Inertial Sensors and Systems

Ellipse, Ekinox, Apogee, Navsight

Technical Reference Manual

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Revision history

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1.3	Jul 10, 18	Alexis Guinamard	[SBGTECHRM-6] Add calibration procedure documentation [SBGTECHRM-7] Add Navsight specific installation recommendations [SBGTECHRM-8] Added firmware versions supported by the Technical Reference Manual [SBGTECHRM-9] Update ShipMotionHP specification (fixed delay reduced) [SBGTECHRM-10] Added ShipMotion RTK documentation [SBGTECHRM-11] Fixed invalid DVL measurement frame with reversed X and Z axes
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1	Jun 9, 16	Alexis Guinamard	First public version Data coming from former “User Manuals”

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Terminology

ADC: Analog to Digital Converter
AHRS: Attitude and Heading Reference System
CAN (Bus): Controller Area Network
DHCP: Dynamic Host Configuration Protocol
DVL: Doppler Velocity Log
EKF: Extended Kalman Filter
EEPROM: Electrically-Erasable Programmable Read-Only Memory
FIR: Finite Impulse Response (filter)
FTP: File Transfer Protocol
FS: Full Scale
FOG: Fiber Optic Gyroscope
GNSS: Global Navigation Satellite System
GPS: Global Positioning System
IIR: Infinite Impulse Response (filter)
IMU: Inertial Measurement Unit
INS: Inertial Navigation System
IP: Internet Protocol
LBL: Long Baseline
MAC (address): Media Access Control
MEMS: Micro Electro-Mechanical Systems
NED: North East Down (coordinate frame)
NA: Not applicable
NMEA (NMEA 0183): National Marine Electronics Association (standardized communication protocol)
PPS: Pulse Per Second (signal)
RAM: Random Access Memory
RMA: Return Merchandize Authorization
RMS: Root Mean Square
RTCM: Radio Technical Commission for Maritime Services (Protocol)
RTK: Real Time Kinematics
SI: International System of Units
TBD: To Be Defined
TCP: Transmission Control Protocol
UDP: User Datagram Protocol
UTC: Coordinated Universal Time
USBL: Ultra Short Base Line
VRE: Vibration Rectification Error
WGS84: World Geodetic System 1984
WMM: World Magnetic Model

1. Introduction

This document describes in details the common concepts used in the whole SBG Systems line of Inertial Systems.

Starting from a complete Theory of Operation and common mathematical background description, the Reference Manual also covers interfaces, installation and operation guidelines.

Covered products

The products covered by this document are:

- **Ellipse series**: Miniature and cost effective line of inertial systems, ranging from a basic AHRS to a high performance dual antenna solutions
- **Ekinox series**: Tactical grade line of inertial Systems, providing modular architecture and high connectivity
- **Apogee series**: The most accurate MEMS inertial system available on the market, providing excellent performance in a compact package.
- **Navsight solution:** A dedicated solution for all survey applications, delivering high performance in a convenient package.

Covered Firmware

This document covers following firmwares:

- **Ellipse** Firmware 1.4.100-stable and above
- **Ekinox, Apogee** and **Navsight** Firmware 2.0.276-stable and above

Figure 1.1: SBG Systems line of Inertial Systems

2. Theory of operation

2.1. Overview

The following diagram shows the basic organization of an inertial system. This is an overview and may slightly vary from one sensor to another.

In most products, the IMU is fully integrated in the same enclosure as the processing and GNSS units. In Navsight solution, the IMU and processing are separated and can be located tens of meters away.

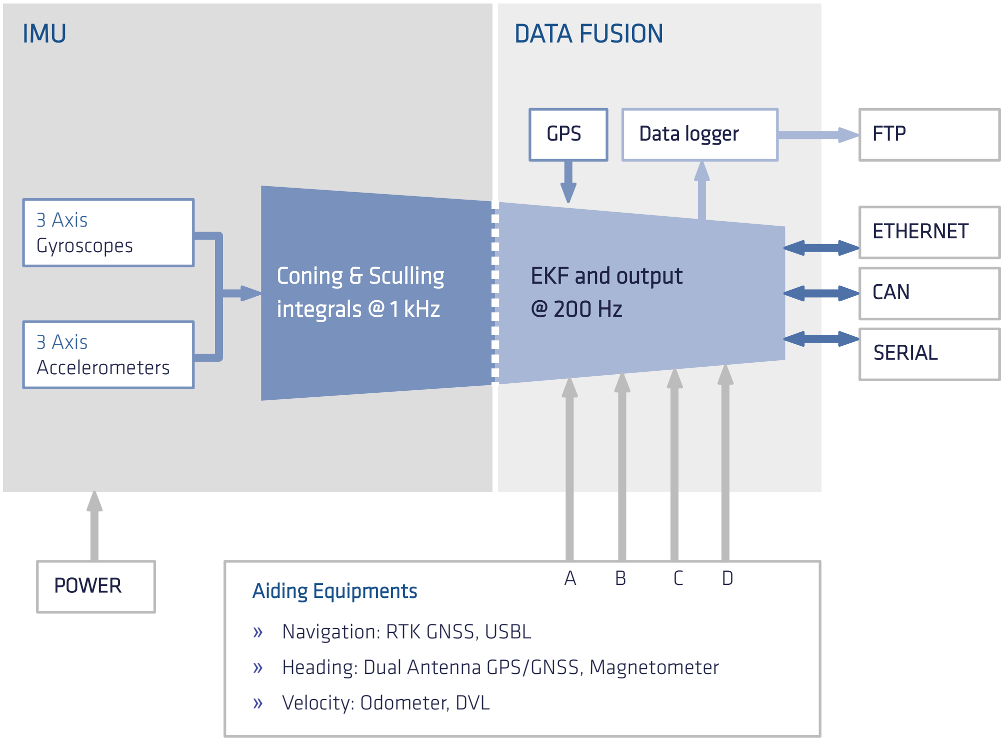

Figure 2.1: Typical block diagram of an inertial system

2.2. Inertial measurement unit

As an IMU is the main component of an inertial navigation system, SBG Systems units have been carefully designed to take full advantage and performance of MEMS technology.

All SBG Systems IMUs contains a set of:

- Three axis Gyroscopes sampled at a high frequency (> 1kHz)
- Three axis Accelerometer sampled at a high frequency (> 1kHz)
- A set of calibration parameters to ensure gyros and accelerometer provide high accuracy outputs
- A high frequency integrator (1KHz coning and sculling integrals) that provide a fully accurate 200Hz output to the other navigation algorithms

2.2.1. MEMS technology

High quality MEMS components have been selected for this IMU. This MEMS technology provides many advantages over competing technologies such as mechanical or FOG gyroscopes, servo accelerometers:

- A miniature design provides smaller, lighter products, enabling new applications to be covered.
- This technology is very robust and provides much higher shock resistance as well as maintenance free operation.
- MEMS designs provide cost effective solutions compared to other technologies such as FOG or RLG.

Note: Although the same MEMS technology is used for consumer applications such as smart-phones and tablets, there is a very large performance gap between low cost MEMS and navigation grade MEMS sensors. SBG Systems has selected for this product tactical grade sensors only.

2.2.2. Factory Calibration and test

In order to provide best quality sensors, SBG Systems has developed unique calibration and test procedures for all inertial sensors. When dealing with sensors error parameters, we consider that a good calibration is always better and more reliable than on-line sensor estimation.

We calibrate and test each product in our factory in order to provide efficient and defect free units. A calibration report is shipped with each product. This calibration procedure allows taking the maximum precision of each sensor over the full temperature range.

The calibration and test procedure provides:

- Functional and accuracy test of all sensors, and subsystems over full temperature range.
- Gain and bias compensation over full temperature range for accelerometers and gyroscopes,
- Non linearity compensation for accelerometers and gyroscopes over full measurement range,
- Cross-axis and misalignment effects compensation for accelerometers and gyroscopes,
- Gyro-G effect compensation for gyroscopes.

2.2.3. Vibration handling

SBG Systems IMUs has been designed for harsh environments. Specific developments led to efficient vibration handling.

When exposed to vibrations, an accelerometer or gyroscope will have some increased bias. This vibration effect on accelerometer is called VRE. So a good starting point is to choose sensors that have low VRE in order to sustain higher levels of vibrations.

The second point is to design efficient hardware and software low pass filters that will reject out noise and unwanted signals to deliver only reliable and anti-aliased motion information.

Coning and sculling integration, described in next section is finally a good way to handle properly fast vibrating motion.

2.2.4. Coning and sculling integration

In modern "strapdown" inertial systems, angular rates from gyroscopes and accelerations from accelerometers must be integrated over time to maintain an orientation and navigation solution.

As this orientation and velocity integration is highly non linear, it may become necessary to use very small integration steps when motion becomes highly dynamic in order to maintain consistent accuracy.

Coning and sculling algorithms provide computation efficient ways to integrate accelerometers and gyroscopes signals at high frequency such as 1 kHz.

All SBG Systems IMUs compute a 1 kHz coning and sculling integration for best accuracy in dynamic environments.

Delta angle filters and delta velocity filters have been designed to provide an equivalent output delay.

2.3. Extended Kalman Filter

2.3.1. Overview

Thanks to a modern processing architecture, SBG Systems inertial systems run a real time loosely coupled Extended Kalman Filter (EKF). The loose coupling between GPS/GNSS and the Kalman Filter allows GPS data to improve inertial sensor performance, and on the other hand inertial data improve overall navigation performance.

More than just a direct EKF implementation, the implemented algorithms include advanced error models and wrong measurement detection to ensure that best navigation performance is provided at any time.

A modular design allows a wide range of aiding sensors to be connected to the INS. GNSS, Odometer, DVL and other aiding sensors can be connected to further enhance navigation performance.

In addition, the Extended Kalman filter is able to estimate some user entered parameters to further improve accuracy, such as GPS lever arm, odometer's gain, and others.

Specialized motion profiles and error models provide optimal options and tuning for each application, and each aiding equipments.

2.3.2. Basic principle

Inertial sensors (accelerometers and gyroscopes) provide very accurate short term motion measurements but suffer from drift when integration time becomes long. Some other systems such as GNSS receivers or odometer provide low frequency measurements that can be fooled by jamming, or short term measurements errors, but these sensors provide good performance over long term.

The basic idea behind the Kalman filter is to take the best of each sensor, without drawbacks. A high frequency prediction (also called propagation) step uses inertial sensors to precisely measure motion and navigation data. When aiding data (GPS position, Odometer data or DVL reading for example) becomes available, the Kalman filter will use it to correct the current state and prevent drift.

As aiding measurements are made at a lower frequency than the prediction step, a small jump can be observed after a correction is applied. This jump should be really small in normal operating conditions.

A covariance matrix maintains up to date each estimated parameter error. When there is no measurement available, estimation error tends to increase; when a new measurement is received, this error will decrease. This covariance matrix is also used to handle the "link" between each estimated parameters.

Besides the EKF, a sensor manager is implemented to check aiding measurements and reject bad ones.

To summarize the EKF operation, the following diagram shows how IMU and external sensors are used

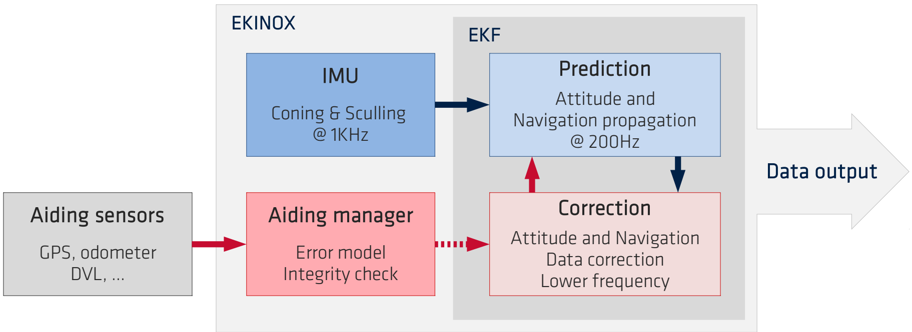

Figure 2.2: EKF simplified block diagram

inside the EKF to provide navigation and orientation data.

2.3.3. Modes of operation

The Kalman filter will run into several computation modes depending on situations:

2.3.3.1. Initialization

This mode is observed at startup only and corresponds to the first attitude initialization using the internal accelerometer as vertical reference. It assumes low accelerations so best initialization is achieved when the device is powered up stationary or at constant speed. If the INS is powered up during motion, the full accuracy may be reached within a few minutes after startup.

2.3.3.2. Vertical Gyro mode

Once roll and pitch angles are initialized, the EKF filter is running in a limited mode, where only roll and pitch angles are valid. This mode uses a vertical reference and internal gyroscopes to estimate orientation. Therefore, heading angle is freely drifting, as well as position and velocity. Ship motion data is provided but may have degraded accuracy in dynamic environments.

