Inertial Products

Principle & Conventions

IXBLUE
DEEP INSIGHT. SHARPER SENSES.

Document Revision History

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Text Usage

bold	Bold text is used for items you must select or click in the software. It is also used for the field names used into the dialog box.
`Courier`	Text in this font denotes text or characters that you should enter from the keyboard, the proper names of disk Drives, paths, directories, programs, functions, filenames and extensions.
italic	Italic text is the result of an action in the procedures.

Icons

The **Note** icon indicates that the following information is of interest to the operator and should be read.

Important

THE **IMPORTANT NOTE** ICON INDICATES THAT THE FOLLOWING INFORMATION SHOULD BE READ TO FORBID OR PREVENT A PRODUCT DYSFUNCTION OR A FAULTY OPERATION OF THE EQUIPMENT

THE **CAUTION** ICON INDICATES THAT THE FOLLOWING INFORMATION SHOULD BE READ TO FORBID OR PREVENT PRODUCT DAMAGE.

THE **WARNING** ICON INDICATES THAT POSSIBLE PERSONAL INJURY OR DEATH COULD RESULT FROM FAILURE TO FOLLOW THE PROVIDED RECOMMENDATION.

Overview of this Document

This document gives generalities, technical principles and conventions that apply to inertial products.

This document is divided into several parts:

- **Part 1: Introduction and Products Concerned** – This part lists the inertial products concerned by this document.
- **Part 2: Abbreviations and Acronyms** – This part lists all abbreviations and acronyms used in the inertial product documentation.
- **Part 3: Terminology** – This part details the terminology used in the inertial product documentation.
- **Part 4: iXBlue Inertial Products Technology** – This part describes the technologies used in an iXBlue inertial product.
- **Part 5: AHRS versus INS Navigation Systems** – This part gives the specificities between AHRS products and INS products.
- **Part 6: Geometrical Conventions** – This part gives conventions and definitions used to configure an inertial product.

A Table of Contents is available in the following pages to get quickly the dedicated information.

Table of Contents

I INTRODUCTION AND PRODUCTS CONCERNED

This document is an introduction to the User Guide for the inertial products manufactured by the Navigation System Division of iXBlue.

This document:

- Lists the abbreviations, acronyms and terminology used in the documentation of the inertial products
- Describes the inertial technology and provides definitions and conventions used in the iXBlue inertial product documentation.
- Also gives the definitions and conventions used in Inertial Measurement Units (IMU).
- Lists the navigation data, standard deviation data and external sensor data provided for by inertial products.
- Serves as an applicable document for the whole iXBlue inertial products user's documentation.

The current edition of this document is applicable to all inertial products:

- AHRS Generation IV:
  - ❑ OCTANS
  - ❑ OCTANS 3000
  - ❑ OCTANS NANO

- INS Generation III:
  - ❑ PHINS (PHINS Surface)
  - ❑ PHINS 6000 (PHINS subsea)
  - ❑ ROVINS
  - ❑ HYDRINS
  - ❑ MARINS
  - ❑ LANDINS
  - ❑ QUADRANS
  - ❑ AIRINS
  - ❑ ATLANS

II ABBREVIATIONS AND ACRONYMS

Abbreviation/Acronym	Meaning
ACC	Accelerometer.
AHRS	Attitude and Heading Reference Sensor.
CTD	Conductivity, Temperature, Depth sensor.
CMR	Compact Measurement Record.
CoG	Center of Gravity.
dbar	Decibar (pressure unit).
DGPS	Differential GPS.
DMI	Distance Measurement Instrument.
DOLOG	Doppler Log.
DVL	Doppler Velocity Log.
EGNOS	European Geo-stationary Navigation Overlay Service.
EM LOG	Electromagnetic Log.
FOG	Fiber Optic Gyroscope.
Galileo	European Satellite Navigation System.
GGA	GPS Fix Data (This sentence contains the position, time and quality of the navigation fix).
GLONASS	Global Navigation Satellite System (operated by the Russian Space Forces).
GNSS	Global Navigation Satellite System.
GPS	Global Positioning System (operated by the United States Department of Defense).
GST	GPS Pseudo-range Noise (PRN) statistics (The GST message is used to support Receiver Autonomous Integrity Monitoring).
GUI	Graphical User Interface.
HRP	Heading, Roll, Pitch.
IMU	Inertial Measurement Unit.
INS	Inertial Navigation System.
IP	Internet Protocol.
LBL	Long Base Line (acoustic positioning system).
Lsb	Least significant bit.

LSB	Least Significant Byte.
LVA	Lever Arms.
MPC	Motorola Power PC.
MSAS	Multi-functional Satellite Augmentation System.
Msb	Most Significant bit.
MSB	Most Significant Byte.
MU	Measurement Unit.
N/A or NA	Not Applicable.
P-P	Peak to Peak.
PPK	Post Processing Kinematic.
PPS	Pulse Per Second.
PPM	Part Per Million.
PROM	Programmable Read Only Memory.
Psia	Pound force per square inch absolute (pressure unit).
QZSS	Quasi-Zenith Satellite System.
RAM	Random Access Memory (volatile).
RFU	Reserved for Future Use.
RTCM	Radio Technical Commission for Maritime services.
RTK	Real Time Kinematic.
SBAS	Satellite Based Augmentation System.
SD	Standard Deviation.
STW	Setting To Work.
TBD	To Be Defined.
UHF	Ultra High Frequency.
USBL	Ultra Short Base Line (acoustic positioning system).
UTC	International acronym for Coordinated Universal Time (CUT).
UTM	Universal Transverse Mercator.
WAAS	Wide Area Augmentation System.
WGS-84	World Geodetic System 1984.
ZDA	Time and Date (The ZDA message identifies UTC time, day, month, and year, local zone number, and local zone minutes).
ZUPT	Zero velocity UpdaTe.

III TERMINOLOGY

Term	Meaning
Roll [(1)]	It is the rotation of a vehicle about its longitudinal (front/back) axis. It mainly applies to surface ships, subsea vehicle and planes.
Pitch [(1)]	It is the rotation of a vehicle about its transverse (side-to-side) axis. It mainly applies to surface ships, subsea vehicle and planes.
Heading [(1)]	The direction in which the longitudinal axis of a vehicle is pointing from true North.
Heave [(1)]	It is the linear periodical vertical (up/down) displacement in vessel horizontal frame (cf. §VI.1.3): its average is null.
Surge [(1)]	It is the linear periodical longitudinal (front/back) displacement in vessel horizontal frame (cf. §VI.1.3): its average is null.
Sway [(1)]	It is the linear periodical lateral (side-to-side) displacement in in vessel horizontal frame (cf. §VI.1.3): its average is null.
Bow	The front of a ship.
Stern	The back of a ship.
Vehicle	Vehicle used to transport/carrying persons, objects or or to handle or transport objects or freight, whatever its means of propulsion, including aircrafts, vessels, and terrestrial vehicles.
Port	The side of a ship or an aircraft that is on the left when you are facing forward.
Starboard	The side of a ship or an aircraft that is on the right when you are facing forward.

(1) See sections VI.2 and VI.4.

IV iXBLUE INERTIAL PRODUCTS TECHNOLOGY

IV.1 Introduction

The fiber optic gyroscope (FOG) is a recent technology generated to meet the requirements of the aeronautical industry. It is totally inert, has no moving parts, and reduces maintenance and recalibration operations. It provides a very wide dynamic range and can tolerate extremely demanding mechanical environments without compromise to its performances. This technology is insensitive to physical shock, can be carried in a case, and is easy to install.

History of iXSea Products

Inertial Products Division of iXBlue (formerly iXSea) has been working on the FOG technology since 1987. This division has developed in 1997 an “Attitude and Heading Reference Sensors” (AHRS) known as OCTANS based on FOG technology. OCTANS is a gyrocompass and motion sensor which can provide true heading, roll, pitch, yaw, heave, surge, sway, rates of turn and accelerations even in highly volatile environments. For example, OCTANS gyrocompass provides a heading accuracy better than 0.1 deg.secLat[1] and 0.01 deg roll and pitch accuracy[2].

In year 2000, iXSea has designed a complete Inertial Navigation System (INS) known as PHINS. PHINS is for PHotonic Inertial Navigation System. It uses 0.01 deg/h FOGs and a Kalman filter. Then, iXSea has developed several INS. An INS delivers heading and attitude information as well as position and speed, to other systems or to displays.

Main of these products is in the field world-wide, mainly on survey vessels or underwater vehicles, but also on terrestrial, aerial and space vehicles.

Both AHRS and INS are based on an Inertial Measurement Unit (IMU) and can receive data from other sensors to improve its accuracy. By extension, IMU may design the core system or iXSea inertial product

Add-on specific to INS

The INS products include a Kalman filter, designed to optimally merge information from GPS, acoustic positioning systems (Ultra Short Base Line positioning system - USBL and Long Base Line positioning system - LBL), Doppler Velocity Log (DVL) and depth sensor with inertial data from the IMU. Depending on their availability, external sensors can be used simultaneously or individually. The INS developed by the Inertial Products Division of iXBlue (formerly iXSea) are able to switch automatically between them. To achieve the best performances, specific error models for each sensor are integrated in the filter. Moreover theses INS are able to detect failures in external sensors and to reject erroneous measurements (i.e., spikes).

[1] secLat= 1/cos(Latitude)
[2] RMS value

The INS family is composed of several products. Each has its preferred environment: marine for PHINS, ROVINS, PHINS 6000, HYDRINS, MARINS, QUADRANS, terrestrial for LANDINS, aerial for AIRINS or space environment for ASTRIX™.
The system design is similar for all these product, consumes only a small amount of power and directly outputs binary data to NMEA 0183 standard and to other standards.
Due to the very high precision of its IMU, iXBlue inertial products are subject to export regulations (see document *Inertial Products - General Information (Ref.: MU-INS&AHRS-AN-007)* for details).

IV.2 System Design and Principles

An iXBlue inertial product is a strap-down IMU that contains fiber optic gyroscopes (FOGs), accelerometers, and a real-time digital signal processor (DSP) supporting the navigation software (see Figure 1). Connectors enable to plug external sensors, interface to Man Machine Interface (MMI) software and connect to third party Navigation package.

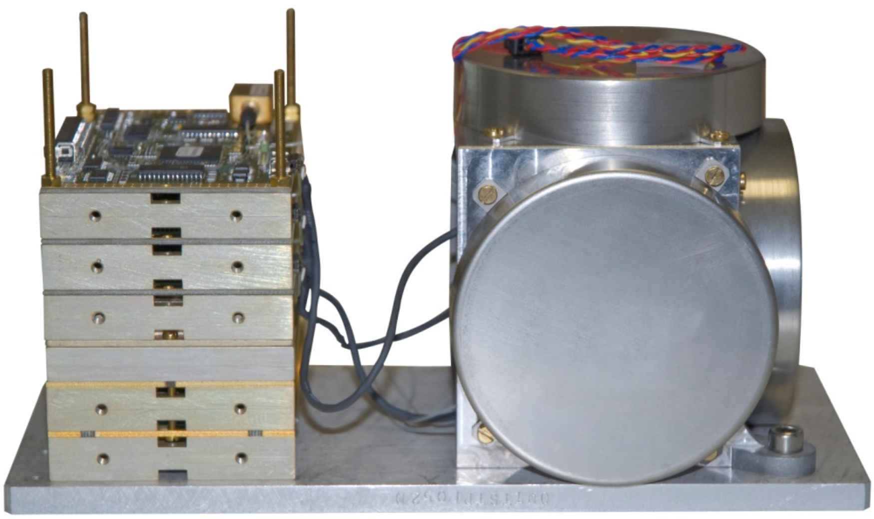


Figure 1 - Example of inertial product: “open” OCTANS unit (Surface Model)

Some of the INS also includes for example a GPS, and/or a data logger.
The main difference between INS and AHRS is that only INS contains a self-consistent navigation algorithm based on Kalman Filtering. Thanks to this difference, an IMU becomes a “heading, attitude, position and speed sensor” from a simple “gyrocompass and motion sensor” it was.
This structure enables an INS to work either as a black box or to be connected to external sensor systems (GPS, Doppler Velocity Log, Depth sensor, acoustic positioning systems …). In conjunction with external sensors, INS Kalman filter exceeds by several orders of magnitude the performances obtained with traditional navigation approaches.

IV.2.1 FIBER OPTIC GYROSCOPES (FOGS)

FOG Definition

Fiber optic gyroscopes (FOGs) do not use the rapidly spinning top employed in mechanical gyroscopes – in fact, they have no moving parts at all. A FOG is a 2-wave ring interferometer made of a multi-turn fiber coil. (see Figure 2). They do not use the gyroscope effect to measure the rotational speeds of mobiles, but a different physical phenomenon – the so-called “Sagnac Effect”.

The Sagnac Effect

The Sagnac Effect is a physical phenomenon of relativistic type. Understanding it requires a good grasp of Special Relativity. However, it is possible to provide a simplified (although inaccurate) physical interpretation of the effect. Imagine a coil of optical fiber. Optical fiber, as is well known, is a good vector for the propagation of light. This coil will in principle have two exits at the two ends of the fiber. If we inject a light pulse into one end, it will come out at the other after a duration equal to the time the light takes to travel through the entire length of the coiled fiber. If we now inject two pulses simultaneously into the two ends of the coil, they will travel in opposite directions, pass each other in the middle and come out at opposite ends of the coil. The time to travel through the coil will be the same irrespective of the direction of travel, and the two pulses will therefore exit the fiber at the same time. If we now imagine that the coil is rotating around its central axis, this movement will “help” one pulse but “hold back” the other. It can be seen therefore that the two pulses will leave the coil at different times. The rotation speed of the coil is assessed through the measurement of this time shift.

FOG description

This time (or phase) shift is measured in optics through interferometry. The interferometer is created by “closing” the coil on itself using an opto-electronic component called an “Integrated Optical Circuit” (see Figure 2).

Dedicated signal processing allows conversion of the information on optical phase, (carrying information on rotation), into a digital signal useable by a calculator.

The difference of transit time is proportional to the product of the rotation rate Ω and the area A enclosed by the coil (counted as many times as the fiber coil turns around A). Then, FOG performance gets better as FOG dimensions get larger. For example, increased fiber length will translate into a larger time shift between waves for a given rotation speed.

iXBlue FOG performance

FOG performance can be measured in terms of many parameters. One of the most relevant is known as bias stability, which means the stability of the zero point, or the intrinsic accuracy of the measurement of rotational movement. Bias stability is usually given in degrees per hour (deg/hour), to be directly compared to Earth’s rotation rate, which is 15 deg/hour. For example, the bias stability of a FOG can be 0.05 deg/hour.

