automatically clears any user-selected output filter and switches to the Uniform Averager setting. This allows you to use the MSync signal as an external request for data, rather than using internally timed data output. However, you may override this behavior by choosing any output filter using the appropriate Output Filter commands provided in Figure 13 on page 13. Be sure to enter the Output Filter commands AFTER you have entered the "**=MSYNC,ext**" command.

NOTE: *Consecutive rising edges of the MSync signal must be between 1.0-2000 ms apart. Pulsing MSync faster than 1.0 ms may result in inaccurate or corrupt data output. If the IMU does not detect a rising edge within 2000 ms, it will output data upon reaching 2000 ms.*

TOV with Internal MSYNC Mode

When the IMU is providing its own data output requests based on its internal source's preconfigured rate, the unit outputs the differential TOV signal with a 10% duty cycle at the same frequency as the data output. See the timing diagram shown in Figure 16 on page 17, as well as the timing parameters in Figure on page 17.

TOV with External MSYNC Active

When the external Master Synchronization Input is configured, the IMU will simply buffer (i.e., repeat) the MSYNC signal back out to the TOV signal. Therefore, the timing should closely mirror that of the external MSYNC signal.

Hardware Restart

Applying a positive RS-422-compliant voltage from pin 5 (EXT-RST (-)) to pin 14 (EXT-RST (+)) will result in a reset. These pins may be left disconnected until you need to restart the IMU.

Mounting the IMU

The 1725 IMU is easily mounted to a structure using the four ∅0.173" (∅4.39 mm) mounting holes on the base of the enclosure (see Figure 20). An alignment hole ∅0.198" (∅5.03 mm) and an alignment slot 0.218" x 0.198" (5.54 mm x 5.03 mm) are provided at the middle edge of the enclosure for alignment purposes. They are designed for ∅5.004-5.012 mm dowel pins with 0.1" (2.5 mm) protrusion.

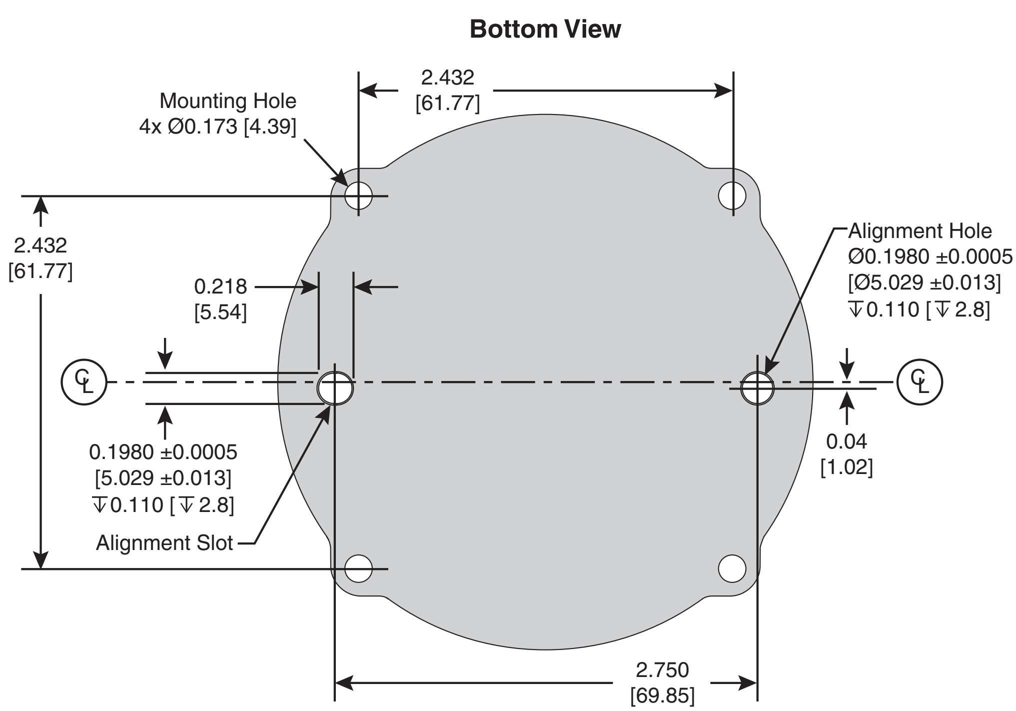
NOTE: *To ensure precise alignment, rotate the IMU clockwise in reference to the top of the unit, before tightening the mounting screws.*

The IMU base material is aluminum with a clear chromate finish per MIL-DTL-5541, class 3. To ensure optimal heat transfer (conductive cooling) and electrical grounding through the chassis, mount the IMU base to a clean, flat, unpainted metal surface.

Also be sure to orient the IMU with the desired measurement axes. As an alternative, you may configure a rotation matrix to set the output axes relative to the physical orientation of the measurement axes (see “Configuration Options” on page 13).

NOTE: *All dimensions are shown in inches [millimeters] format.*

Figure 20: Mounting Holes (Bottom View)



Troubleshooting

This chapter explains how to diagnose basic problems.

IMPORTANT!

The 1725 IMU is supplied as a sealed unit. Breaking the QA seals voids the warranty and may violate the contract under which the unit was supplied. The warranty does not apply if the unit has been damaged by misuse or as the result of service or modification other than by KVH Industries.

Figure 21: Basic Troubleshooting

Problem	Solution
The unit does not power up.	Check the input power supply. 12 VDC (nominal) is recommended for stable performance. The supply should also draw between 3-8 W over the entire operating temperature range. If the power supply is OK, check the power cable and wiring.
The unit does not communicate.	Check the interface cable and make sure your equipment's serial port settings match the IMU's settings (see Figure 8 on page 10).
Incoherent data is streaming.	Ensure the baud rate of your interface port is set to one of the valid configurable baud rates (see Figure 8 on page 10 for details). Also make sure your parsing algorithm is correct.
The unit is not sending data at the set data rate.	Ensure the set baud rate is fast enough to support the chosen data rate (see Figure 22 on page 23). Verify with an oscilloscope.

Figure 22: Recommended Baud Rate/Data Rate Limits

Baud Rate	Maximum Data Rate (Hz)
9600	10
19200	25
38400	50
57600	100
115200	100
460800	500
576000	750
921600	1000

Built-In Test (BIT)

The IMU's built-in test (BIT) monitors system performance and status to ensure it is operating within its specifications. BIT test results are output in five ways:

- **Continuous BIT** – The Continuous BIT is output as part of the IMU's output message during operation (see "Continuous BIT Status Information" on page 24).
- **Startup Extended BIT** – When the IMU is powered on, it outputs the extended BIT status message (see "Extended BIT Status Information" on page 24).
- **User-requested Extended BIT** – When you enter the "**?bit**" command in Normal mode, the IMU outputs the extended BIT status message (see "Extended BIT Status Information" on page 24).
- **User-requested Extended BIT, 2** – When you enter the "**?bit,2**" command in Normal mode, the IMU outputs expanded diagnostics information (see "Extended BIT, 2 Status Information" on page 25).

NOTE: *Extended BIT, 2 may impact high-speed outputs while transmitting.*

- **BIT Log** – When BIT information is generated, a log report is created. This log is accessible by entering the "**?logs**" command in Configuration mode.

Continuous BIT Status Information

As detailed in the message structure data table example on page 11, byte 24 of the IMU's output message (excluding the message header) reports the general status of the gyros and accelerometers. Converted to hexadecimal, a "77" status byte indicates normal status. For more information, refer to "Appendix C: Electrical Signaling ICD" on page 31.

Figure 23: Status Byte Format

Datum	Bit #	Notes
Gyro X	0 (LSB)	1 = Valid data, 0 = Invalid data
Gyro Y	1	1 = Valid data, 0 = Invalid data
Gyro Z	2	1 = Valid data, 0 = Invalid data
Reserved	3	Always 0
Accelerometer X	4	1 = Valid data, 0 = Invalid data
Accelerometer Y	5	1 = Valid data, 0 = Invalid data
Accelerometer Z	6	1 = Valid data, 0 = Invalid data
Reserved	7	Always 0

Extended BIT Status Information

When the IMU is first powered on, and upon user request, the IMU outputs an extended BIT message consisting of a header, six data bytes, and checksum. The six data bytes indicate the status information for built-in diagnostic tests. For more information, refer to Figure 24. Converted to hexadecimal, the following message indicates normal status: "FE 81 00 AA 7F 7F 7F 7F 7F 7F 23".

Figure 24: Extended BIT Message Format

Function	Total # Bytes	Description
Header	4	0xFE8100AA
Message data	6	Refer to "Appendix C: Electrical Signaling ICD" on page 31.
Checksum	1	Calculated by accumulating the sum of each byte of data, modulo 256

Extended BIT, 2 Status Information

Upon user request, the IMU outputs an extended BIT message consisting of eight bytes of expanded status information for diagnostics. For more information, refer to Figure 25. Converted to hexadecimal, the following message indicates normal status: “FE 81 00 AB 7F 7F 7F 7F 7F 7F 7F 7F 22”.

Figure 25: Extended BIT, 2 Message Format

Function	Total # Bytes	Description
Header	4	0xFE8100AB
Message data	8	Refer to “Appendix C: Electrical Signaling ICD” on page 31.
Checksum	1	Calculated by accumulating the sum of each byte of data, modulo 256

Technical Support

For technical support, please email your question or a description of your problem to fogsupport@kvh.com.

Appendix A: Patent Protection

One or more of the following U.S. and international patents* protect the technology in KVH fiber optic gyros:

KVH Patent Numbers	
DE 69722994	US 6,041,149
DE 69734809.1	US 6,134,356
EP 60130780 T2	US 6,351,310 B1
EP 1,314,002	US 6,370,289 B1
FR 0802397	US 6,429,939
GB 0802397	US 6,466,596
US 5,126,666	US 6,542,651
US 5,340,371	US 6,563,589
US 5,444,534	US 6,718,097
US 5,481,358	US 6,763,153
US 5,552,887	US 6,836,334
US 5,739,944	US 7,120,323
US 5,768,462	

**Additional patents pending*

Appendix B: Warranty Information

KVH Industries Limited Warranty 1725 IMU Technical Manual IMU

LIMITED WARRANTY ON HARDWARE

KVH Industries, Inc. warrants the Inertial Measurement Unit purchased against defects in materials and workmanship for a period of ONE (1) year from the date of original retail purchase by the original purchaser. If you discover a defect, KVH will, at its option, repair, replace or refund the purchase price of the product at no charge to you, provided you return it during the warranty period, transportation charges prepaid, to the factory direct.

Please attach your name, address, telephone number, a description of the problem and a copy of the bill of sale or sales receipt as proof of date of original retail purchase, to each product returned to warranty service.

This Limited Warranty does not apply if the product has been damaged by accident, abuse, misuse, or misapplication or has been modified without the written permission of KVH; if any KVH serial number has been removed or defaced; or if any factory-sealed part of the system has been opened without authorization.

THE EXPRESS WARRANTIES SET FORTH ABOVE ARE THE ONLY WARRANTIES GIVEN BY KVH WITH RESPECT TO ANY PRODUCT FURNISHED HEREUNDER; KVH MAKES NO OTHER WARRANTIES, EXPRESS, IMPLIED OR ARISING BY CUSTOM OR TRADE USAGE, AND SPECIFICALLY DISCLAIMS ANY WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. SAID EXPRESS WARRANTIES SHALL NOT BE ENLARGED OR OTHERWISE AFFECTED BY TECHNICAL OR OTHER ADVICE OR SERVICE PROVIDED BY KVH IN CONNECTION WITH ANY PRODUCT.

KVH's liability in contract, tort or otherwise arising out of or in connection with any product shall not exceed the price paid for the product. **IN NO EVENT SHALL KVH BE LIABLE FOR SPECIAL, PUNITIVE, INCIDENTAL, TORT OR CONSEQUENTIAL DAMAGES OR LOST PROFITS OR GOODWILL (INCLUDING ANY DAMAGES RESULTING FROM LOSS OF USE, DELAY IN DELIVERY OR OTHERWISE) ARISING OUT OF OR IN CONNECTION WITH THE PERFORMANCE OR USE OR POSSESSION OF ANY PRODUCT, OR ANY OTHER OBLIGATIONS RELATING TO THE PRODUCT, EVEN IF KVH HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.**

If any implied warranty, including implied warranties of merchantability and fitness for a particular purpose, cannot be excluded under applicable law, then such implied warranty shall be limited in duration to ONE (1) YEAR from the date of the original retail purchase of this product by the original purchaser.

Some states do not allow the exclusion or limitation of implied warranties or liability for incidental or consequential damages, so the above limitations may not apply to you. This warranty gives you specific legal rights, and you may also have other rights which vary from state to state.

Appendix C: Electrical Signaling ICD

The Electrical Signaling Interface Control Document (ICD) describes in detail the serial communications, electrical, and physical interfaces between the 1725 IMU and outside systems. The ICD also provides a thorough overview of all commands, queries, and configuration options. Refer to the ICD for comprehensive details about the following:

- Overview of the electrical interface
- Description of operating modes and message formats, Time of Validity output, and MSYNC
- Instructions for conducting and interpreting the results of a Built-In Test
- Comprehensive list of all user commands, queries, and configuration options
- Description of every command and query
- Overview of data output signal processing formats

1725 Inertial Measurement Unit

External Electrical Signaling

Interface Control Document

56-0324 Rev B

November 12, 2015

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Revision History

Date	Description	Rev
1/20/2015	Document Creation	A
11/12/2015	Rev. B ECO #11456	B

Rev. B list of changes:

1) Updated signal interface to add differential signals; pins 5-8 used to be no-connects; pin 15 now recommended as no-connect
2) Added extended BIT,2 mode; eliminated Gyro PZT Temperature Status in BIT test results (byte 2 changed to Reserved)
3) Significant rewrite to intro and summary descriptions
4) Added signal processing theory (see Section 12)
5) Improved command descriptions; esp. =AXES and filtering related; added 100ths mode to temperature units
6) Added internal BIT logging of certain unit conditions to aid customer support.
7) Added optional arguments to TESTFILT to control output by sensor and number of samples.

1 Scope

This Interface Control Document (ICD) describes the serial communications and the electrical and physical interfaces between the 1725 Inertial Measurement Unit (IMU) and the outside world.

The “1725 IMU,” also referred to as “the unit,” “the IMU,” or “the system,” is the product at large.

Other related documents include the Technical Manual (KVH part no. 54-1054) and the Interface Control Drawing (KVH part no. 99-0379).

2 Terms and Definitions

Table 2-1: List of Terms and Definitions Used

Term	Definition
Accel	accelerometer and acceleration
ASCII	American Standard Code for Information Interchange; a character-encoding standard that specifies 128-characters into a 7-bit binary value.
BIT	Built-in Test
Baud	Communications rate as symbols/sec (typical unit symbol is Bd); the IMU outputs at 1 bit per symbol therefore baud equates to bits/sec.
CRC	Cyclic Redundancy Check
DELTA	In reference to accelerometer or gyro data output, DELTA type is computed as the output value multiplied by the time since the last output data. Therefore, it is a measure of motion since the prior data message.
DISC	Discrete data format, as opposed to an integer or floating-point value. For our purposes, discrete values are bit fields (e.g., bit 0 of a status byte indicates whether gyro X is outputting valid data).
DSP	Digital Signal Processor
Float	Same as SPFP
FOG	Fiber Optic Gyro
FPGA	Field Programmable Gate Array
g	Unit designation for g-force when associated with accelerometer data output
GCB	Gyro Control Board; a sub-system for gyro measurement
Gyro	Gyroscope
Hex	Hexadecimal notation. Often denoted by preceding the number with “0x”
ICB	IMU Control Board; a sub-system for overall unit control and user-interface
ICD	Interface Control Document or Interface Control Drawing
IMU	Inertial Measurement Unit
MEMS	Micro-Electro-Mechanical Systems
Modulo N	A count sequence from 0 to N-1; ex. modulo 256 would range from 0 to 255, then restart at 0.
MSYNC	Master Synchronization
RS-422	Electrical signal level interface using balanced differential pairs typically on twisted-pair wires at up to 10MBd (bits/sec) rates, in accordance with ANSI/EIA-422-B
SPFP	Single Precision Floating Point (IEEE-754 Big-endian format)
SW	Software
TOV	Time of Validity

3 System Overview

The 1725 IMU is a compact, commercial strap-down inertial sensor system using KVH's advanced Fiber Optic Gyros combined with low-noise MEMS accelerometers. It is intended for use in precision guidance and stabilization applications where high bandwidth, low noise, and bias stability performance levels are important. The 1725 IMU is lightweight, low power, and rugged, offering accurate performance in extreme environments. Its flexible digital data and power interface is designed for ease of integration in new applications and upgrades to existing systems. It is part of a family of commercial IMUs, which includes the 1725 and 1775 IMUs, which offer the same physical package, but different price and performance specifications.

3.1 Functional Overview

The 1725 IMU is a six-Degree of Freedom (6-DOF) inertial sensor package containing three single-axis accelerometers and three single-axis gyroscopes. All sensors are directly fixed to the housing frame.

Internally, three single-axis interferometric Fiber Optic Gyros (FOGs) are used to measure the angular rate about three orthogonal axes. The 1725 IMU uses three single-axis MEMS accelerometers to measure linear acceleration along these orthogonal axes.

The 1725 IMU provides a full-duplex, asynchronous, RS-422 level serial interface for signal communications to an external control system. The serial communications interface transmits sensor and status data from the IMU and receives commands and data from the user. Serial baud is configurable and is stored in non-volatile/persistent memory. The digital control signals and status use RS-422 differential signaling. Digital control signal pairs are External Reset (In), Time of Validity (Out), Master Synchronization Clock (In), and Configuration Software Reset (In).

The 1725 IMU electronics offers user options for changing its run-time configuration, such as operating services (e.g., filters, serial communications, and other characteristics as described in this document).