Heading Rough alignment procedures

When operated in “vertical gyro” mode, the EKF will continuously try to make a first heading angle alignment using different procedures. These procedures have some constraints and the following table explains how they are used and in which situations:

Method	Availability	Constraints – Remarks
GNSS Dual antenna Heading	When GNSS dual antenna Heading is activated as an aiding input	This method uses input GPS true heading provided by dual antenna GPS. Open sky condition is preferred for initialization due to the dual antenna system sensitivity to multi-path effects. Device must be in static or constant heading condition.
Kinematic alignment	In Automotive, Airplane and Marine motion profiles.	This method is enabled in most dynamic applications. It uses GPS course as an input, considering that preferred direction of travel is forward. The device must drive/fly in forward direction, at least at 3.0 m/s.
GPS True Heading	When GPS True Heading is activated as an aiding input	This method uses GNSS true heading provided by a dual antenna GNSS receiver. Good GNSS condition is preferred for initialization due to a higher dual antenna system sensitivity to multi-path effects.
Acceleration Alignment	In Helicopter motion profile	This method uses GNSS and inertial accelerations to define a heading. This allow any motion, in any direction. Due to higher sensitivity to GNSS signal reflection, the sensor should be initialized in good GNSS conditions. The device must be accelerated at 2.5m/s² or more for at least 2seconds.
Magnetic Heading	Available when Magnetic heading aiding is enabled.	This mode is not recommended for most applications. If magnetometers are enabled, this signal is available at startup. A good magnetic field must be available for proper operation.

As a result of heading alignment, several jumps on heading angle may be observed when the system is operated in vertical gyro mode.

2.3.3.3. AHRS mode

In this mode, a full orientation set is estimated using a vertical reference and a heading input (external dual antenna GNSS heading). Roll, Pitch and Yaw angles are accurate. Position and velocity are freely drifting and cannot be considered as valid.

Position and velocity initialization

As for heading alignment, the system continuously tries to initialize the position and velocity using GNSS inputs when operated in AHRS mode. Several jumps on velocity and position may then be observed in this mode.

2.3.3.4. Navigation modes

Navigation Velocity mode

In this mode a velocity input (GPS, or Odometer + vehicle constraints, or DVL) is provided to maintain accurate orientation and velocity data. Position output is unreferenced but should not drift as much as in AHRS mode.

Full Navigation mode

In this mode, the EKF provides the full outputs: Orientation, absolute position and velocity are fully estimated.

The Kalman filter will always try to use the best or highest computation mode. In some situations such as long GPS drop outs, the computation mode may be downgraded from Full Navigation to Navigation Velocity or AHRS mode depending on outage duration. This makes it possible to maintain reliable orientation even during long GPS outages, with an accuracy similar to AHRS systems.

> **Note:** AHRS units behavior slightly differ from one product line to another: The Ellipse-A cannot accept aiding data so it only runs in the AHRS mode. However, Ekinox and Apogee A series accept an external GNSS input to allow navigation mode to be used internally. This improves orientation output performance. Only orientation outputs remain available in this case.

2.3.3.5. Heading observability in Navigation modes

Using single Antenna GNSS

Depending on the device configuration, the EKF will make use of all available measurements to estimate orientation and navigation parameters. GPS or odometers will be able to stabilize navigation data but also orientation data. Roll and pitch are always accurately estimated when GPS is available.

When the sensor is subject to acceleration, the EKF is also able to stabilize heading angle. In case the reported Yaw angle standard deviation becomes high or the error increases, then doing some dynamic maneuver can improve accuracy.

In addition, the Automotive motion profile will enable accurate heading measurement as soon as the car is moving (no specific acceleration required in this mode).

Using dual antenna GNSS

Thanks to a dual antenna aiding, some units will provide reliable heading, even in static condition. This type of aiding might be helpful in applications where the dynamics are low, and in particular marine applications.

Compared to a stand-alone GNSS dual antenna system, the inertial/GNSS coupling will smooth GNSS heading and reject wrong measurements in order to provide best output accuracy. The internal gyro will also provide reliable heading information during temporary GNSS drop outs.

2.3.3.6. Operation during long aiding outages

When there is no aiding measurement available (no GNSS fix or between measurements), the propagation step maintains navigation and orientation data up to date, but navigation error will increase. This condition is also referred as “dead reckoning”. After a long dead reckoning period, the first correction applied can generate large jumps depending on actual error.

When the estimated position error reaches 500m, the system will fallback into the “Navigation Velocity” mode, and when the estimated velocity accuracy reaches 50m/s, the system will fallback into the “AHRS” mode in order to ensure at least a reasonable roll and Pitch angles accuracy.

Position and velocity are still computed and propagated in these fallback modes but their status is not valid.

There are ways to limit dead-reckoning drift by using other sensors such as odometer, or by making stops (check out next section).

2.3.4. Performance enhancements

2.3.4.1. Automatic ZUPT detection

The EKF is able to automatically use "Zero Velocity Updates" (ZUPT) in some motion profiles. When the sensor stops moving, the Kalman filter detects the zero velocity condition and uses that information to correct the states, and then limit the position drift.

2.3.4.2. Augmented state estimation (lever arms, alignments)

In most applications, measuring lever arms or misalignment angles can be very difficult tasks. That's why the EKF is able to estimate several additional states that will ensure maximum accuracy:

- Lever arms (GPS, Odometer, DVL) estimation makes it possible to improve user measurements. It is still required to enter those lever arms, but with a reasonable accuracy of 5 cm, the Kalman filter will finish the adjustments with less than 1 cm accuracy.
- Alignments (Vehicle alignment, GPS True Heading or DVL alignments) can also be estimated. User entered alignments angles can be performed with only 3° accuracy to ensure good operation using these algorithms.
- DVL / Odometer Gains are also constantly estimated to minimize dead reckoning errors when using this type of sensor.
- DVL Water layer current is finally estimated to allow short term navigation using only the DVL water layer information (can be useful when bottom tracking data is not available for some time).

Note: All these "augmented states" are only enabled when relevant with an application. In addition, most of these states require some dynamic motion, so for example GPS True heading alignment estimation can only be used in airborne or land applications.

Note 2: On the Ekinox, Apogee and Navsight series, this online estimation is performed during the calibration procedure. Once lever arms and alignments are properly calibrated and stored in non volatile memory, their estimation is stopped to ensure best performance.

2.3.4.3. Automotive vehicle constraints

The Extended Kalman Filter will pretty well improve its performance in automotive applications, where it's possible to make assumptions on the vehicle dynamics (lateral velocity is likely to be small or zero).

These assumptions can greatly reduce the drift rate in case of dead reckoning. It will also significantly improve performance in difficult GNSS environments such as Urban Canyons which are really common in automotive applications. The use of an Odometer can complete this type of improvement.

2.3.5. Performance monitoring

The EKF provides various indicators that provide efficient feedback about the system performance:

- **Standard Deviations**: Each navigation parameter comes with an associated instantaneous estimated error.
- **Output validity flags**: Based on a standard deviation check these flags quickly inform user about each measurement validity. The following flags and thresholds are defined:
  - **Attitude valid:** (Roll / Pitch): Valid when Poll/Pitch Standard deviations are lower than a predefined level.
  - **Heading valid:** Valid when Yaw angle standard deviation is lower than than a predefined level.
  - **Velocity valid:** Valid when the total estimated velocity error (3D) is lower than than a predefined level.
  - **Position valid**: Valid when the total estimated position error (3D) is lower than than a predefined level.
- **Alignment validity flag**: This flag checks internally estimated parameters error such as gyro and accelerometer bias to ensure that the system will correctly behave in case of bad GNSS data or dead-reckoning. When this flag is set, the EKF is considered as running in optimal performance conditions.
- **Used in solution flags:** In addition to the validity flags, the EKF also provides feedback about which aiding inputs are used in the solution. It can be useful when integrating the system in a new application to ensure the installation was correct.

2.3.6. Motion profiles and aiding sensors error models

Each application has specific requirements and constraints such as angular rate dynamics, vibrations, presence of long term accelerations and others. Instead of having different products for each environment, SBG Systems has developed a cutting edge technology able to adapt the sensor to each situation.

The Motion Profile technology is tightly integrated with the embedded Kalman Filter and inertial sensors. It provides with a simple application selection a deep and fine device configuration. Different motion profiles have been designed to fit most typical applications and should provide optimal performance.

A similar technology is used to specialize error models for each aiding device. A single click allows the user to choose an aiding sensor model and everything will just work properly.

> **Note:** Most applications should find a suitable motion profile and error models to obtain optimal performance. However, if a specific application requires fine tuning, it is still possible to design a specific motion profile for that application. Feel free to contact our SBG Systems support team that will assist you during this operation.

2.3.7. Earth Geodetic, Gravity and Magnetic models

SBG Systems products internally compute the navigation parameters using the standard WGS-84 ellipsoid.

The mean sea level altitude is computed by the INS using a built in EGM96 model with a resolution better than 15 arc second.

Finally, for products using magnetometers, the World Magnetic Model 2015 is used to compensate the magnetic declination and inclination.

2.4. Aiding sensors

Many different aiding sensors can be used to aid the INS.

2.4.1. GNSS receiver

In SBG Systems product variants, all models N and D embed a GNSS receiver. A second external receiver can also be connected to Ekinox and Apogee series if required. Other INS products accept one or two external GNSS data inputs to enhance navigation performance.

All GNSS receivers will provide velocity and position aiding. Dual antenna systems can also provide a True Heading aiding. RTK GPS receivers can be used to improve positioning accuracy.

2.4.2. Odometer

In addition to the GNSS aiding, all INS models provide an odometer input which can greatly improve performance in challenging environments such as urban canyons. The odometer provides a reliable velocity information even during GNSS outages. This increases significantly the dead reckoning accuracy.

Our products handle quadrature output or compatible odometers in order to support forward and reverse directions.

> **Note:** Odometer integration is made really simple as the EKF will finely adjust odometer's gain and will correct residual errors in the odometer alignment and lever arm.

2.4.3. Internal magnetometer

On Ellipse series, an internal magnetometer is available as heading sensor. In many applications such as airborne or sometimes in marine environment, this magnetometer can provide an efficient heading aiding input.

> **Note:** Magnetometer use requires an in-situ calibration to compensate surrounding ferromagnetic materials. Please read the Iron Calibration Tools documentation for more information.

2.4.4. Doppler Velocity Log

In many marine or underwater applications, the DVL is a good choice to improve navigation when GPS is not available. DVL has been fully coupled with the EKF to provide full navigation performance in both bottom tracking and water layer conditions. No calibration is required as the EKF will automatically adjust alignments and gain parameters.

The fusion of DVL data with the EKF can provide very accurate and reliable underwater position data in real conditions. A carefully chosen mission pattern such as a lawn mower one can also dramatically limit the position error growth.

In addition to the Kalman filter integration with DVL, the inertial sensor can store and output back the DVL messages (PD0) for water profiling applications.

2.4.5. Other aiding sensor

The SBG Systems product line has been designed to be highly modular and can be connected to a variety of other aiding equipment such as USBL or depth sensors.

> **Note:** Please contact SBG Systems support for more information about those sensors as they are not part of the standard package.

2.5. Ship motion computation (Heave, Surge, Sway)

Mainly used in marine applications, we refer here to ship motion computation. Vertical motion is called heave; Surge and Sway are the two horizontal components of the ship motion. You can find more details about heave conventions in the dedicated section Ship motion conventions.

Two different heave computations algorithms are proposed depending on application requirements:

- Real Time Ship Motion that provides instantaneous heave information for real time applications.
- ShipMotionHP that provides fixed 450s delayed heave information for greatly enhanced precision.

> **Note:** As these outputs are relative to mean position, Ship motion data cannot be used as navigation data.

2.5.1. Real time Ship Motion

Aside from the EKF, the SBG Systems inertial sensors computes at 50Hz ship motion data from accelerometers double integration. As this double integration generates drift due to orientation error or sensor bias, the best way to get a stable output is to use a high pass filter design that will remove any constant component in the motion.

SBG Systems has developed an advanced filter design that ensures no phase and gain errors are generated. In addition, an automatic filter tuning ensures proper behavior is obtained with swell periods up to 25 seconds.

Due to high pass filter design, the heave, surge and sway data will always return to zero in static conditions. If a step is performed, the heave output will show the step and then will smoothly come back to zero. It may take a few minutes for the output to be stabilized after a step.

The ship motion computation is more accurate in the vertical direction than in horizontal ones. This is why surge and sway can only measure motion periods up to 2.5 s.

For best accuracy, the when available, we use GNSS data to compensate accelerations that could disturb ship motion computations during turns or acceleration phases.

> **Note:** Surge and sway data availability depends on the product lines (ie. not available on Ellipse series)

2.5.2. Delayed Heave (ShipMotionHP)

Available on higher grade units (Ekinox and Apogee), the shipMotionHP algorithm makes use of past measurements to greatly enhance heave performance. Common phase errors observed in real time Heave operation are seamlessly corrected and the filter will provide even better performance under long swell period conditions.

ShipMotionHP algorithm has a fixed delay of 150s. The output messages have the same format as real time ship Motion mode and a time-stamp can be used to correctly date the ship Motion data.