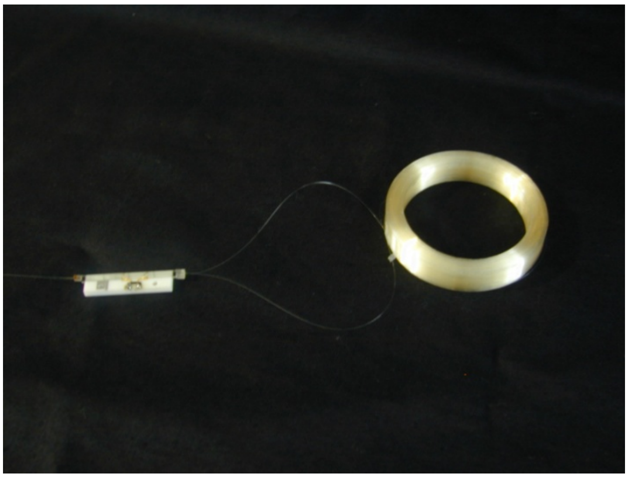


Figure 2 - The heart of a FOG (i.e., the optical fiber coil with its integrated optical circuit)

FOG vs. RLG

High performances FOGs are equivalent or superior in terms of performances to the best Ring Laser Gyroscopes (RLG). RLGs are based on the same relativistic effect as FOGs, however they use a ring configuration of mirrors instead of a fiber coil. Due to the use of mirrors, the manufacturing process of RLGs is much more delicate than the one of FOGs. Moreover, RLGs show poor performances at low rotation speed; to overcome this effect RLG are based on vibrating components which makes their lifetime shorter than FOGs.

FOGs manufactured by the Inertial Products Division of iXBlue (formerly iXSea) cover the medium to very high performances range: from 0.1 deg per hour bias to 0.0003 deg per hour bias (for space applications).

IV.2.2 INERTIAL MEASUREMENT UNIT (IMU)

IMU composition

The inertial measurement unit (IMU) is the core component of the systems (INS and AHRS): it is the assembly of three Fiber Optic Gyroscopes (FOGs) and three accelerometers mounted on three orthogonal axis.

Actually, a single FOG measures the projection of the instantaneous rotation along the main axis of its coil, and three FOGs are necessary to measure the rotation rate vector for the coil.

This triad of gyroscopes is usually combined with a set of three accelerometers. An accelerometer enables measurement first of the instantaneous acceleration along a given axis (and thereby, through successive integrations, speed and position), and second, knowledge of apparent local gravity, and thereby the local vertical axis.

FOG Gyrocompass: Underlying Principles

By definition, a gyrocompass is a gyroscope-based system for the measurement of true heading, that is to say, angular measurement of a position in relation to geographical North, whatever the movements made by the object on which the gyrocompass is located. This means for example, that the gyrocompass must remain relatively insensitive to pitch and roll movements, which may be at high levels on some ships. In this way, the gyrocompass is to be distinguished from North finders, which need to remain totally immobile in relation to the Earth when the measurement is performed.

North finders

We can begin by assuming that our initial objective is to produce a “static” indicator of North, that is to say, an indicator without any mechanical system (which means that we cannot rotate a single horizontal-axis gyro in order to find the position which cancels out the signal, which will correspond to the East). In order to measure the rotation vector of the Earth **Ω**, the first thing we need is three gyros for the three spatial axis. However, that is not enough yet to indicate a heading, because we lack information on the horizontality of the assembly. This information can be obtained through measurement of the local gravity vector **g** using either a plumb line, or electrolytic levels or accelerometers. By projecting the Earth rotation vector **Ω** onto the horizontal plane orthogonal to **g**, the direction of geographical North is obtained (see Figure 3). The intrinsic accuracy of this measurement depends on the accuracy of the sensors (the bias of the gyros b_{gyro} and of the accelerometers b_{acc} for example) and on the latitude L.

It can be expressed in radians as:

$$\Delta\Phi = \frac{b_{gyro}}{\Omega}\,\mathrm{Sec}\ L + \frac{b_{acc}}{g}\,\tan L$$

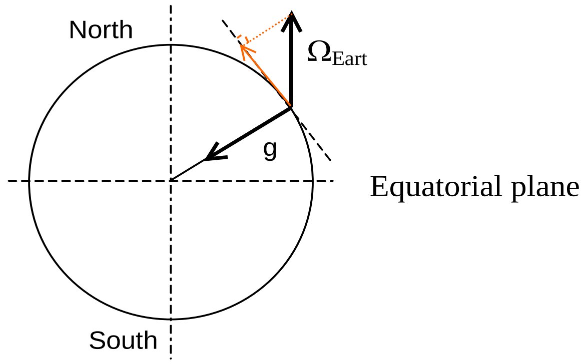


Figure 3 - North Finder / basic concept

To achieve a North finder capable of rivaling commercially available conventional gyrocompasses, accurate to a few tenths of a degree of the secant of the latitude, it is necessary to select gyros offering accuracy of at least one-hundredth of terrestrial rotation rate (15 °/h), such as the FOG 90 (0.05°/h) produced by iXBlue, and accelerometers precise to one-hundredth of apparent gravity.

Gyrocompass

The gyrocompass represents a step up from the above in terms of complexity. At this level, the system has to withstand random movements – which may be violent, such as a ship’s pitch and roll. The difficulty is twofold compared with the previous design: first, measurement of terrestrial rotation is disturbed by enormously high rotational values (several orders of magnitude greater than the Earth’s rotation rate), and second, measurement of gravity is disturbed by centrifugal accelerations which may also prove to be relatively high.

The basic idea is therefore to abandon the direct use of the measurement of the Earth’s rotation rate related to the gyroscopic frame, in favor of a “fixed” reference frame, which is called the Inertial Space.

Described briefly, the system comprises three gyrometers and three accelerometers: the three gyros enable the rotation rate of the moving object to be measured at any given instant (including the Earth's rotation rate), and the three accelerometers give the sum of the acceleration and apparent gravity. These measurements are both related to a reference bound to the moving object itself. The angular attitude of the moving object compared to the Inertial Space is then computed by integration of the rotation rate. The accelerometer data, which is the sum of the acceleration and gravity, is then expressed within the Inertial Space. After filtering out the acceleration values, it is possible to "observe" the slow drift of apparent gravity due to the rotation of the Earth. In fact, it is easy to show that the apparent gravity expressed within the Inertial Space defines a cone whose main axis is the rotational axis of the Earth (see Figure 4). Examination of the movement of **g** can therefore tell us where geographical North is without need of an external reference.

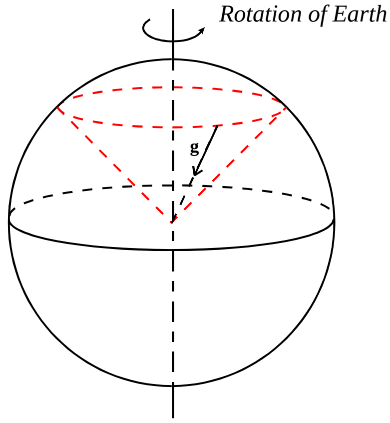


Figure 4 - Conical movement of the local gravity g in relation to the Inertial Space

Conclusion of IMU design

The compact assembly formed by the three gyroscopes and the three accelerometers is called an "Inertial Measurement Unit" (IMU) and forms the heart of any inertial reference system. When an IMU is coupled to a calculator and an interface, the result is an *inertial reference system*.

IV.2.3 Digital Signal Processor (DSP) unit

The unit contains a Digital Signal Processor chip enabling complex real-time computation for Gyrocompass or INS algorithms that are designed by iXBlue.

IV.2.4 Interface Unit (CINT)

In front of the DSP board, the interface board holds a microprocessor that handles input and output protocols and web based MMI in both serial ports and Ethernet.

IV.2.5 EXTERNAL SENSOR POSSIBILITIES IN INS CONTEXT

One or several external sensors can be plugged to the inertial products, depending of the product.

The initial design of the INS was directed to marine and underwater applications.

For example, for underwater applications, PHINS is used as the positioning system of Autonomous Underwater Vehicles (AUV) or Remotely Operated Vehicle (ROV) diving down to 6000 m and doing 24 hours long pipeline or field surveys without any human intervention. During these missions, the INS generally receives external information from acoustic positioning systems and/or Doppler Velocity Log (DVL). Acoustic positioning systems use acoustic transponder and compute position by triangulation. DVL are based on Doppler Shift of acoustic waves reflecting on the seabed. In general, acoustic positioning systems are used mainly during the diving phase of the AUV or of the ROV, so the INS must be able to maintain its position with only velocity aiding for hours with a low position drift. During most missions, mapping of the seabed is done using a multibeam echo sounder requiring true heading and attitude from an INS as PHINS. Depending on the seabed or the depth, part of the mission can be done without any external aiding (pure inertial mode).

For marine applications some INS are used both to provide true heading, attitude and depth to multi-beam echo sounder and as a positioning system available during GPS outages. It also provides measurement of depth merging IMU sensor data with all available data from external sensors: depth sensor, USBL/LBL transponder depth, DVL vertical speed.

To cope with such a mission, the iXBlue INS (as PHINS) are designed to:

- Align at sea
- Optimize the integration of data from GPS (resp. USBL/LBL) positioning systems
- Integrate data from GPS (resp. USBL/LBL) and reject GPS (resp. USBL/LBL) outlier
- Keep a metric position accuracy during GPS (resp. USBL/LBL) outages
- Navigate using only DVL information at low update rate with less than 0.1% of traveled distance drift.
- Navigate using DVL water track data

PHINS and MARINS are also successfully used in naval applications for ship navigation robust to GPS outages using EM Log, and weapon control.

LANDINS or AIRINS are used in mobile mapping applications, coupled with RTK GPS to provide accurate positioning and attitude to laser scanner LIDAR systems.

For detailed setup guidelines on how to use the system in a particular context, see the application notes provided with this manual.

V AHRS VERSUS INS NAVIGATION SYSTEMS

AHRS

The AHRS is both fiber-optic gyrocompasses and Motion Reference Units mainly used for marine applications. The AHRS can provide true-heading, roll, pitch, heave, surge, sway, rates of turn and accelerations even in highly dynamic environments.

INS

INS products are AHRS with the capability to provide position and speed, with or without external sensor data. Navigation without external data is called “pure inertial navigation”. Thanks to the Kalman filtering principle, navigation with external sensor data gives better accuracy.

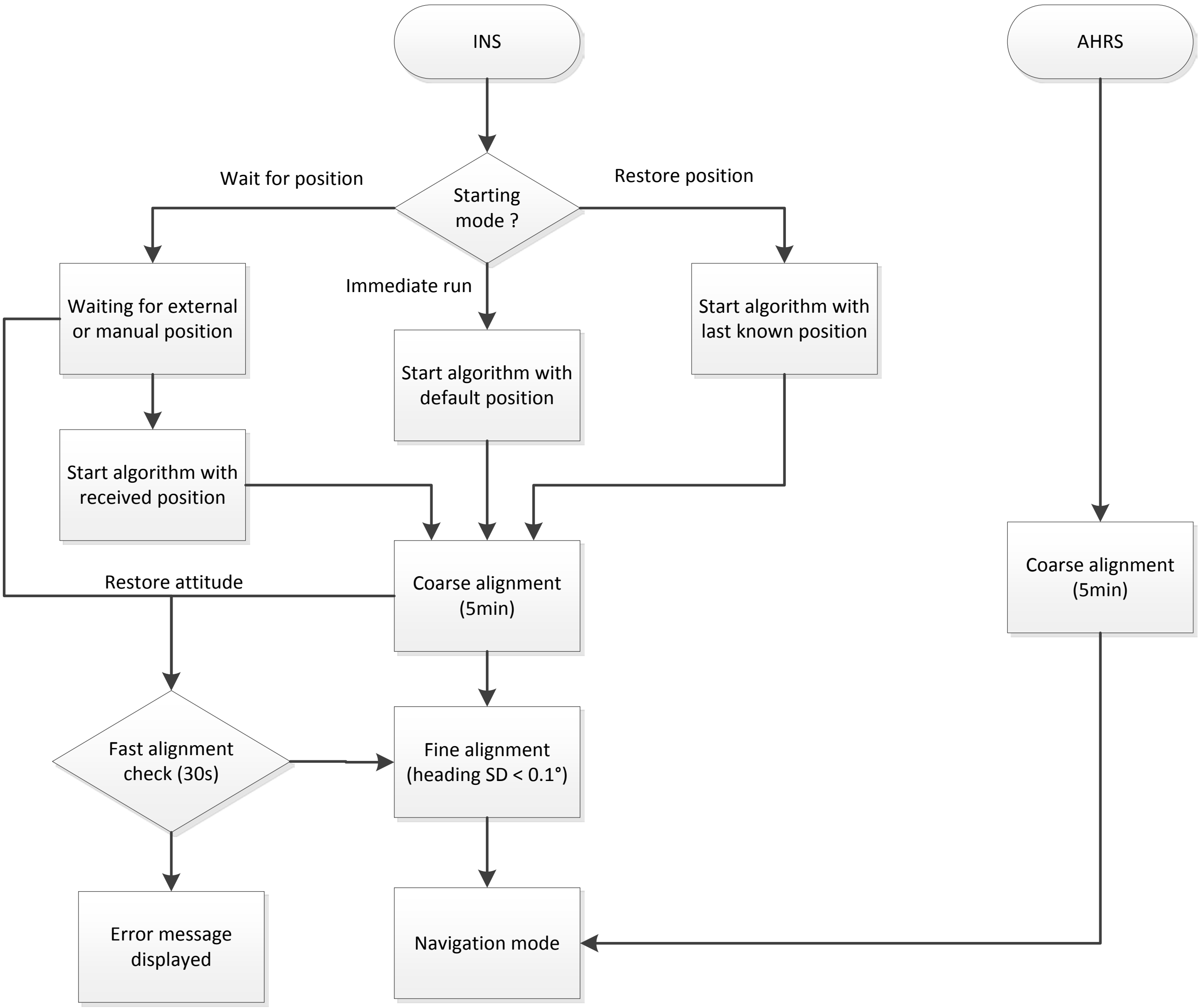
Both systems

Both systems must be initialized before giving full accurate information. This initialization is performed using external data, during several phases, depending on the product and on the environment.

V.1 Start-up procedure

V.1.1 START-UP DIAGRAM

The steps of the start-up procedure are in the order of the following diagram:



V.1.2 Initial Alignment

Following the starting mode, the inertial product performs an initial alignment which starts by a coarse alignment. If the product is a marine product, there is also an initialization of a heave filter. For INS, coarse alignment is followed by a fine alignment phase.