3.2 Electrical Interface Overview

The 1725 IMU uses a MIL-DTL-83513 Micro-D interface connector located on the top face of the housing. For more information, refer to the Interface Control Drawing (KVH Drawing 99-0379) and the Technical Manual (KVH part no. 54-1054), part of which is copied below, for easy reference (see Figure 3-1). Figure 3-2 below shows the signals and associated pin numbers.

Figure 3-1: 1725 IMU Interface Block Diagram

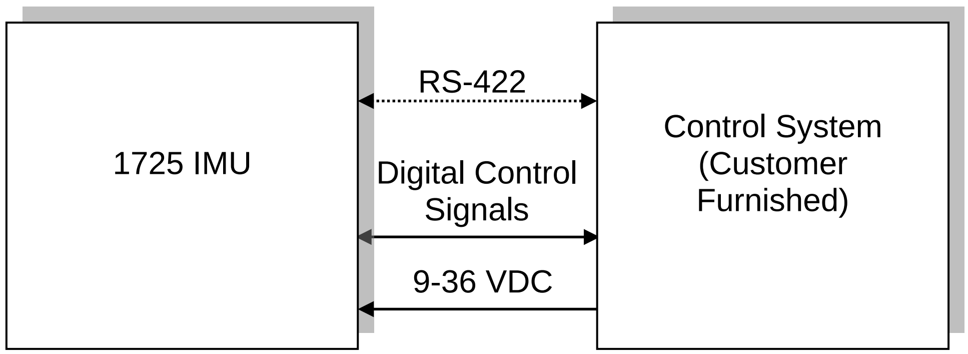
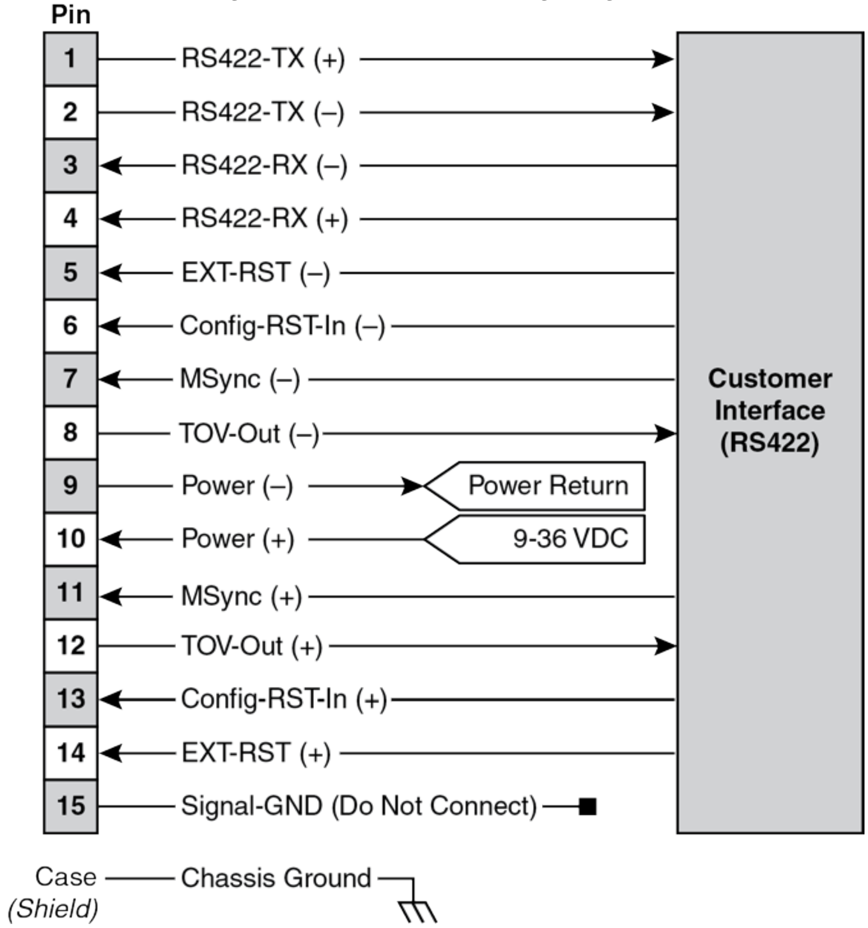


Figure 3-2: 1725 IMU Wiring Diagram



3.2.1 Input Power

The 1725 IMU accepts input power of 9-36 VDC (max) through the Micro-D interface connector pin 10 (**Power (+)**). Typical voltage input ranges 10 to 32 VDC. Typical power consumption is 5 Watts, 8 Watts maximum.

3.2.2 Electrical Grounding

The 1725 IMU has a separate common ground (**Power (-)**) and chassis ground. The common ground is used for input power return and electrical signals. It is located on pin 9 of the Micro-D interface connector (see KVH Drawing 99-0379). Chassis ground is through the IMU metallic case via one of the mounting holes for personnel safety (electric shock) and EMI (noise) emission/susceptibility immunity.

NOTE: A signal ground reference (Signal-GND) is also available on the I/O connector at pin 15 (see KVH Drawing 99-0379 and Figure 3-2). This pin is reserved for factory testing and may be subject to change in the future. Do not connect Signal-GND to the power return externally.

3.2.3 Serial port Interface

The 1725 IMU provides a full-duplex, differential RS-422 serial data port for communication to connected test equipment, control, guidance, or navigation electronics. The RS-422 serial port transmits sensor and status data and receives commands and control data for configuration, test, or maintenance. Multiple baud rates are supported. For more information, contact KVH Technical Support.

3.2.4 Auxiliary Signals

The 1725 IMU provides a number of auxiliary signals as differential RS-422 level inputs and outputs for the following functions:

a) Reset the system
b) Set all configuration options to the default value
c) Master Synchronization Input (e.g., external data request)
d) Time Of Validity (TOV) indicator

3.3 Operating Modes

The 1725 IMU has two operating modes: Normal and Configuration Mode. When initialized, the IMU runs in Normal Mode by default. The operating mode can be changed from Normal Mode to Configuration Mode through serial port commands to allow changes to the IMU configuration settings.

Table 3-1: Operating Modes

Operating Mode	Description
Normal Mode (default)	The unit will output binary (non-human-readable) data messages at the preconfigured rate. The data messages will have the formats specified and typically include a header, message body, and CRC code (see Section 5). The unit will listen for permissible commands as simple ASCII text.
Configuration Mode	The unit will stop output of binary data and will respond to any commands and queries that are received (see Section 6). This mode allows the user to configure the unit and query its status prior to returning to normal mode. Interaction is simple character-based using ASCII-encoded text making it easy to communicate with terminal emulators.

3.4 Built-In Test

The 1725 IMU has Built-in-Test (BIT) functions for: a) power-up built-in self-test, b) continuous built-in self-test, and c) user-requested built-in self-test. BIT verifies operational status of essential IMU services and resources including microprocessors, memory, software, power levels, sensor status, timing, temperature, and communications. BIT outputs include error conditions or information to aid diagnostics.

Power-up BIT is performed at startup. Power-up BIT results are output via the serial port using a BIT message (see Section 5.3). Continuous BIT is performed during normal operation to indicate the validity status of each sensor data message. Continuous BIT results are output via the serial port in a message status byte. A user-requested BIT may be initiated any time through a serial data port command.

4 Data Communications and Unit Control

The 1725 IMU provides a digital interface for the following functions:

- Output of sensor data and status messages including built-in test messages.
- Receipt of external commands to configure and control the IMU assembly.
- Data output control, timing, and reset functions.

4.1 Interface Connector

The 1725 IMU is equipped with a type MIL-DTL-83513 15-pin (male-pin) Micro-D interface connector for data communications and power. Table 4-1 below describes the function of each pin. These were also shown in Figure 3-2.

Table 4-1: Electrical Interface Signals

Pin # Number	Pin Name	Description	Comments
1	RS422-TX+	Output: differential positive	RS-422 serial port for primary data output and command input; the commands that can be sent to the RS-422 port are listed in Section 7.2
2	RS422-TX-	Output: differential negative	
3	RS422-RX-	Input: differential negative	
4	RS422-RX+	Input: differential positive	
11	MSYNC+	Input: differential positive	Master Synchronization for external data request (see Section 10.3)
7	MSYNC-	Input: differential negative	
13	CONFIG-RST-IN+	Input: differential positive	Configuration Reset (see Section 10.1)
6	CONFIG-RST-IN-	Input: differential negative	
14	EXT-RST+	Input: differential positive	External Reset (see Section 10.2)
5	EXT-RST-	Input: differential negative	
12	TOV-OUT+	Output: differential positive	Time Of Validity (TOV) (See Section 11)
8	TOV-OUT-	Output: differential negative	
10	POWER +	Power positive	10-32 VDC typical; (9-36 VDC max) (see Figure 3-2)
9	POWER -	Power return and signal ground	
15	NC	Do Not Connect	For factory/future use

4.2 Character Data Format

Communications to/from the unit use the RS-422 serial port connections defined in Table 4-1. The message characters are comprised of words of 10 bits: one start bit, eight data bits, one stop bit, and no parity (8-N-1). The default baud rate is listed in Section 10.

When in Configuration Mode, the characters listed in Table 4-2 are reserved for use as delimiters. No other characters are reserved in any mode. The character set in use is a subset of standard ASCII. The only characters that are used are those with values between 0x20 and 0x7E, as well as any listed in Table 4-2. All other characters are unused.

Table 4-2: Reserved Characters in Human-Readable Modes

Character	ASCII Hex Code Value	Purpose
<CR>[1] (carriage return)	0x0D	End of command delimiter
<LF>[1] (line feed)	0x0A	End of command delimiter
Note 1: A carriage return, a line feed, or both are all valid end of command delimiters.		

When in Configuration Mode, either an illegal character may be ignored or the unit’s response will indicate an error and possibly suggest the correct message syntax.

When in Normal Mode, user input commands or queries and commands that include illegal characters will be ignored without any response. However, a few special input commands are permitted as ASCII text. (See Section 5 for a description of the output in Normal Mode.)

When in Normal Mode, the data output is in binary format (not ASCII encoded) and there are no reserved characters; all characters from 0x00 to 0xFF are legal at all times. (See Section 5 for a description of the output in Normal Mode.)

5 Normal (Default) Mode Messages

5.1 Description

After the unit powers up and completes its initialization routines, it will place itself into Normal Mode and output a single BIT (Built-In Test) message (see Section 5.3), followed by repeated periodic output of motion data messages. Typically, the unit will output data at the previously configured data rate, although user-driven data output timing is supported. The output data is in binary format and is not human-readable within typical terminal emulator programs (i.e., it is not ASCII-encoded text).

While outputting data in Normal Mode (see Table 5-1 and Table 5-2), the unit will listen for ASCII commands, so that a user can type in commands using a terminal emulator program (e.g., RealTerm or equivalent). The available commands are shown in Table 7-1. Most commands are not recognized in Normal Mode and there will be no response from the unit unless it is permitted in Normal Mode. If one of the permissible subset of commands is recognized (e.g., =config,1 or ?bit), then the unit will respond appropriately.

The unit outputs two basic message types while in Normal Mode. The first type of output message carries sensor data and status and is output at the configured data rate in one of the available data formats. (See Section 5.2 for a description of the available data formats.) The second output message type contains BIT results, which are output at power-up and on user command. (See Section 5.3 for a description of the BIT data formats.)

Normal Mode output data messages include a header code, message packet and a CRC code. The user should ignore any output from the unit that has an invalid header code or bad CRC. Binary output follows the big-endian format convention.

The header codes are unique bit patterns that can be used to synchronize to the binary bit stream. This allows operation with a computer serial port and RS-422 converter. It is also possible, but not required, to use the TOV output as a synchronization method to the binary data output when using other host systems.

5.2 Normal Mode Data Output Format

Data Format A (see Table 5-1 and Table 5-2) is the standard 1725 IMU message output.

This format includes a modulo 128 counter that increments with each data output message and wraps back to 0 after reaching 127. This can optionally be used to verify sequential data reception.

The output format includes a unique header pattern that can be used to identify and synchronize to the binary bit stream. An alternative for synchronization would be to use the TOV output signal to indicate the start of an output message.

Table 5-1: Normal Operating Mode Message
(Default binary data output format)

Item	Byte Numbers	Description
Header	1-4	Always 0xFE81FF55 (transmitted 0xFE first)
Message Data	5-32	(refer to Table 5-2)
CRC (*Cyclic Redundancy Check*)	33-36	(refer to Table 5-4)
TOTAL	*36*	

Table 5-2: Normal Operating Mode Data
(Default binary data output format)

Datum	Byte Numbers	Data Type*	Units	Notes
X rotational data	5,6,7,8	SPFP	Radians or degrees, selectable	MSB (Byte 5) is output first; delta-angle or rate of rotation, selectable
Y rotational data	9,10,11,12	SPFP	Radians or degrees, selectable	MSB (Byte 9) is output first; delta-angle or rate of rotation, selectable
Z rotational data	13,14,15,16	SPFP	Radians or degrees, selectable	MSB (Byte 13) is output first; delta-angle or rate of rotation, selectable
X Acceleration	17,18,19,20	SPFP	g	MSB (Byte 17) is output first
Y Acceleration	21,22,23,24	SPFP	g	MSB (Byte 21) is output first
Z Acceleration	25,26,27,28	SPFP	g	MSB (Byte 25) is output first
Status	29	DISC	1 = valid data 0 = invalid data	(refer to Table 5-3)
Sequence number	30	UINT8	0-127	Increments for each message and resets to 0 after 127
Temperature	31,32	INT16	°C, 1/100 °C, °F, 1/100 °F, selectable	MSB (Byte 31) is output first

* *SPFP = Single Precision Floating Point (IEEE-754 Big-endian format); DISC = Discrete Data; UINT8 = Unsigned 8-bit integer; INT16 = Signed 16-bit integer*

Table 5-3: Status Byte Format
(Default binary data output format)

Function	Bit Number	Notes
Gyro X status	0 (LSB)	1 = Valid data, 0 = Invalid data
Gyro Y status	1	1 = Valid data, 0 = Invalid data
Gyro Z status	2	1 = Valid data, 0 = Invalid data
Reserved	3	Always 0
Accelerometer X status	4	1 = Valid data, 0 = Invalid data
Accelerometer Y status	5	1 = Valid data, 0 = Invalid data
Accelerometer Z status	6	1 = Valid data, 0 = Invalid data
Reserved	7	Always 0

*NOTE: In addition to this general status information, an extended built-in test (BIT) may be initiated at any time by entering the "**?bit**" command. (Extended BIT data is also output whenever the IMU is first powered on.) The extended BIT provides six bytes of diagnostic data, which are defined in Table 5-7 through Table 5-14.*

The constant zero bits are intentionally inserted in the status to prevent it from taking on a value that, combined with the sequence number and temperature, could be misinterpreted as a message header code.

Table 5-4: CRC Format
(Default binary data output format)

Parameter	Value
Width	32
Polynomial	0x04C11DB7
Reflect In	False
XOR In	0xFFFFFFFF
Reflect Out	False

The output data is aligned to an end-user-configurable axis of orientation. By default, axes X_{User}, Y_{User} and Z_{User} are equal to X_{Sensor}, Y_{Sensor}, and Z_{Sensor}, respectively. The BIT status, however, is always indicated relative to the physical sensors inside the device (axes X_{Sensor}, Y_{Sensor}, and Z_{Sensor}). The end-user is responsible for determining what course of action should be taken if one or more of the input axes fail. (See Section 9 for a description of the input axes and see Section 8.1 for details about the =AXES command needed to change the alignment of the axes as desired.)

5.2.1 Sample Output

An example data output string follows. In this example, all sensor outputs are assumed to be valid. Spaces are shown for ease of reading and the ASCII text values displayed would be replaced with the hexadecimal values they represent. (See Table 5-5 for a detailed description of the string.)

FE 81 FF 55 37 A9 6A 6E 38 58 6C 1F B7 5B F8 62 BF 80 3E 78 BB 65 0D 28 3B 0A 37 AC 77 3D 00 28 4B FA 34 D8

Table 5-5: Breakdown of Sample Output

Item	Hex Data	Interpreted Data	Units
Header	0xFE81FF55	N/A	Header code
Gyro X	0x37A96A6E	2.019593E-5	Configuration dependent (default: delta radians)
Gyro Y	0x38586C1F	5.159911E-5	Configuration dependent (default: delta radians)
Gyro Z	0xB75BF862	-1.3111248E-5	Configuration dependent (default: delta radians)
Accel X	0xBF803E78	-1.0019064E0	g
Accel Y	0xBB650D28	-3.34950469E-3	g
Accel Z	0x3B0A37AC	2.1090312E-3	g
Status	0x77	All sensors are valid	DISC
Sequence #	0x3D	74	Modulo 128 count
Temperature	0x0028	40	Configuration dependent (default: ºC)
CRC	0x4BFA34D8	1274688728	N/A

5.3 Built-In Test and Extended Built-In Test

At power-on or external reset, the IMU will report its Built-In Test results prior to beginning output of Normal Mode binary data. This behavior is the same as when a ?bit command is received. The user can optionally choose to ignore or capture and decode the startup BIT message. If the IMU is configured for external MSYNC mode, the IMU will output the startup BIT results automatically, regardless of whether the user sends an MSYNC pulse. During Normal Mode operation, if the user wants the unit to perform a BIT, they must request it using the “?bit” command or the extended “?bit,2” command, described in Section 8. The output of a BIT is described in Table 5-6. The user-requested ?bit results are performed without affecting real-time operations or high-speed message output. The user-requested ?bit,2 results contain extended test diagnostics information and may impact high-speed message outputs during the extended BIT communication time.

Table 5-6: Normal Mode BIT Output

Item	Number of Bytes	Description
Header	4	Always 0xFE8100AA or 0xFE8100AB (transmitted 0xFE first)
Test Results	6 bytes or 8 bytes	The data is described in Table 5-7 through Table 5-14. Is 6 bytes for ?bit (header 0xFE8100AA) Is 8 bytes for ?bit,2 (header 0xFE8100AB)
Checksum	1	The checksum will be calculated by accumulating the sum of each byte of data, modulo 256.