This algorithm is ideal for applications that don't require strict real time operation such as seabed mapping.

The real time Heave operation remains available to get a first heave estimate before the delayed heave data becomes available.

> **Note 1:** As ShipMotionHP is a delayed algorithm, the unit must remain turned ON in normal operating conditions at least 5 minutes before, and 3 minutes after the actual survey path is performed to enable full data acquisition.

> **Note 2:** Only vertical ship motion (heave) is available in ShipMotionHP mode. Surge and Sway are not provided in this mode of operation.

2.5.3. Centre of Rotation and Deported heave operation

When analyzing the heave motion, we can find that part of the heave motion is due to the vessel rotations. This part differs from one place to another, and is canceled at the Centre of Rotations. Another part affect the whole vessel in a constant way.

The following picture shows the effect of the rotation induced heave at different locations on the vessel:

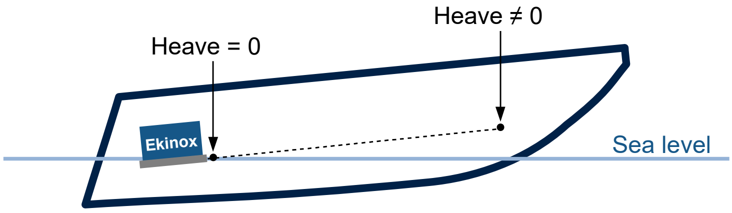

Figure 2.3: Effect of pitch angle on heave output

Normally, the heave computation is the most accurate when computed at the vessel Centre of Rotation because the sensor measures less motion than anywhere else on the vessel.

However, SBG Systems have designed specific algorithms that take into account the Centre of Rotation lever arm (primary lever arm) in order to obtain optimal heave performance even while placing the sensor away from this location. This algorithm requires you to correctly measure and enter the Primary Lever Arm in the sensor settings. Because of that, it is recommended to place the sensor as close as possible to the monitoring point (ie. close to the sonar head).

For large ships or long primary lever arms such as 10 meters or more, we recommend to keep the inertial sensor close to the Centre of Rotation if the heave measurement should be provided.

When the point of interest is not located at the IMU position, it is possible to configure one or several external lever arms to deport the heave measurements to those monitoring points.

Note: When the boat is stationary, IMU misalignment with vessel should be precisely accounted for by mechanical design, or software configuration in order to provide consistent heave values on secondary points.

2.5.4. Heave enhanced altitude (shipMotionRTK)

In the marine survey industry, there is often the question whether using the heave output or the Kalman filtered altitude output. In case of good GNSS condition the RTK altitude can be very precise and simplifies the setup as the surveyor don't need to bother with tide compensation. However, even when fused with inertial sensors, the RTK altitude might be disturbed in case of difficult GNSS environment such as bridge crossing.

On the other hand, the heave algorithm allows precise relative measurements, without specific errors during difficult GNSS conditions. However its more complex to use due to the tide compensation needed.

shipMotionRTK (or Enhanced Altitude mode) algorithm takes the best of these two worlds by merging the heave output with the RTK altitude, providing accurate and absolute altitude measurement in both good and challenging GNSS conditions.

Ship Motion RTK algorithm can only be used with the marine motion profile and in combination with a precise position like RTK or PPP with fixed carrier ambiguities. It can be disabled if needed.

2.6. Time and synchronization

When dealing with external devices, latency and synchronization can be important points to consider because of different calculation delays within each device and transmission times.

2.6.1. Output Latency

A specific software design has been implemented to provide the minimum output latency. Once sensor data are sampled, the Extended Kalman Filter only runs a very small and constant time computations before the outputs are generated. Therefore, a computation delay of less than one millisecond is observed.

CAN Logs are all sent after all serial outputs because the CAN protocol cannot guarantee in any case the output delay.

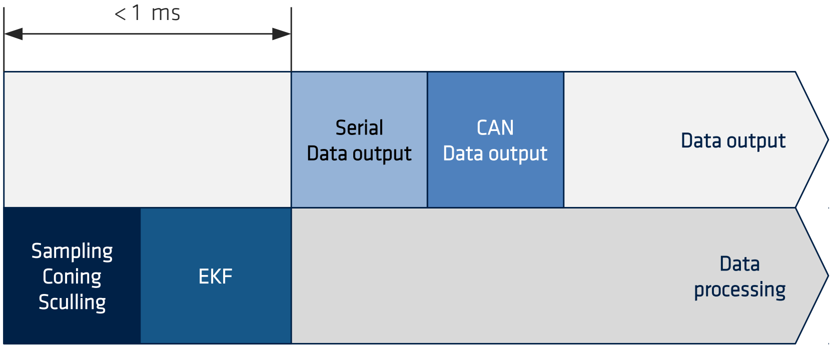

Figure 2.4: Data processing and output

Note that the processing latency should be added to the data transmission latency if you want to get total delay. This transmission latency vary from one interface to another.

2.6.2. Event inputs

The Inertial sensors can includes up to 5 synchronization inputs that can be used for different purposes:

- Event input: All pulses received generate events that can generate specific Logs output. Any output log can be triggered by an event pulse.
- Event Marker: An event marker log can be sent each time a pulse is received in order to time mark each event.
- PPS input: When connected to an external GNSS system, the PPS signal is used to realign and synchronize internal clock to GPS clock.
- Other aiding input time-stamping: If a specific aiding sensor generates pulses that time stamp the following output, the corresponding event input can be used for data synchronization.

2.6.3. Event triggered logs

The following example shows how event triggered logs are generated. In this example, three processing loops are shown, from N to N+3. Event received during loop N generates an output after N+1 computation. Event received during N+1 loop generates an output after N+2 computation.

SBG Systems sensors handle up to 200Hz input. In case of higher frequency events, only the last received event will be taken into account.

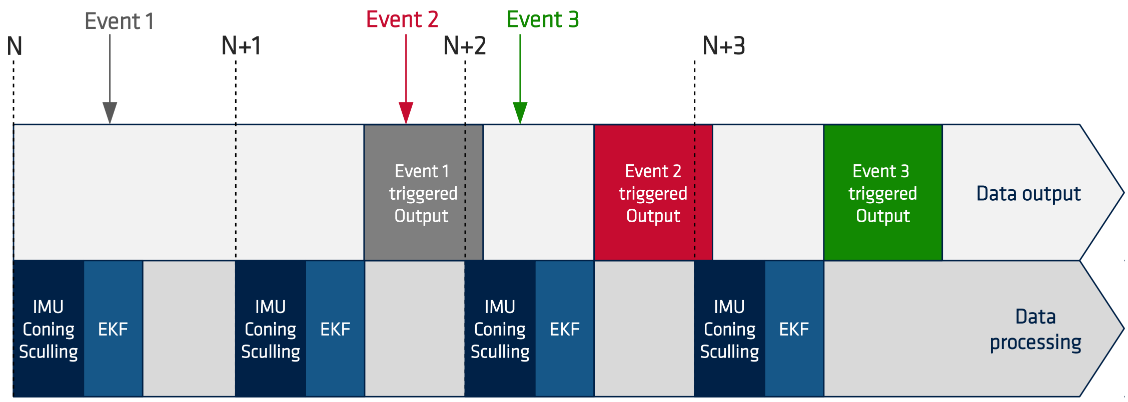

Figure 2.5: Event triggered log example

2.6.3.1. Event markers handling

Event marker handling is very similar to the event triggered logs. Events received are stacked in the system and an event marker message can be sent at each computation loop. This log will include all events details during previous loop.

SBG Systems sensors handle up to 1kHz event Markers input. Sending more than 1KHz events may overload the internal CPU.

The following diagram explains this behavior:

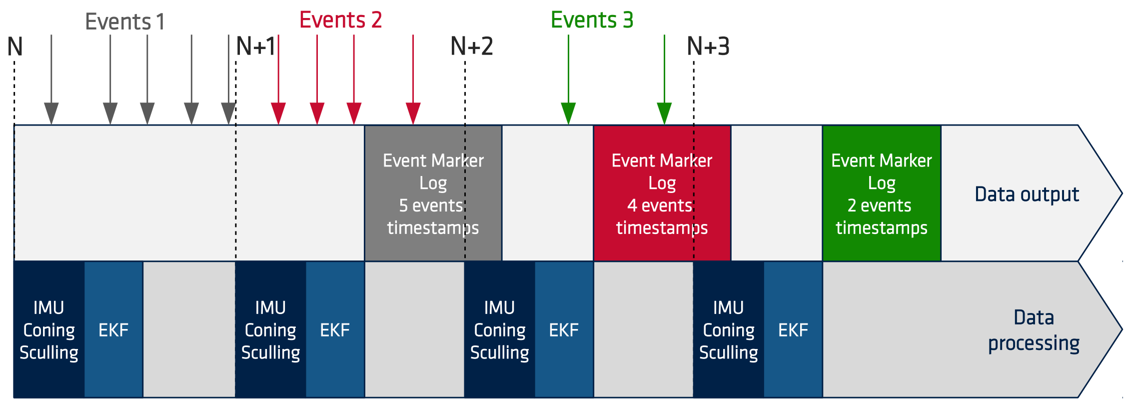

Figure 2.6: Event markers

2.6.4. Event Output

A synchronization output pin allows pulses generation in following conditions:

- Main loop divider: This event is activated at the sensor sample time, but its frequency is divided by the output divider. If the divider is set to 4, pulse output frequency will be 200Hz / 4 = 50Hz.
- PPS: This output will also be synchronized with the sample time, but it will be provided at 1Hz only when clock is correctly estimated. So this output is provided at each top of a second in UTC time.

2.6.5. Clock bias and gain estimation with GPS and PPS

SBG Systems sensors are able to improve their internal crystal accuracy by using a PPS signal from a GNSS receiver.

This PPS signal also allows GPS data synchronization, required for good navigation accuracy, as well as internal clock bias and gain estimation. It is generally sent at each top of a UTC time second.

Clock estimation is made in two steps:

- The first step is to realign the main loop to the PPS: each pulse received on the PPS must correspond to a new sample data.
- The second step is to finely adjust the clock gain by comparing the actual PPS time with internal clock time.

> **Note:** When two GNSS receivers are used at the same time, a single PPS signal is required to enable both clock estimation and GNSS synchronization

2.6.6. Internal time and UTC time

SBG Systems sensors internal clock reference is always started at 0 when the sensor is powered on. During clock bias estimation, the internal time may slide up to +/- 2.5 ms in order to align internal time with UTC time. Once synchronized, the internal time keeps counting from power up without being affected by UTC.

When internal clock has been synchronized to PPS and UTC time is available from the GNSS system, the device will also provide a UTC time reference, with corresponding internal time. Thanks to the internal time and UTC offset, it is possible to recalculate a UTC time for each received log.

> **Note:** Before GPS is available, the UTC time starts at the date configured in settings. When the GPS becomes available, a first value of UTC (based on GPS time) is provided but it can be a few seconds away from the actual UTC time. When "leap seconds" information becomes available, a jump can be observed to realign output on actual UTC time. A specific flag informs the user about the UTC time validity.
>
> For more information, please search "GPS Leap Seconds" on the Internet to find some more details about this notion.

3. Conventions

3.1. Reference coordinate frames

Although this matter requires some mathematics skills, it may be important to take some time to fully understand how navigation and orientation are represented.

We remind that an inertial frame is a frame in which Newton's laws of motion apply. An inertial frame is therefore not accelerating, but can be in uniform linear motion.

All Inertial sensors (accelerometers, gyroscopes) produce measurements relative to an inertial frame.

3.1.1. Earth Centered Earth Fixed (ECEF) Coordinate frame

This coordinate frame has its origin placed at the center of Earth. The frame is rotating with Earth so that constant coordinates will point to a single point on Earth. The frame rotation rate ω_{ie} is 360° per day plus 360° per year.
Due to this frame rotation, the ECEF frame is not an inertial frame.

Note: The navigation algorithms take into account this frame rotation rate in order to ensure best navigation accuracy.

There are two main coordinate systems used to represent positions within this ECEF frame.

3.1.1.1. ECEF Cartesian coordinate system

The first is the Cartesian where the origin is placed at the Earth Center of mass; *X* axis is pointing to the equator and prime meridian intersection. *Z* axis is pointing to the North pole and *Y* axis complete the right hand rule.

This system is widely used inside GPS systems because of its easy and precise computations, but is not easily understood by human beings.

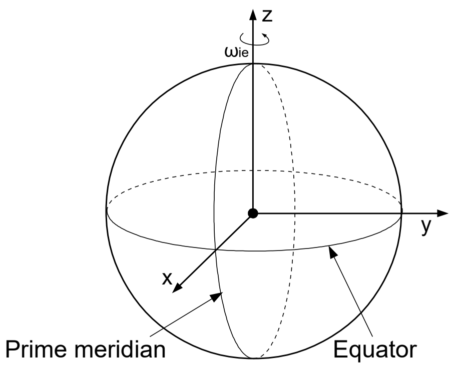

Figure 3.1: ECEF Coordinate system

3.1.1.2. Geodetic coordinate system (WGS84)

The second coordinate system is the most commonly used to represent positions relative to Earth. It uses an ellipsoid to represent the overall Earth shape.