Following diagrams details alignment process for AHRS, INS, QUADRANS and OCTANS NANO:

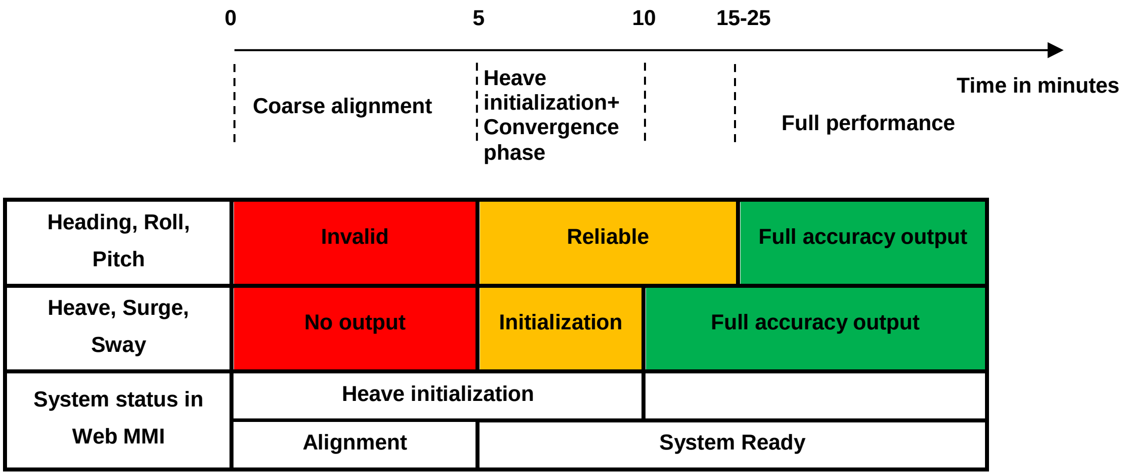


Figure 5 – AHRS starting sequence (at powering-on or restart)

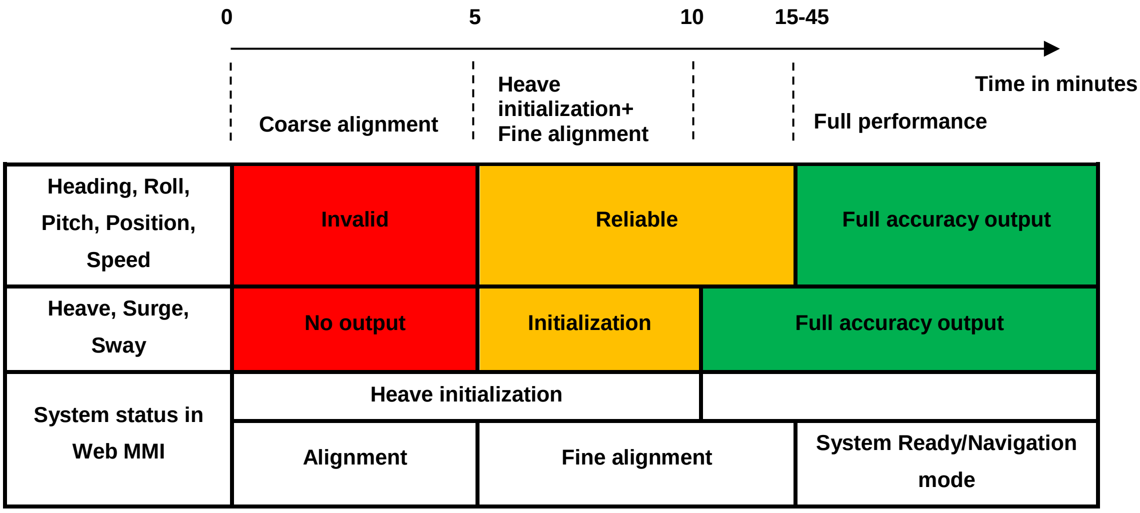


Figure 6 – INS starting sequence (at powering-on or restart)

	0	5	30
	Coarse alignment phase	Convergence phase	Time in minutes
Heading, Roll, Pitch	Invalid	Reliable	Full accuracy output
System status with WEB MMI	Alignment	System Ready/Navigation mode	

Figure 7 – QUADRANS AHRS starting sequence (at powering-on or restart)

	0	5	30
	Coarse alignment phase	Convergence phase	Time in minutes
Heading, Roll, Pitch	Invalid	Reliable	Full accuracy output
System status with WEB MMI	Alignment HRP not valid	Fine Alignment	System ready

Figure 8 –OCTANS NANO AHRS starting sequence (at powering-on or restart)

V.1.3 COARSE ALIGNMENT

Important

COARSE ALIGNMENT PHASE IS A KEY PHASE. IF THE CONDITIONS DESCRIBED BELOW ARE NOT OBSERVED DURING THIS PHASE, IT IS BETTER TO START AGAIN THIS PHASE.

Initial Data

To initialize the coarse alignment phase, knowledge of actual latitude and speed is needed. A null average speed is preferable. During this phase the position is initialized according to the most recent position saved in the non-volatile memory of the system or this position may have been entered manually. If valid GPS data is received the position will be initialized on the GPS position.

Principle

During this phase, the inertial product seeks for the local gravity vector and to the East vector. Refer to section IV.2.2 for details. Then, attitude and heading is computed.

Available Data

During this phase heading, roll and pitch data are computed and sent but have not reached full accuracy (they are flagged as “non-valid”).
For INS, position is not computed during this phase.
Heading is not sent during alignment for certain telegrams (i.e.: HETHS) to be compliant with NMEA standard.

Conditions

The product should be kept as steady as possible during this phase to minimize gravity vector estimation errors. Oscillations around a mean position and constant low speed movements are tolerated, but accelerations must be avoided during this sequence

In aerial and terrestrial environment, the coarse alignment must be carried out with static vehicle. The aircraft/helicopter engines may be working.

In marine environment, the coarse alignment can be carried out at quay side or at drift when sea state is calm. Otherwise, it is advised to sail a constant route, ideally East/West, without changes in direction and at low and constant speed (below 10 knots).

No estimation of position or speed, or errors, is done by the product during the coarse alignment: the data provided by external sensors (lever arm compensated) are used directly.

The coarse alignment duration is displayed by the "Remaining Alignment Time" message in the STATUS area of the web-based interface. This time is decreased until the end of the coarse alignment. Heading and attitude are flagged as invalid during the whole coarse alignment phase.

V.1.4 INITIALIZATION OF THE HEAVE FILTER

Applicable only to marine products, QUADRANS/OCTANS NANO excluded.

Heave measurement is used (in AHRS and INS) to compensate for vertical movement due to sea waves in application such as multi-beam or sonar imagery.

Heave is obtained from a double mathematical integration of the vertical geographical accelerometer data. To avoid this data to drift, it is filtered (i.e.: high pass filter). The heave filter is designed to measure periodic vertical movement of a surface vessel related to the average sea level.

Heave measured at a specific monitoring point is the addition of the heave measured at the unit location and the heave induced by the rotations(roll & pitch) applied to the lever arms from the unit to the specific monitoring point.

Same filtering method does apply to Surge and Sway, respectively, the two geographical horizontal filtered displacements.

For more details see *Inertial Products – Application Note - Installation and Configuration of AHRS and INS for Seabed Mapping Measurements (Ref.: MU-HEAVAPN-AN-001).*

Heave initialization occurs at each powering ON or soft restart (see Figure 5 and Figure 6). The duration of the heave initialization phase is roughly 10 minutes, and is performed in parallel of the coarse alignment phase.

During the heave filter initialization phase, the heave, surge and sway outputs have not reached full accuracy. Once the heave filter completes its initialization, it will accurately measure any variations of inertial product positions in the three directions (heave, surge and sway).

AHRS and INS can output two distinct heave measurements (Real Time Heave, Smart Heave); the choice of the heave measurement can be defined in the Web-based User Interface.

For example:

- Real Time Heave which provides heave in real time mode. There is a sea-state selection to optimize the heave accuracy depending on sea conditions. To limit filter oscillations, it is recommended to adjust the filter response according to the sea state: for example: slight, moderate, rough, or in harbors and channels.
- Smart Heave™ provides a measurement of heave with a 100 sec fix delay. This data will give the best accuracy in all sea conditions. This data is only available in certain output protocols (i.e., POS MV GROUP111, SEATEX DHEAVE).

V.1.5 Convergence Phase

Applicable only to AHRS, QUADRANS and OCTANS NANO.

After coarse alignment the system will need some more time to converge and reach full accuracy output. The more stable the coarse alignment is, and the faster this phase will be. In degraded conditions with high sea state during coarse alignment phase, the convergence phase may take up to 25 minutes to complete (see §V.1.2). Direction or speed changes and external sensor use will reduce the time required to complete the convergence time.

V.1.6 Fine Alignment

Applicable only to INS products.

After the coarse alignment phase, the INS is ready for navigation. Kalman filter is activated to compute and estimate position and speed with optimal accuracy. The INS switches automatically to the “fine alignment” phase to get full accuracy on roll, pitch and heading by estimating the residual biases of accelerometers and gyroscopes.

Any movement is allowed during the fine alignment. Large heading changes, such as 90 degrees rotations are even recommended so that the Kalman filter faster assesses the sensors bias on different axis.

There is no limitation of linear velocity or turn rate during fine alignment.

The fine alignment is ended automatically by the product when the heading covariance is below 0.1 degree for INS products (i.e.: PHINS, ROVINS, PHINS6000..) or after a fixed time for AHRS products (i.e.: QUADRANS, OCTANS NANO...).

However, the INS Kalman filter will continuously estimate internal sensor biases in navigation mode as long as external sensor data is available.

Fine Alignment in motion

During the fine alignment phase, movements of the vehicle are required.

The INS product fine alignment sequence requires some external sensor data to provide valid data to the algorithm.

For AHRS products no external sensors are required but external sensor aiding (speed or position) will improve the heading accuracy.

INS products use both inertial sensors and external sensors to compute optimal estimates of position, speed, attitude and heading.

Error estimations from the product Kalman Filter are improved when optimal trajectories are performed. The optimal trajectory to achieve fast fine alignment are "staircase" or " 8" shaped , as illustrated in Figure 9.Typical duration of each step is 3 to 5 minutes. Such a trajectory allows the Kalman filter to quickly assess all sources of errors of the system, to correct them and to achieve optimal performances at the end of the fine alignment process.

When a "staircase" or a "8" shaped trajectory is performed, the fine alignment phase would typically last for less than 30 minutes.

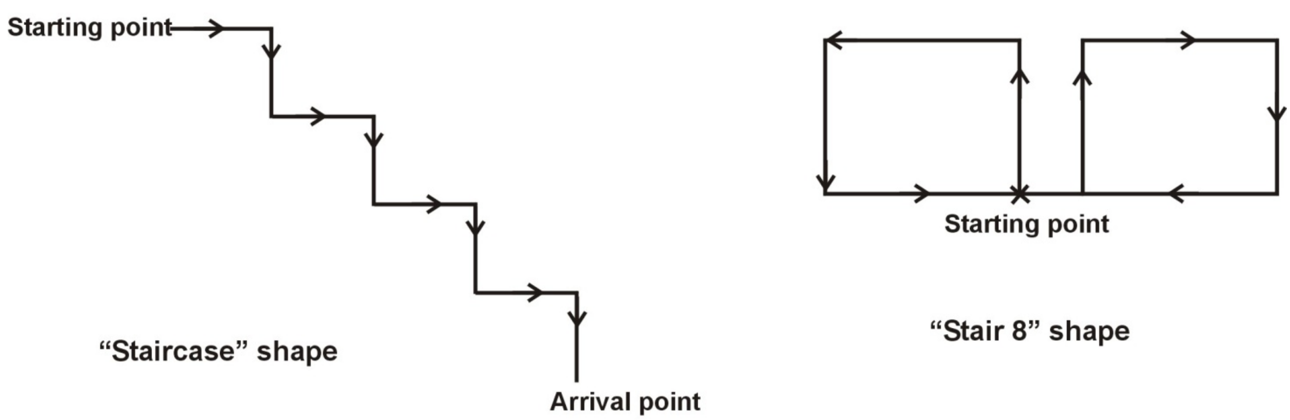


Figure 9 - Illustration of optimal trajectory for fine alignment

The above fine alignment trajectories are optimal to rapidly get the full performances of the product. However, they are not mandatory to perform. Instead, if duration to reach the full performances is not critical, "any trajectory" may be sufficient.

Also, if the operational condition allows, it is of interest to switch ON the product (to start the initialization), way in advance, with an external sensor aid so that the product can perform its fine alignment during a transit, and be fully operational while reaching the operational area).

Fine Alignment with Static product

Fine alignment can also be performed if the INS product is not installed onboard a moving vehicle, for example in the lab. The procedure for successful fine alignment in such case is described in the following.

Even if static, the INS product requires input of position and/or speed to achieve fine alignment. This can be done with the following options:

- By connecting a GPS sensor to the INS product, with the GPS sending valid data to the INS product.
- By simulating input of GPS data into the INS product with a software simulator. The input data can be kept constant, and should be equal to the real position (or speed) of the system.
- Without any external input (no sensor connected, no simulator used), by using the ZUPT mode (i.e.: Autostatic Bench, Man Pos). In such case, initial manual input of INS product geographical position is required.

Once the configuration has been achieved, fine alignment is performed by setting the INS product with different orientations typically 90 degrees apart.

The time interval between two 90 degrees apart orientations is roughly 8 to 10 minutes. From the initial orientation, the recommended procedure is to leave the INS product still for 10 minutes, then perform a 90 degrees rotation clockwise, then let the INS product still for 10 more minutes, and finally rotate the INS product 90 degrees counter-clockwise back to its initial orientation.

V.2 Bias and Errors for AHRS Products

V.2.1 IMPACT OF SPEED ON HEADING MEASUREMENT

All gyrocompasses, iXBlue products included, are sensitive to the speed of the vehicle/vessel. However very precise speed measurement is not imperative. The following section gives an insight of the error due to inaccurate speed input to the INS or the AHRS.

V.2.1.1 Heading Error Due to the Speed Log

For OCTANS

The heading output of all gyrocompasses is sensitive to the speed of travel of the vessel towards North. The international standard (ISO 8728) definition is:

> *"Course error in degrees for a gyrocompass aligned north-south is determined by the formula V/5π x the secant of the latitude, where V is the North component of the speed in knots".*

This speed correction applies whatever the technology used for the gyroscopes. Indeed, the linear speed of a boat traveling on the terrestrial "sphere" produces, with respect to the Earth and therefore with respect to the inertial frame of reference, a rotational speed V/R, where R is the radius of the Earth. This rotation speed (Coriolis force) has an influence on the measurement of the speed of rotation of the Earth and therefore on the detection of North.

Using the above formula, it is easy to compute the maximum speed $V\ North_{max}$ for which the heading error due to speed is higher than the heading accuracy specification.

Example, considering a Gyro dynamic accuracy of ± 0.1 degree x secant of latitude, the speed limit is:

$$V\ North_{max} = 0.1 \times 5\pi \approx 1.6 \text{ knots.}$$

The conclusion is OCTANS will remain within specifications in terms of accuracy as long as the North component of the speed is fed to the product with accuracy better than ± 1.5 knots.

For OCTANS NANO

It will remain within specifications in terms of accuracy as long as the North component of the speed is fed to the product with accuracy better than 4 knots.

V.2.1.2 Accounting for Speed for Accurate Heading Measurement

Even though the tolerance on speed measurement is large, it is recommended to enter the speed into the inertial product for automatic compensation of speed error and full accuracy performances of the gyrocompass.
Vehicle or Vessel speed can be input either manually or through an external Speed Log or GPS/GNSS sensors. Speed input from an external sensor (GPS or Speed Log sensor) allows automatic and real-time update.

To get details on your product configuration, refer to one of these documents:

- For AHRS unit: Configuration & Operation with the Web-based User Interface (Ref.: MU-AHRS-AN-001)
- For INS unit, Marine applications – Web-based Interface User guide (Ref.:MU-INSIII-AN-021)
- For INS unit, Land & Air applications – Web-based Interface User guide (Ref.: MU-INSIII-AN-022)

For AHRS, in case of external speed sensor drop out, the product will keep using last received external speed. When speed data from the external speed sensor is received again, the AHRS will update the speed used for the computation with the values from the sensor. A Built In Test allow the operator to monitor these changes.

V.2.2 IMPACT OF LATITUDE ON HEADING MEASUREMENT

All gyrocompasses, iXBlue products included, are sensitive to the operational latitude. This data must be fed to the product. However latitude needs to be updated into the AHRS only if the ship changes latitude quite substantially. The following section gives an insight of the error due to inaccurate latitude input.