The results of each test are indicated with a 1-bit pass/fail flag, 1 indicating a “pass” condition, while a 0 indicates reduced confidence in the measurement (“fail”). (See Table 5-7 through Table 5-14 for the complete test list.) See Table 5-15 for which bits are relevant for each sensor.

In the following tables (Table 5-7 through Table 5-14), the reserved bits are the most significant bits of their respective bytes. Byte 0 is the first transmitted, byte 7 is the last. The number in parentheses in the “Bit Number” column is the number referenced by Table 5-15.

Table 5-7: Test Results Byte 0

Datum	Bit Number	Sequential Bit Number	Notes (Unless Otherwise Noted: 1 = PASS, 0 = FAIL)
Gyro X SLD	0	(0)	
Gyro X MODDAC	1	(1)	
Gyro X Phase	2	(2)	
Gyro X Flash	3	(3)	
Gyro Y SLD	4	(4)	
Gyro Y MODDAC	5	(5)	
Gyro Y Phase	6	(6)	
Constant Zero	7	(7)	Always 0

Table 5-8: Test Results Byte 1

Datum	Bit Number	Sequential Bit Number	Notes
Gyro Y Flash	0	(8)	
Gyro Z SLD	1	(9)	
Gyro Z MODDAC	2	(10)	
Gyro Z Phase	3	(11)	
Gyro Z Flash	4	(12)	
Accel X Status	5	(13)	
Accel Y Status	6	(14)	
Constant Zero	7	(15)	Always 0

Table 5-9: Test Results Byte 2

Datum	Bit Number	Sequential Bit Number	Notes
Accel Z Status	0	(16)	
Reserved	1	(17)	Always 1
Gyro X SLD Temperature Status	2	(18)	
Reserved	3	(19)	Always 1
Gyro Y SLD Temperature Status	4	(20)	
Reserved	5	(21)	Always 1
Gyro Z SLD Temperature Status	6	(22)	
Constant Zero	7	(23)	Always 0

Table 5-10: Test Results Byte 3

Datum	Bit Number	Sequential Bit Number	Notes
Accel X Temperature Status	0	(24)	
Accel Y Temperature Status	1	(25)	
Accel Z Temperature Status	2	(26)	
GCB Temperature Status	3	(27)	
IMU Temperature Status	4	(28)	
GCB DSP SPI Flash Status	5	(29)	
GCB FPGA SPI Flash Status	6	(30)	
Constant Zero	7	(31)	Always 0

Table 5-11: Test Results Byte 4

Datum	Bit Number	Sequential Bit Number	Notes
IMU DSP SPI Flash Status	0	(32)	
IMU FPGA SPI Flash Status	1	(33)	
GCB 1.2V Status	2	(34)	
GCB 3.3V Status	3	(35)	
GCB 5V Status	4	(36)	
IMU 1.2V Status	5	(37)	
IMU 3.3V Status	6	(38)	
Constant Zero	7	(39)	Always 0

Table 5-12: Test Results Byte 5

Datum	Bit Number	Sequential Bit Number	Notes
IMU 5V Status	0 (40)	(40)	
Reserved	1 (41)	(41)	Always 1
GCB FPGA Status	2 (42)	(42)	
IMU FPGA Status	3 (43)	(43)	
Hi-Speed SPORT Status	4 (44)	(44)	
Aux SPORT Status	5 (45)	(45)	
Sufficient Software Resources	6 (46)	(46)	
Constant Zero	7 (47)	(47)	Always 0

Table 5-13: Test Results Byte 6 - ?bit,2 Command Only

Datum	Bit Number	Sequential Bit Number	Notes
Gyro EO Volts Positive	0	(48)	
Gyro EO Volts Negative	1	(49)	
Gyro X Volts	2	(50)	
Gyro Y Volts	3	(51)	
Gyro Z Volts	4	(52)	
Reserved	5	(53)	Always 1
Reserved	6	(54)	Always 1
Reserved	7	(55)	Always 0

Table 5-14: Test Results Byte 7 - ?bit,2 Command Only

Datum	Bit Number	Sequential Bit Number	Notes
GCB ADC Comms	0	(56)	
MSYNC External Timing	1	(57)	
Reserved	2	(58)	Always 1
Reserved	3	(59)	Always 1
Reserved	4	(60)	Always 1
Reserved	5	(61)	Always 1
Reserved	6	(62)	Always 1
Reserved	7	(63)	Always 0

To determine the status of a given sensor, verify that each bit listed in Table 5-15 has a value of 1. Bits indicating degraded confidence indicate a suspicious error or behavior of internal sub-systems, but the readings are likely reliable (e.g., they may not meet specifications). Bits that indicate zero confidence indicate more serious problems and the reported values should be disregarded.

Table 5-15: Validity Test Bits For Each Sensor

Sensor	Bits Indicating Degraded Confidence	Bits Indicating Zero Confidence
Accel X	24, 28, 32, 33, 37, 38	13, 40, 43
Accel Y	25, 28, 32, 33, 37, 38	14, 40, 43
Accel Z	26, 28, 32, 33, 37, 38	16, 40, 43
Gyro X	17, 18, 27, 29, 30, 34, 35	0, 1, 2, 3, 36, 42, 44, 45
Gyro Y	19, 20, 27, 29, 30, 34, 35	4, 5, 6, 8, 36, 42, 44, 45
Gyro Z	21, 22, 27, 29, 30, 34, 35	9, 10, 11, 12, 36, 42, 44, 45

5.3.1 Samples of BIT Output

When the IMU is first powered on, and upon user request, the IMU outputs an extended BIT message consisting of a header, six (BIT) or eight (BIT,2) data bytes, and checksum. The six data bytes indicate the status information for built-in diagnostic tests.

5.3.1.1 Expected BIT Output

Converted to hexadecimal, the following message indicates normal BIT output status:

FE 81 00 AA 7F 7F 7F 7F 7F 7F 23

5.3.1.2 Error Condition BIT Output

In the following message, the gyro X Flash (non-volatile memory) and gyro X SLD sensor (light source) temperature tests have failed BIT. Spaces are shown for ease of reading and the ASCII text values displayed would be replaced with the hexadecimal values they represent.

FE 81 00 AA 77 7F 7B 7F 7F 7F 17

Table 5-16: Breakdown of Sample BIT Output (Error Condition) - ?bit

Item	Hex Data	Interpreted Data
Header	0xFE8100AA	N/A
Byte 0	0x77	Gyro X Flash Failed
Byte 1	0x7F	All good
Byte 2	0x7B	Gyro X FOG Temperature Failed
Byte 3	0x7F	All good
Byte 4	0x7F	All good
Byte 5	0x7F	All good
Checksum	0x17	N/A

5.3.1.3 Expected BIT,2 Output

Converted to hexadecimal, the following message indicates normal BIT,2 output status:

FE 81 00 AB 7F 7F 7F 7F 7F 7F 7F 7F 22

5.3.1.4 Error Condition BIT,2 Output

In the following message, the gyro Y Voltage detected a voltage that is outside accepted ranges. Spaces are shown for ease of reading and the ASCII text values displayed would be replaced with the hexadecimal values they represent.

FE 81 00 AB 7F 7F 7F 7F 7F 7F 77 7F 1A

Table 5-17: Breakdown of Sample BIT Output (Error Condition) - ?bit,2

Item	Hex Data	Interpreted Data
Header	0xFE8100AB	N/A
Byte 0	0x7F	All good
Byte 1	0x7F	All good
Byte 2	0x7F	All good
Byte 3	0x7F	All good
Byte 4	0x7F	All good
Byte 5	0x7F	All good
Byte 6	0x77	GCB Y Volts Failed
Byte 7	0x7F	All good
Checksum	0x1A	N/A

6 User Configuration Mode

Configuration Mode is intended for use by installers to configure the operation for their application and for field technicians who need to perform diagnostics on the unit. It will allow users to set and/or query configuration parameters, including but not limited to the following:

- Baud rate of the main serial communications interface
- Data rate of the system transmissions during Normal Mode
- Data output request, source – data transmission relative to an internal clock or external synchronization signal
- Data message format – selects from Normal Mode output data formats
- Linear output format – acceleration or delta-velocity
- Rotational output format – angular rate of rotation or delta [incremental] angle
- Axis orientation – adjusts reference frames relative to the default axes or directions (+/-)
- Output data filters – adjusts accelerometer and gyro filters independently
- Units – select degrees vs. radians or Celsius vs. Fahrenheit
- Temperature data resolution – degrees or 100ths of degrees
- Extended BIT test
- Bit log – accesses logged BIT history from startup and extended BIT records
- Serial numbers and software revision information

In Configuration Mode, the unit does not output data unless prompted by the user and it communicates in ASCII-encoded text. The summary list of commands is shown in Table 7-1.

7 Commands and Queries

All commands and their responses are terminated with either one or both of the ASCII codes for a carriage return (often symbolized as <CR> or '\r' and ASCII code 0x0D) or a line feed (<LF> or '\n' and ASCII code 0x0A). Command and response parameters are delimited using the comma character (',', ASCII code 0x2C).

Input commands are case-insensitive. Responses to commands will be in all upper case (capital letters) unless otherwise indicated in the appropriate command description sections that follows.

All commands are prefixed with either the '?' or the '=' character. The '?' character indicates that the command is a query (a request for data). The '=' character indicates a command and the unit will perform an action. An example command would be =DR,100. An example query would be ?DR.

All commands have responses unless otherwise indicated. By default, commands to the unit will generate a response that is identical to the command itself, except that the '=' prefix character will not be transmitted in the response. By default, queries to the unit will receive a response that is lacking the '?' prefix character, has the full text of the command, and then provides the answer to the query, allowing ease of automation and a positive feedback mechanism when manually entering commands. Deviations from this default are described in the subsections below. An example response to the =DR,100 command would be DR,100. The query response would be the same.

Invalid commands are ignored in Normal Mode. When in Configuration Mode, unknown or unaccepted input commands will result in a response message starting with the word "INVALID," followed by an echo of the string received by the IMU. An example response to the query ?foo would be INVALID,?FOO.

Invalid input parameters (e.g., out of range value, unexpected numeric argument, etc.) to a recognized command keyword should result in a prompt to the user starting with either the keyword USAGE or INVALID followed by a description of how to use the command. In rare cases, the keyword "ERROR" with a brief description may be returned if IMU cannot execute the command (e.g., an error was encountered during a non-volatile storage operation). These responses to unexpected inputs are intended as helpful reminders for a human operator, not for an automated system. Automated systems that detect a USAGE, INVALID or ERROR response may need to request operator assistance due to a likely communications problem (e.g., incorrect programming, intermittent cable connection, cable crosstalk, etc., or simply retry the command). Some examples of invalid parameter responses follow.

For the command =dr,100.0 the IMU should respond with the following two lines since it only accepts integer values and a float was sent:
INVALID,DR
Data rate must be one of 1, 5, 10, 25, 50, 100, 250, 500, 750, 1000

For the command =FILTEN,ON the IMU should respond with:
USAGE: =FILTEN,<0|1>

For the cases of out-of-range or invalid command parameters and for commands not defined by this document, the users should not rely on preservation of observed responses or behavior in future firmware versions (e.g., usages text or helpful reminders may be added or improved as features are added).

Most commands will result in parameters being stored in non-volatile memory and recalled on the next reset/power-on. Exceptions will be described in the command descriptions below. Command defaults can be restored by command or by an input signal to the interface.

7.1 Command Definition Conventions

In the following command description sections, the following conventions will be used:

- Any parameter surrounded by square brackets (e.g., [example]) is a required parameter name, which will be accompanied by an additional description
- Any parameter surrounded by angle brackets (e.g., <example>) indicates a set of acceptable values
- Multiple parameters with a "|" separator indicate acceptable discrete values (e.g., <0|1> indicates that only the values 0 or 1 are acceptable)
- Multiple parameters with "-" separator indicate an inclusive range of acceptable values (e.g., <1-1000> indicates a parameter in the range of 1 through 1000, inclusive, is acceptable)
- Optional parameters are described in command descriptions
- Where more complicated alternatives are used, they may be shown in a separate usage line definition
- In the command line usage and responses, the terminating <CR> and <LF> symbols are implied and not shown
- Typically Boolean type parameters that accept a value as <0|1> are defined as FALSE or OFF if 0 and TRUE or ON if 1

Numeric parameters may be ASCII-encoded string representations of one of either integer or floating-point values (i.e., floats or SPFP) depending on the specific command. Integer type values, when received as float types (e.g. 100.0 instead of 100), are rejected with a usage response. Floating-point type parameters may be entered as integers (without decimal places). Exponential notation is accepted also (e.g., 1.2345E-5 instead of 0.000012345). Single precision float values in IEEE-754 format are only precise to approximately seven places after the decimal point.

7.2 Command List

All user commands are listed below, along with the operating modes where they are available. A "Y" indicates that the command is available. Details of each command follow.

Table 7-1: Summary of Commands

String	Command Description	Normal	Configuration
=axes	Sets the X, Y and Z output axis orientations relative to default sensor reference frame; applies to gyros and accelerometers		Y
?axes	Gets the X, Y and Z output axis orientations relative to default sensor reference frame; applies to gyros and accelerometers		Y
=baud	Sets the baud rate of the system		Y
?baud	Gets the baud rate of the system		Y
?bit	Performs a built-in-test (similar to the self-test)	Y	
=config	Forces the unit into or out of Configuration Mode	Y	Y
?config	Queries if the unit is in Configuration Mode		Y
=dr	Sets the output data rate of the system when in Normal Mode		Y
?dr	Gets the output data rate of the system when in Normal Mode		Y
=echo	Useful for verifying communications with the unit		Y
?echo	Same as =echo		Y
=fc	Set filter coefficients		Y
?fc	Get filter coefficients		Y
=filten	Enables/disables the filter		Y
?filten	Gets whether the filter is enabled or disabled		Y
=filttype	Set the filter type		Y
?filttype	Gets the filter type		Y
=help	Prints a list of the available commands		Y
?help	Same as =help		Y
?is	Gets the serial number of the system		Y
=linfmt	Sets the linear format of the Normal Mode output		Y
?linfmt	Gets the linear format of the Normal Mode output		Y
=linunits	Sets the linear units of the Normal Mode output		Y
?linunits	Gets the linear units of the Normal Mode output		Y
?logs	Gets the logs written to flash		Y
=msync	Sets the device to an internal or external signal/clock		Y
?msync	Gets whether the device is set to an external signal/clock		Y
=outputfmt	Sets the message output format in Normal Mode		Y
?outputfmt	Gets the message output format in Normal Mode		Y
=restart	Performs a restart of the system		Y
=rotfmt	Sets the rotational format of the Normal Mode output		Y
?rotfmt	Gets the rotational format of the Normal Mode output		Y
=rotunits	Sets the rotational units of the Normal Mode output		Y
?rotunits	Gets the rotational units of the Normal Mode output		Y
=rstcfg	Resets all user configuration options to factory defaults		Y
?temp	Gets the temperature of the unit		Y
=tempunits	Sets the output temperature units		Y
?tempunits	Gets the output temperature units		Y
=testfilt	Tests the filter that's currently implemented		Y
?testfilt	Same as =testfilt		Y
?volt	Gets all voltages on internal power rails		Y
?ws	Gets the software versions		Y

8 Command Descriptions

8.1 =axes

8.1.1 Description

This command sets the axes of reported motion relative to the physical orientation of the motion sensors. This allows the unit to measure motion in three arbitrarily orthogonal axes instead of being locked into the physical orientation axes. This does not affect the axis reference for the BIT status. The new matrix values are stored persistently until the defaults are restored. Any 3x3 matrix will be accepted; the user is responsible for ensuring that the matrix is a valid rotation matrix.

8.1.2 Usage

=AXES,[X_0],[X_1],[X_2],[Y_0],[Y_1],[Y_2],[Z_0],[Z_1],[Z_2]
[$X_{0\text{-}0}$],[$Y_{0\text{-}1}$],[$Z_{0\text{-}2}$] are floating-point values and define a 3x3 rotation matrix.

The matrix is applied as follows:

$$\begin{bmatrix} X_{User} \\ Y_{User} \\ Z_{User} \end{bmatrix} = \begin{bmatrix} X_0 & X_1 & X_2 \\ Y_0 & Y_1 & Y_2 \\ Z_0 & Z_1 & Z_2 \end{bmatrix} \begin{bmatrix} X_{Sensor} \\ Y_{Sensor} \\ Z_{Sensor} \end{bmatrix}$$

Where X_{Sensor}, Y_{Sensor}, and Z_{Sensor} are the sensing axes, X_{User}, Y_{User}, Z_{User} are the user-defined output axes. The default matrix is:

1 0 0
0 1 0
0 0 1

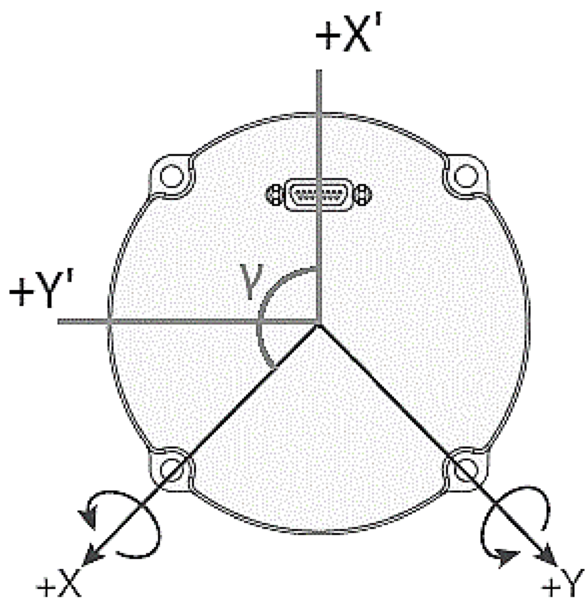
The angles specified in the rotation matrices below are from the sensor axis to the desired user axis. The sign of the angle is consistent with the angle of rotation, positive (counterclockwise) and negative (clockwise), following the right-hand rule (see Figure 9-1).