Several geodetic models exist, but nowadays, the WGS84 ellipsoid is probably the most common one due to its use as the GPS standard. When talking about Geodetic coordinates, we will always refer to WGS84 referenced coordinates.

A geodetic coordinate is a set of three parameters: Latitude (Φ), Longitude (λ) and Altitude (h).

The Latitude is the angle in the meridian plane from the equatorial plane to the ellipsoid normal. Note that in most situations, the ellipsoid normal will not intersect the center of the Earth.

The Longitude is the angle in the equatorial plane from the prime meridian to the projection of the point of interest onto the equatorial plane.

The Altitude is the length, along the ellipsoid normal, from the ellipsoid surface to the point of interest.

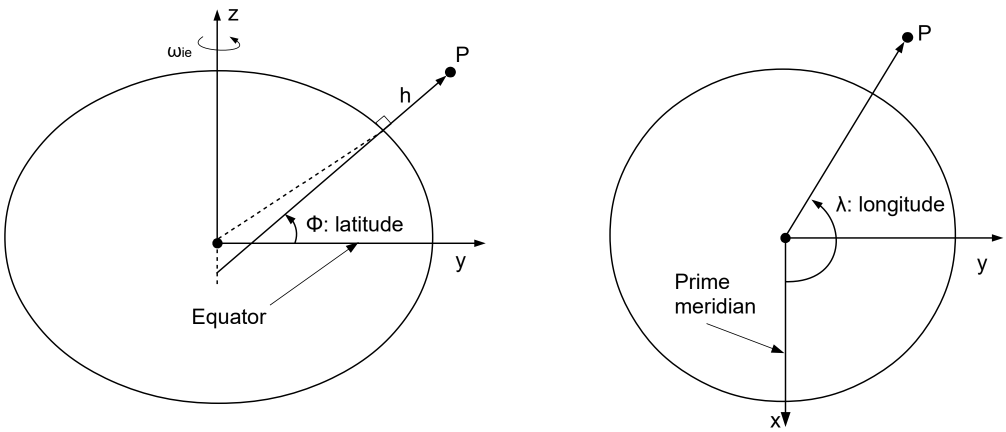

Figure 3.2: Latitude, Longitude, and Altitude definition

Altitude reference

As mentioned above, the WGS84 altitude reference is the ellipsoid surface. Unfortunately, this surface does not exactly match the actual Earth surface.

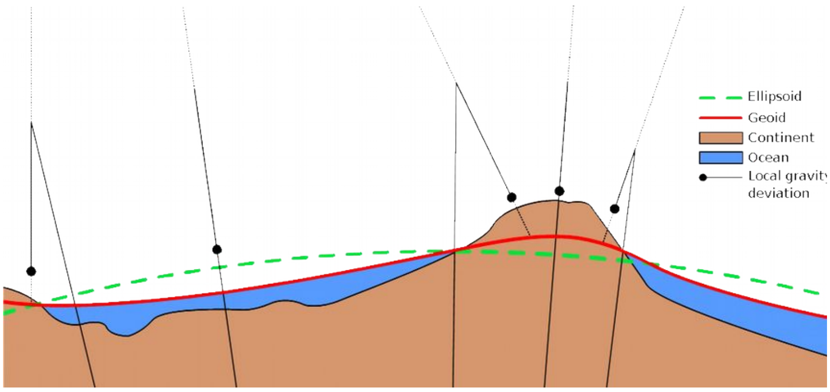

Figure 3.3: Geoid representation with ellipsoid and actual Earth shape

A geoid shape which is based on complex gravity models is often used to give a better Earth shape approximation than typical spherical or ellipsoidal models. The total variation between the WGS84 ellipsoid shape and a geoid is less than 200m.

When an altitude is provided with respect to the geoid model, it becomes consistent with the Mean Sea Level (MSL). Geoid based altitude will then be called altitude above MSL.

The INS provides both altitude referenced to the Ellipsoid and Mean Sea Level using a built in EGM96 model with 15 arc sec resolution.

3.1.2. Local Geodetic frame

The local Geodetic frame refers to the North, East, Down rectangular frame (NED).

This frame is obtained by fitting the local ellipsoid shape by a tangent plane at the current position. This coordinate frame is attached to a fixed point relatively to the Earth surface.

X axis is turned toward North, *Z* axis turned down, along the local ellipsoid normal, and *Y* axis completes the right hand rule, pointing East.

As it's impossible to perfectly fit the ellipsoidal shape by a plane, this frame is only suitable for local measurements.

> **Note:** The navigation algorithms internally account for this frame rotation when the vehicle moves at high speed in order to ensure best navigation performance.

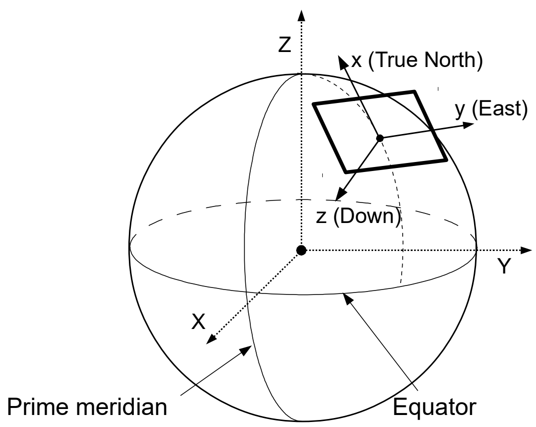

Figure 3.4: Local Geodetic coordinate frame representation

3.1.3. Vehicle coordinate frame

Depending on application, a vehicle coordinate frame is defined as follows: *X* axis is turned in Forward direction, *Z* axis is turned Down, and *Y* axis, thanks to right hand rule is turned to the right of vehicle.

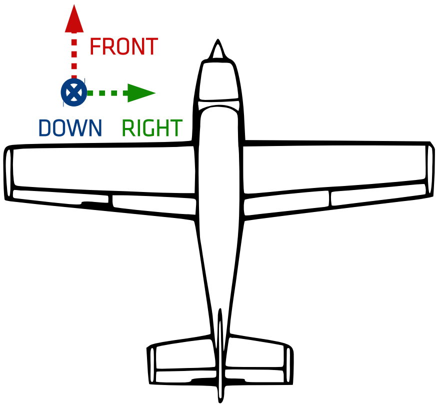

Figure 3.5: Vehicle coordinate frame

3.1.3.1. Ship motion conventions

The ship motion outputs are in a specific vessel coordinate frame:

- Heave is the vertical position, with positive sign downwards
- Surge is the longitudinal position, horizontal and turned toward the vessel bow
- Sway is the transverse position; horizontal and turned in boat starboard

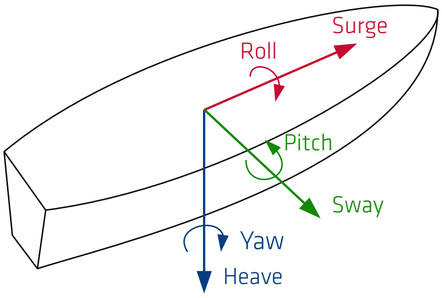

Figure 3.6: Ship motion conventions

3.1.4. Sensor (body) coordinate frame

This frame is attached to the IMU.

The following diagram shows the body coordinate frame as configured by default. In most situations, the body coordinate frame must be aligned with vehicle coordinate frame. Sensor alignment in vehicle can be rotated by software if the sensor coordinate frame cannot be aligned mechanically. Check section 3.3 Accounting for Misalignment for more details about this software alignment.

Figure 3.7: Default body coordinate frame in a surface enclosure

Figure 3.8: Default body coordinate frame in a surbsea enclosure

3.1.4.1. Origin of measurements

We have defined the sensor axes directions, but we also need to know where is the Origin of this coordinate frame. This coordinate frame origin is the intersection of the three accelerometers and corresponds to the center of velocity and position measurements.

This origin must be considered when measuring lever arms.

A ⊕ symbol in the mechanical specifications defines and locates this Origin of measurements.

3.2. Rotations between two coordinate frames

3.2.1. Positive rotation direction

According to the “Right Hand Rule”, the positive direction for rotations is clockwise in the axis direction:

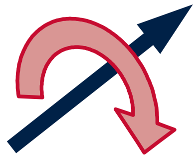

Figure 3.9: Positive rotation direction

3.2.2. Rotations representation

There are several ways to represent the orientation of the device that are provided by the sensor. Some are easy to understand, others are very efficient such as quaternion form.

3.2.2.1. Euler Angles

Euler angles are a commonly used representation of spatial orientation. Euler angles are in fact a composition of rotation from the Local Geodetic Coordinates System. This orientation is defined by the sequence of the three rotations around the Local Frame *X*, *Y* and *Z* axes.

Euler angles are widely used because they are easy to understand. The three parameters: Roll, Pitch and Yaw define rotations around the fixed frame's axes:

- Roll (φ): Rotation around *X* axis. $\varphi \in [-\pi ; \pi]$
- Pitch (θ): Rotation around *Y* axis. $\theta \in \left[-\frac{\pi}{2} ; \frac{\pi}{2}\right]$
- Yaw (ψ): Rotation around *Z* axis. $\psi \in [-\pi ; \pi]$

Note: As Euler angles suffer from a singularity called "Gimbal lock", when Pitch approaches ± π/2, we do not advise to use Euler angles if the device has to be used in a wide range of orientations. Quaternions and rotation matrices do not have any singularity.

3.2.2.2. Rotation matrix (Direction Cosine Matrix)

The Direction Cosine Matrix (DCM) is a rotation matrix that transforms one coordinate reference frame to another. Rotation matrices are a complete representation of a 3D orientation, thus there is no singularity in that model.

A DCM locates three unit vectors that define a coordinate frame. Here the DCM transforms the body coordinate frame to the Local NED coordinates. The DCM is the combination of the three rotation matrices RM_φ , RM_θ and RM_ψ respectively around Local Geodetic (NED) *X*, *Y* and *Z* axes.

Here is defined a DCM in terms of Euler Angles:

$$DCM = RM_\psi RM_\theta RM_\varphi$$

$$DCM = \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{pmatrix}$$

$$DCM = \begin{pmatrix} \cos\theta\cos\psi & \sin\varphi\sin\theta\cos\psi - \cos\varphi\sin\psi & \cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi \\ \cos\theta\sin\psi & \sin\varphi\sin\theta\sin\psi + \cos\varphi\cos\psi & \cos\varphi\sin\theta\sin\psi - \sin\varphi\cos\psi \\ -\sin\theta & \sin\varphi\cos\theta & \cos\varphi\cos\theta \end{pmatrix}$$

As for any rotation matrix, the inverse rotation equals to the transposed matrix:

$$DCM^{-1} = DCM^{T}$$

In order to transform a vector expressed in the Body coordinate system into the NED frame, user will use the DCM as expressed below:

$$V_{NED} = DCM \cdot V_{body}$$

Reciprocally:

$$V_{body} = DCM^{T} \cdot V_{NED}$$

3.2.2.3. Quaternions

Quaternions are an extension of complex numbers as defined here:

$Q = q_0 + i \cdot q_1 + j \cdot q_2 + k \cdot q_3$ Where i, j and k are imaginary numbers.

Particular quaternions such as $\|Q\| = 1$ can represent, as DCMs, a complete definition of the 3D orientation without any singularity.

Quaternion algebra do not require a lot of computational resources, they are therefore very efficient for orientation representation.