V.2.2.1 Amplitude of Error Due to Latitude Data

As a general physical rule, for all gyro, whichever the technology is used, heading performances depends on the latitude: heading cannot be defined at the geographical poles. However, it is not this error which is considered in this chapter, but rather intrinsic system inaccuracy when the AHRS algorithm uses inaccurate latitude data input in comparison to its actual geographical location.
The AHRS has to know the latitude of its location in order to find geographical North rapidly. If the latitude information input is incorrect, the AHRS will generate an error. **This error is nevertheless very small.**

The curve in Figure 10 shows the heading error in degrees multiplied by the secant of the latitude versus the latitude of the current location, assuming that the latitude entered in iXBlue AHRS is incorrect by one degree.

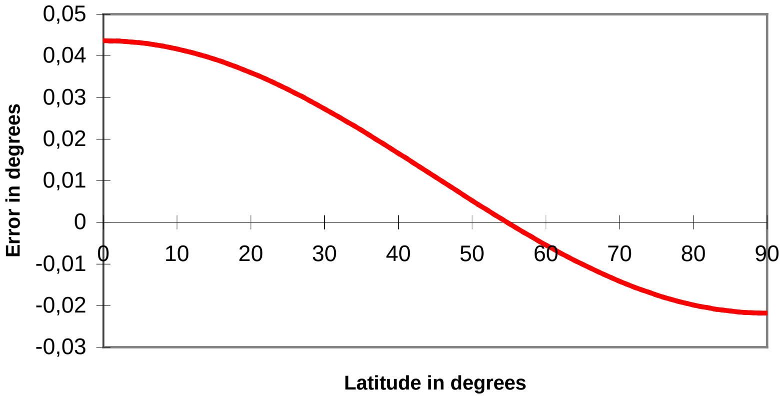


Figure 10 - Heading error in degrees by secant of latitude (for a 1 degree latitude error)

Example: at 40° latitude, a 3 deg error in latitude input will cause 3x0.02 = 0.06° sec Lat error on heading.

In practice, the AHRS needs to know the latitude only to an accuracy of 3 degrees at 45 degrees latitude. This dependency is more important at low latitudes.

V.2.2.2 Accounting for Latitude for Accurate Heading Measurement

It is recommended to enter the current latitude in the system. Accuracy required on the latitude input depends on the current latitude as shown in Figure 10. Standard figures are 3 degrees accuracy on latitude at 45 degrees latitude, and 1 degree accuracy for latitudes below 30 degrees.

Latitude can be updated into the AHRS during operation, either manually or by connecting an external GPS as an input. Refer *to* document *AHRS / Configuration & Operation with the Web-based User Interface (Ref.: MU-AHRS-AN-001)* for details.

When entered manually, the latitude is positive for the northern hemisphere, and negative for the southern hemisphere.

Latitude input from an external GPS sensor allows automatic and real-time update of the vehicle/vessel latitude. In case of external GPS sensor drop out, the AHRS will use the last latitude value received from GPS. When valid latitude data from GPS is received again, the AHRS will update the latitude with the value received from the sensor.

V.3 Pure Inertial Navigation System (INS Products)

V.3.1 General Description

Functional Block Diagram

The functional block diagram of INS pure inertial navigation system is given on Figure 11. The computation involves two different processes: first the gyrometers and accelerometers measurements are integrated in the body frame to provide elementary angle and speed variations, then these elementary variations are integrated to yield attitude, velocity and speed.

Non linearity Corrections

The integration of gyrometers and accelerometers in the body frame corresponds to the integration of a non-linear differential equation. Due to the finite integration rate, the sums of angles and accelerations do not correspond exactly to the real movements of the body and they have to be corrected to account for the non-linearity which can lead to resonant errors. The non-linear corrections are called coning and sculling compensations.

Attitude Computation

The attitude update is based on a quaternion algorithm. The elementary angle variations obtained after coning compensations are integrated. Since the gyros output rotations with respect to an inertial frame, the earth rotation and craft rate must be subtracted before integration (the craft rate is the rotation of the body in the inertial frame due to the velocity of the body on the surface of the spherical earth).

Velocity and Position Computations

Velocity and position are then updated taking into account the dependence of gravity on the position and the ellipsoidal shape of the earth.

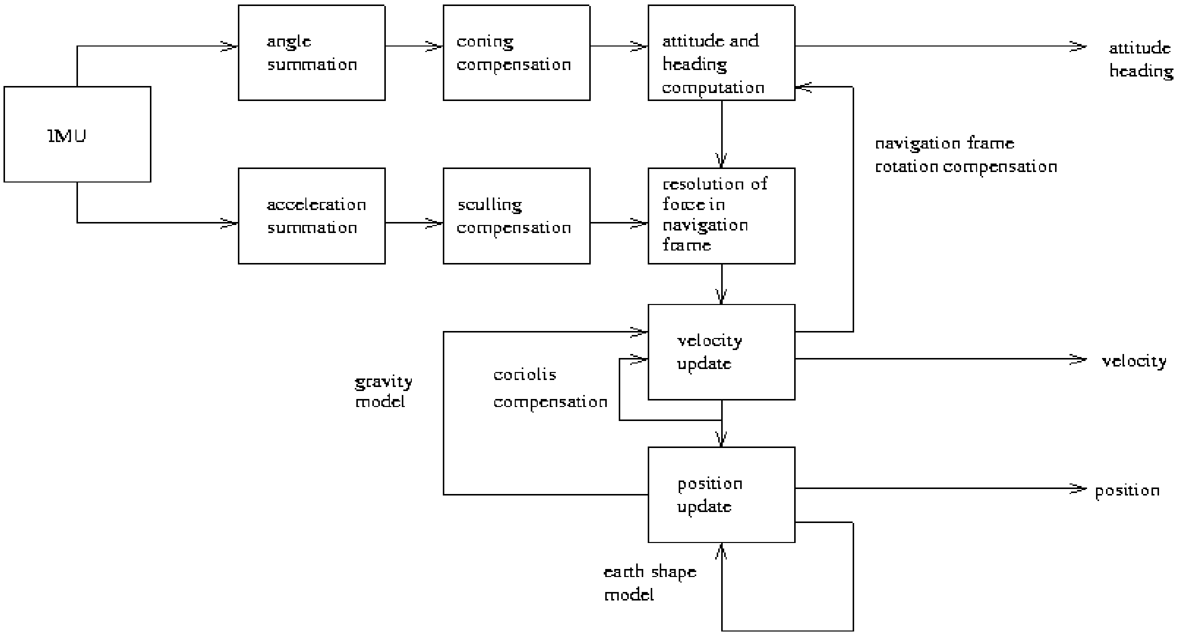


Figure 11 - Functional block diagram of INS pure inertial navigation system

V.3.2 KALMAN FILTER

The functional block diagram of an INS Kalman filter is given on Figure 12.

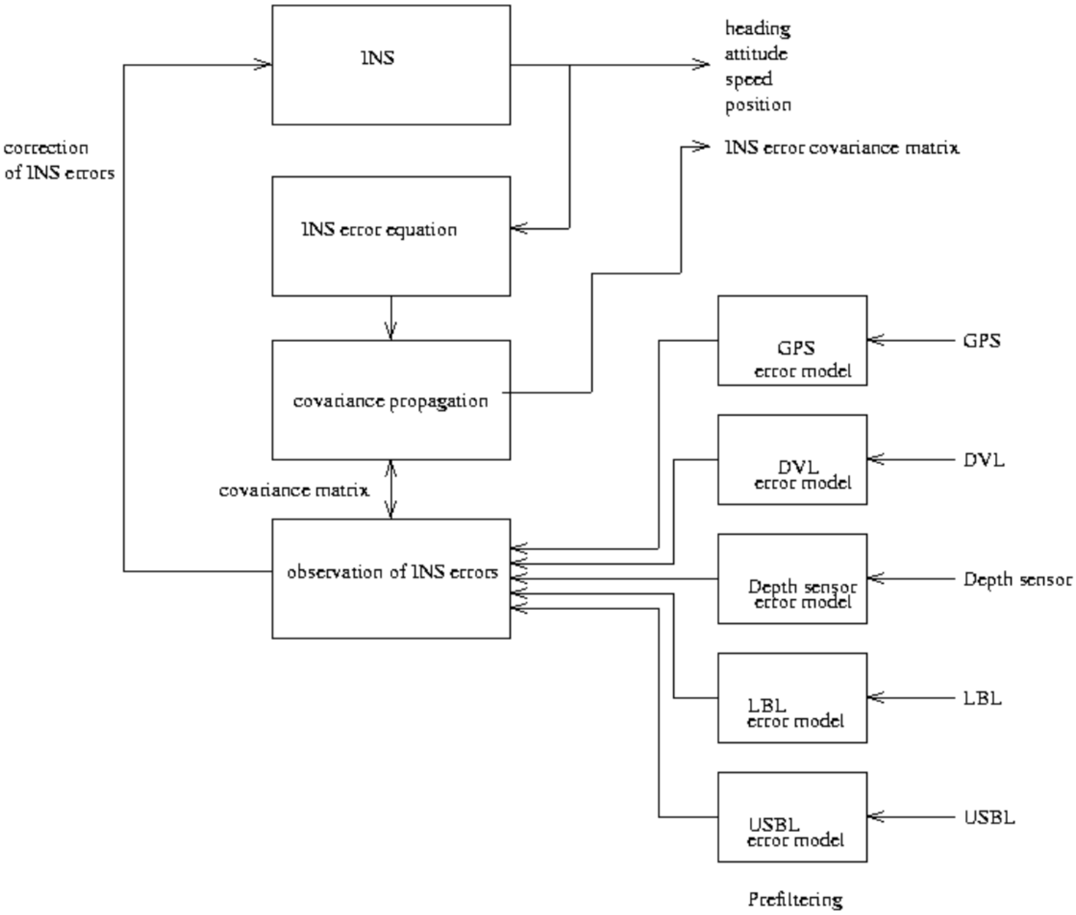


Figure 12 - Functional block diagram of the INS Kalman filter

Kalman Filter

The Kalman filter uses the data provided by the external sensors and/or automatic ZUPT mode (for terrestrial applications) to improve the accuracy of the pure inertial system. Unlike classical approaches used in civil marine applications like Dead Reckoning, where external sensors are used to replace inertial data, the INS Kalman filter algorithm provides an optimal integration of both external and inertial data. In brief, each time that external information is received by the INS (whether from GPS, DVL, USBL/LBL, DMI interface or from depth sensor…), this information is compared to the information provided by the INS and errors of the INS and the external sensors are estimated.

The computation process of the Kalman filter is based on models of external and inertial sensors errors. The error models of external sensors are specific for each type of sensor and some of them will be discussed in the next section. In general, error of external sensors can be modeled as white noise or as a first-order Markov process.

Error propagation

The *INS error equation* of an INS contains the following states: attitude and heading errors, velocity errors, position errors, FOG errors and accelerometers errors. All these errors propagate with time: for instance an error in the north speed propagates into an error in latitude which in turn propagates into an error in gravity model and so on. The equation of error propagation is obtained through partial derivation of the pure inertial navigation equations: for instance, derivative with respect to heading provides the dependency of the INS errors with respect to the heading error.

Extended Kalman Filter

Since the navigation equations are not linear, the linearization of the error differential equation is only accurate to first order and classical Kalman filter cannot be used. Instead an Extended Kalman filter is used. The main algorithmic difference between classical and extended Kalman filter is the dependency, in the extended filter, of the error equation on the trajectory of the vehicle.

Covariance Matrix

Apart from the error models, the key component of the Kalman filter is the *covariance matrix*. The covariance matrix is the covariance of the “error” vector made up of all the errors modeled in the filter (attitude, position, speed …). In particular, it contains estimates of bounds of all errors and also correlations between different errors. The estimates of error bounds are crucial for quality monitoring. The correlations can be thought of as the “memory” of the filter.

For instance suppose that the standard deviation of north speed given by the covariance matrix is 0.1 m/s: since the error in north speed propagates into an error in latitude, at the next step the standard deviation of latitude error will increase and the correlation between latitude error and north speed error will also increase. This means that at the next step speed information can be used to correct latitude error.

In the same way, since heading error propagates into speed and then position error, any speed or position information can be used to correct the heading.

Computation Process

The computation process of the Kalman filter is as follows. On one side the pure INS is computing attitude, velocity and position based on inertial data (accelerometers and gyrometers.

These data are used to update the coefficients of the error equations and the error equation is in turn used to update the covariance matrix of the Kalman filter. If no external sensor is ever connected to the INS, this process continues forever. Then the only function of the Kalman filter is to provide error bound estimates. Once an external information is received (and after a pre-filtering stage), this information is compared to the estimates of the INS. For instance: if a position is received from a GPS receiver, the difference between GPS position and INS position is calculated.

This difference is the sum of the errors of the GPS receiver and the errors of the pure inertial system. These errors are discriminated in the Kalman filter observation unit based on the error covariance matrix.

For instance and to simplify, if the difference between GPS and INS position is 10 meters while the standard deviation of the INS is 1.0 m and the standard deviation of the GPS is 20 meters, it is likely that most of the error is due to the GPS. The possibility to discriminate between different types of errors is called *observability.*

In general observability is not possible right after the first measurement, but it does increase with time since the differential equations of different errors are different: estimates of the Kalman filter tend to improve with time. Once the error has been discriminated, the errors of the inertial system are fed back into the INS and the errors of each instrument are fed back into the instrument error model.

For terrestrial applications, navigation filter is able to estimate DMI Scale factor and misalignment variations which could come from tire pressure or vehicle load. Therefore no scheduled DMI calibration is required.

V.4 Bias and Errors for INS Products

V.4.1 Propagation of Errors in Pure Inertial Mode

Data Accuracy

The accuracy of data computed by the pure inertial system is dependent both on the accuracy of accelerometers and gyrometers sensors and on the initial attitude, velocity and position errors obtained after the alignment. Since the gyrometers and accelerometers data are integrated over time and since the velocity, position and attitude computations form a closed loop, all these errors propagate with time and influence each other.

Error Bounding

However the propagation of errors is bounded except for the longitude error. The heading, roll, pitch, velocity and latitude errors of the pure inertial navigation system oscillate with time with three different periods: the Schuler period (84 minutes), the earth rotation period (24 hours) and the Foucault period (24 hours secant latitude).

In an INS, the amplitude of the oscillation in heading, attitude and latitude is roughly bounded by the initial error in heading and the initial error in position. If the initial heading error is 0.1 deg, the latitude error will oscillate with amplitude of 0.1 deg and reciprocally, if the initial latitude error is 0.1 deg the heading error will oscillate with amplitude of 0.1 deg.

Unlike attitude, velocity and latitude errors, longitude error is not bounded: it is the sum of three oscillating components with time periods given above plus a linear drift proportional to the bias of the gyros. Since the bias of the gyros used in INS is very small, the drift in longitude becomes significant only after a very long time: over short periods of time, it is masked by oscillations due to initial errors.

V.4.2 KALMAN FILTER: ROBUST OBSERVATION AND CHECKING OF EXTERNAL DATA

Applicable only to INS products.

External sensor and Inertial Errors Separation

Some Kalman filters used for navigation integrate external sensor and inertial sensor errors in the same covariance matrix. In the INS, we have tried to separate the different error models when possible. The main advantages of the separation of error models are a better observability, a better numerical stability and a reduced computation time. Achieving a better observability is a key to prevent the system to drift towards weird estimations under specific circumstances.