$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & \sin(\alpha) \\ 0 & -\sin(\alpha) & \cos(\alpha) \end{bmatrix}$$

$$R_y(\beta) = \begin{bmatrix} \cos(\beta) & 0 & -\sin(\beta) \\ 0 & 1 & 0 \\ \sin(\beta) & 0 & \cos(\beta) \end{bmatrix}$$

$$R_z(\gamma) = \begin{bmatrix} \cos(\gamma) & \sin(\gamma) & 0 \\ -\sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Example: to configure the IMU to use the user axes X' and Y' in the figure below, instead of the sensor axes at the default locations of +X and +Y, use the $\boldsymbol{R_z}$ rotation matrix. The value of γ will be -135 degrees representing clockwise rotation about the Z axis, when viewed along the Z axis, following the right-hand rule (see Figure 9-1).



Example (the default axes alignment):

=AXES,1.0,0.0,0.0,0.0,1.0,0.0,0.0,0.0,1.0

8.1.3 Response

AXES,[X_0],[X_1],[X_2],[Y_0],[Y_1],[Y_2],[Z_0],[Z_1],[Z_2]
[X_{0-0}],[Y_{0-1}],[Z_{0-2}] are floating-point values typically in exponential notation.
Response to above (default) would be:

AXES,+1.000000E+00,+0.000000E+00,+0.000000E+00,+0.000000E+00,+1.000000E+00,+0.000000E+00,+0.000000E+00,+0.000000E+00,+1.000000E+00

8.2 ?axes

8.2.1 Description

This command queries the user-configured alignment axes relative to the true physical orientation of the measurement axes.

8.2.2 Usage

?AXES

8.2.3 Response

AXES,[X_0],[X_1],[X_2],[Y_0],[Y_1],[Y_2],[Z_0],[Z_1],[Z_2]
[X_{0-0}],[Y_{0-1}],[Z_{0-2}] are floating-point values reported in exponential notation that define a 3x3 rotation matrix as described in the =AXES command.

8.3 =baud

8.3.1 Description

This command sets the baud rate of the system. Not all baud rates are usable at all data rates. For instance, selecting a baud rate of 57600 with a data rate of 1000 Hz would not work, because the full output data packet cannot be transmitted in 1 ms at that baud rate. Therefore, care must be taken when using non-default data rate and baud rate combinations. For more information, see the data rate (=DR) command and information in Section 9.

The baud value is stored in non-volatile memory and recalled on power-on/reset. The baud can be restored to a known default value (921.6 KBd) by asserting the Config-RST signal on power-on/reset.

8.3.2 Usage

=BAUD,<9600|19200|38400|57600|115200|460800|576000|921600>

The integer value for baud is in Bd units and must be one of the acceptable values above.

8.3.3 Response

BAUD,<9600|19200|38400|57600|115200|460800|576000|921600>

Response will be at the new baud rate. Depending on software revision, the response may or may not include the new value as a parameter.

8.4 ?baud

8.4.1 Description
This command queries the baud rate of the system.

8.4.2 Usage
?BAUD

8.4.3 Response
BAUD,<9600|19200|38400|57600|115200|460800|576000|921600>
Where the value is an integer in Bd units and is one of the permitted baud rates.

8.5 ?bit

8.5.1 Description
This command is used to perform a Built-In-Test of the unit while it is running in Normal (binary) Mode. This command will return the results of internal background built-in tests that are continually being done on various pieces of hardware and software in the system to guarantee that valid readings are being made. For the most part, this reflects that internal devices are communicating appropriately and within expected times. The response will appear in the format specified by Section 5.3. The response time will vary based on system load and the selected data rate, but typically, a response will be available within 100 ms of the command being issued. After a response becomes available, it will be transmitted immediately following the next data message. This is done to guarantee that the normal data message is not delayed.

The BIT results message will be appended to one of the Normal Mode data output messages following an MSYNC input signal. There may be a short delay of one or more MSYNC signals to allow the system to complete the BIT process. The user should make sure to pulse the MSYNC input signal one or more times between 90 µs and 2 s after sending the ?bit command. Failure to do so may result in bit 43 (IMU FPGA Status) of the response being set to the error state. Most users will not need to handle this as a special case, as the typical user requests data far faster than the 1/2 Hz limit. The 1725 IMU has a 90 µs hold off time from reception of one MSYNC to the next and this must also be taken into account.

8.5.2 Usage
?BIT<,2>
The optional 2 parameter specifies the alternate extended BIT test results.

8.5.3 Response
The response to ?BIT and ?BIT,2 queries are not human-readable, because the unit is operating in Normal (binary) Mode. See the sections about built-in test for details related to the response.

8.6 =config

8.6.1 Description

This command places the unit into/out of Configuration Mode. In Configuration Mode, the IMU stops sending binary data and allows the user to enter ASCII-based commands and responses to configure the unit. Configuration Mode is not stored in non-volatile/persistent memory, so the unit can be returned to Normal Mode by command or via power-on/reset.

8.6.2 Usage

=CONFIG,<0|1>

Where 0 indicates Normal Mode (Configuration Mode OFF) and 1 indicates Configuration Mode ON.

8.6.3 Response

CONFIG,1

The unit will never respond with CONFIG,0 because that would imply it is in Normal Mode and is outputting data in binary format.

8.7 ?config

8.7.1 Description

This command queries the Configuration Mode status.

8.7.2 Usage

?CONFIG

8.7.3 Response

CONFIG,1

8.8 =dr

8.8.1 Description

This command sets the output data rate in Hz that will occur while operating in Normal Mode and with the =MSYNC,IMU configuration. The output rate must be specified as one of the permitted values between 1 and 1000 Hz. This configuration is saved in non-volatile memory and recalled on reset/power-on. Not all data rates are usable at all baud rates. For instance, selecting a data rate of 1000 Hz with a baud rate of 57600 would not work, because the full output data packet cannot be transmitted in 1 ms at that baud rate. Therefore, care must be taken when using non-default data rate and baud rate combinations, or the IMU will be unreliable. See the baud rate (=BAUD) command and information in Section 9.

NOTE: If the currently selected filter type is either Chebyshev or Butterworth (i.e., not the Uniform Averager or a customer-defined filter) then setting the data rate has the side effect of modifying the anti-aliasing filter coefficients so that the cutoff frequency is 1/2 of the data rate.

8.8.2 Usage

=DR,<1|5|10|25|50|100|250|500|750|1000>

The integer value for data rate is in Hz units and must be one of the acceptable values above.

8.8.3 Response

DR, <1|5|10|25|50|100|250|500|750|1000>

8.9 ?dr

8.9.1 Description

This command queries the binary output data rate in Hz that will occur while operating in Normal Mode.

8.9.2 Usage

?DR

8.9.3 Response

DR,<1|5|10|25|50|100|250|500|750|1000>

8.10 =echo

8.10.1 Description

This command keeps a running count of how many times the echo command has been called. The counter can be incremented, set to any value, or reset to zero. This is intended to aid users establishing and testing communication links to the unit. Any set value of the echo command is not stored in non-volatile/persistent memory (the value will reset to 0 upon reset).

8.10.2 Usage

=ECHO	increment counter
=ECHO,[Value]	set counter to [Value]; response will be the same value
=ECHO,Reset	reset counter to 0; same as =ECHO,0

8.10.3 Response

ECHO,[Counter Value]
Where Counter Value is an integer that increments each time the command is used.

8.11 ?echo

The ?ECHO command is identical to the =ECHO command.

8.12 =fc

8.12.1 Description

This command allows the user to change the final output low-pass filtering from the built-in Butterworth, Chebyshev II, or Uniform Averager, to a custom, user-specified filter (see Figure 12.1). The user can define the filters used for accelerometer and/or gyro data individually directly through the coefficients. If the RESET parameter option is sent, this will engage the default output filters that will scale automatically with the output rate. For more information on data filtering in the IMU, see the =FILTTYPE command.

The final output filter is used for proper decimation (low-pass filtering and downsampling) of the internal processes to the output data rate. Normally, the final stage filter characteristic is adjusted automatically, according to the selected data rate and filter type.

The final output filter is implemented as a four stage cascaded biquadratic (biquad) filter (8th order total). The coefficients specify the direct form 1 of each biquad having the classic transfer function in the z-domain as follows:

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}}$$

In the z-domain, z^{-n} represents a time delay of n sample periods. The b_n coefficients specify the feedforward coefficients for the new sample and its time-delayed values, the a_n coefficients specify the feedback coefficients of the time-delayed outputs, and the a_0 coefficient is normalized to a value of 1.

The IMU signal-processing will implement each of the biquad stages as the following:

$$y[n] = b_0 * x[n] + b_1 * x[n-1] + b_2 * x[n-2] + a_1 * y[n-1] + a_2 * y[n-2]$$

Where y[n] is the output and x[n] is the input and the n-1 and n-2 terms are their time-delayed values.

When designing custom filters, the user should be conscious of anti-aliasing (Nyquist-Shannon sampling theorem) based on the output data rate. The filtering operation uses single-precision floating-point values. Installing filter coefficients that span a large numeric range (i.e., have high precision) may result in quantization errors and numerical instability. After installing custom coefficients, be sure to use the =TESTFILT command to verify the impulse response of the system is as you intended.

Both custom and built-in filters are executed at an input sample rate that is controlled by the output data rate configuration (see the =DR command description for setting the output data rate). When using a custom filter, the filter coefficients will **not** be automatically recomputed for changes to the data rate. Therefore, if the data rate is changed to a value that changes the internal gyro or accelerometer signal-processing rate, the filter should be adjusted to account for the change to the filter's input data rate. Please refer to the table below for the input sample rate for which you should design your filter's decimation factor (i.e., input rate/output rate) according to the configured final data output rate.

Table 8-1: 1725 IMU Internal Sensor Sample Rates

(All values are listed in Hz units)

Output Data Rate (Hz)	Gyro Signal-Processing Rate (Hz)	accelerometer Signal-Processing Rate (Hz)
Data Rate >= 100	10000	8312.5
100 > Data Rate >= 10	1000	831.25
Data Rate < 10	100	83.125

NOTE: When the output data rate is externally controlled by the external MSYNC signal, the unit will default automatically to use the Uniform Averager type filtering. However, the internal signal-processing rate and hence the filter's input sampling rate, is still controlled by the =DR command as shown in the table. Through the =FC command it is possible to change the default filter in =MSYNC,EXT mode to instead use a custom filter. The filter's frequency response should be designed to prevent aliasing at the user-driven MSYNC rate.

Coefficients for all stages must be sent even if a lower order filter is specified. Unused filter stages should be set with the all-pass coefficient values of a_1=0.0, a_2=0.0, b_0=1.0, b_1=0.0, b_2=0.0. That is, according to the equation above, y[n] = x[n].

The =FC command will automatically switch the filter type to <custom>. Therefore, after defining a filter with this command the unit will respond to the ?FILTTYPE query indicating that the custom filter is in use. Custom filter coefficients set with this command are stored in non-volatile memory and last until they are either reprogrammed or overridden by another configuration (e.g., =MSYNC,EXT, which defaults to using the Uniform Averager filter type or the =FILTTYPE command to set a different filter).

NOTE: Depending on software revision, there may be a limit to the number of command line characters allowed. Older software versions may limit the command line to 256 characters including the <CR> and <LF>. Due to the length of filter coefficients, the input may need to be trimmed to fit the input limit. Input with more than seven digits of precision are not required, especially if using exponential notation, since typical float precision is not valid for more than seven digits.

8.12.2 Usages

=FC,<A|G>,[A_{01}],[A_{02}],[B_{00}],[B_{01}],[B_{02}],[A_{11}],[A_{12}],[B_{10}],[B_{11}],[B_{12}],[A_{21}],[A_{22}],[B_{20}],[B_{21}],[B_{22}],[A_{31}],[A_{32}],[B_{30}],[B_{31}],[B_{32}]
=FC,<A|G>,RESET

Values for coefficients A_{01} to B_{32} specify the biquad coefficients as single precision floating-point values for the four 2nd order stages of biquads.

8.12.3 Response

To limit the response to typical terminal emulator character limits the response is broken up into four text lines, each with <CR><LF> termination. Succeeding lines may have additional white space indentation as prefix.

Example:

FC,[A|G],[A_{01}],[A_{02}],[B_{00}],[B_{01}],[B_{02}]
[A_{11}],[A_{12}],[B_{10}],[B_{11}],[B_{12}]
[A_{21}],[A_{22}],[B_{20}],[B_{21}],[B_{22}]
[A_{31}],[A_{32}],[B_{30}],[B_{31}],[B_{32}]

The response to the =FC,<A|G>,RESET will be the same as above, with the default coefficients returned as values.

8.13 ?fc

8.13.1 Description

This command queries the accelerometer or gyro filter coefficients. See the =FC command and examples for the typical response and filter description. This can be used to query the coefficients in use in both custom type and non-custom filters except for the Uniform Averager type.

8.13.2 Usage

?FC,<A|G>

8.13.3 Response

See the =FC command response.

8.14 =filten

8.14.1 Description

This command sets whether or not the final output filter is enabled on the output data. This only applies to the final filtering, prior to data output, and does not change the intermediate anti-aliasing filter operation or any the other internal filtering used. For more information on data filtering in the IMU, see the =FILTTYPE command.

NOTE: KVH recommends that users should not operate the unit with the filter disabled as they can expect aliasing of the output data. This may especially be a problem when using the delta-velocity and delta-angle type of outputs as the possibly-noisy computed value will be applied over the entire output period. This does not change filter coefficients or filter types, so they can be disabled and enabled. Like most other commands, this configuration is saved in non-volatile memory and recalled on power-up.

8.14.2 Usage

=FILTEN,<0|1>

8.14.3 Response

FILTEN,<0|1>

8.15 ?filten

8.15.1 Description

This command queries whether the filter is enabled on the output data.

8.15.2 Usage

?FILTEN

8.15.3 Response

FILTEN,<0|1>

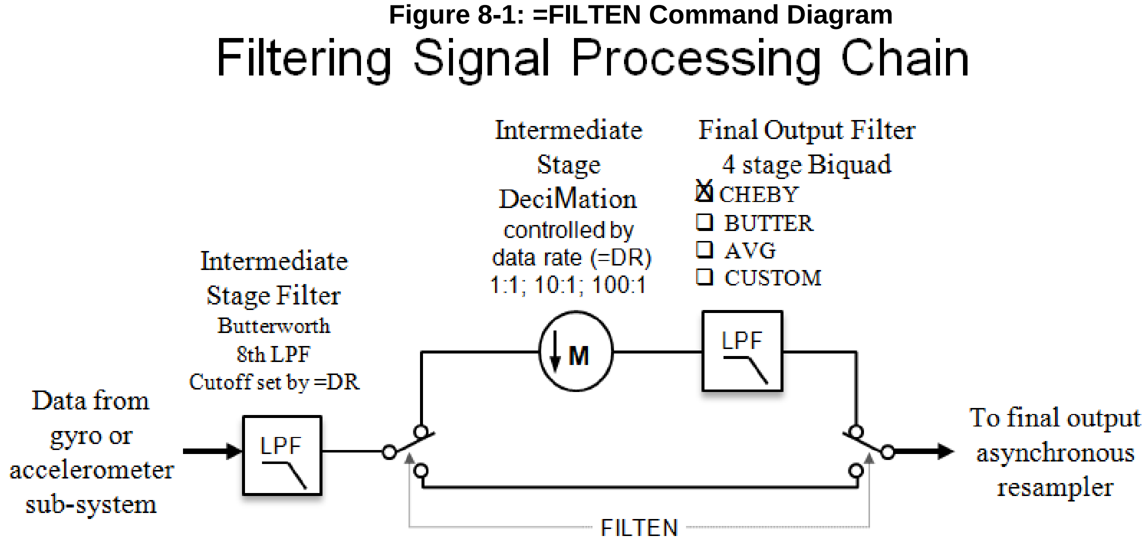
8.16 =filttype

8.16.1 Description

This command allows the user to define the type of low-pass filter being used in the final output data of the IMU. The =FILTTYPE command can be used to select from one of the built-in types including a Chebyshev type II filter (also known as an inverse Chebyshev), Butterworth filter, or a Uniform Averager. The command acts independently on the accelerometer and gyro filters, so each sensor type must be specified using a separate command. Command syntax usage varies according to the type of low-pass filter chosen. See Section 12 for additional information concerning signal processing and, specifically, Section 12.3 for example filter responses.

The diagram below shows the relationship of the intermediate filter/decimation stages followed by a final output filter. The =FILTTYPE and the =FC commands control the Final Output Filter 4 Stage Biquad. The Intermediate Stage Filter and Intermediate Stage Decimation are controlled indirectly based on the configuration of the data rate; see the =DR command for more information. The =FILTEN command can be used to disable the final output filter and the decimation. These are represented in the diagram as switches; see the =FILTEN command for more information.

Figure 8-1: =FILTEN Command Diagram



Based on the configured data rate, the unit will compute the appropriate filter coefficients to implement the Butterworth or Chebyshev II filter types as low-pass, 8th order, and unity gain. The coefficients will be recomputed automatically to adjust the low-pass cutoff frequency according to any subsequent data rate command.

Selection of the Uniform Averager type low-pass filter results in accumulation of data followed by averaging over the output period (i.e., it is **not** a moving average). This filter type is automatically selected as the default when the unit is configured for external output rate control (=MSYNC,EXT command) operation. The period of average will be based on the ratio of input sampling rate to output sampling rate where input sampling rate is controlled by the data rate command according to the sample rate in Table 8-1.

After setting filter type for Butterworth or Chebyshev, the ?FC command can be used to review the coefficients in use and the =TESTFILT command can be used to receive the impulse response. The ?FC and =TESTFILT commands cannot be used with the Uniform Averager type, since that filter type does not use the biquad stage coefficients.