The inverse rotation of Q is defined by the complex conjugate of Q , denoted $\overline{Q}$:

$$\overline{Q} = q_0 - i \cdot q_1 - j \cdot q_2 - k \cdot q_3$$

Quaternion can be defined as a function of DCM coefficients:

$$q_0 = \frac{1}{2}\sqrt{1 + DCM_{11} + DCM_{22} + DCM_{33}}$$

$$q_1 = \frac{1}{4 q_0}\left(DCM_{32} - DCM_{23}\right)$$

$$q_2 = \frac{1}{4 q_0}\left(DCM_{13} - DCM_{31}\right)$$

$$q_3 = \frac{1}{4 q_0}\left(DCM_{21} - DCM_{12}\right)$$

Or as a function of Euler Angles:

$$q_0 = \frac{1}{2}\sqrt{1 + \cos\theta \sin\psi + \sin\varphi \sin\theta \sin\psi + \cos\varphi \cos\psi + \cos\varphi \cos\theta}$$

$$q_1 = \frac{1}{4 q_0}\left(\sin\varphi \cos\theta - \cos\varphi \sin\theta \sin\psi + \sin\varphi \cos\psi\right)$$

$$q_2 = \frac{1}{4 q_0}\left(\cos\varphi \sin\theta \cos\psi + \sin\varphi \sin\psi + \sin\theta\right)$$

$$q_3 = \frac{1}{4 q_0}\left(\cos\theta \sin\psi - \sin\varphi \sin\theta \cos\psi + \cos\varphi \sin\psi\right)$$

3.2.2.4. Other useful conversion formulas

Some other conversion formulas can be useful for many users, and are listed below:

Quaternion to DCM

It may be useful to compute a DCM based on the quaternion parameters:

$$DCM=\begin{pmatrix} 2q_0^2+2q_1^2-1 & 2q_1q_2-2q_0q_3 & 2q_0q_2+2q_1q_3 \\ 2q_1q_2+2q_0q_3 & 2q_0^2+2q_2^2-1 & 2q_2q_3-2q_0q_1 \\ 2q_1q_3-2q_0q_2 & 2q_2q_3+2q_0q_1 & 2q_0^2+2q_3^2-1 \end{pmatrix}$$

Quaternion to Euler

Here is quaternion translated into Euler angles.

$$\varphi=\tan^{-1}\left(\frac{2q_2q_3+2q_0q_1}{2q_0^2+2q_3^2-1}\right)$$

$$\theta=-\sin^{-1}\left(2q_1q_3-2q_0q_2\right)$$

$$\psi=\tan^{-1}\left(\frac{2q_1q_2+2q_0q_3}{2q_0^2+2q_1^2-1}\right)$$

DCM To Euler

Finally, DCM matrix is converted into Euler Angles.

$$\varphi=\tan^{-1}\left(\frac{DCM_{32}}{DCM_{33}}\right)$$

$$\theta=-\sin^{-1}\left(DCM_{31}\right)$$

$$\psi=-\tan^{-1}\left(\frac{DCM_{21}}{DCM_{11}}\right)$$

3.3. Accounting for Misalignment

The sensor alignment procedure involves two steps: an axis alignment, and a fine alignment. Some aiding sensors must also take into account misalignment, that will be measured like it has been done for the IMU, comparing the external sensor with vehicle coordinate frame.

3.3.1. Axis misalignment

The following example shows how to measure IMU axis misalignment. The IMU axes must be compared to the Vehicle axes as follows:

IMU Axis	Vehicle direction
X	LEFT
Y	FRONT
Z	DOWN

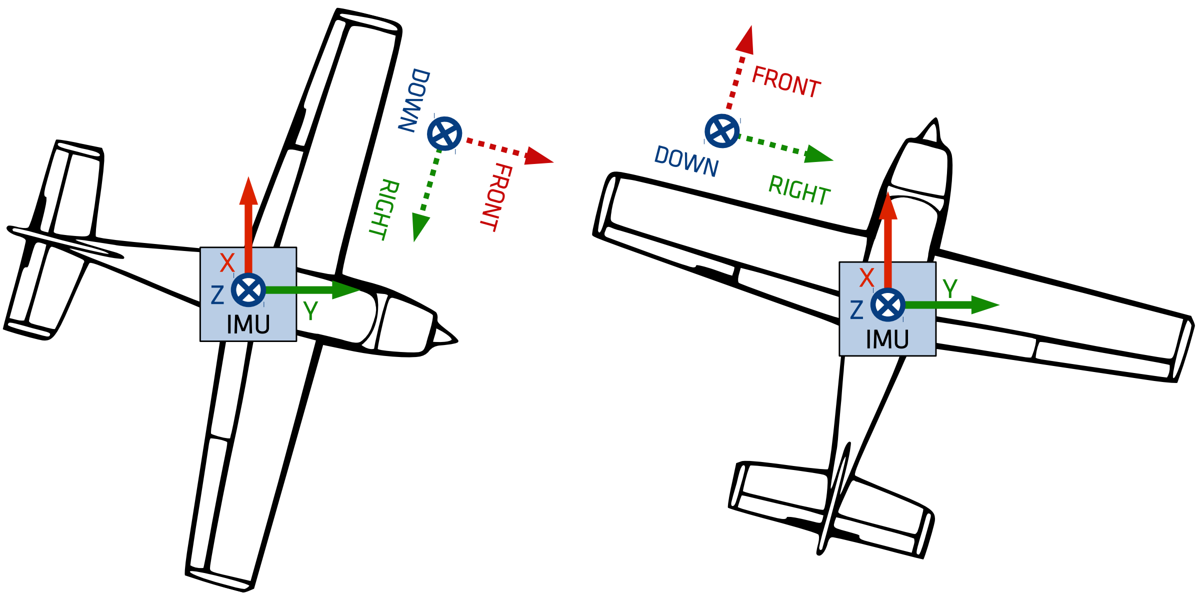

Figure 3.10: Axis alignment example.
Left: Initial mechanical installation. *Right: IMU coordinate frame after axis alignment.*

3.3.2. Fine misalignment

Once axes axis misalignment is performed, the small residual angles must then be measured as follow. Misalignment angles correspond to the residual rotation required to pass from the IMU coordinate frame to the vehicle coordinate frame. In our example, alpha corresponds to the misheading and its sign is negative.

Most applications will only have low angles on roll and pitch misalignment. If large angles on roll and pitch are expected (> 5°), user must consider the rotation composition order: roll, then pitch, then yaw.

Mis Angles	Value
misroll	Not shown
mispitch	Not shown
misheading	- α (negative)

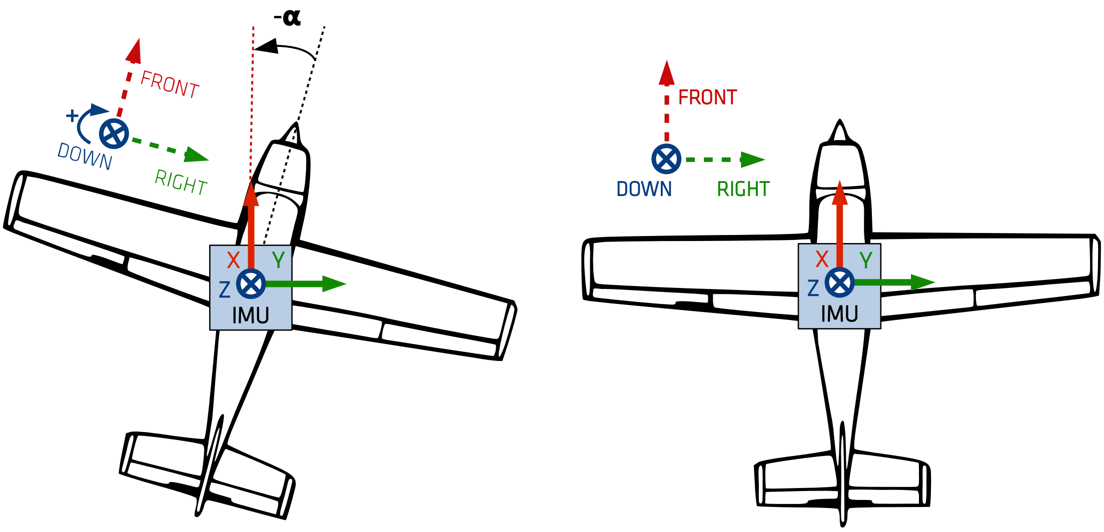

Figure 3.11: Misalignment residuals measurement
Left: Residual measurement. Right: IMU coordinate frame after fine alignment.

Once the fine misalignment angles are measured and entered into the device configuration, the sensor coordinate frame is assumed to be aligned with the vehicle coordinate frame.

3.4. Accounting for Lever arms

All lever arms are considered in the vehicle (body) coordinate frame, and are measured FROM the IMU, TO the point of interest.

Here is an example showing a GNSS antenna lever arm measurement:

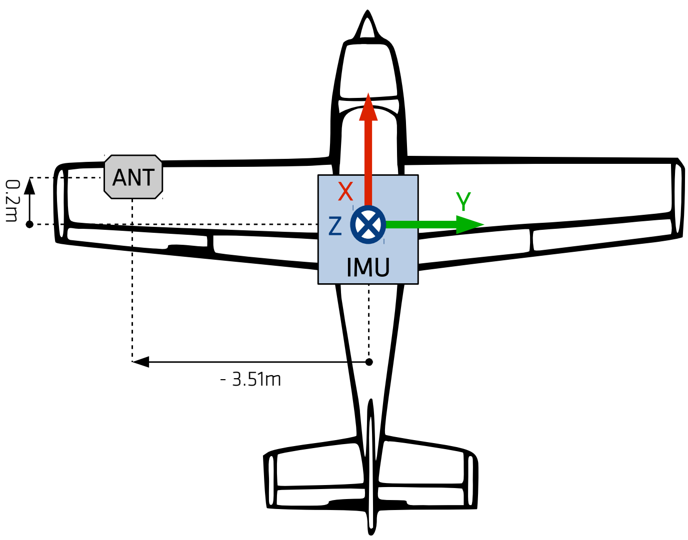

Figure 3.12: GPS antenna Lever Arm example

4. Interfaces specifications

4.1. Overview

All SBG Systems sensors can communicate over different types of interfaces. Each interface availability should be checked in the sensor Hardware Manual. Here we present the different types of interfaces available and what are their main use.

The following interfaces types are available:

- Physical RS-232/RS-422 serial ports
- Ethernet interface with different services available:
  - Web server
  - FTP server
  - Virtual serial interfaces (UDP; TCP/IP)
- Internal data logger
- CAN bus interface

Most interfaces provide both input and output capabilities. The next section presents more in details the capabilities of each type of interface.

4.2. Serial interfaces

Physical serial interfaces are designated as Port A, B, C (etc). The serial ports have different characteristics that depend on the sensor hardware. Typical specifications are as follows:

- RS-232 or RS-422 operation (RS-422 is preferred for long distance communication)
- 4 800 to 921 600 baudrate with automatic EMI reduction under 230 400 bps
- No Parity, 8bits data, 1 stop Bit
- Independent input and output functions: A Tx pin can generate data for a third party equipment while the Rx is used to feed GNSS aiding data

Some ports offer special functionality. For example, on Ellipse series, the Port A can only accept sbgECom protocol in input while it can output any protocol available.

In the same way, some ports might be multiplexed with special features such as Sync Input, or Odometer connection.

Note: Please read carefully your sensor Hardware Manual to see the actual serial interfaces available and their specificity.

4.3. Ethernet specifications

Ekinox and Apogee series feature an Ethernet 100BASE-T interface. This interface is used for the device installation and configuration through an embedded web page.

This Ethernet interface is a key feature that provides the following services:

- A Bonjour service used to easily discover any connected device and get its IP address
- An embedded web interface used to configure the device and visualize output data
- An FTP access to download logs recorded in the internal Flash memory
- Five virtual serial ports Eth0 to Eth4 that support either UDP or TCP/IP protocols

Note: In order to ensure proper behavior, user is advised to connect the Ethernet interface on an isolated network to avoid overloaded Ethernet traffic such as sometimes generated by echo-sounders.

4.3.1. Zero Configuration Networking (Bonjour)

In order to facilitate the device configuration, the device acquires automatically a private IP as soon as the device is connected to a network. This private IP allows the device to broadcast its name and ip address automatically using the Bonjour protocol. Thanks to this system, there is always an easy way to access the device configuration and in particular to change its TCP/IP configuration.

Thanks to the ZeroConf technology, it is easy to access the web services using the sensor name and serial number. Indeed, the device broadcasts a web service so you can connect to different services using a comprehensive address instead of an IP address:

For instance, on an Ekinox sensor, SN#020000001 unit, you can connect on the different services typing this address:

For web page browsing: http://ekinox_020000001.local.

For FTP access: ftp://ekinox_020000001.local.

Note 1: Please, don't forget to append the last "." character to get a valid URL address.

Note 2: The ZeroConf technology, uses multicast addresses and an UDP connection on the port 5353. Please make sure that your network allows these connections.

4.3.2. TCP/IP configuration

As for any device connected to a network, the device TCP/IP configuration should be set according to the network topology.

SBG Systems Ethernet implementation only supports IPv4 addresses and offers the following TCP/IP configurations:

- Automatic DHCP address attribution (default setting)
- Static address, mask and router definition

You can easily read the current MAC address and IP address in the information tab of the embedded web interface.

Note: Even if the device is configured with an invalid TCP/IP configuration, the device should still be accessible thanks to the ZeroConf technology.

4.3.3. Embedded web interface

The embeds web interface is powerful and easy to use. It has been designed to provide an easy and efficient way to configure the Ekinox and a quick solution to display real time data and check the device status.

If your web browser supports DNS Service Discovery such as Safari, you should directly see a link to all Ekinox devices available on the network.

Note: On the first load or if the device firmware has been updated, the device will cache the entire embedded website to optimize the responsiveness. This preload operation may take up to two minutes according to your system configuration.

4.3.4. Virtual serial interfaces

Virtual serial interfaces are a simple and powerful way to increase the number of inputs/outputs without adding cables and connectors. A virtual serial interface is handled exactly as the physical RS-232 or RS-422 serial interfaces, enabling asynchronous and bidirectional communication with another equipment.

Some equipment directly an Ethernet connection, and others, that only have standard RS-232/RS-422 connections, can still use virtual serial interfaces trough an Ethernet to serial converter.