The observation scheme of the INS Kalman filter is based on robust estimation. In traditional Kalman filter, the correction to the INS when external information is acquired depends linearly on the information received. This would be correct if external sensor errors could be modeled as white noise (or any process linearly driven by white noise). However in general external sensor data contain outliers with unbounded errors (for instance GPS jumps due to reflections or bad weather conditions). The direct integration of these outliers into the Kalman filter would lead to unbounded errors in the estimated INS correction.

Robust Estimation

The principle of robust estimation (see Figure 13) is to replace the linear dependency of the correction on the measured error by a bounded dependency and hence to reduce the impact of large deviation. This technique would be sub optimal from a theoretical point of view if we had to consider that the external sensors errors were perfectly modeled by white noise because it would slow down the correction of inertial errors. However experience has shown that it is much better than the traditional approach in real conditions, not only because of the robustness of the Kalman filter induced, but also because M-estimates enable to give much more confidence to external sensors (bad data will have few influence) and hence to quickly compensate for inertial system errors. In INS Kalman filter, information from each sensor is scaled before being input to the observation unit, and statistics of scaling over time are used to check for permanent errors of external sensors. Hence external data cannot only be attenuated but also rejected. The rejection and bad quality flags provided for each sensor can then be used to monitor the integrity of the instruments and the quality of data provided by the system.

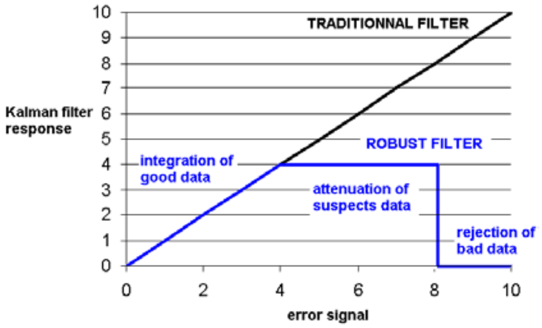


Figure 13 - Principle of robust estimation

V.5 Management of the Age of the Sensor Data

The INS can keep its position in memory for 10 seconds, and its speed for 3 seconds.

So:

- All position sensor data are accepted if their age is < 10 s
- All speed sensor data are accepted if their age is < 3 s

V.6 Conclusion on INS Technology

iXBlue INS are the first field-proven, high performance inertial navigation system based on fiber optic gyroscopes. Their compact size, low weight and low power consumption make them particularly suitable as the navigation system of small vehicles for which accurate positioning is a critical issue. It has been designed with a particular emphasis on quality checking both for data coming from external sensors and for data provided by the INS itself. This not only improves the performances of the system but also provides the user with the possibility to monitor in real time the quality of the navigation. This is a key feature for certain applications or for post processing. Designed first for marine and underwater applications, it can be connected not only to GPS and depth sensor but also to any type of acoustic sensors (USBL, LBL, DVL) used in the field, or to DMI, depending on the application (marine, submarine, terrestrial or aerial).

VI GEOMETRICAL CONVENTIONS

The geometrical conventions given in this part are used in all the documentation of iXBlue inertial products. To give its best results, the iXBlue inertial product must be configured using these conventions.

VI.1 Definition of Reference Frames

VI.1.1 PRODUCT REFERENCE FRAME

Depending on the iXBlue product form factor, the reference frame definition is adapted: for cylindrical shape and cubic shape products. Refer to *your Product User Manual*, to know the precise definition of the reference frame of your product.

Axis definition

The horizontal plane of the inertial products is defined as the bottom interface plane of the product (referred to as “Bottom Side” in Figure 14). Three orthogonal axis define a reference frame as follows:

- Axis X_1 is in the product horizontal plane:
  - For cubic shape products, it is parallel to the fin shape arrow going from the rear side (usually the connector side) to the front side (see the example of AIRINS product in Figure 14)
  - For cylindrical shape products, an alignment notch located near the bottom side points towards the positive side of X_1 axis (see Figure 15). Or axis convention is engraved on product (i.e. OCTANS NANO)

- Axis X_3 is vertical and perpendicular to the iXBlue product horizontal plane, going from the bottom plate and pointing upward
- Axis X_2 is in the horizontal plane, perpendicular to X_1, pointing to the left of the product (top view) such as $\vec{X}_2 = \vec{X}_3 \wedge \vec{X}_1$

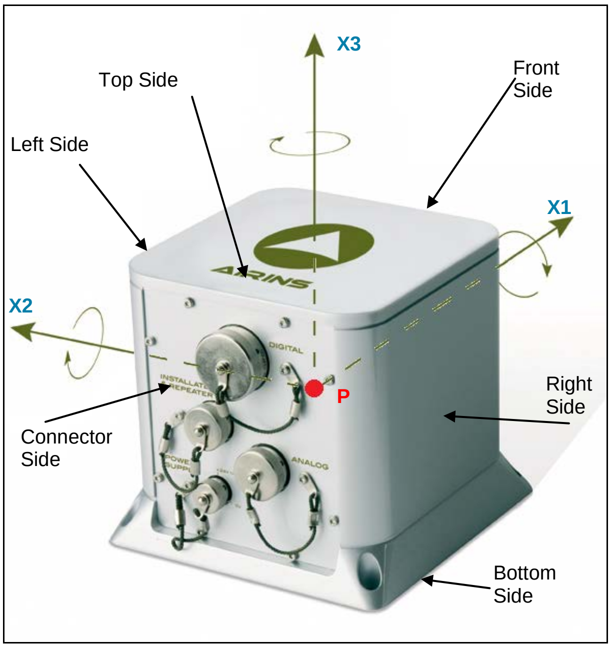


Figure 14- Definition of axis (X1, X2, X3) and sides for non-cylindrical inertial products (AIRINS example)

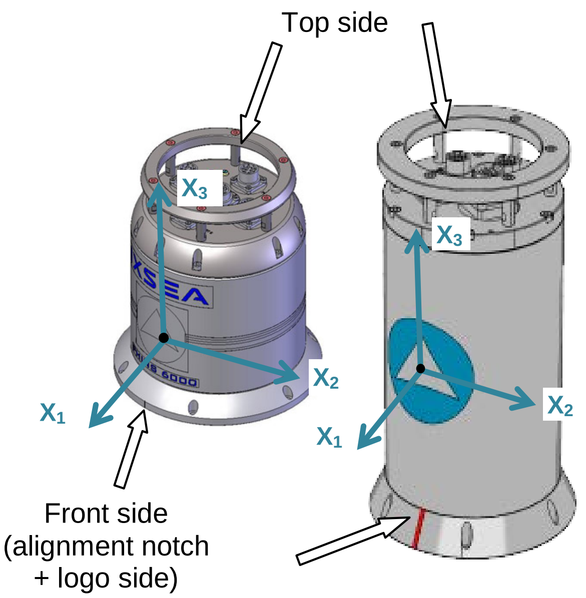


Figure 15 - Definition of axis X1, X2 and X3 and sides for cylindrical inertial products

Side definition

The six sides are also defined in Figure 14. Sign convention for each axis is positive in the direction of the axis indicated by the blue arrow on Figure 14.

The three axis intersect at point P, which is the inertial product reference point (refer to the *Product User Manual* for a full description).

The logo side and the connector side are used in the installation procedure (refer to *the Product User Manual*) to configure the inertial product orientation with respect to vehicle/vessel (rough misalignment).

VI.1.2 VEHICLE/VESSEL REFERENCE FRAME

The vehicle/vessel reference frame is defined by the three orthogonal axis XV_1, XV_2 and XV_3 (see Figure 16):

- XV_1 is in the vehicle/vessel horizontal plane, pointing forward to front/bow,
- XV_2 is in the vehicle/vessel horizontal plane, pointing from right/starboard to left/port,
- XV_3 is perpendicular to the vehicle/vessel horizontal plane, pointing upward.

This frame is used to specify sensor lever arms. Computed data are output in this reference frame on main and secondary lever arms.

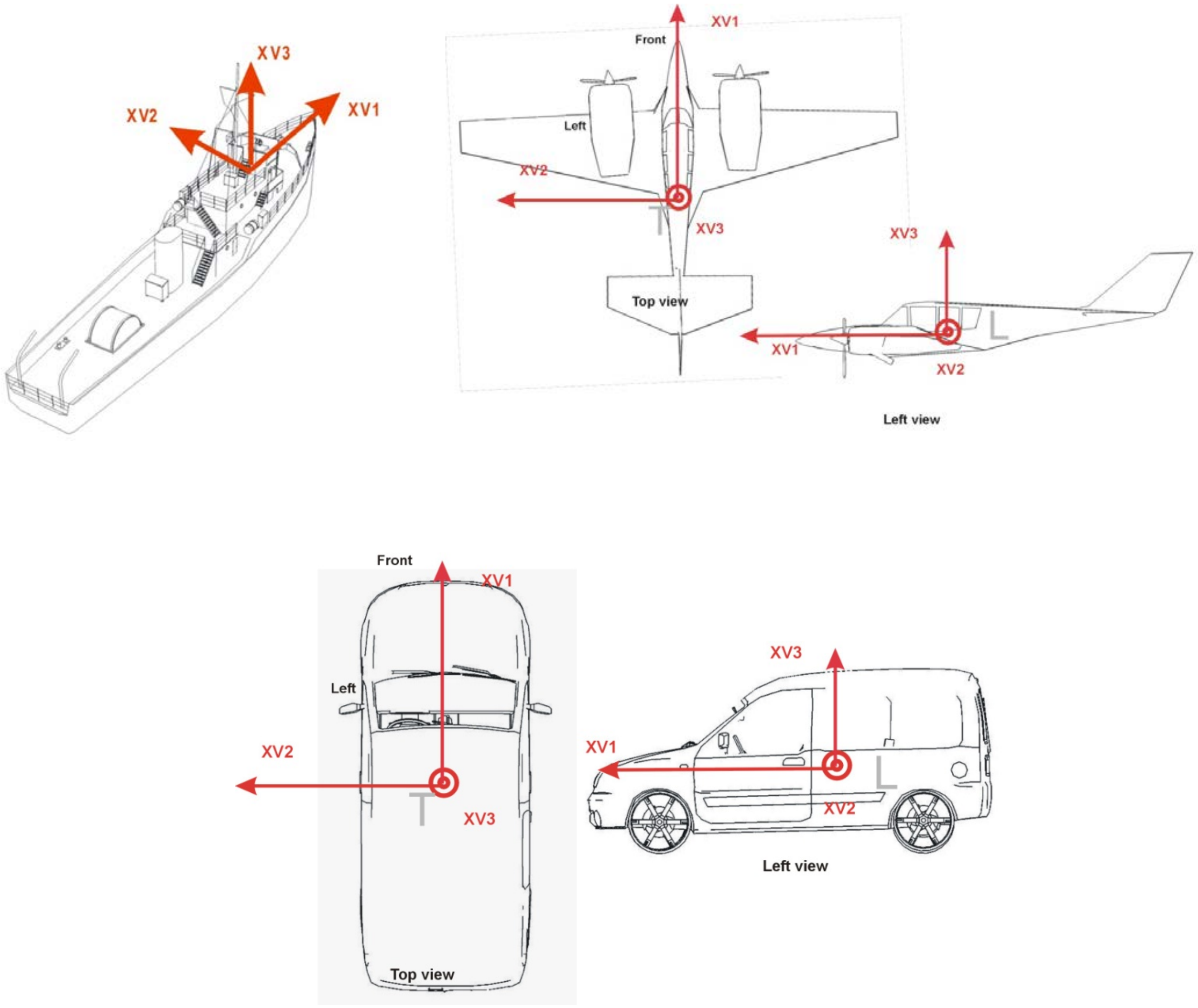


Figure 16 - Definition of vehicle/vessel reference frame

Note: Some application or vehicle use different axis conventions (i.e. Vertical axis pointing downward, side axis pointing right …). Special caution must be taken to use iXBlue product convention during the installation process.

VI.1.3 VEHICLE/VESSEL HORIZONTAL FRAME

This is the vehicle/vessel frame compensated from roll and pitch. It is defined by the three orthogonal axis XVH_1, XVH_2 and XVH_3. This frame is used to output heave, surge, sway and associated speeds. It is also used to output longitudinal and transverse speed data.

VI.1.4 NAVIGATION FRAME

The navigation frame is the local geographic frame defined by the three axis (see Figure 17):

- X_N, in the local horizontal plane, pointing towards North
- X_W, in the local horizontal plane, pointing towards West
- X_{up}, parallel to the local vertical, pointing up

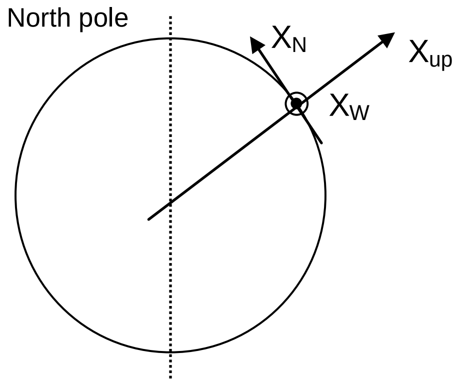


Figure 17 - Definition of the navigation reference frame

VI.2 Conventions for Attitude and Heading

The angular position of the vehicle is provided in roll, pitch and heading coordinates.

Roll, pitch and heading comes from the rotational transformation between the vehicle's frame (XV_1, XV_2, XV_3) – see Figure 16- and the local geographic frame (X_N, X_W, X_{up}) – see Figure 17.

This rotational transformation is fully described in section VI.5 and is illustrated in Figure 18, with positive heading and roll angles and negative pitch angle.

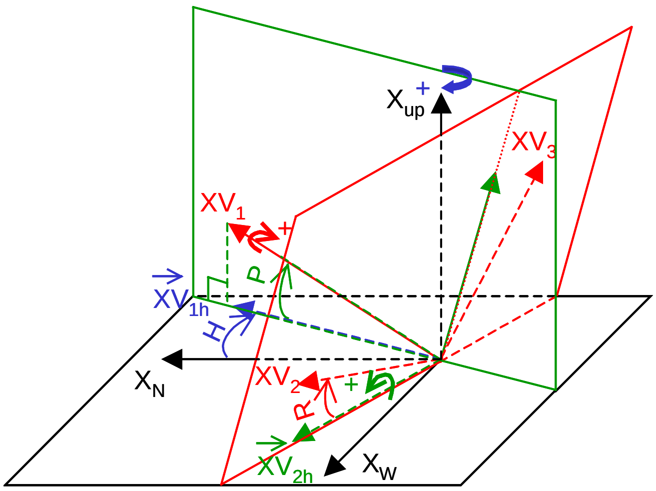


Figure 18- Definition of heading (H), roll (R) and pitch (P)

The three next sections give the definitions of roll, pitch and heading. They also give simplified situations for a best understanding.

VI.2.1 DEFINITION OF ROLL

Roll is the angular rotation around the XV_1 vehicle axis which transforms the vehicle axis XV_2 into $\vec{X}V_{2h}$ (see section VI.5). $\vec{X}V_{2h}$ is included into to the local horizontal plane defined by vectors X_N and X_W.

Roll is counted positively when turning counter-clockwise around XV_1. That means that the **roll is counted positive when vehicle left side (or vessel port side) is up**.