The default output filtering can be restored using the =FC command's RESET parameter or by using the CHEBY keyword type.

Changing the Master Synchronization Input to external (=MSYNC,EXT) will automatically change the filter type to the Uniform Averager type. This filter type will remain active even after changing the Master Synchronization Input back to =MSYNC,IMU type later on. When using the external MSYNC mode, if the user wants a different filter than the Averager type they must configure it with the =FILTTYPE command **after** issuing the =MSYNC,EXT command.

8.16.2 Usage

=FILTTYPE,<A|G>,<CHEBY|BUTTER|AVE>

Uniform Averager USAGE: =FILTTYPE,<A|G>,AVE
When selecting this low-pass filter, the output data will represent the average of the motion samples during the period since its previous output. As mentioned in the previous description section, this will not be a moving average since the averaging is reset for each data output sample period. Therefore, the averaging period will automatically adjust with the chosen data rate. While the Uniform Averager filter type is not a great low-pass filter, it may be useful for asynchronous output of data when using the external MSYNC data request. See the description above and Section 10.3 for more information on use of the MSYNC capability. As with other final output filters, use of the data rate (=DR) command may affect the Uniform Averager filter input rate by changing the internal sampling rates. When using the Uniform Averager filter and external MSYNC output request, KVH recommends setting the data rate configuration to 1000 Hz, even if the user does not expect to drive the MSYNC request at that rate. This will configure the intermediate filter and decimator to use the fastest averaging rates.

Butterworth USAGE: =FILTTYPE,<A|G>,BUTTER
This low-pass filter is 8^{th} order and the cutoff (-3dB gain) frequency is at 1/2 of the configured data rate.

Chebyshev USAGE: =FILTTYPE,<A|G>,CHEBY
The Chebyshev (type II) is the default final output filter. This low-pass filter is 8^{th} order. The stop gain is -40dB and the stop band frequency will be 0.545*data rate.

8.16.3 Response

FILTTYPE,<A|G>,<CHEBY|BUTTER|AVE>

8.16.4 Examples and Further Information

Examples for =FILTYPE command:

Table 8-2: FILTYPE Commands and Responses

Commands (CR/LF not shown)	Response	Final Output Filter Description
=filttype,a,butter	FILTTYPE,A,BUTTER	Default Butterworth applied to accelerometers, cutoff at 0.5 data rate
=filttype,g,ave	FILTTYPE,G,AVE	Uniform Averager applied to gyros
=filttype,g,cheby	FILTTYPE,G,CHEBY	Default Chebyshev type II applied to gyros

Certain commands can have an impact on other, previously entered commands. The following is an example of commands being input in sequence and a description of their resulting interaction.

Table 8-3: 1725 IMU Command Behavior

Commands (CR/LF not shown)	Responses	Discussion and Unit Status
=config,1	CONFIG,1	The user enters Configuration Mode; unit stops output of binary data.
=msync,ext	MSYNC,EXT	The user sets unit to external MSYNC mode; unit is now configured to output one set of data for each external MSYNC input. Output filtering of gyro and accelerometer data is automatically set to Uniform Averager type filtering. There is no binary data output yet because the unit is still in Configuration Mode.
?filttype,a	FILTTYPE,A,AVE	Confirms the Averager type is active for accelerometer data.
?filttype,g	FILTTYPE,G,AVE	Confirms the Averager type is active for gyro data.
=filttype,g,butter	FILTTYPE,G,BUTTER	Gyro data filter reconfigured from Averager to the default Butterworth 8^{th} order and at 1/2 the configured data rate (whatever was set previously).
=dr,1000	DR,1000	The user sets data rate to 1000 Hz; gyro filter is internally recalculated to Butterworth, 8^{th} order at 500 Hz cutoff. Still in external MSYNC mode with output driven by user supplied signal.
=dr,100	DR,100	The user sets data rate to 100 Hz; gyro filter is internally recalculated to Butterworth, 8^{th} order at 50 Hz cutoff. Accelerometer filter is still the Averager type.
=config,0	Unit will begin output of binary data; one set of data for each external MSYNC signal seen.	The user leaves Configuration Mode; unit will now output one data set for each external MSYNC signal, gyro data has an 8^{th} order Butterworth filter at 50 Hz cutoff and the accelerometer data is using the Uniform Averager.

8.17 ?filttype

8.17.1 Description

This command queries the type of filter being used; it acts independently on the accelerometer and gyro filters, so each must be specified as a separate query. This returns custom type if the =FC command was used to define the coefficients.

8.17.2 Usage

?FILTTYPE,<A|G>

8.17.3 Response

FILTTYPE,<A|G>,<CHEBY|BUTTER|AVE|CUSTOM>

Example.
?FILTTYPE,A
FILTTYPE,A,CHEBY

8.18 =help

8.18.1 Description

This command displays a list of implemented commands.

8.18.2 Usage

=help
=help[,command]

8.18.3 Response

When using the help command without any parameters, the output lists all of the available commands and their descriptions.

8.19 ?help

?HELP is identical to =HELP.

8.20 ?is

8.20.1 Description

This command returns the main serial number of the unit.

8.20.2 Usage

?IS

8.20.3 Response

IS,151001234
Serial number is a text string, typically with a numeric value.

8.21 =linfmt

8.21.1 Description

This command sets the linear (accelerometer) data format used for output in Normal Mode. It can be set to either acceleration in g's (default) or delta-velocity. If setting to delta-velocity, be sure to set the units using the =LINUNITS command.

8.21.2 Usage

=LINFMT,<ACCEL|DELTA|RESET>

8.21.3 Response

LINFMT,<ACCEL|DELTA|RESET>

8.22 ?linfmt

8.22.1 Description

This command query returns the linear (accelerometer) data output format used in Normal Mode, either acceleration in g's or delta-velocity.

8.22.2 Usage

?LINFMT

8.22.3 Response

LINFMT,<ACCEL|DELTA>

8.23 =linunits

8.23.1 Description

This command sets the linear (accelerometer) data output units. Only applies if the linear data output format is **not** set to acceleration in g's, which is the default selection. See the =LINFMT command for details on changing the linear data output format.

As an example, if the format is set to delta-velocity and you select the output units to be meters (default), the data you receive will be measured in delta meters per second. If you change the units to feet, you will receive data in delta feet per second.

8.23.2 Usage

=LINUNITS,<METERS|FEET|RESET>

8.23.3 Response

LINUNITS,<METERS|FEET|RESET>

8.24 ?linunits

8.24.1 Description

This command query returns the linear (accelerometer) data output units. This setting only has meaning if the linear data output format is changed from the default value of acceleration in g's. See the =LINFMT command for details.

8.24.2 Usage

?LINUNITS

8.24.3 Response

LINUNITS,<METERS|FEET>

8.25 ?logs

8.25.1 Description

This is a diagnostic command that gets the BIT status logs stored in flash. A user might be requested to do this as part of service support. (See Table 5-7 through Table 5-14 for details on logged bit statuses.)

8.25.2 Usage

?LOGS

8.25.3 Response

Start of log entries!
Log 1:
 Source - Start up
 Format - BIT Status
 Data - 0x7F7F7F7F7F7F7F7F7F
Log 2:
 Source - ?BIT
 Format - BIT Status
 Data - 0x7F7F7F7F7F7F7F7F7F
End of log entries!

8.26 =msync

8.26.1 Description

This command configures the system's data output request method for Normal Mode. It can be set to use an internally generated periodic clock in IMU mode, or to use the external interface MSYNC signal in EXT mode. (See Section 10.3 for important information regarding the use of the Master Synchronization Input.)

8.26.2 Usage

=MSYNC,<EXT|IMU>

IMU mode generates the Normal Mode data output messages based on the data rate defined by the =DR command. EXT mode uses the Master Synchronization Input signal on the interface connector to request data output at a user-driven rate. The user-driven output rate can be either periodic or aperiodic. Setting this to EXT will automatically engage the Uniform Averager type output filtering on both the accelerometer and gyro data (see the =FILTTYPE command). It will not change the filter enable configuration however.

8.26.3 Response

MSYNC,<EXT|IMU>

8.27 ?msync

8.27.1 Description

This command queries whether the system is expecting timing synchronization via the Master Synchronization Input or if it internally controls the output timing. (See Section 10.3 for details about the Master Synchronization Input.)

8.27.2 Usage

?MSYNC

8.27.3 Response

MSYNC,<EXT|IMU>

8.28 =outputfmt

8.28.1 Description

This command configures the output format of the binary data message used in the Normal Mode. The value is stored in non-volatile memory.

The 1725 IMU currently supports only output format A. This command is reserved for future expansion and for compatibility with the 1775IMU.

8.28.2 Usage

=OUTPUTFMT,A

8.28.3 Response

OUTPUTFMT,A

8.29 ?outputfmt

8.29.1 Description

The command query responds with the currently configured output format of the binary data used in the Normal Mode.

8.29.2 Usage

?OUTPUTFMT

8.29.3 Response

OUTPUTFMT,A

8.30 =restart

8.30.1 Description

This command restarts the system. This is equivalent to asserting the External Reset input on the Micro-D interface connector. It should result in the system reboot of programmable devices and configurations. It is similar to a power cycle in that certain parts of the system will experience a hardware reset signal. However, not all devices (e.g., power supplies) will be reset.

8.30.2 Usage

=RESTART

8.30.3 Response

The system does not respond to the RESTART command with any direct confirmation messages. It should result in the unit output of Normal Mode data in the configured format.

8.31 =rotfmt

8.31.1 Description
This command configures the rotational (gyro) data format that is output in Normal Mode to either delta-angle or rate of rotation. The RESET parameter restores the factory default configuration (see Section 9).

8.31.2 Usage
=ROTFMT,<DELTA|RATE|RESET>

8.31.3 Response
ROTFMT,<DELTA|RATE|RESET>

8.32 ?rotfmt

8.32.1 Description
This command queries the rotational (gyro) data format being output in Normal Mode, either delta-angle or rate of rotation.

8.32.2 Usage
?ROTFMT

8.32.3 Response
ROTFMT,<DELTA|RATE>

8.33 =rotunits

8.33.1 Description
This command sets the rotational (gyro) data units being output in Normal Mode, either degrees or radians. If ROTFMT command was set for DELTA, then this will set units for degrees or radians. If ROTFMT is RATE, then this will set units for degrees/sec or radians/sec. The RESET parameter selects the factory default configuration (see Section 9).

8.33.2 Usage
=ROTUNITS,<DEG|RAD|RESET>

8.33.3 Response
ROTUNITS,<DEG|RAD|RESET>

8.34 ?rotunits

8.34.1 Description

This command queries the rotational (gyro) units being output in Normal Mode, either degrees or radians.

8.34.2 Usage

?ROTUNITS

8.34.3 Response

ROTUNITS,<DEG|RAD>

8.35 =rstcfg

8.35.1 Description

This command resets all configuration settings back to the factory defaults. The settings include the output data rate, filter settings, output units, axes, etc. (See Section 10 for the settings that are reset to defaults.) This is similar to asserting the Configuration Reset signal on the Micro-D Interface.

Errata Note: in earlier software versions, this command also defaults the serial communications baud rate. If necessary, users will have to adjust host communications to the default baud and then reprogram the baud back to the desired value after issuing this command.

8.35.2 Usage

=RSTCFG

8.35.3 Response

RSTCFG

8.36 ?temp

8.36.1 Description

This command query returns the main temperature sensor of the system as an integer string. The units returned depend on the configuration defined by the =TEMPUNITS command.

8.36.2 Usage

? TEMP

8.36.3 Response

TEMP,[Temperature Value]

Example, temperature in degrees C for 45^{o} C:
TEMP,45

Example, temperature in 100ths of degrees C for 45.02^{o} C:
TEMP,4502

8.37 =tempunits

8.37.1 Description

This command sets the temperature units used when the device outputs in Normal Mode, or when given the ?TEMP command. The user can use the C_100 and F_100 to increase resolution to two decimal places. The units will still report a whole number integer and the user must divide by 100 to get the decimal equivalent. The configuration is saved in non-volatile memory.

8.37.2 Usage

=TEMPUNITS,<C|F|C_100|F_100>

8.37.3 Response

TEMPUNITS,<C|F|C_100|F_100>

8.38 ?tempunits

8.38.1 Description

This command queries the temperature units being reported, either degrees C or F or their corresponding 100ths of degree units.

8.38.2 Usage

?TEMPUNITS

8.38.3 Response

TEMPUNITS,<C|F|C_100|F_100>

8.39 =testfilt

8.39.1 Description

This command tests the filter that is currently implemented for the accelerometers and gyros. It is intended for verification of custom filters, but can be used with the built-in Chebyshev and Butterworth filter types.

This command does **not** apply for the Uniform Averager type filter or for when the filter is disabled. The output results may be undefined in such cases.

When run, this zeroes the state variables, then applies a unit impulse to the configured filter and outputs the results of the first 2^{16} (65536) output values of each filter. The user can then capture the results, which can be run through an FFT using third party analysis software to verify that the magnitude and phase response of the filter matches the desired implementation.

Depending on the configured baud, the response can take several minutes to return all the values for each of the accelerometer and gyro output filters. The numeric values returned are ASCII-encoded strings of floating-point values and may be in decimal or exponential notation.

Each numeric value represents one sample period at the internal sampling rate of the particular filter. The internal sampling rate (i.e., the filter input rate) depends on the configured data rate. Please refer to the sample rate table in the =DR command for the input sample rates relation to the data rate (e.g., at 1 KHz data rate, the accelerometer filters sample rate is 8.3125 KHz, so each sample represents a time period of (1.0 / 8312.5) Hz, or approximately 0.1203 ms, and the command reports up to 7.88 secs of impulse response time).

Errata Note: In newer software versions, the response will indicate the number of samples and the sample period that can be used to compute the FFT of the filter response. Example is shown below.

8.39.2 Usage

=TESTFILT

Default reports accel first and then gyro impulse responses with 65536 samples each.

=TESTFILT,<A|G>,<SAMPLES>

A for accel; G for gyro, optional argument to get only the specific filter response

SAMPLES is an optional argument as an integer value from 2 to 65536 (must be preceded by A or G option) to request less than default number of samples.

8.39.3 Response

Example 1: for command =testfilt
TESTFILT
Testing accel filter impulse response; 65536 samples
(Accel sample period is 0.1203 ms)
+0.00989369862
+0.01022341289
…
+0.00000000000
+0.00000000000
+0.00000000000
Accel filter test complete
Testing gyro filter impulse response; 65536 samples
(Gyro sample period is 0.0500 ms)
+0.00910380296
+0.00664431229
+0.01628635451
…
+0.00000000000
+0.00000000000
Gyro filter test complete

Example 2: for command =testfilt,g,20
TESTFILT
Testing gyro filter impulse response; 20 samples
(Gyro sample period is 0.0500 ms)
+0.00819911063
-0.00015651807
+0.00477615930
+0.00683800876
+0.00767558068
+0.00821539760
+0.00892141461
+0.00997492671
+0.01139687002
+0.01312804222
+0.01507931948
+0.01716038585
+0.01929408312
+0.02142292261
+0.02350741625
+0.02552491426
+0.02746337652
+0.02931761742
+0.03108656406
+0.03276658058

8.40 ?testfilt

?TESTFILT is identical to =TESTFILT. See the appropriate section for details.

8.41 ?volt

8.41.1 Description

This command is a diagnostic query that returns the primary supply voltages on the system. It might be run at the request of sales/service and is not typically needed by a user.

8.41.2 Usage

?VOLT

8.41.3 Response

VOLT,[1 Volt],[3 Volt],[5 Volt]

[1 Volt] indicates the voltage on an internal 1.2V supply.
[3 Volt] indicates the voltage on an internal 3.3V supply.
[5 Volt] indicates the voltage on an internal 5.0V supply.

All values are returns as ASCII strings representing float values.

Example response with approximate typical values:
VOLT,1.187,3.307,4.974

8.42 ?ws

8.42.1 Description

This is a diagnostic command to query the software versions of the various internal programmable devices. It is intended for software update utility programs to determine existing versions for field firmware update purposes. Normally users do not need to operate this command. Software versions relate to internal programmable devices including DSPs and FPGAs.

8.42.2 Usage

?ws

8.42.3 Response

1750 IMU
ICB DSP Rev F Version: 2.30
ICB FPGA Rev: 0x06
GCB DSP Rev B Version: 1.01
GCB FPGA Rev: A

9 Configuration Options

The major configuration parameters are summarized in Table 9-1. All options are configurable using the commands in Section 8. Axes of rotation and linear motion reference frames are shown in Figure 9-1.