A virtual serial interface is just a TCP/IP or UDP connection that can send and receive raw data. The following modes have been implemented to create a virtual serial interface:

- Raw UDP to reduce latency and allow high throughput
- TCP/IP client or server to guarantee message delivery and ordering

Virtual serial ports can be used indifferently to input aiding data and to output log messages.

Note: Virtual serial interfaces are handled internally exactly the same way as physical interfaces. For example, you can either connect an external GNSS to Port C or to ETH 1.

4.3.4.1. Raw UDP connection

UDP connection is the preferred way to implement a virtual serial port because of its simplicity and to ability to provide minimum latency. However, there is no guaranty of delivery, ordering or duplicate protection but UDP provides checksums for data integrity.

To configure an UDP virtual serial port, the following settings have to be defined:

- Output ip address and port, the device will send UDP datagram to this ip address and port
- Input port, the device will listen for incoming UDP datagram from any ip address on this port

The devices also support UDP broadcast to output log messages to everyone on the network. Raw TCP/IP connection

TCP/IP connection is a connected protocol with a server and a client. The main advantage of this type of connection is to guarantee message delivery thanks to an acknowledgment system. The drawback is a network, processing overhead and higher latency.

Unlike UDP mode, a TCP/IP connection has to be established before any data can be sent or received. To establish a TCP/IP connection, a TCP/IP client has to connect to a listening TCP/IP server. The created TCP/IP connection can then be used to both send and receive data in a secured manner.

Our devices supports both TCP/IP client and TCP/IP server modes to allow maximum compatibility and flexibility with third party materials.

The TCP/IP virtual serial port configuration depends on the selected mode:

- In TCP/IP server mode, you just have to enter a listening port. The device will then wait until a TCP/IP client establish a valid connection.
- In TCP/IP client mode, you have to enter the server ip address and port to connect to. The device will try to establish the connection at startup and every second if needed.

> **Note:** In TCM/IP client mode, and in case the connection is lost, the device will try to reconnect to the server every second.

4.3.4.2. Ethernet to serial converter

If you would like to use Ethernet virtual serial ports with a material that only have RS-232 or RS-422 connectivity, you can easily do it using an Ethernet to serial converter.

SBG Systems has tested the IOLAN DS1 serial to Ethernet converter manufactured by Perle Systems. It features a standard DB9 plug for RS-232/RS-422 and an RJ-45 connector for the Ethernet part. Both raw UDP and raw TCP/IP connections are handled.

Figure 4.1: Ethernet to serial converter

4.3.5. FTP Server access

Data stored in the internal datalogger can be downloaded from the device using the embedded FTP server. You can find FTP access details in the information tab of the embedded web page.

The following settings are used to access the FTP server:

Parameter	Value
address	ftp://xxx.xxx.xxx.xxx
port	21
login	anonymous
password	No password

4.4. Internal Datalogger

The Ekinox and Apogee include an internal datalogger capable of storing all data at 200Hz for 48 hours. The internal datalogger is composed of a high speed memory buffer and an 8 GB flash storage. To allow high bandwidth and to reduce power consumption, the memory buffer is saved to the flash storage ten times per second.

4.4.1. Overview

Each time the device is powered on, a new session directory is created. This session directory will store all log data until the device is powered off / on again. Based on the internal UTC time, each day, a directory is created to store a log file every hour. This directory is named using the following date format: *YYYY_MM_DD*

You can see in the screenshot below a typical datalogger files organization.

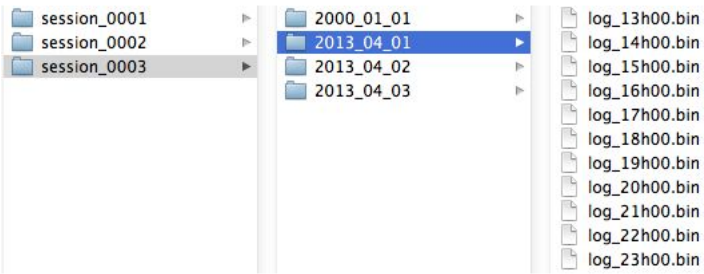

Figure 4.2: Datalogger files organization

The device doesn't maintain an absolute UTC time when it is powered off. However, an initial UTC time can be configured to be used at device power on. Until the internal time becomes a valid UTC time, the datalogger uses the initial UTC time as a reference.

As you can see on the screenshot above, there is a directory named *2000_01_01.* This directory has been created at the device startup and log files are being stored in it until a valid UTC time is received. As soon as the internal time jumps to a valid UTC time, the directory *2013_04_01* is created to store upcoming log files.

Note: The internal datalogger only stores raw bytes so an sbgECom binary log or an NMEA message can be split in two consecutive files.

Note 1: The datalogger never deletes files automatically so please make sure to release some space to store new logging sessions.

Note 2: If the datalogger cannot store new log files because the internal flash storage is full, a status flag will be updated to warn the user.

4.5. CAN 2.0 A/B interface

SBG Systems sensors also embed a CAN 2.0 A/B interface that supports transfer rate at up to 1 Mbits/s. This CAN interface is mainly used to output log messages. By default, the CAN interface is disabled.

The CAN bus implementation and especially timing settings complies with the CAN in Automation (CiA) DS-102 standard.

The CAN interface supports the following bus bitrates:

- 1 000 kBit/s
- 500 kBit/s
- 250 kBit/s
- 125 kBit/s
- 100 kBit/s
- 50 kBit/s
- 20 kBit/s
- 10 kBit/s

Note: SBG Systems sensors do not include any termination resistor, and it belongs to user to ensure that the CAN bus includes termination resistors in order to get proper communications.

4.5.1. Configuration

For each log message the user can define the following parameters:

- Enable or disable a CAN message
- Message CAN ID (Standard or Extended)
- output Mode (continuous with defined frequency, new data, event)

4.6. Supported protocols

SBG Systems inertial devices support many input and output protocols. This section describes briefly which protocols are supported and how outputs are generated. All these protocols can be used in the serial interfaces as well as in the Ethernet virtual interfaces and the datalogger.

> **Note:** For a complete description of the sbgECom and other supported protocols, please refer to the Ekinox and Apogee Firmware Reference Manual.

4.6.1. Input protocols

Input protocols are used to handle user commands as well as external aiding information such as GNSS, DVLs and others. These input protocols can be fed into one of the available serial or virtual serial interfaces available. Following protocols are supported (may depend from one product to another).

4.6.1.1. Configuration commands

Device configuration can be made through the use of the sbgECom protocol. This protocol allows a great flexibility in configuring parameters one by one and handles also full settings import/export features.

> **Note:** For quick and easy configuration, the Ekinox and Apogee series provide most configuration capabilities through its web interface

4.6.1.2. GNSS aiding protocols

The following protocols are handled for GNSS aiding:

- Novatel binary protocol for GNSS aiding and RAW data logging
- Septentrio SBF protocol for GNSS aiding and RAW data logging
- Trimble binary protocol for GNSS aiding and RAW data logging
- NMEA protocol for GNSS aiding

4.6.1.3. DGPS / RTK corrections protocols

RTCM and other popular differential corrections protocols can be used for RTK and DGPS positioning. This depends on the internal GNSS receiver specification and may vary from one product to another.

4.6.1.4. DVL aiding protocols

PD0 and PD6 protocols can be used for DVL aiding.

4.6.2. Output protocols

SBG Systems sensors have been designed to be connected to a large range equipment and materials.

All serial and virtual serial interfaces (including datalogger) can generate the supported output protocols in a very modular way. These outputs can be configured independently from the input protocols.

Supported protocols are the following:

- sbgECom binary protocol which is the native and recommended way to output data from our devices
- NMEA standard and some proprietary NMEA messages are also supported to ensure fast and straightforward system transition
- Other popular third party protocols such as TSS1, SIMRAD and others.

> **Note:** The CAN interface also handles log outputs in the same way; However, due to the CAN bus limitations, the available protocols are different. Please refer to the Ekinox and Apogee Firmware Manual.

4.6.2.1. Logs configuration

For a particular interface, the user can configure how each log message should be outputted using the following options:

- Disabled, this log message is never generated
- Continuous, this log message is outputted according to the configured output frequency
- New data, this log message is sent each time a new data is available
- Event #, this log message is sent each time a signal is received on the Event # pin

Continuous mode

The continuous mode is recommended to output log data on a regular basis. It is usually used to output inertial data, computed attitude, velocity and position. When this mode is selected, a divider can be set for each log message to reduce the output rate from 200 Hz down to 1 Hz.

When the device is correctly fed with UTC data and a PPS signal, the device time is aligned to UTC. In this case, configuring a log message in continuous mode to 1 Hz means that at each top of a UTC second, the log is sent.

This feature is very useful to ease data synchronization between multiple equipment.

New data

The new data mode is the only available mode for asynchronous data such as GPS position or odometer velocity. It's the best way to get the most recent data without logging duplicates.

Event input signals

SBG Systems sensors can be configured to generate log messages when an event input signal is detected. An input signal can be generated on a rising edge, falling edge or both rising and falling edges.

When an event signal is detected, a log message can be outputted using the latest available data.

4.6.2.2. NMEA Talker Id

A NMEA talker id can be defined for each output interface. The NMEA talker id is appended at the beginning of the NMEA frame to form a complete NMEA identifier.

For example if the Ekinox has to output the log message GGA and the NMEA talker id is set to GP, the resulting NMEA message name will be GPGGA.

This feature is useful to increase the NMEA log messages compatibility with external equipment.

4.6.2.3. Output monitoring points

The Ekinox and Apogee can compute and output navigation and heave data at several different monitoring points. For each output interface, it is possible to define which monitoring point should be used to generate log messages. The following monitoring points are available:

- IMU location
- Centre of Rotation (Primary Lever Arm)
- 3x additional User specified locations

5. Installation

5.1. Integrated system vs Remote IMU solution (Navsight)

SBG Systems provides a range of inertial sensors with some specificity:

- Ellipse, Ekinox and Apogee product lines are all fully integrated sensors, with a self contained package including IMU, GNSS and all computations features.
- Navsight solution is dedicated for survey markets, with separated IMU and processing enclosures.

Same installation recommendations apply for both type of products. However, please note that in the case of Navsight, all sensor installation requirement apply only to the IMU unit, with the possibility to install the processing unit remotely.

In the following sections, the term "sensor" will refer to the Navsight IMU, or any of the Ellipse, Ekinox or Apogee units.

5.2. Sensor installation

5.2.1. Sensor placement in vehicle frame

The normal orientation in the vehicle frame is to align sensor X axis to the vehicle forward direction. Sensor Z axis should be turned down.

When this mechanical alignment is not possible, the IMU misalignment with respect to the vehicle coordinate frame must be measured, as described in section 3.3–Accounting for Misalignment.

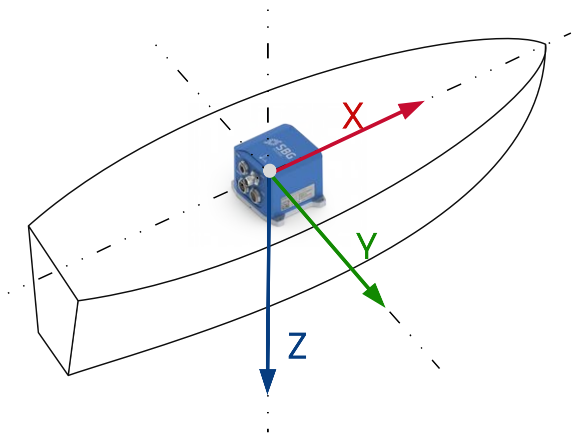

Figure 5.1: IMU typical placement in marine applications

5.2.1.1. Centre of Rotation (Primary lever arm)

As a rule of thumb, SBG Systems sensors can be placed anywhere in the vehicle. However, in case of large vehicles or vessels, we recommend to place the sensor within 10 meters around the Centre of Rotations.

In any case, the primary lever arm between the sensor and the Centre or Rotation must be measured within 5 cm accuracy. It is the signed distance FROM the sensor TO the Centre of Rotation, expressed in the vehicle coordinate frame.

A correct measurement will ensure optimal performance, and particularly in the following applications:

- Marine applications. The heave motion computation is dependent on a good lever arm measurement
- Automotive applications, where the main lever arm is used internally to take into account the motion constraints assumed in this type of application.

5.2.2. Sensor Placement restrictions

5.2.2.1. Vibration considerations

SBG Systems has designed IMUs with high quality MEMS sensors combined with high sampling frequency as well as efficient anti aliasing FIR filters to limit vibration issues as much as possible. Nevertheless, a good mechanical isolation will ensure getting the full sensor performance:

High amplitude vibrations can cause a bias in accelerometer reading. Thanks to a superior factory calibration, this effect is limited. Nevertheless it cannot be fully avoided. This effect is called the VRE (Vibration Rectification Error) and comes from the internal accelerometer non-linearity.

Ultimately, very strong vibrations cause the sensor to saturate. The bias observed will be drastically increased, leading to a huge error on orientation.

Note: SBG Systems typically recommends a high accelerometer range to reduce the VRE effect for most application, except Marine application which need very precise acceleration measurement.