The following figure shows a simplified description of roll when heading and pitch are null and no misalignment is accounted for.

Roll varies from – 180 up to 180 degrees.

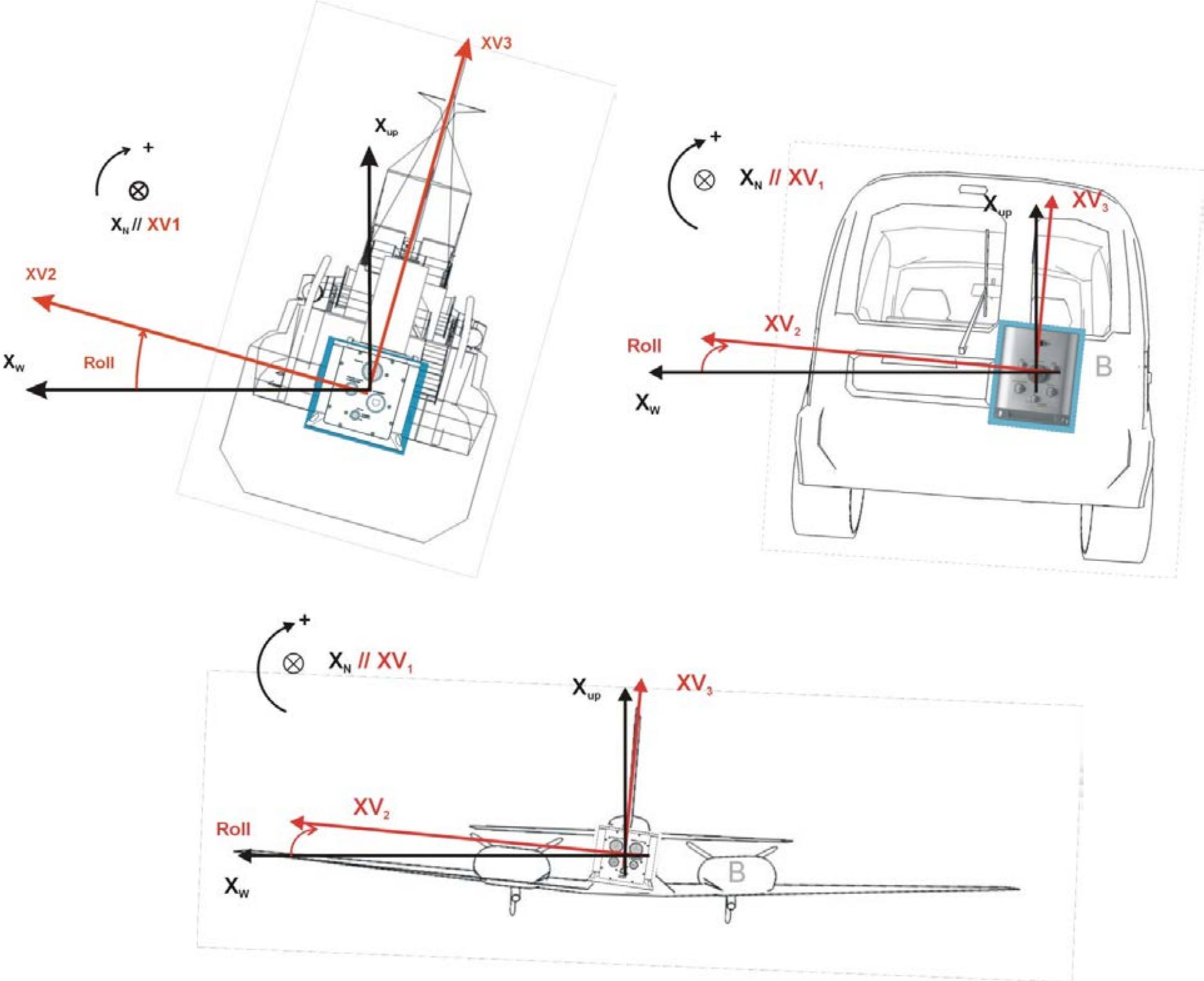


Figure 19- Definition of the roll angle in case of null heading and pitch, and no misalignment

VI.2.2 DEFINITION OF PITCH

Pitch is the angle between the XV_1 vehicle axis and $\vec{XV}_{1h}$. $\vec{XV}_{1h}$ is the XV_1 axis projection in the local horizontal plane defined by the two vectors X_N and X_W.

Pitch is counted positively from the local horizontal plane to the XV_1 axis when turning counter-clockwise around XV_2. That means that the **pitch is positive when vehicle's front (or vessel's bow) is down.**

The figure below gives a simplified description when heading and roll are null, and no misalignment is accounted for.

Pitch varies from – 90 up to 90 degrees.

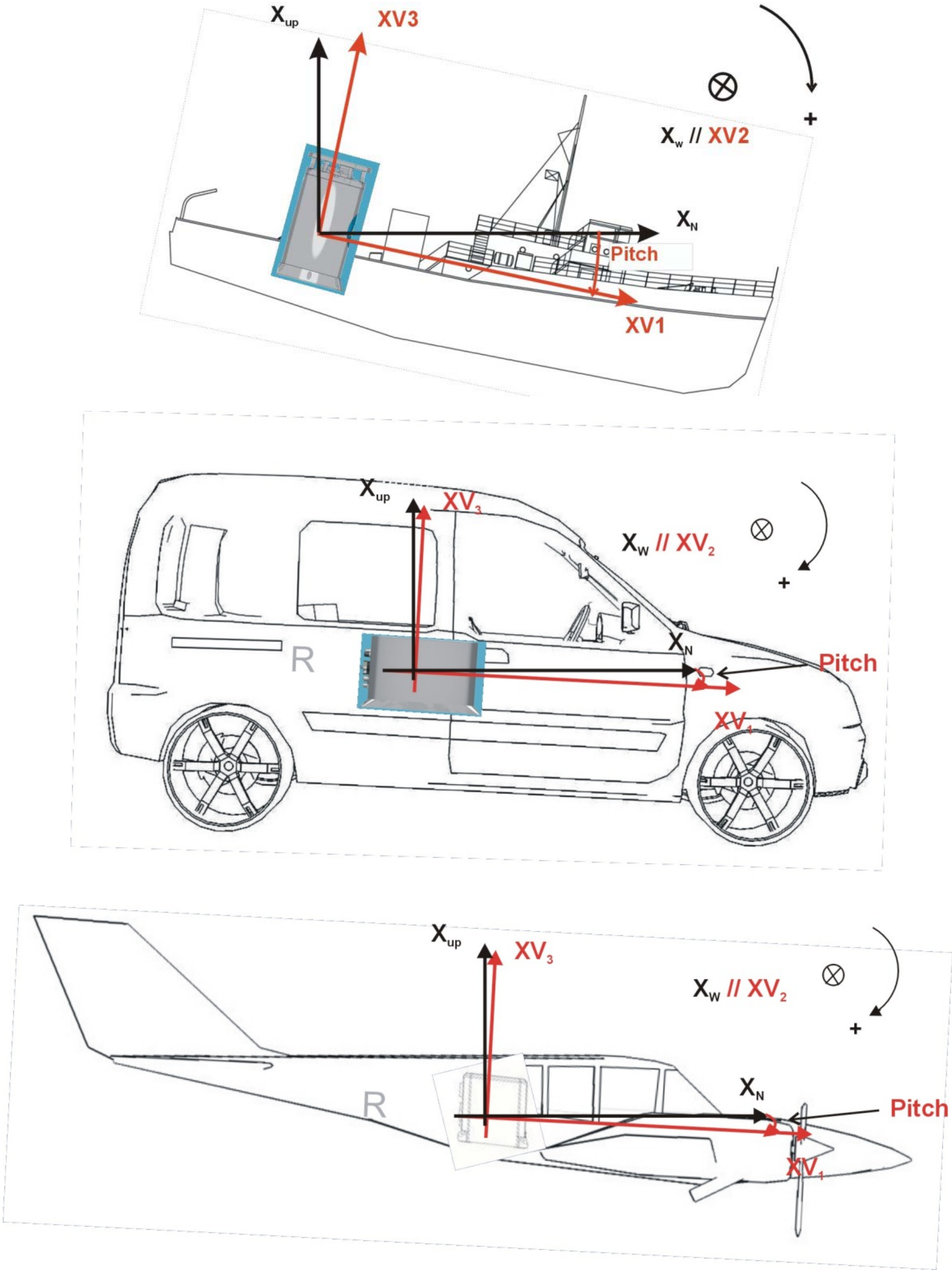


Figure 20- Definition of pitch angle in case of null heading and roll, and no misalignment

VI.2.3 DEFINITION OF HEADING

Heading is the angle between the north axis X_N and the projection $\vec{XV}_{1h}$ of the XV_1 vehicle axis in the local horizontal plane defined by the two vectors X_N and X_W.

Heading is counted positive eastwards from X_N.

The figure below gives a simplified description when pitch and roll are null, and no misalignment is taken into account.

Heading varies from 0 to 360 degrees.

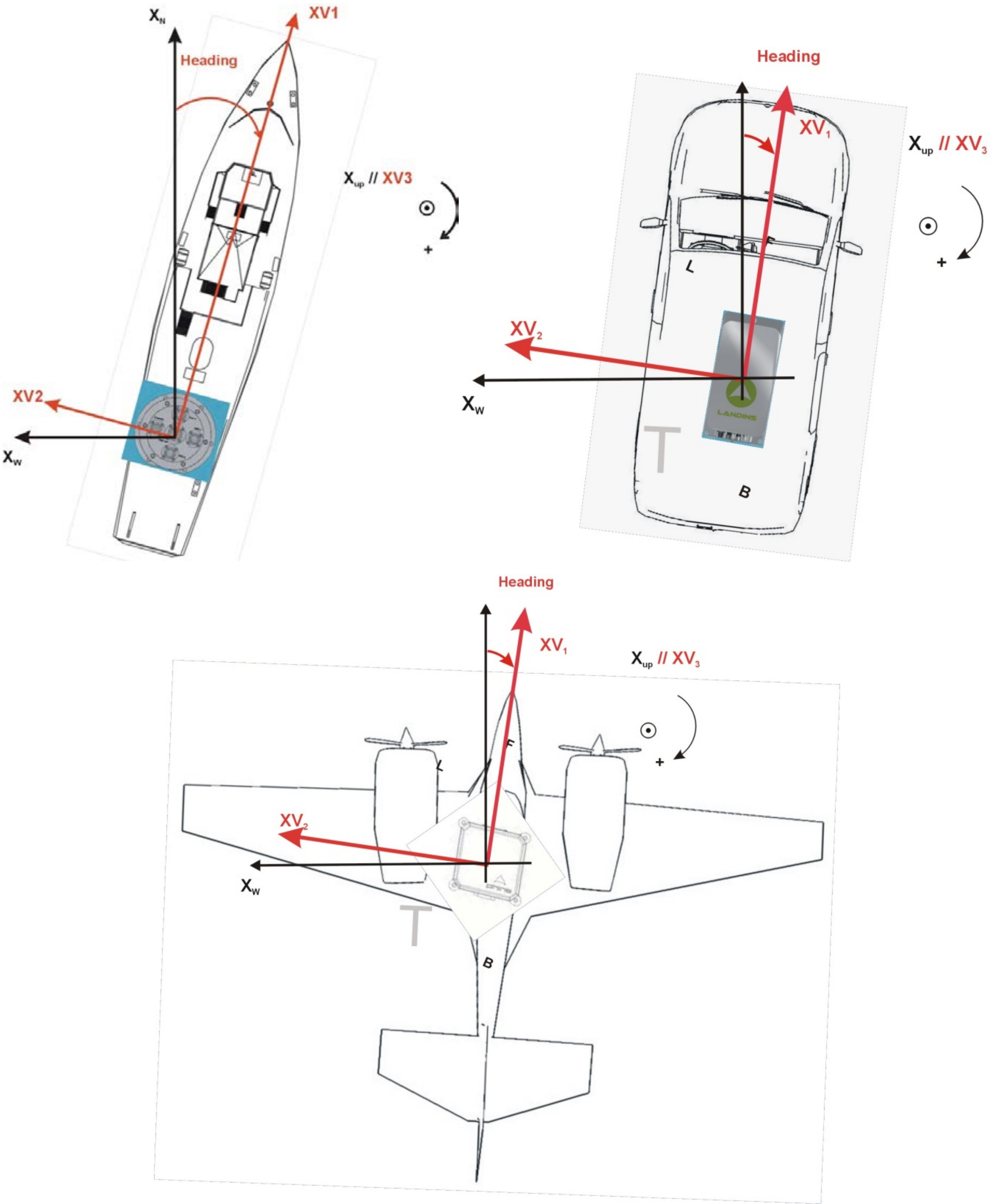


Figure 21- Definition of heading angle in case of null pitch and roll, and no misalignment

VI.2.4 Vectorial Transformation between Local Geographic Frame and Vehicle

The relationship between the coordinates (a_{v1}, a_{v2}, a_{v3}) in the (XV_1, XV_2, XV_3) frame and the coordinates (a_N, a_W, a_{up}) in the (X_N, X_W, X_{up}) frame of the vector $\vec{V}$ is:

$$\begin{pmatrix} a_N \\ a_W \\ a_{up} \end{pmatrix} = M_\Psi(Heading) \times M_\theta(Pitch) \times M_\varphi(Roll) \begin{pmatrix} a_{v1} \\ a_{v2} \\ a_{v3} \end{pmatrix}$$

The matrices M_Ψ, M_θ and M_φ are defined in section VI.5.

VI.3 Convention for Rotation Rates and Accelerations

Rotation Rates

Rotation rates measure the speed of roll, pitch and heading. They are default counted positive clockwise when looking in the direction of (XV1, XV2, XV3).

Rotation rates are measured around the three axis XV_1, XV_2 and XV_3. **Resolution is limited to comply with export regulations** (see document *Inertial Products - General Information (Ref.: MU-INS&AHRS-AN-007)* for details)**.**

Default unit: °/s

Linear Accelerations

Linear accelerations are measured along XV1, XV2 and XV3 axis. **Accuracy is limited to comply with export regulations** (see document *Inertial Products - General Information (Ref.: MU-INS&AHRS-AN-007)* for details).

Linear accelerations are counted positive along XV1, XV2 and XV3 axis.

Default unit: m/s^2

VI.4 Conventions for Heave, Surge and Sway

Heave

The heave is the altitude of the vehicle/vessel referenced to the mean altitude (the average value of heave over a long period of time is always zero). It is obtained by filtering and integrating vertical acceleration. The heave is counted positively upward along the local vertical axis X_{up}, in meters.

For example, heave measurement is used to compensate for vertical movement due to sea waves in multi-beam or sonar imagery.

Surge

The surge is the forward position of the vehicle/vessel referenced to the mean position (the mean of the surge over a long period of time is always zero). The surge is counted positively forward along the $\vec{XV}_{1h}$ axis, which is the projection of the XV_1 axis in the local horizontal plane, in meters.

Sway

The sway is the starboard position of the vehicle/vessel referenced to the mean position (the mean of the sway over a long period of time is always zero).The sway is counted positively left along the $\vec{XV}_{2h}$ axis), in meters.