Table 9-1: Configuration Options Summary

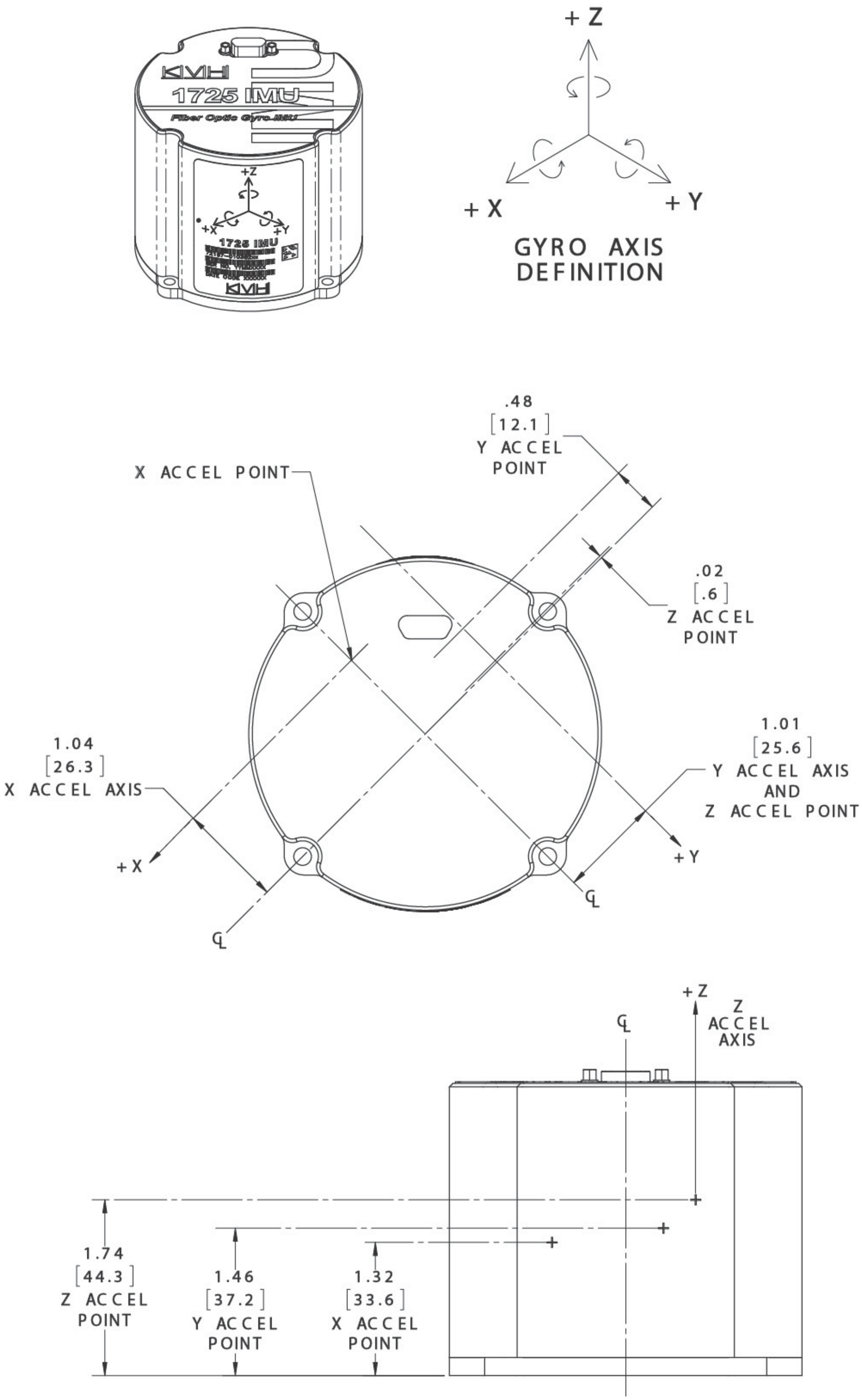
Parameter	Options	Default Value	Units	Configuration Command
Baud rate[(1)]	9600, 19200, 38400, 57600, 115200, 460800, 576000, 921600	921600	Bd (same as bits/sec)	=BAUD to set ?BAUD to query
Data rate[(2)]	1, 5, 10, 25, 50, 100, 250, 500, 750, 1000	1000	Hz	=DR to set ?DR to query
Temperature Units	ºC, ºF, ºC_100, ºF_100	ºC	N/A	=TEMPUNITS to set ?TEMPUNITS to query
Angular Units	Radians, degrees	Radians	N/A	=ROTUNITS to set ?ROTUNITS to query
Rotational data (gyro) format	Rate of rotation (radians/sec or degrees/sec) delta-angle[(3)] (radians or degrees)	Delta angle	Varies by option	=ROTFMT to set ?ROTFMT to query
X, Y, Z axis definitions[(4)]	Rotation matrix[(5)] from reference axes shown in Figure 9-1	1 0 0 0 1 0 0 0 1	N/A	=AXES to set ?AXES to query
Linear Units	Meters, Feet	Meters	N/A	=LINUNITS to set ?LINUNITS to query
Linear data (accelerometer) format	accelerometer, Delta	Acceleration in g (g-force) units	Acceleration in g or delta-velocity	=LINFMT to set ?LINFMT to query
Output filter enable/disable	Enabled (1) disabled (0)	Enabled	N/A	=FILTEN to set ?FILTEN to query
Output filter type	Chebyshev, Butterworth, Uniform Averager, customer defined 8th order filter	Chebyshev (type II) filter	N/A	=FILTTYPE to set ?FILTTYPE to query
Output filter coefficients	Infinitely configurable 8th order filter coefficients	Chebyshev (type II) filter	N/A	=FC to set ?FC to query
Output Request synchronization	Internal clock, External request[(6)]	Internal clock (IMU mode)	N/A	=MSYNC to set ?MSYNC to query

Parameter	Options	Default Value	Units	Configuration Command

Table 9-1 Notes:

1) Reducing the baud rate from the default increases the time duration of the data being output from the unit. If the baud rate is decreased too much, it may result in an inability to achieve the set data rate. (Refer to Section 9.1 for recommended baud rate/data rate limits.) Baud rate will set to default for Config-RST-IN signal assertion. Baud rate will not change for RSTCFG command.
2) The data rate command (=DR) directly controls the data output rate when the MSYNC is configured for IMU, which is the default. If the external MSYNC signal is configured (=MSYNC,EXT), any data output rate from 1 to 1000 Hz is available and controlled by user request. However, the user is responsible for ensuring the output filters are appropriately set. See the entry named “Output Request Synchronization” in this table.
3) Delta angle differs from rate of rotation in that it uses the rate of rotation over the time since the last data output to compute the angular displacement (it integrates the rate of rotation over time).
4) The three axes of rotation are coincident with the linear acceleration axes. Positive rotation is a counterclockwise rotation about an axis, following the right-hand rule (see Figure 9.1). Linear acceleration polarity is such that the IMU will report +1 G due to Earth gravity when its positive axis is up. The rotation matrix only applies to gyro and accelerometer data.
5) Any matrix will be accepted by the unit. It is up to the user to ensure that the matrix is a valid rotation matrix and does not result in any scaling issues (e.g., entering =axes,4,0,0,0,1,0,0,0,1 would make the X axis measurements four times as large as they should be). This is not intended as a means of changing scale factors.
6) The MSYNC,EXT mode will automatically select the Uniform Averager type filtering. Interaction with the =DR and filtering commands is command-order specific. The user should refer to appropriate sections to describe these interactions.

Figure 9-1: Axis Definitions Relative to the Unit



9.1 Configuration Limits

Some configuration options associated with data rate and communications baud should not be set beyond certain limits.

Table 9-2: Maximum Data Rates At Given Baud Rates

Baud Rate (Bd)	Maximum Data Rate (Hz)
9600	10
19200	25
38400	50
57600	100
115200	100
460800	500
576000	750
921600	1000

10 Control Signal Inputs

10.1 Config-RST-In (Configuration Reset) Input

The 1725 IMU has a differential input labeled Config-RST-In+/Config-RST-In- on the external connector that can be used to perform a configuration reset of the system. This input is only monitored at startup and is ignored during normal operation. These pins may be left disconnected at the unit interface connector unless use is desired.

To reset all configuration settings (including baud) to their factory defaults, assert a positive RS-422 compliant voltage from the Config-RST-In+ pin to the Config-RST-In- pin before restarting the unit. The unit may be restarted by one of the following: applying power, applying external reset, or sending the =RESTART command. If used, the configuration reset condition should be held until the unit starts outputting Normal Mode data. This will default unit configuration similar to the =RSTCFG command. The differences are that =RSTCFG command does not require an actual unit restart.

The default configuration parameters are listed in Section 9.1.

10.2 EXT-RST (External Reset) Input

The 1725 IMU has a differential input labeled EXT-RST+/EXT-RST- on the external connector that can be used to perform a hardware reset (cold start) of the system. Asserting a positive RS-422 compliant voltage from the EXT-RST+ pin to the EXT-RST- pin at any time will result in a reset. These pins may be left disconnected at the unit interface connector unless reset is desired.

External reset operation is similar to a power-cycle of the power inputs in that certain parts of the system will experience a hardware reset signal. It should result in the system reboot of programmable devices and configurations. However, not all devices (e.g., power supplies) will be reset.

A unit in Configuration Mode (=CONFIG,1 command) will restart to the configured Normal Mode. Other configuration parameters will be recalled from non-volatile memory.

10.3 MSYNC (Master Synchronization) Input

By default, the 1725 IMU will internally self-time the output message rate according to the configuration of the =DR command.

The 1725 IMU provides an optional RS-422 differential input (named MSYNC+/MSYNC-) that allows the user to request data output within the limits of the unit. When configured for external MSYNC mode, asserting a positive RS-422 compliant voltage from the MSYNC+ pin to the MSYNC- pin will result in the unit sending out a data message in the configured format. These pins may be left disconnected at the unit interface connector unless external MSYNC is desired. The configuration of the internal or external data output requests is controlled by the =MSYNC command.

Internal to the IMU, the MSYNC signal, whether internally or externally generated, will be captured and will cause the IMU to sample its sensor data and prepare and transmit a data message (see Figure 10-1). MSYNC is shown in the diagram as a single signal and assumes that MSYNC+ and MSYNC- operate together as a differential pair to define the active (high) or deasserted (low) state.

Figure 10-1: MSYNC Signals

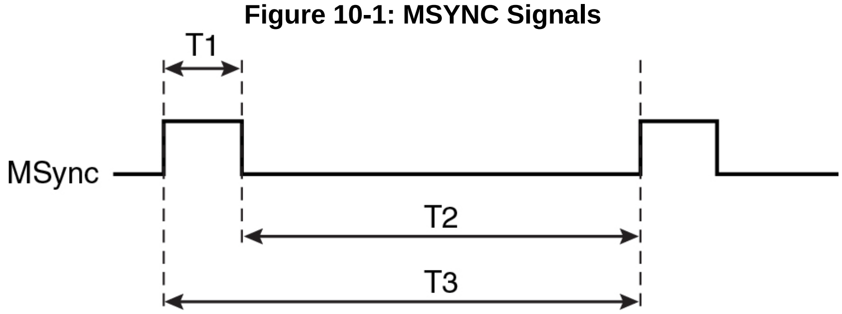


Table 10-1: MSYNC Timing Parameters

Timing Parameter	Description	Value
T1	MSYNC active	MSYNC+ high and MSYNC- low ≥ 30 µs; Recommended high time is less than approximately 90 µs (see note below).
T2	MSYNC deasserted	MSYNC+ low and MSYNC- high ≥ 30 µs
T3	Period between rising edges	1.0-2000 ms

The external MSYNC input has a short debounce protection time on its active (rising MSYNC+/ falling MSYNC-) edge of approximately 0.5 µs. This is followed by a hold-off time of approximately 92 µs before it will recognize another active edge. This hold-off time is to prevent retriggering the output, possibly from noise on the interface cable. There is also a short (~ 1 µs) debounce protection time on its falling edge. Noise such as signal reflections or crosstalk of the external wiring should be avoided by careful design of the external wiring harness. However, setting the timing of the MSYNC input duty cycle such that the falling edge of external MSYNC falls within the hold-off period can help ensure proper MSYNC operation.

When selecting the external MSYNC signal as the output data request source, the system will automatically switch the filter to use the Uniform Averager type. This will override any previous filter type selection the user has configured (including a custom filter), but will not change the filter enable/disable configuration. The change to Uniform Averager is done so the user is not forced to provide a regular periodic clock, but rather use the Master Synchronization Input as an arbitrary aperiodic request for data. You may override this and install any filter you choose. You can select from a predefined or custom eighth-order filter by using a combination of the =DR, =FILTTYPE, =FC, and =FILTEN commands. These must be sent **after** the =MSYNC,EXT command.

NOTE: The unit assumes that the user will always want data at a frequency greater than 1/2 Hz. If a rising edge of the MSYNC signal is not detected within two seconds, the unit will consider this a fault condition and will output data at the two-second interval. When the next MSYNC signal rising edge is detected, the unit will resume synchronized output. This may be convenient as an indication that the user's MSYNC signal was not recognized by the unit (e.g., perhaps due to cabling or other error condition).

10.3.1 Example 1

The user wishes to use a Uniform Averager with MSYNC. The Averager is the default filter when using MSYNC, so no additional configuration is needed.

```
=config,1
=msync,ext
=config,0
```

10.3.2 Example 2

The user wishes to enable MSYNC while turning off the filters entirely (i.e., user does not want the IMU to implement either a Uniform Averager, or any kind of 8th order anti-aliasing filter; this is not recommended by KVH due to aliasing of the output data). The =FILTEN configuration is not changed automatically by the =MSYNC command, so this could be done in reverse order or at some time previously. Send the following commands to the unit:

```
=config,1
=msync,ext
=filten,0
=config,0
```

10.3.3 Example 3

The user wishes to enable external MSYNC and wants to have the IMU implement a Butterworth anti-aliasing filter with a 3dB cutoff of 50 Hz. Send the following commands to the unit. The user may drive MSYNC input at any desired rate, not necessarily 100Hz. In the latter incorrect example, the filter types are set prior to the external MSYNC command and will be overridden with the Uniform Averager type filters.

Correct:

=config,1
=msync,ext
=dr,100
=filttype,a,butter
=filttype,g,butter
=config,0

Incorrect

=config,1
=filttype,a,butter
=filttype,g,butter
=msync,ext
=dr,100
=config,0

10.3.4 Example 4

The user wishes to enable external MSYNC and implement a custom filter. Enter the desired coefficients using the =FC command. The internal signal-processing rate is determined by the =DR command. Enter the following commands (the filter coefficients are completely made up in this example):

=config,1
=msync,ext
=dr,1000
=fc,a,0.1,0.2,0.3,0.4,0.5,0.1,0.2,0.3,0.4,0.5,0.1,0.2,0.3,0.4,0.5,0.1,0.2,0.3,0.4,0.5
=fc,g,0.4,0.3,0.2,0.1,0.0,0.4,0.3,0.2,0.1,0.0,0.4,0.3,0.2,0.1,0.0,0.4,0.3,0.2,0.1,0.0
=config,0

Just as in Example 3, you must send the =MSYNC,EXT command **before** changing the filter type. Also, you must send the =DR command **before** setting the custom filter.

11 Time of Validity Output (TOV)

11.1 TOV Summary

The 1725 IMU provides an optional RS-422 differential output on the external connector (named TOV-OUT+/TOV-OUT-) to indicate the time at which the data being output on the serial port can be considered relevant. This output is only relevant when the unit is in Normal Mode (i.e., unit is set to output binary data on the serial port). When the unit is not in Normal Mode (e.g., it is in Configuration Mode) the TOV indication should be ignored.

When used, KVH recommends that this signal be connected to a properly terminated RS-422 receiver to prevent signal reflections and crosstalk. If not used, it may be left unconnected.

The TOV signal can be used as an indication that output of a data message is going to occur. It can also be used by a system to timestamp the subsequent data message as it will be very close in time to the IMU's sampling of its rotational and linear sensors (refer to Table 11-1).

The behavior of the TOV signal depends on whether the unit is generating its own (internal) timing (default or =MSYNC,IMU) or if it is relying upon the user-driven timing associated with the Master Synchronization Input (see Section 11.3 for details).

11.2 TOV Timing

TOV is shown in the diagram as a single signal and assumes that TOV+ and TOV- operate together as a differential pair to define the active (high) or deasserted (low) state.

Figure 11-1: TOV Output Timing Relative to Serial port Activity

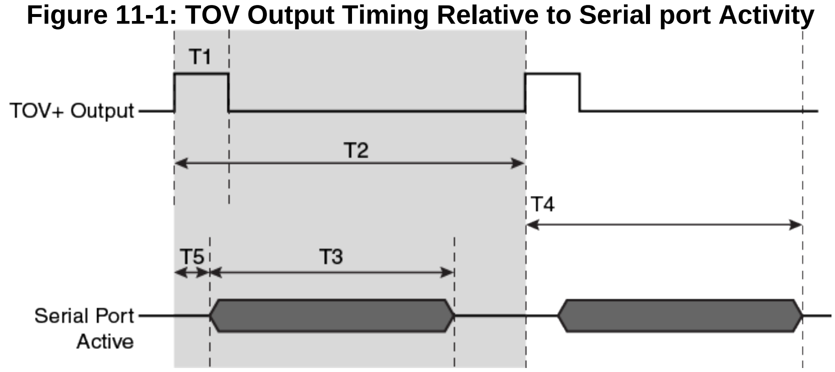


Table 11-1: TOV Timing Parameters

Timing Parameter	Description	Value
T1	TOV High	MSYNC,IMU: high time is 10% of the TOV period (e.g., at a default baud rate of 1,000 Hz, the T1 high time will be 100 µs for internal clock mode) MSYNC,EXT: high time is approximately the same as the external MSYNC signal active time
T2	TOV period	MSYNC,IMU: Period is determined by the output data rate (e.g., at default data rate of 1,000 Hz, T2 = 1000 µs) MSYNC,EXT: period reflects the external MSYNC signal
T3	Duration of the serial port output	Depends on output format and baud rate; approximately equal to the number of characters output multiplied by the number of bits per character (10) divided by the baud rate (e.g., at default baud rate of 921600 Bd, T3 is approximately 390 µs)
T4	Time between rising edge of TOV-Out and the end of data transmission	<500 µs (at default baud rate of 921600 Bd)
T5	Time between start of TOV and the start of T2	30 to 100 µs (typical)

11.3 TOV with Internal MSYNC Mode

When the IMU is providing its own data output requests based on its internal source's preconfigured rate, the unit outputs the differential TOV signal with a 10% duty cycle at the same frequency as the data output (see the diagram in Figure 11-1 and the parameters in Table 11-1).

11.4 TOV with External MSYNC Active

When the external Master Synchronization Input is configured, the IMU will simply buffer (repeat) the MSYNC signal back out to the TOV signal. Therefore, the timing should closely mirror the external MSYNC signal.