Warning: Heave and delayed heave computations is more sensitive to vibrations than other algorithms. When using the heave outputs, please take care to reduce as much as possible the vibration level to enable full performance.

5.2.2.2. Magnetic field influence on Ellipse series

When the internal magnetometer is used as heading reference, care should be taken with ferromagnetic environment.

Ferromagnetic materials or magnets that are placed in the vicinity of the device can generate error in the magnetometers readings by distorting the magnetic field. High current power supplies or the associated wires may also generate magnetic fields.

The sensor should be placed as far as possible from ferromagnetic materials, particularly those who can be moved independently with respect to the sensor. In practice placing the device more than 2 meter away from disturbing materials is enough to avoid generating error.

In most cases, a calibration procedure can be performed to map the magnetic distortions and therefore get the full performance of the unit. The calibration can compensate both Hard and Soft iron interference.

Note 1: See Hard & Soft Iron calibration Manual for more information about the magnetometers calibration procedure.

Note 2: Some disturbances cannot be predicted: a magnet passing suddenly near the device or a cell phone communication for example.

The internal EKF is able to cope with short term magnetic disturbances. Ultimately if magnetic field direction changed for a long period, the heading will be realigned to the new magnetic field direction.

Note 3: When the internal magnetometers are not in use, the magnetic influence on performance is weak but very strong magnetic fields can affect gyroscopes performance and such high amplitude magnetic fields should be avoided.

5.3. Aiding sensors installation

5.3.1. GNSS installation

5.3.1.1. Single GNSS antenna placement

The GNSS antenna should be placed on a location with a clear view of sky.

Once installed, the lever arm **FROM** the IMU **TO** the GNSS antenna should be measured within a 5 cm accuracy to ensure optimal performance.

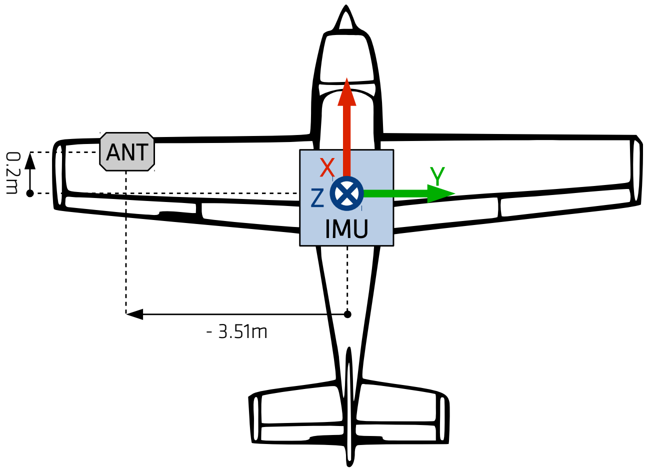

Figure 5.2: GNSS antenna lever arm measurement

5.3.1.2. Dual GNSS antenna placement

For optimal performance, dual antenna systems require some extra considerations during installation. We consider in the following example a device with internal GNSS, or any supported external GNSS using the its binary protocol.

- The primary antenna is the one used for position computation. Therefore, the Lever arm should be measured **FROM** the IMU **TO** the antenna. The GPS lever arm is a signed distance, expressed in the vehicle coordinate frame.
- The secondary antenna (also called rover) away from the primary antenna from at least 1m. This antenna is only used for True Heading measurements. As for the primary GPSS antenna, the lever arm from IMU to the Antenna must be measured.
- The same type of antenna must be used for primary and secondary antennas. In addition, these antennas must be placed in the same orientation, as shown in the figure below. Finally, the cables used for both antennas must have the same type and same length.
- Small patch antennas must be placed on a ground plane, and ideally, more than 20cm away from the ground plane edges.

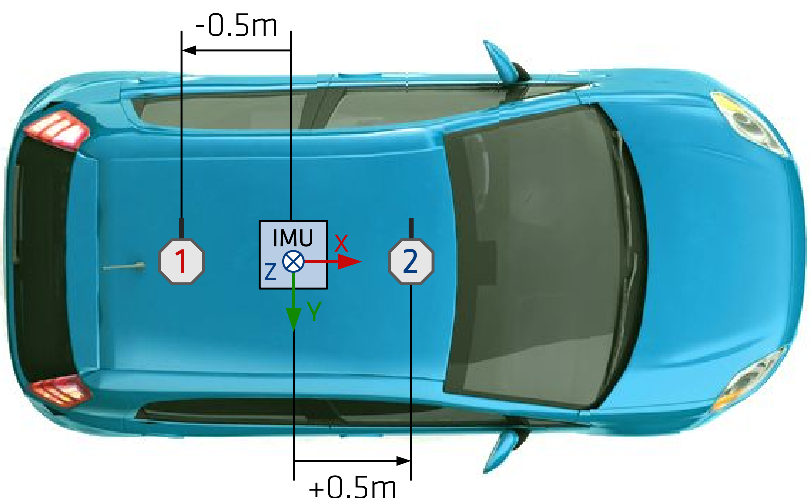

Figure 5.3: Dual GNSS antennas installation in the vehicle with corresponding lever arm along vehicle X axis

5.3.1.3. External GNSS receiver electrical connections

When using an external GNSS receiver, the following electrical connections must be performed:

- RS-232 or RS-422 GPS data output has to be connected on a dedicated serial port input. You can also use an Ethernet port to send GNSS data to the device
- GPS PPS signal must be connected to a Sync In pin to time stamp GNSS data and re-align the device internal clock.

Note 1: When two GNSS receivers are connected in the same time, a single PPS signal is required for proper operation.

Note 2: Some GNSS receivers only provide a weak PPS signal that is not capable of driving our Synchronization input pin. In such case, a signal amplifier should be used to enable correct synchronization.

5.3.2. Odometer installation

5.3.2.1. Mechanical installation

As for the GPS or external navigation sensor, the odometer requires a lever arm (signed distance from the IMU to the odometer) to be measured, within 5cm accuracy for optimal use.

You can find below an example of how to setup the odometer Lever Arm.

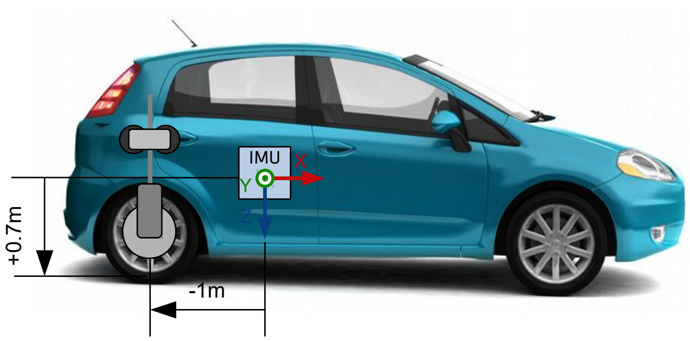

Figure 5.4: Odometer lever arm measurement

5.3.2.2. Electrical connections

SBG Systems INS devices support pulse output odometers, and for direction finding, quadrature and direction output odometers. The following pictures show the connections for each type of odometer;

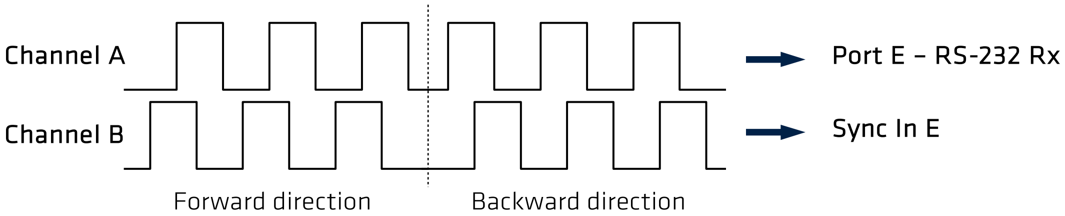

Figure 5.5: Quadrature output connection example

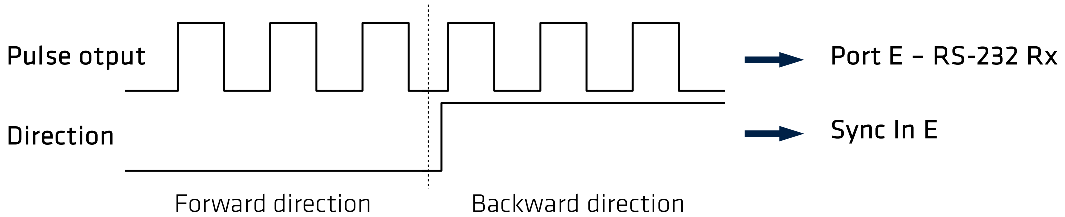

Figure 5.6: Direction output connection example

> **Note:** In case of single channel odometer, then tie the second odometer input pin to GND to force the system in normal direction.

5.3.3. DVL installation

5.3.3.1. Mechanical installation

DVL must be rigidly fixed to the vessel structure. It is typically recommended to align the DVL forward mark toward the vessel bow. In that case, the nominal alignment angle to enter in the inertial system configuration is +45°. You can mount the DVL in any orientation by entering appropriate misalignment angles.

Note that the native DVL instrument frame (displayed DVL_X and DVL_Y on the diagram) is a left handed frame whereas the SBG Systems products operate in a right handed coordinate system. Therefore we internally invert the DVL X and Z velocity before applying user alignment angles. Following diagram shows DVL instrument frame as well as the inverted DVL X (pink arrow) axis that is used for DVL to vessel misalignment determination.

The lever arm from the IMU to the DVL must also be measured accurately.

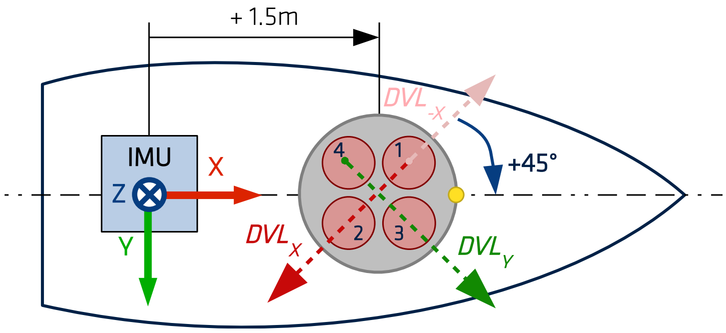

Figure 5.7: Typical DVL installation: alignment with IMU is set to +45°
View from above.

5.3.3.2. Electrical connections

When using an external DVL sensor, the following electrical connections must be performed:

- RS-232 or RS-422 DVL data output has to be connected on a dedicated "Rx" port.
- DVL synchronization with the device must be performed either:
  - Driven by the navigation sensor, by triggering the DVL pings by a Sync Out pin signal.
  - Driven externally, by connecting the external trigger signal to an Ekinox Sync In pin, and to the DVL synchronization input.

6. GNSS lever arm and alignment calibration procedure

The Ekinox, Apogee and Navsight series include a very intuitive and accurate calibration procedure that simplifies a lot the installation while allowing highest performance level.

As a rule of thumb, measuring GNSS antenna lever arms can be very complex in typical situations where the IMU is installed inside the vehicle cabin and the GNSS antennas are located outside. Moreover, a dual antenna setup is even more complex due to the fact that a good knowledge of the mechanical alignment is required to allow proper measurement of the lever arms.

Considering this challenge, the automated calibration procedure developed allows the user to:

- Enter rough GNSS lever arm for the primary GNSS antenna – within 5 – 10cm
- If the vehicle dynamics are sufficient, let the system determine automatically the secondary antenna lever arm – nothing to enter
- In case of lower dynamics, enter a rough estimation of secondary lever arm – within 5 – 10cm.
- Run a one time calibration procedure to refine the GNSS lever arms
- Store parameters in the non-volatile memory to obtain highly accurate measurements in following missions.

Note: Instead of including this calibration procedure module, the Ellipse series refines the lever arms and angles in real time without possibility to store the parameters in the non-volatile memory.

6.1. Step by step calibration procedure

6.1.1. First step: define rough GNSS lever arms in configuration page

In the GNSS aiding settings, you have the possibility to select the GNSS heading mode between three options:

- Single antenna mode
- Dual antenna mode (auto lever arm)
- Dual antenna mode (known lever arm)

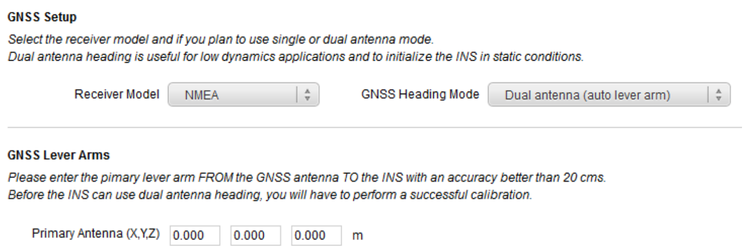

Figure 6.1: GNSS aiding configuration page

In the first two options, only the primary GNSS antenna lever arm can be entered. The third option requests a user first guess for the secondary antenna lever arm.