VI.5 Rotational Transformation between Frames

This section describes the conventions used to perform a transformation between two frames each defined by a triplet of three orthogonal vectors ($\vec{A},\vec{B},\vec{C}$) and ($\vec{A}',\vec{B}',\vec{C}'$). This transformation is described by three plane rotations around 3 orthogonal axis, with angles Ψ, θ and φ (Euler angles) that correspond to heading, roll and pitch angles

This rotational transformation is used for defining the inertial product fine misalignment with respect to the vehicle reference frame (see section VI.6.2) and to define the angular position of the vehicle with respect to the local geographic frame.

To transform the ($\vec{A},\vec{B},\vec{C}$) frame into the ($\vec{A}',\vec{B}',\vec{C}'$) frame the following plane rotations are performed:

1) Rotation of ($\vec{A},\vec{B},\vec{C}$) around the $\vec{C}$ axis, **angle Ψ** (see Figure 22) to yield ($\vec{A}'_h,\vec{B}'_h,\vec{C}$).

This plane rotation is described by the orthogonal matrix $M_\Psi(\Psi)$, defined as:

$$M_\Psi(\Psi) = \begin{pmatrix} \cos(\Psi) & \sin(\Psi) & 0 \\ -\sin(\Psi) & \cos(\Psi) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Ψ is defined positive clockwise around $\vec{C}$: in Figure 22, Ψ is positive so that it corresponds to heading sign convention (opposite to usual Euler sign convention)

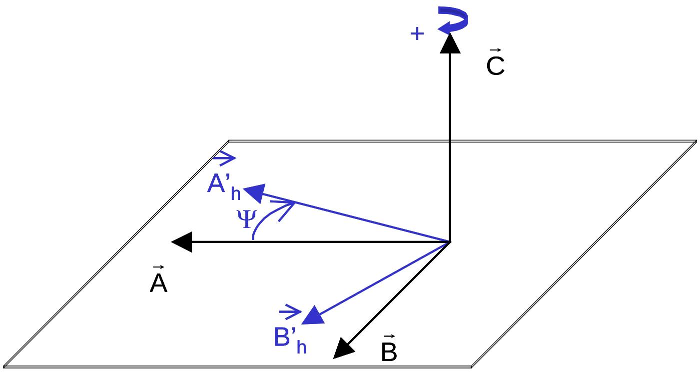


Figure 22 - Illustration of the first rotation around $\vec{C}$

2) Rotation of ($\vec{A}'_h,\vec{B}'_h,\vec{C}$) around $\vec{B}'_h$, **angle θ** (see Figure 23) to yield ($\vec{A}''$, $\vec{B}'_h$, $\vec{C}''$).

This plane rotation is described by the orthogonal matrix $M_\theta(\theta)$, defined as:

$$M_\theta(\theta) = \begin{pmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{pmatrix}$$

θ is defined positive counter-clockwise around $\vec{B}'_h$: in Figure 23, the rotation angle θ is negative.

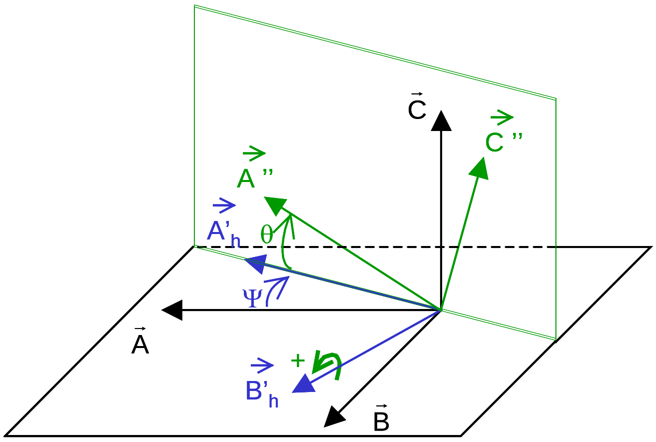


Figure 23 - Illustration of the second rotation around $\vec{B}'_h$

3) Rotation of ($\vec{A}''$, $\vec{B}'_h$, $\vec{C}''$) around $\vec{A}'' = \vec{A}'$, **angle φ** (see Figure 24) to yield ($\vec{A}', \vec{B}', \vec{C}'$).

φ is defined positive counter-clockwise around $\vec{A}'' = \vec{A}'$: in Figure 24, φ is positive.

This plane rotation is described by the orthogonal matrix $M_\varphi(\varphi)$, defined as:

$$M_\varphi(\varphi) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\varphi) & -\sin(\varphi) \\ 0 & \sin(\varphi) & \cos(\varphi) \end{pmatrix}$$

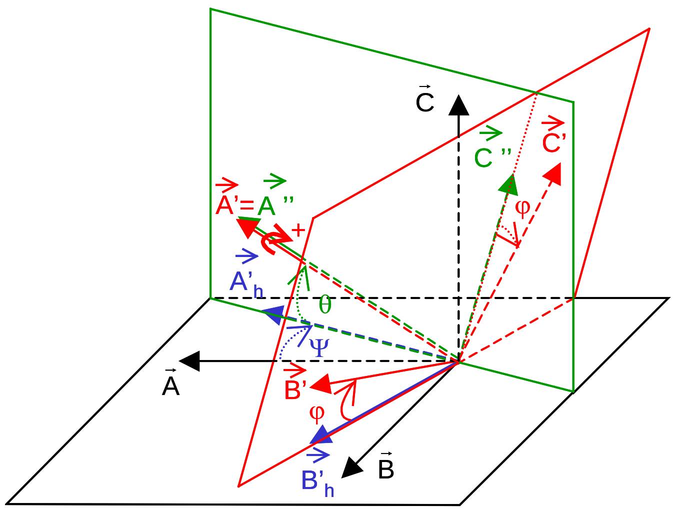


Figure 24 - Illustration of the third rotation around $\vec{A}'' = \vec{A}'$

THE RELATIONSHIP BETWEEN THE COORDINATES (a, b, c) IN THE ($\vec{A}, \vec{B}, \vec{C}$) FRAME AND THE COORDINATES (a', b', c') IN THE ($\vec{A}', \vec{B}', \vec{C}'$) FRAME OF A VECTOR $\vec{V}$ IS:

$$\begin{pmatrix} a \\ b \\ c \end{pmatrix} = M_\Psi(\Psi) \times M_\theta(\theta) \times M_\varphi(\varphi) \begin{pmatrix} a' \\ b' \\ c' \end{pmatrix}$$

VI.6 Inertial Product Misalignment: from Product to Vehicle's Reference Frame

All measurements are default-done in the iXBlue inertial product reference frame defined by the 3 vectors X_1, X_2 and X_3 (see section VI.1).

Misalignments angles can be entered by the user to account for any orientation of iXBlue inertial product with respect to the vehicle/vessel. This feature allows to "virtually rotate" the product, to align its reference frame with vehicle reference frame (usually called "baseline").

Two types of angular misalignments between the product and the vehicle are considered and described in the following sections: rough misalignment, then fine misalignment.

VI.6.1 Product to Vehicle Rough Misalignment (Product Axis Inversion)

The iXBlue inertial product can be set with any orientation with respect to the vehicle/vessel. Product rough misalignment allows to roughly align the product reference frame (X_1, X_2, X_3) to the vehicle reference frame (XV_1, XV_2, XV_3) by performing a product axis inversion. The axis inversion transforms the product reference frame (X_1, X_2, X_3) into the (X'_1, X'_2, X'_3) frame with the following relationships $X'_i = \pm X_j$ for (i, j) = (1, 2, 3).

Orientation example

Figure 25 is an illustration of a product rough misalignment, when the product front side is facing vessel's stern (back of the vehicle):

- In case of surface product: connector side is facing vehicle front side
- In case of subsea product: logo side is facing back of the vehicle

In this case, rough misalignment is then described through the following axis inversions: $X'_1 = -X_1$, $X'_2 = -X_2$ and $X'_3 = X_3$.

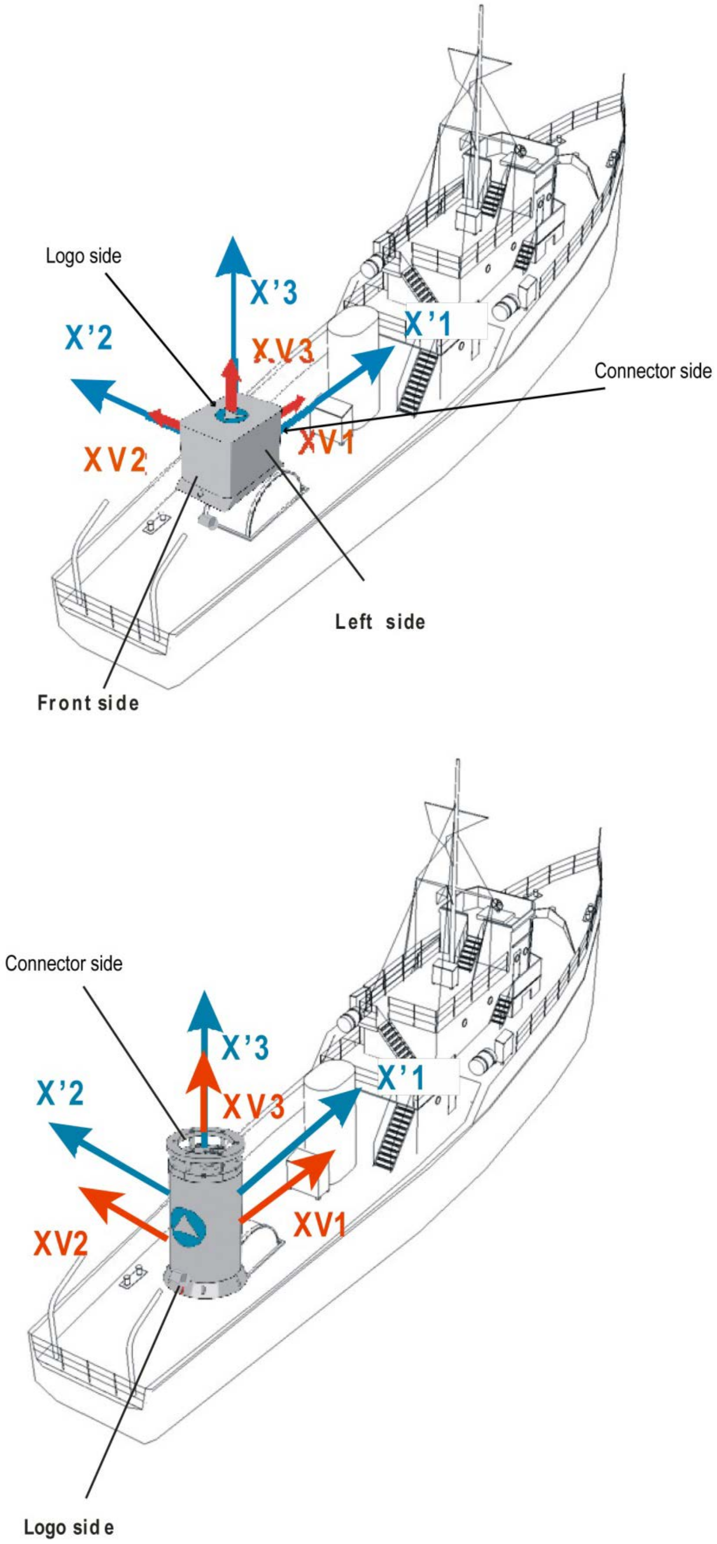


Figure 25 - Illustration of inertial products rough misalignment

VI.6.2 PRODUCT TO VEHICLE FINE MISALIGNMENT

Once rough misalignment has been taken into account, fine misalignments are determined to correct the residual angular offset between the new product axis (X'_1, X'_2, X'_3) and the vehicle/vessel's axis (XV_1, XV_2, XV_3).

Usually, these residual angular offsets are small as they are due to small angular misalignment of the product with respect to vehicle/vessel. However, any angular correction must be taken into account by setting with caution the fine misalignment angles.

Product misalignment with respect to the vehicle is obtained through the rotational transformation between the (X'_1, X'_2, X'_3) frame and the vehicle's frame (XV_1, XV_2, XV_3), which is described in its general form in section VI.5. This rotational transformation is the product of three plane rotations which are described by the three Euler angles misRoll (roll misalignment), misPitch (pitch misalignment) and misHeading (heading misalignment).

Important

AS ROTATIONS DO NOT COMMUTE, PLEASE PERFORM MEASUREMENTS AND CORRECTIONS OF THE MISALIGNMENTS IN THE FOLLOWING ORDER:

1- ROLL MISALIGNMENT

2- PITCH MISALIGNMENT

3- HEADING MISALIGNMENT

The following sections give the definition for roll, pitch and heading misalignments, which come from the general definition of the rotational transformation described in section VI.5.

VI.6.2.1 Roll Misalignment Offset

The roll misalignment offset (called *misroll* in the illustration) is the angle of the rotation around X'_1 axis which brings X'_2 axis into the vehicle horizontal plane (XV_1, XV_2). In the Figure 26, the value of the roll misalignment offset to be entered in the Web-based User Interface to configure the inertial product is negative.

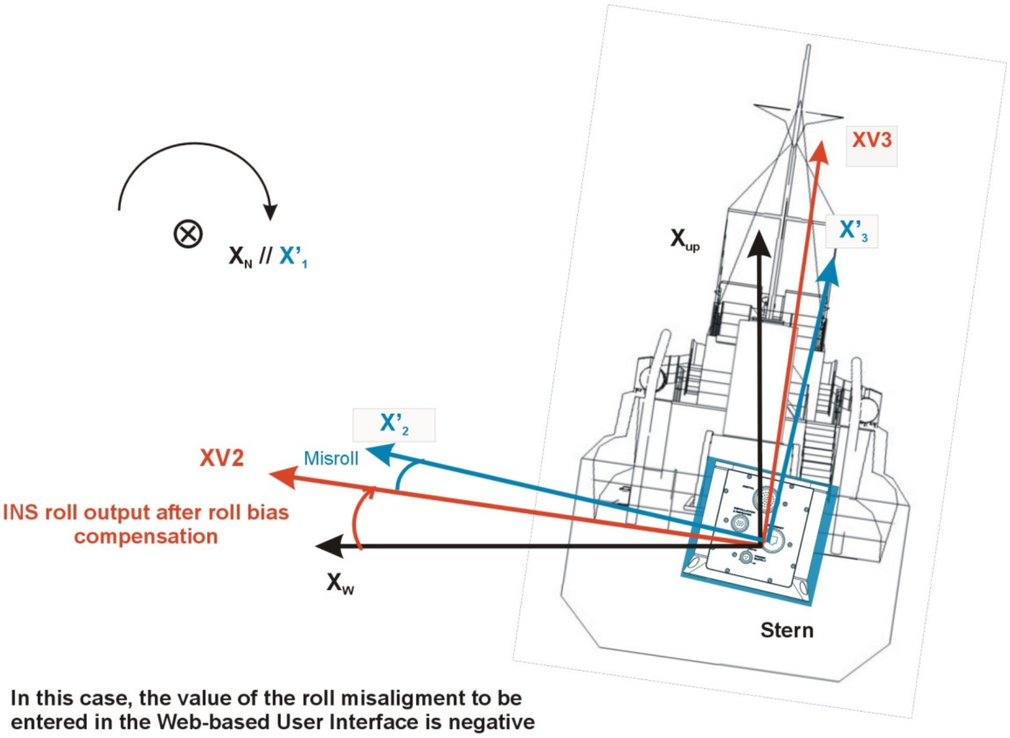


Figure 26 - Roll misalignment offset (in case of null pitch and heading)

VI.6.2.2 Pitch Misalignment Offset

Pitch misalignment offset (called *mispitch* in the illustration) is the angle between X'_1 axis and its projection in the vehicle horizontal plane (XV_1, XV_2). On Figure 27, the value of the pitch misalignment offset to be entered in the Web-based User Interface to configure the inertial product is negative.