12 Data Output Signal-Processing

During Normal Mode operation, the IMU Controller Board (ICB) needs to process data from its sensor sub-systems and prepare it for output to the user system. The IMU is continually sampling its various sensor data sub-systems and is checking for user requests for data and commands. It does this through a variety of interrupt-driven DMA (direct memory access) and polled signals. A simplified diagram of the primary processes related to the gyro and accelerometer signal-processing is shown in Figure 12.1.

12.1 Signal-Processing Diagram and Key

Table 12-1 describes some of the symbols used in the diagram.

Table 12-1: Signal-Processing Symbols

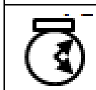
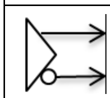
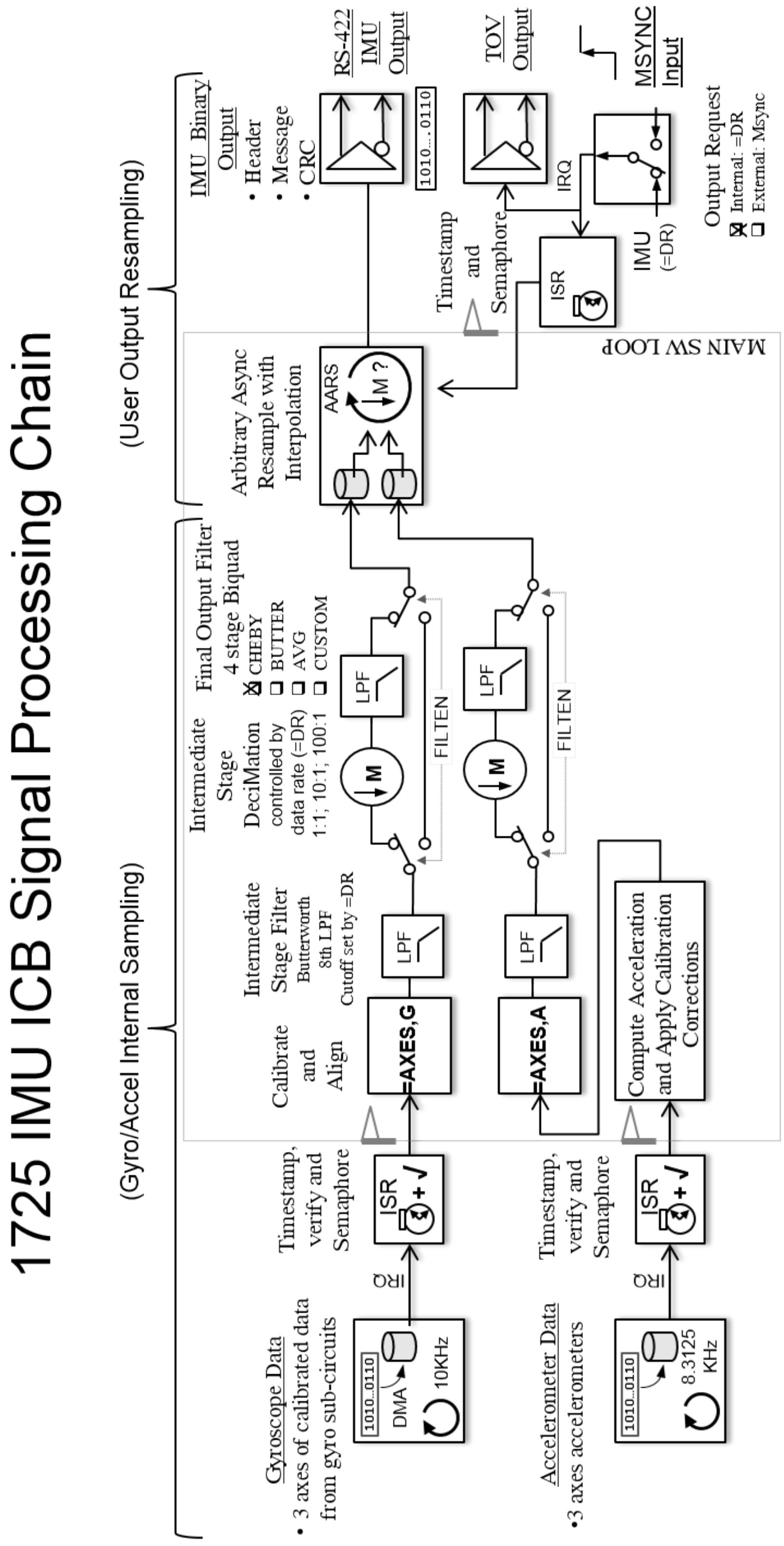
Symbol	Description
	Data container; memory storage of data together with meta-data such as timestamps
	Indicates a timestamp process. The ICB uses an internal clock with better than 20ns resolution to track relative times of various events
LPF 	Indicates a low-pass filter process
↓ M	Indicates the downsampling portion of sample rate reduction by a factor of M; (M is an industry standard operator symbol for deciMation)
	Indicates a switchable data path;, possibly a virtual switch as in a software path rather than a physical switch
	Indicates a differential signal output
1010….0110	Indicates serial data stream
	Indicates a semaphore flag for inter-process communications

Figure 12-1: IMU ICB Signal-Processing Diagram



Summary and Notable Features

- Final output sample period is arbitrary and asynchronous to internal sampling of gyro and accel sensor data.
- Timestamps of output request and internal data samples are used to interpolate output data to reduce output uncertainty and jitter
- Final output filter's input rate is decimated sensor sample rate; typically decimation is set by data rate
  - Uniform Averager type accumulates sensor data throughout the output period (it is not a moving average)
- Intermediate stage filter is always enabled; cutoff frequency set by data rate (=dr) command

12.2 Description of Processing Diagram

12.2.1 Sample Data from Sensor Sub-systems

The gyro and accelerometer sub-systems supply data to the ICB at different rates, but the data processing is similar. In the diagram above, the ICB is internally accepting and processing the gyro data from three axes (X, Y, and Z) at 10 KHz. The sub-system process details are not shown, but do include rotation rate calculation and processing at much higher rates. The accelerometer data from three axes (X, Y, and Z) is sampled at 8.3125 KHz and sent to the ICB for further processing. Both of these are shown on the left side of Figure 12-1 as serial bit streams from the gyro and accelerometer sub-systems flowing into data containers at their sample rates. As this data is updated in the ICB, an interrupt-driven process will verify the data, add a timestamp, and then notify other software processes with semaphore flags.

In the case of the gyro data, the values have already been calibrated for bias, scale factor, and linearity versus temperature by the gyro sub-system. The ICB applies any user-configured change in axes rotation and any other calibration factors (not shown) as needed. For the accelerometer data, the ICB performs the temperature calibration needed and then applies user axes rotation.

12.2.2 Intermediate Stage Processing

Because the final output sample rate to the user is much slower than the internal input sample rates from the sub-systems, data for gyros and accelerometers must be downsampled internally. The associated anti-alias filtering is automatically adjusted based on the ratios of the *expected* output rate to the internal rates. Note the term "*expected,*" since for external MSYNC-controlled output, the actual output rate is not known. However, for internally timed output, the data rate is configured by command and the output rate is known.

Decimation, filtering followed by downsampling, in the ICB has an intermediate stage and a final stage. The final stage can be disabled by command (=FILTEN,0) and it can be configured by command (=FILTTYPE) to be either a Chebyshev or Butterworth type, a custom filter, or to use as a Uniform Averager function. The intermediate stage filter is always enabled as a Butterworth type filter, but its low-pass filter cutoff frequency and downsampling rate, shown in the diagram as ⇂M, are determined by the set data rate.

The intermediate filter stage is run at the ICB input data rate. That is, for each data sample accepted from the gyro or accelerometer sub-system, the data is put into its intermediate stage filter function. This generates a filter output as well. The intermediate filter runs a biquad filter function that is always configured to use the Butterworth type (8^{th} order) coefficients, independent of output filter configuration, to implement the low-pass filter prior to downsampling at typically either a 1:1, 10:1, or 100:1 ratio. The output of the intermediate filter/downsampler is synchronous to the input and this is, therefore, an integer downsample of the input data. The downsampling ratio is controlled by data rate and the output filter selection. Intermediate filter cutoff is set by the data rate in very coarse steps to prevent aliasing the downsampled data. The intermediate filtering and downsampling used at various data rates is shown in Table 12-2.

Table 12-2: 1725 IMU Filtering and Downsampling

Output Data Rate (=DR) (Hz)	Gyro Internal Sample Rate (Hz)	Gyro Filter Cutoff Frequency (Hz)	accelerometer Internal Sample Rate (Hz)	accelerometer Filter Cutoff Frequency (Hz)	Decimation Downsample Ratio (if used)
>= 100	10000	5000	8312.5	4156.25	1:1
>= 10 to < 100	1000	500	831.25	415.625	10:1
< 10	100	50	83.125	41.56	100:1

12.2.3 Processing With Final Output Filter Disabled

As shown in the Signal-Processing Diagram (see Figure 12.1), the FILTEN configuration determines the data path that selects whether the intermediate stage downsampler and the final output filters are used. Even when a user disables the filtering with the =FILTEN,0 command, the data is passed through the intermediate stage filtering portion of the decimator, but not the downsampler. When the final output filter is disabled, the output of the intermediate stage filter is made available to the final output stage for arbitrary resampling and interpolation. This is shown in the diagram as being stored into the output data containers.

12.2.4 Processing With Final Output Filter Enabled

When the final stage filtering is enabled, the intermediate downsampling process is done and the data is passed into the user-configured final output filter. The filter output is then stored with the timestamps into the output data containers. Since the internal sampling rates of the gyros and accelerometers are different, they require different final stage filter coefficients, even though they share the same final output rate.

12.2.4.1 Final Output Filter As Chebyshev/Butterworth/custom

The final output filters must be designed using the internal sampling rates defined in the table shown in Table 12-2. The final stage filter input rate (i.e., its sampling rate) is the output of the intermediate stage decimation. For the Chebyshev, Butterworth, and user-customized filters, the final stage filtering is done with a 4-stage cascaded biquad process. This allows up to an 8th order filter. The diagram shows this as low-pass filtering and this is the typical type of filtering used to convert from the higher internal sample rates to the lower output rate. However, for a custom filter, the user can define the filter coefficients as desired to implement a pure low-pass filter or a combination of low-pass, band-pass, and/or band-reject filtering.

12.2.4.2 Use with the Uniform Averager Type Filter

The Uniform Averager type is a special filter case and does not use the biquad filter stages. When selected, data is still passed through the intermediate decimator (filter and downsampler) and then into the Uniform Averager's accumulation process. This accumulation process uses two accumulators: one for the newest downsampled gyro/accelerometer data and one for one sample back in time. There is also a data counter, so it can later compute the average when final output is needed. The final accumulated data is later interpolated and then finally averaged just prior to when the output data is packaged. The Uniform Averager type filter is thus computing the average of the samples over the output period and is not a simple moving average. This filter type is automatically configured if the user selects the external MSYNC type of output data request, but can be subsequently overridden to use the biquad stages for filtering.

12.2.5 Final Output Data Request

Depending on the configuration, the output of data is triggered from either the MSYNC input or a divided clock generated by the unit. This is shown in the diagram as an Output Request selection check box below a selection switch. The data output request will be converted to the TOV signal output and will trigger the ICB to take a timestamp and signal the process needed to generate the output according to one of the configured data formats. If the ICB does not see an output request within 2 secs (1/2 Hz), the ICB will output data on its own, essentially acting like a watchdog timer. The ICB does not change any filtering to limit aliasing in this case. One benefit of this is that during testing or development with the IMU, it can be a useful indication that the unit is working, but perhaps not receiving an external MSYNC. However, the 1/2 Hz output is not intended to be used as a normal means of obtaining data.

When the ICB's main software loop process sees the request for data output, it will "freeze" the output data containers by making a copy. This is shown as "AARS" or arbitrary asynchronous resampling. The original containers can then continue to be updated while the frozen values can be prepared for output. These containers hold the gyro or accelerometer data for each channel and the timestamps associated with when they were received from the sub-systems. They also contain a similar set of data/timestamps for the prior sample set (i.e., one internal decimated time period old). The difference in time between the new and older samples would thus depend on the configured data rate and the output filter configuration.

The filtered data old/new pair is then operated on by an interpolation function to compute an output value based on a linear interpolation model of the new and old values and the delta time between the internal samples and the output sample request. This is described in detail in a subsequent section.

The interpolated value is then further processed to do some of the following:

- If Uniform Averager is active, then the interpolated value is divided by the number of internal samples it contains.
- Any limits to rate (or acceleration) are checked and enforced and the validity status is updated as needed. The application of limits is required to verify the operating conditions match the range of unit calibration (e.g., operation outside of expected temperature ranges or range of motion specifications will result in the output data being flagged as invalid). Unit conversion is applied as configured. This changes rate (or acceleration) to delta-angle (or delta-velocity) and also the configured rotation units (radians or degrees) or linear units (meters or feet).

The output process then goes on to combine the various data as needed by the output format into the final output message. This would include the appropriate header word, status values, temperatures, CRC word, etc.

12.2.6 Additional Information: Output Rate Resampling

In the 1725 IMU family, the data output rate is configurable in a number of ways. It is, however, asynchronous to the internal sampling rate of both the gyro and the accelerometer sub-systems and it occurs at a lower data rate. Therefore, there is a need to do the following:

1) resample the internal discrete data points at a slower and arbitrary rate
2) limit latency to preserve real-time response used for stabilization applications

Ideally, sample rate conversion should be done at integer multiples, up or down, of the input sampling rate. Then some simple integer interpolation-upsampling and/or decimation-downsampling can achieve the sample rate conversion. If the output to input rates can be related by ratios of integers, then both interpolation-upsampling followed by decimation-downsampling can be applied.

Generally, in a system where the input and output rates are not direct integer multiples or integer-ratio related (i.e., they are asynchronous and, by some definitions, arbitrary) there are some non-realtime or near-realtime algorithms that can be used. For systems that can tolerate some latency (e.g., music sampling conversion or imaging), these include use of processing buffers to achieve low sample jitter rates, highly complex FIR filtering to minimize phase distortion and other techniques that are compatible with non- or near-real-time systems.

Some Optional References About Asynchronous Resampling Include:

1) http://www.iet.ntnu.no/courses/fe8114/slides/upsanddownsofasrc.pdf
2) http://www.analog.com/media/en/technical-documentation/technical-articles/5148255032673409856AES2005_ASRC.pdf

When there is a need to provide on-demand, real-time output with minimal data latency, there are limits to using some of these techniques, which forces some compromises (e.g., we use cascaded biquad (IIR) stages rather than wide FIR filtering to simplify processing burden and achieve steep anti-alias roll-off, but this sacrifices phase shifting resulting in frequency-specific distortion that some applications such as music or imaging might not tolerate).

When we use the term “arbitrary” in “arbitrary sample rate conversion,” we mean that the output sample rate may be different (asynchronous) from the input sample rate and possibly non-uniform in time (non-isochronous) with respect to itself. Specifically, in our system the output can be configured to a repeatable rate (isochronous) driven by an internal timer or on-demand (arbitrary and non-repeatable) driven by the user-interface. Where our output rate is isochronous, it is not an integer multiple or ratio of the internal data sampling rates of sub-systems. In fact, internally the sample rates of each gyro and each accelerometer are separate and unique. Therefore, we cannot simply provide integer downsampled data as an output.

If the output sampling rate is much less than the input sampling rate (i.e., it is a highly oversampled system) then it may be sufficient to simply apply a low-pass filter to the input samples and resample at some other discrete times and accept the added slight jitter.

In the IMU, the user-interface output rates are lower than the internal sampling (input) rates, but can be in the same order of magnitude, so conversion requires use of some multi-rate asynchronous arbitrary downsampling. To reduce jitter and uncertainty in the sample rate conversion, the output value is interpolated using timestamps.

12.2.7 Output Data Interpolation

Arbitrary sample rate conversion involves computing the output sample values based on the input sample values and the timing relationships of the output to the input. Therefore, by nature, it is an interpolation process.

One way to think of this would be to interpolate by conversion of the input samples from discrete/digitized values back to the continuous/analog domain and then filtering and re-digitizing at the new output rate. This would be analog interpolation. We can also use purely discrete time algorithms to interpolate the input samples to generate new output data values by constructing a model of the behavior of the signal based on nearby samples. The IMU uses simple linear interpolation whereby a percentage of the prior sample mixed with a complementary percentage of the latest sample is used for the output. Thus, the interpolation model used between the samples is a straight line.

For the 1725 IMU family, the interpolation algorithm uses the last two internal data points along with their timestamp information to derive the output value. While this adds a single internal sample rate period of latency, it provides a more accurate output value, with less jitter and uncertainty than a simple sample-and-hold output based on the most recently available internal data. A better description of the operation of the interpolation algorithm follows.

In the timing diagrams below, the *Intermediate Data Available* timing represented by the higher speed internal sampling rates as data (D1, D2, D3, etc.) is updated internally. The *Output Request* represents the signal to the system that output of data to the user is requested. This may be from an internal clocked signal or the external MSYNC signal.

```
        ____ ______________________ ___________________
Intermediate  ____X________D1____________X_______D2__________
Data Available   |           |
          |<-------- T1 -------->|<-- T2 -->|
                           |_____
Output Request ______________________________________|   |____
```

As seen in the diagram above, the output request is asking for data at time T2 after sample D2 becomes available, since its leading edge occurs after D2. However, no data is available for that point in time yet, since D2 is the latest data available. Therefore, the system instead makes a translation in time to output data associated with the time T2 after D1 (one internal sample prior). This is followed by linear interpolation between the D1 and D2 data to derive a value between them. The timing diagram below shows how the system interprets the output request signal.

```
                ____ ______________________ ___________________
Intermediate   ____X________D1____________X_______D2__________
Data Available    |           |
          |<-------- T1 -------->|
          |<-- T2 -->|
               |____
Output Request ________________|  |__________________________
```

If time T2 is nearly 0, then even though the D2 values would be available, we would output virtually nothing of them and instead output data primarily based on the D1 values. As time T2 increases, we would output more and more of D2 and less of D1. We would thus maintain the output of data at one internal sample period delay.