6.1.2. Second step: Start the calibration

Before starting the calibration, it is recommended to place the vehicle in a good GNSS environment to enable best performance. Although it is not required, we recommend the calibration procedure to be performed with high precision GNSS like PPP or RTK as it will provide faster results, with a better confidence.

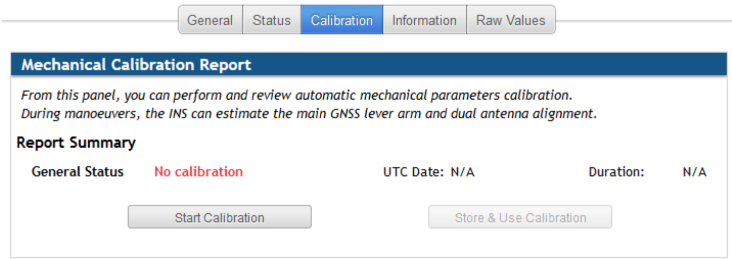

Figure 6.2: Default calibration page with no calibration applied

From the web page, in the calibration tab, you can simply start the calibration by pressing "Start Calibration" or "Restart Calibration" button.

This will cause the Extended Kalman filter to restart in a specific mode that enables estimation of GNSS parameters.

6.1.3. Third step: Running calibration and check progress

Once started, the calibration status will typically go into "Waiting" state. In order to actually run the calibration, we need to operate the Kalman filter in Full navigation mode, which means we need heading, and position resolved.

In case the setting "Auto lever arm" has been set, please note that the system will not be able to initialize the heading in static condition, so the EKF will transition to Full navigation only after a short period of motion in forward direction.

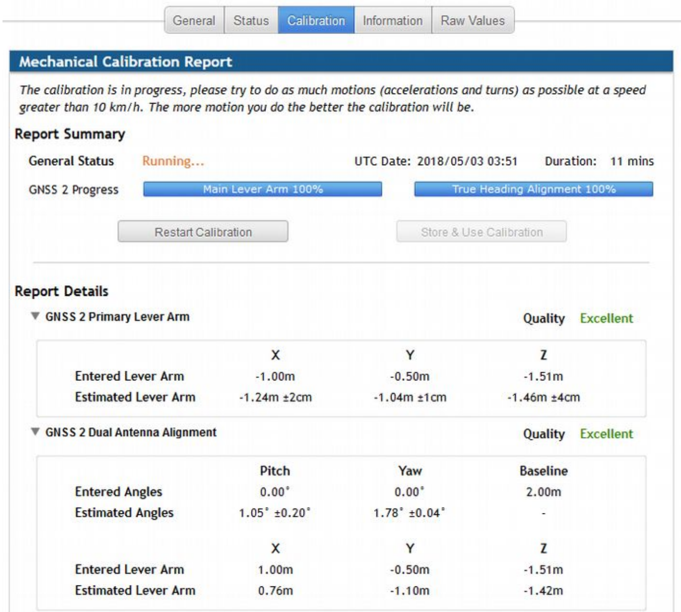

Figure 6.3: Running calibration in known lever arm mode

Once the calibration is started and the vehicle is operated at a sufficient speed (higher than 2.5m/s), the calibration status will transition to "running" mode. Two progress bars now display the calibration progress: one for the primary GNSS lever arm estimation, and one for the dual antenna heading alignment (linked to the secondary lever arm). The more dynamics we can get, the faster the calibration will be.

The typical recommendation is to perform high speed maneuvers, eight shape patterns, accelerations and deceleration phases.

To get more advanced feedback on the performance of estimated parameters, the calibration page also displays the estimated lever arms and angles, in comparison to what you entered initially, with associated standard deviations.

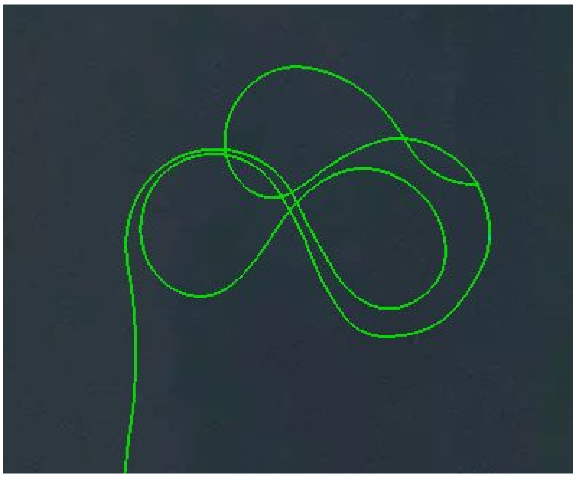

Figure 6.4: Typical maneuvers during a calibration

Depending on the GNSS environment and precision (RTK or not) and vehicle dynamics, the calibration can be performed within a few minutes, or can take more than half an hour. In case of low dynamics it may be impossible to reach a 100% finished calibration

6.1.4. Fourth step: Ending calibration

When active, the calibration continuously improves the lever arm and alignments. Even after reaching 100% completion, it is still possible to enhance the estimated values again by keeping maneuvering.

On the opposite side, in case of poor GNSS environment and/or low dynamics, it might be challenging/impossible to reach a 100% complete calibration.

That's why in the end, it belongs to the user to decide when the calibration should be stopped. User should also verify the consistency of the estimated parameters with respect to the entered values and actual setup. A minimum of 20% completion on each estimated parameter is required to unlock the calibration ending.

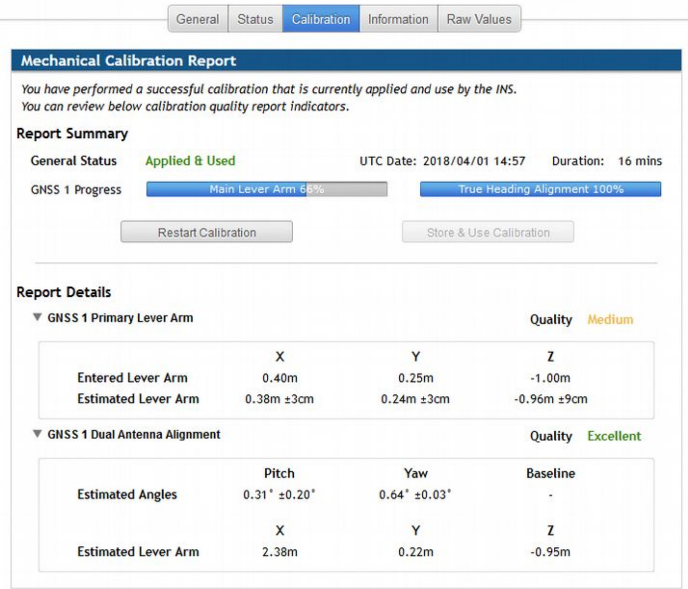

Figure 6.5: Applied calibration in auto lever arm mode

Once the calibration results are satisfactory, user can click on "Store & Use Calibration" button. This action will not restart the Kalman filter and he can move on to the actual mission directly. At next start, the unit will automatically load calibrated lever arms.

In case of inconsistency between actual setup and estimated parameters, user has the possibility to:

- Try a new calibration from scratch by pressing "Restart Calibration"
- Enter rough estimate of secondary GNSS lever arm to help the calibration procedure; then restart the calibration.

6.2. Checking what is actually applied, clearing calibration data

In any case, the parameters applied in the navigation filter are the one displayed in the configuration panel that can be freely edited. In case the setup is changed – compared to the previously applied calibration – it is always possible to modify the settings and start a new calibration, based on the newly entered values.

The calibration page always reflect the report from last calibration performed. In the same time, it checks whether this calibration is consistent with currently applied settings, using status "Applied and used" or "Not used".

7. Normal Operation

This section describes the basic operation scenario and provides some performance checking information. We consider previous installation guidelines were carefully followed: The AHRS/INS is correctly installed and configured.

7.1. Initialization and alignment

7.1.1. Recommendations

The sensor initialization and alignment is probably the most critical phase in the sensor operation. At this stage, the inertial system is greatly dependent on aiding inputs quality such as GNSS, vertical reference or magnetic measurements. As no history is available, it's impossible for the sensor to detect bad GNSS or magnetic data in a robust way.

Therefore, good conditions are required to ensure that the sensor will correctly initialize to a robust navigation solution:

- Low acceleration can be tolerated, but in general a static power up will provide better performance and faster initialization
- GNSS environment should be good with low multipath effects. In particular, when using a dual antenna heading, or an Acceleration Alignment method (Helicopter motion profiles), this recommendation becomes critical.
- Magnetic environment should be clean if the magnetometer is used as aiding input.

Warning: If the sensor is initialized in bad conditions, it's possible (although unlikely) that the Extended Kalman filter fails to converge to a valid solution. In that case, there will be no other way than restarting the initialization sequence in a better location.

7.1.2. Vertical gyro mode

When powered ON, the device will first initialize to an approximated attitude (roll / pitch angles), based on accelerometers used as a vertical reference. Initial heading and velocity are set to 0, and initial position is defined as set in configuration. During this time, the Kalman filter runs in a “vertical gyro” mode.

The orientation performance is here dependent on the quality of the “gravity” observation. In case of high dynamics, the accuracy may slowly degrade.

7.1.3. Rough alignment and INS initialization

Once reasonable roll/pitch angles are estimated, heading alignment procedures are tried until a first valid heading guess is found. Those procedures such as Dual antenna, Magnetic alignment, or Kinematic alignment are chosen according to user configuration and the selected Motion profile.

As soon as an alignment procedure has been successful, the Kalman filter will start full AHRS computations.

As in the vertical gyro mode, the quality of the orientation is dependent on the dynamics.

When navigation aiding data becomes available (Odometer, GNSS, ...) the device will make use of it to initialize velocity and position.

7.1.4. Fine alignment

Once all estimated parameters (attitude, heading, velocity, position) are initialized, the extended Kalman filter starts running in full INS mode, but with sub-optimal accuracy. The system is continuously estimating sensors error to improve performance.

In this phase, it's greatly recommended to observe dynamic motion such as 8 shape turns, acceleration, deceleration phases. It may take about 15 minutes to fully align the system. Good GNSS conditions are recommended to ensure a robust and fast alignment.

7.1.5. Checking when the alignment phase has ended

The Extended Kalman Filter provides a simple feedback about this initialization phase. The "Alignment Valid" flag will be set to Valid when the internal parameters such as sensor bias estimation are considered as fully accurate.

It is possible to use the navigation and orientation data before the alignment is finished, but the accuracy may be degraded, particularly in case of GNSS drop-out.

7.2. Full performance Orientation and navigation tracking

Once the system is fully aligned, all outputs can be used with nominal accuracy. The sensor is robust to difficult GNSS or magnetic environments and can provide optimal dead reckoning performance.

In case a dead reckoning period is observed, the nominal performance is obtained back after at least an equivalent period of navigation under good GNSS conditions.

7.2.1. Performance monitoring

The Extended Kalman filter provide an easy way to check the validity of the various outputs:

- Attitude and Heading valid flags should be checked to ensure that the provided roll, pitch and yaw angles are considered as precise.
- Velocity and Position valid flags should also be checked en ensure the system runs in a normal condition with a good precision
- Standard deviations are also provided for each output and they can provide a fine information about the system health.

8. Troubleshooting

8.1. Orientation & Navigation performance issues

If you observe abnormal behavior or large errors and standard deviations, this section may guide you in understanding what's going on.

8.1.1. Checking sensor status

Internal sensor provides useful status information, and it is important to keep an eye on this information in order to check output accuracy.

Gyroscopes include a built in test that continuously checks if each gyro channel is performing in a correct way. A gyro over-range error status informs about the orientation integrity: In case of over-range, orientation accuracy is degraded in an unlimited way until normal gyro operation is recovered.

Accelerometers include an over-range status that informs about navigation integrity. In case of high acceleration or strong vibrations, this status may be in error, informing about what's wrong.

8.1.2. Checking External devices data reception and use in Kalman filter

In order to check proper operation with external sensors, the first thing to check is whether consistent data are retrieved from those external devices or not.

For each aiding data, a status flag indicates if data were received in the last seconds or not. Data may be valid or invalid, but the main thing here is that we want to know if the device is well connected to the device.

Once External devices connection has been checked, it's then possible to check if the Kalman filter is able to use incoming data. Each aiding data has a dedicated status flag indicating:

“OK” when the corresponding aiding data could be used by the Kalman filter in the last seconds

“NO” when the Kalman filter was not able to use the aiding data. Possible reasons can be:

- Invalid data is provided (e.g. no GNSS fix is available)
- Kalman filter rejected the data (data is currently not consistent with current estimated state)

8.1.3. Checking the lever arms and alignment parameters

Using the sensor with a wrong lever arm setup can lead to sub-optimal performance. If the installation setup has been changed after last calibration, please verify the entered lever arms.

In particular, the alignment errors of a dual antenna setup can affect performance. If necessary, a new calibration should be performed to re-estimate new lever arms.

9. Support

Our goal is to provide the best experience to our customers. If you have any question, comment or problem with the use of your product, we would be glad to help you, so feel free to contact us:

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