The alternatives to this would be to output the newest data available or, possibly, to attempt prediction of the output based on the history. In the first case, we would end up with an output timing variation of zero to as much as one internal data sample period as the time T2 varied from 0 to T1. The use of interpolation mitigates this output uncertainty (jitter). In the second, predictive case, there is less latency and justification to do this might be if the error can be bounded by the filtering used and how far out in time the prediction is made. However, the result is technically non-causal, since we cannot be certain of the value at a time in the future.

The intermediate sampling period latency associated with interpolation mentioned above will depend on the system configuration.

- If the system's final output filter is disabled, then the intermediate sample period is based on the internal highest data rate sample timing (10 KHz for 1725 IMU gyros, 8.3125 KHz for accelerometers).
- If the system output filter is enabled (e.g., Uniform Averager, Chebyshev, Butterworth, or custom) the intermediate output rate (i.e., final stage input sample rate) is determined by the data rate configured. Therefore, the relative latencies will change as well. Note: the Averager filter type is still subject to the downsampled time period associated with the data rate configuration. In the case when using the Averager with the external MSYNC mode, it may be useful to set the data rate to 100 Hz or above, so the internal intermediate downsampling is set to minimize the decimation. The Averager can then operate at full speed.

Based on the interpolation scheme, data is output according to the following formula:

$$D\_out = D1 * (1 - T2 / T1) + D2 * (T2 / T1)$$

where D1 is the prior internal data value and D2 is the most recent internal data value

As T2 shrinks toward 0, this results in more of the interpolated value being a result of D1 and less of it being D2. Similarly, as T2 approaches T1, it uses more of D2 and less of D1. This results in a linear interpolated value, with the compromise of adding one data cycle of latency. The data cycle here would be based on the internal time tags of the D1 and D2 points.

Optimization of the calculation of the equation above is as follows:

D_out = D1 * (1 - T2 / T1) + D2 * (T2 / T1)
= D1 * ((T1 - T2) / T1) + D2 * (T2 / T1)
= (1 / T1) * (D1 * (T1 - T2) + D2 * T2)
= (1 / T1) * (D1 * T1 - D1 * T2 + D2 * T2)
= (1 / T1) * (D1 * T1 + (D2 - D1) * T2)
= D1 + (T2 / T1) * (D2 - D1)

Based on the final equation, we see this is simply the equation of a line in the equation below:

Y = mx + b; where:

- m = (D2 - D1) / T1 ; is the line's slope
- x = T2 ; time since last data and requested data
- b = D1 ; the prior data value

12.2.8 Biquad Filtering (Additional Information)

A biquad filter stage is simply a two-pole infinite impulse response (IIR) filter, where both the numerator and denominator are quadratic equations. The numerator coefficients, typically b_n, define the feedforward values. The denominator coefficients, typically a_n, define the feedback coefficients. Based on the selection of coefficients, it can behave as an FIR filter when no feedback is used. Below are some basic references about biquad filtering.

- https://en.wikipedia.org/wiki/Digital_biquad_filter – this is a good explanation of the basics of biquad operation along with some useful references
- http://www.earlevel.com/main/2003/02/28/biquads/ – note their usage of a_n and b_n coefficients is swapped from our nomenclature; there is no industry standard for this. This site has some basic calculators to compute coefficients, but only for single stage (non-cascaded) biquads.
- http://www.ti.com/lit/an/slaa447/slaa447.pdf – some basic biquad information and some other information more targeted at the TI DSP chip. Appendices have some Matlab scripts for single stage biquad determination.

There is not an industry-standardized nomenclature for coefficient designation as a_n or b_n and some literature will swap them. In addition, some literature will show the feedback equations in the denominator as additions, the negative feedback being in the coefficients themselves. Alternatively, some will show the feedback equations as subtractions and assume positive coefficients. At the user configuration level, the 1725 IMU implements feedback addition, so the a_n coefficients should incorporate the appropriate negative signs.

In the 1725 IMU, the filter calculations are done with SPFP values (32-bit) so they are somewhat less sensitive to quantization and overflow than if they were fixed-point. Although not strictly necessary, it is a good idea, when cascading stages to order them in increasing order of Q and/or gain to improve stability. This is particularly true if any stages result in significant gain peaking near the cutoff point; those stages should be implemented later in the cascade. This allows the prior stages to reduce the signal energy subjected to the peaking. This is typically required when using fixed point calculations. There are a number of alternatives for computation of custom filter coefficients, including software from some sources such as those below (listed in order of decreasing cost):

- Matlab with DSP toolboxes: http://www.mathworks.com/products/matlab/
- Mathcad with DSP toolboxes: http://www.ptc.com/engineering-math-software/mathcad
- Iowegian: https://iowegian.com/scopeiir
- Iowa Hills: http://iowahills.com/4IIRFilterPage.html

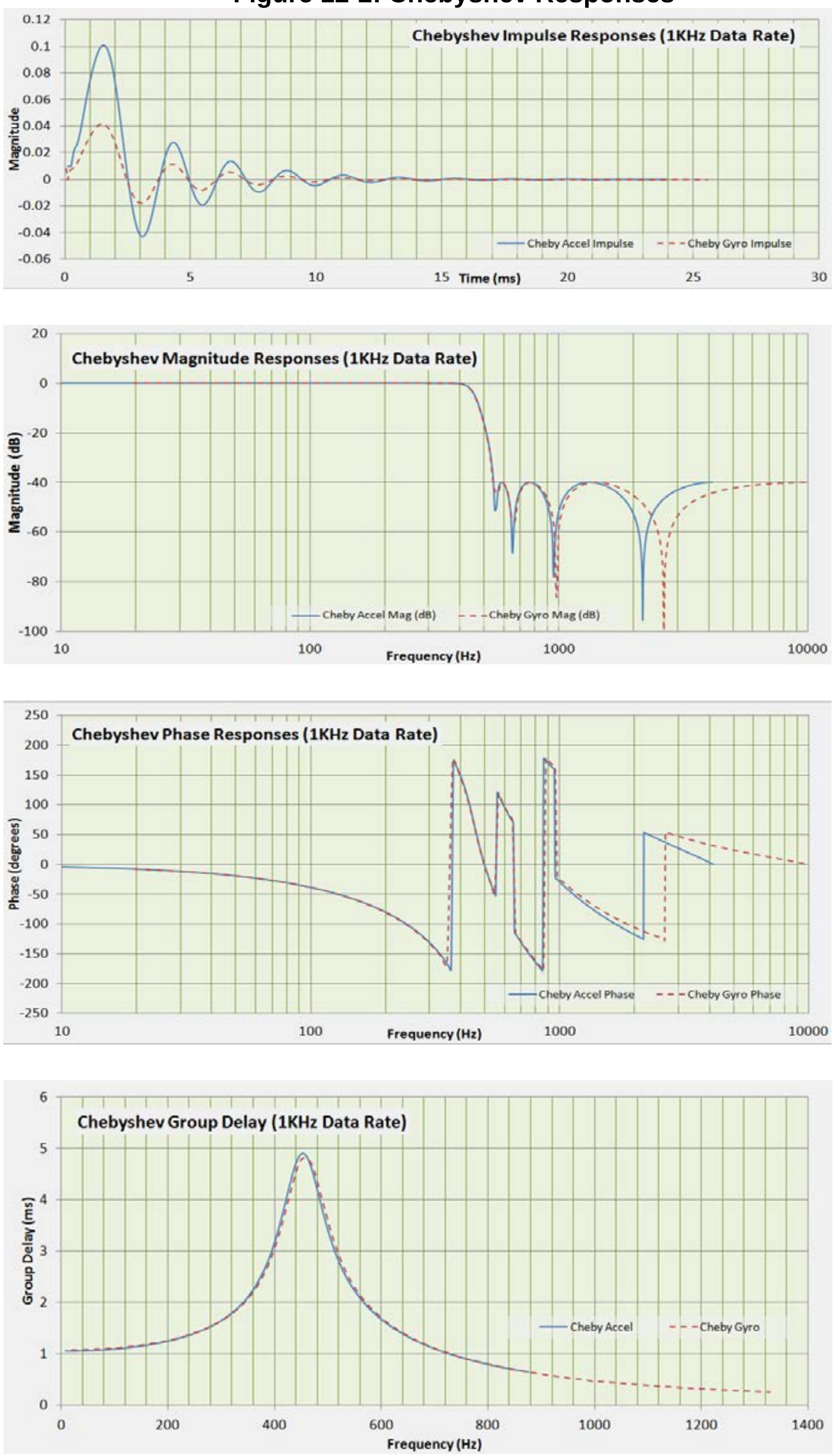
KVH makes no specific endorsements or recommendations and has not tested the above for compliance with the 1725 IMU. When designing filters, we recommend testing the behavior using the IMU's "=TESTFILT" command to extract the impulse response. The behavior inside the IMU can then be verified against theoretical performance for stability, frequency response, and to ensure that there are no unexpected issues (e.g., due to coefficient quantization or coefficient entry errors).

12.3 Default Final Output Filter Responses

12.3.1 Chebyshev

Figure 12-2 shows the plotted impulse, magnitude, phase responses and group delays of the default Chebyshev (type II) filter at a 1000 Hz data rate; =FILTTYPE,<A|G>,CHEBY,8,0.01,545
N= 8th order, GSTOP = 0.01 (-40dB) FSTOP = 545 Hz

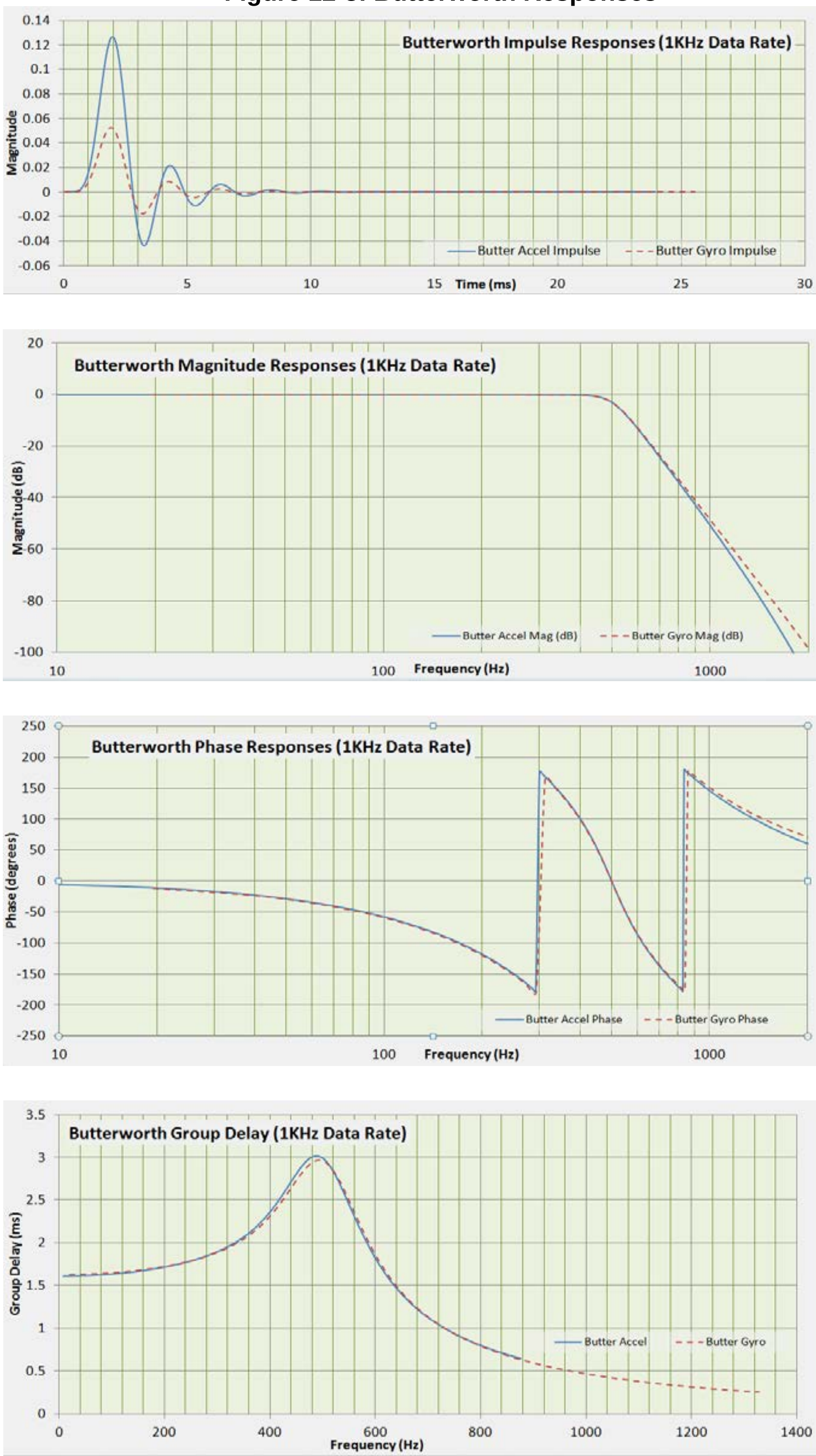
Figure 12-2: Chebyshev Responses



12.3.2 Butterworth

Figure 12-3 shows the plotted impulse, magnitude, phase responses, and group delays of the built-in Butterworth filter at a 1000 Hz data rate. =FILTTYPE,<A|G>,BUTTER,8,500 8th order, FCUTOFF = 500 Hz

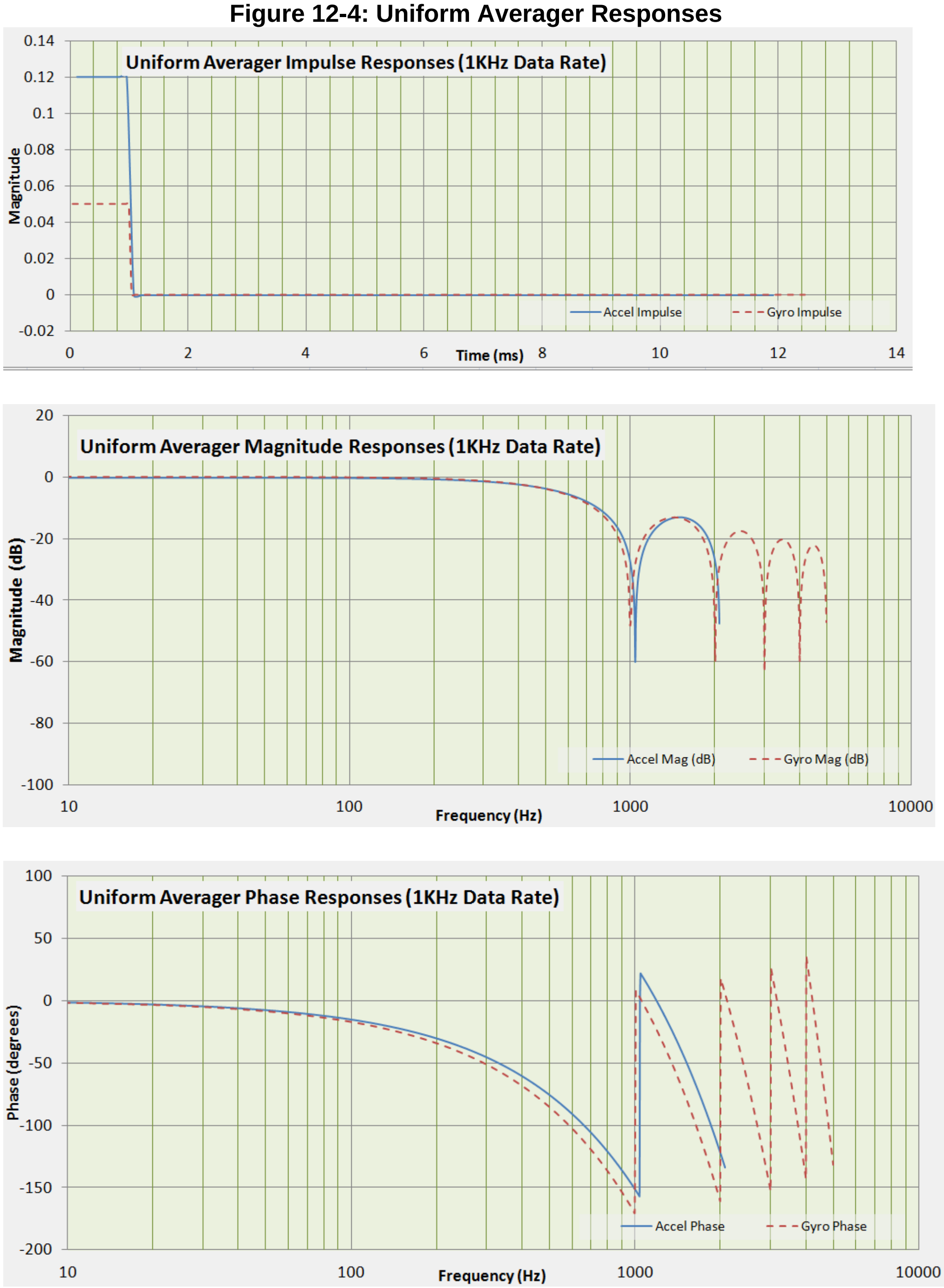
Figure 12-3: Butterworth Responses



12.3.3 Uniform Averager

Figure 12-4 shows the plotted impulse, magnitude and phase of the built-in Uniform Averager filter at a 1000 Hz data rate; =FILTTYPE,<A|G>,AVE. For gyros, this represents a 10:1 sample reduction and for accelerometers, it is an 8.3125:1 reduction. The group delay of the Uniform Averager is a constant and is computed as 0.5/FOUT, where FOUT is the frequency of the final output; for 1000 Hz output rate the delay is 0.5ms.

Figure 12-4: Uniform Averager Responses



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