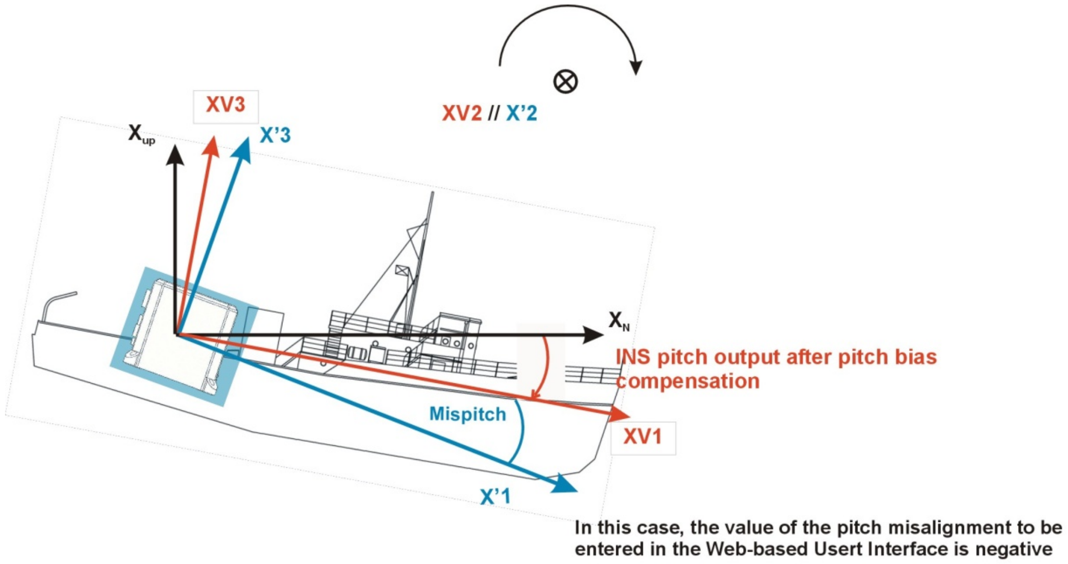


Figure 27 - Pitch misalignment offset in case of null roll and heading

VI.6.2.3 Heading Misalignment Offset

The heading misalignment offset (called *misheading* in the illustration) is the angle between the projection of the inertial product X'_1 axis into the vehicle horizontal plane (XV_1, XV_2) and the vessel axis XV_1. In the Figure 28, the value of the heading misalignment offset to be entered in the Web-based User Interface to configure the inertial product is positive.

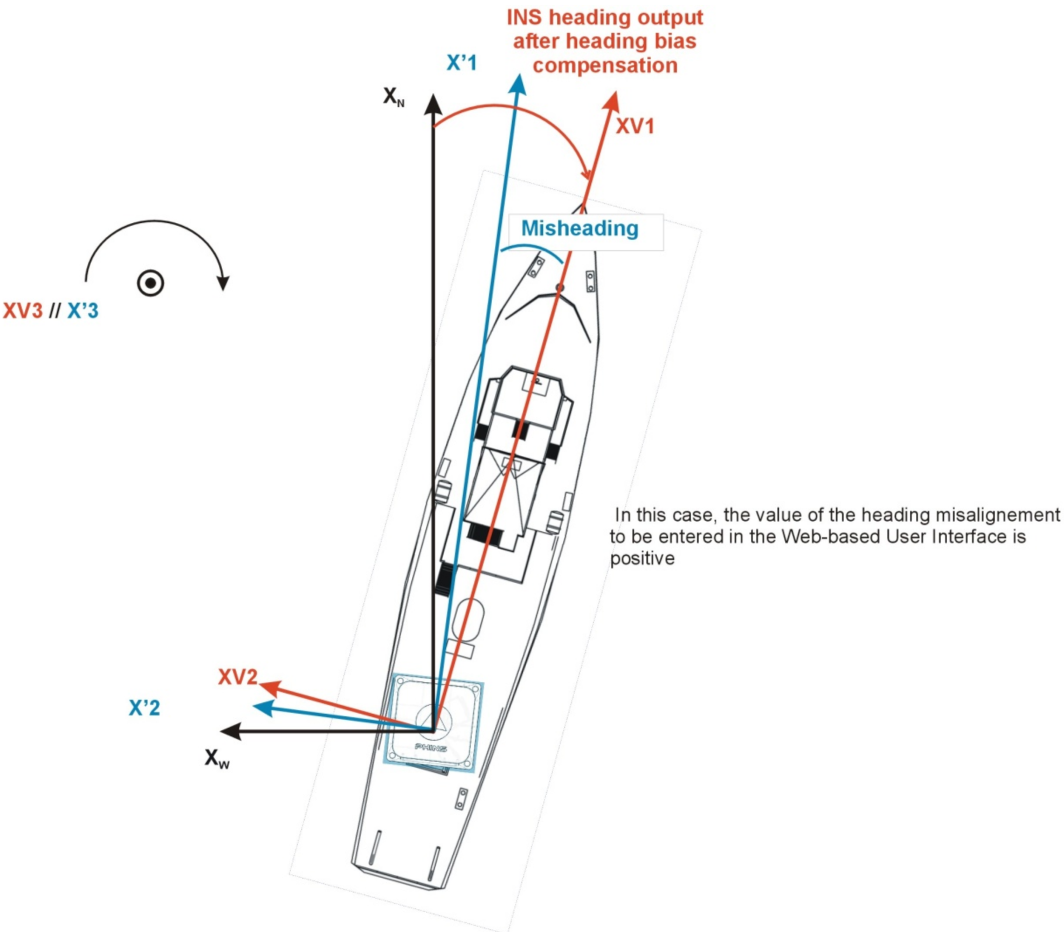


Figure 28- Heading offset misalignment in case of null roll and pitch

VI.6.2.4 Estimation of misalignment offset in comparison to an existing AHRS or INS

In case another Gyrocompass and/or motion sensor is available onboard the vehicle/ship, it might be required to align the new product to the existing one.

H0, R0, P0 are the heading, roll, pitch output from the AHRS/INS before entering the angular offsets mH1, mR1, mP1 and H1, R1, P1 the heading, roll pitch that the AHRS/INS should output. The angular offsets to enter into the system are the following:

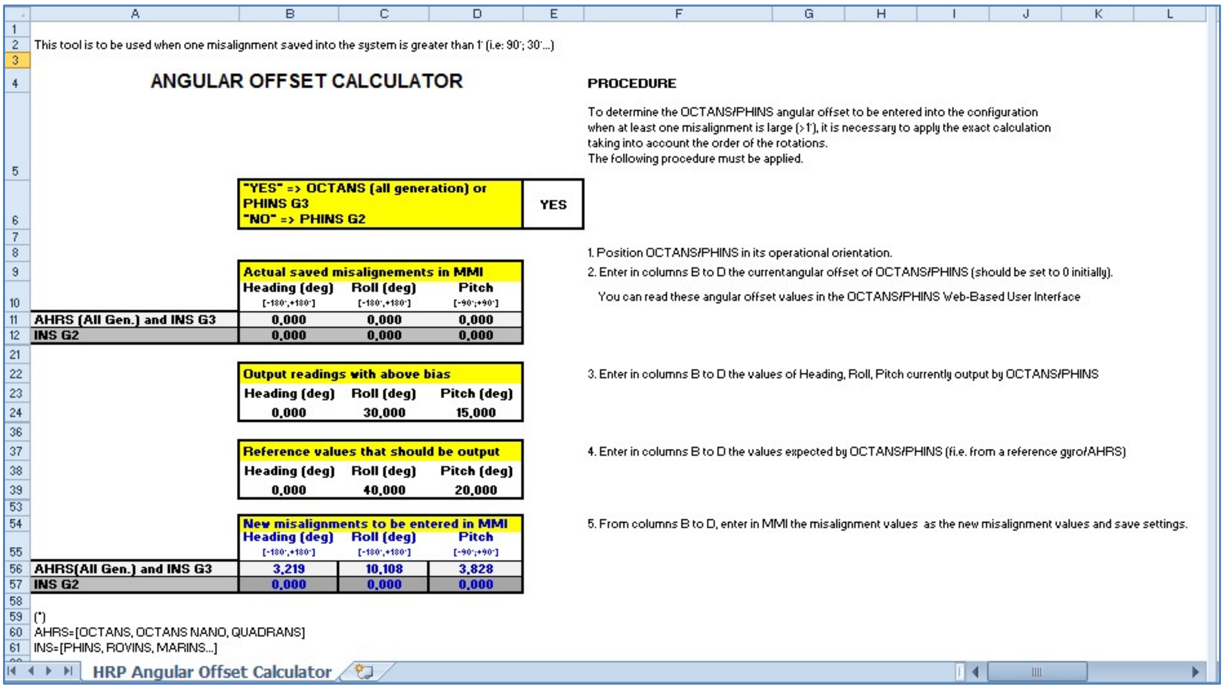
mR= R1-R0

mP=P1-P0

mH= H1-H0

THIS IS ONLY TRUE IF ALL ANGLES R1, R0, P1, P0, H1-H0 ARE << 1°
IF ANY ANGLE DOES NOT MEET THIS CONDITION YOU NEED TO USE THE "M-F0-SIN-003-A_HRP ANGULAR OFFSET CALCULATOR.XLS" TOOL DELIVERED ON YOUR CDROM TO COMPUTE ACCURATE VALUES.

In this case, such reference frames alignment (also called boresighting) can only be achieved with a rotation matrix calculation since rotation matrix do not commute for large angles.



This tool is to be used when one misalignment saved into the system is greater than 1° (i.e: 90°; 30°...)

ANGULAR OFFSET CALCULATOR

"YES" => OCTANS (all generation) or PHINS G3 "NO" => PHINS G2	YES

Actual saved misalignements in MMI	Heading (deg) [-180°,+180°]	Roll (deg) [-180°,+180°]	Pitch [-90°;+90°]
AHRS (All Gen.) and INS G3	0,000	0,000	0,000
INS G2	0,000	0,000	0,000

Output readings with above bias		
Heading (deg)	Roll (deg)	Pitch (deg)
0,000	30,000	15,000

Reference values that should be output		
Heading (deg)	Roll (deg)	Pitch (deg)
0,000	40,000	20,000

New misalignments to be entered in MMI	Heading (deg) [-180°,+180°]	Roll (deg) [-180°,+180°]	Pitch [-90°;+90°]
AHRS(All Gen.) and INS G3	3,219	10,108	3,828
INS G2	0,000	0,000	0,000

(*)
AHRS=[OCTANS, OCTANS NANO, QUADRANS]
INS=[PHINS, ROVINS, MARINS...]

PROCEDURE

To determine the OCTANS/PHINS angular offset to be entered into the configuration when at least one misalignment is large (>1°), it is necessary to apply the exact calculation taking into account the order of the rotations.
The following procedure must be applied.

1. Position OCTANS/PHINS in its operational orientation.
2. Enter in columns B to D the currentangular offset of OCTANS/PHINS (should be set to 0 initially).
You can read these angular offset values in the OCTANS/PHINS Web-Based User Interface
3. Enter in columns B to D the values of Heading, Roll, Pitch currently output by OCTANS/PHINS
4. Enter in columns B to D the values expected by OCTANS/PHINS (fi.e. from a reference gyro/AHRS)
5. From columns B to D, enter in MMI the misalignment values as the new misalignment values and save settings.

HRP Angular Offset Calculator

VI.6.2.5 Vectorial Transformation between Product and Vehicle (Rotation Matrix)

THE RELATIONSHIP BETWEEN THE COORDINATES (a_{v1}, a_{v2}, a_{v3}) IN THE (XV_1, XV_2, XV_3) REFERENCE FRAME AND THE COORDINATES (a'_1, a'_2, a'_3) IN THE (X'_1, X'_2, X'_3) FRAME OF VECTOR $\vec{V}$ IS:

$$\begin{pmatrix} a_{v1} \\ a_{v2} \\ a_{v3} \end{pmatrix} = M_{\Psi}(misheading) \times M_{\theta}(mispitch) \times M_{\varphi}(misroll) \begin{pmatrix} a'_1 \\ a'_2 \\ a'_3 \end{pmatrix}$$

The matrices M_{Ψ}, M_{θ} and M_{φ} are defined in section VI.5.

VI.7 Log Sensor to Inertial Product Misalignment

Some inertial products can use speed inputs received from external sensors. Refer to your *Product User Manual* for compatibility details. Inertial products that do not take into account Log Sensor are not concerned by this section.

VI.7.1 General Case

When navigating with speed inputs from an external log sensor, the INS product expects to receive the 3 speed coordinates from the Log sensor in a frame linked to the sensor, without any compensation. The Log sensor reference frame (XS_1, XS_2, XS_3) is either the sensor body frame or the sensor beam frame. Speed inputs from external Log Sensor are then corrected for angular misalignment between the vehicle reference frame (XV_1, XV_2, XV_3) and the Log Sensor reference frame (XS_1, XS_2, XS_3). Log Sensor to INS product misalignment angles are the three Euler angles R_S, P_S and H_S, which allow switching from the vehicle reference frame (XV_1, XV_2, XV_3) to the Log Sensor reference frame.

These angles are defined in Figure 29, where R_s is positive, P_s is negative and H_s is positive.

R_s and P_s define the misalignment between the Log Sensor horizontal plane and the INS product horizontal plane. These angles are generally quite small.

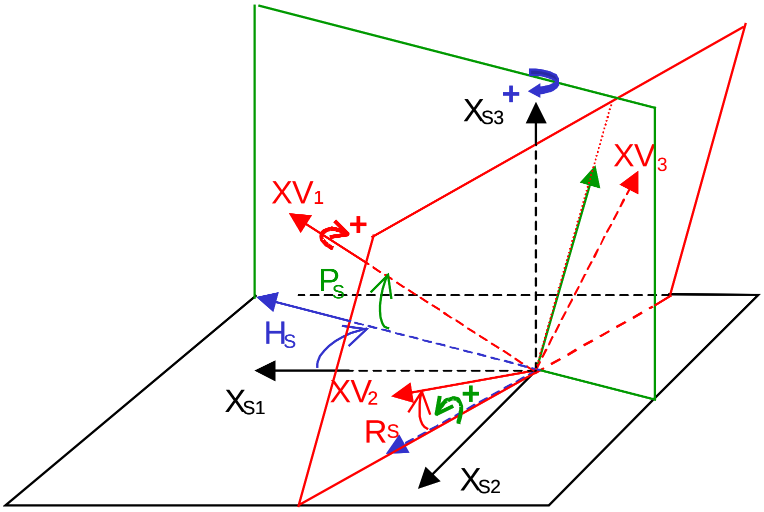


Figure 29 - Definition of Log sensor to INS product misalignment

VI.7.2 Terrestrial Vehicle (DMI Sensor / LANDINS)

LANDINS expects to receive the longitudinal speed (car wheel sensor or gear box sensor). The DMI sensor reference frame is assumed to be the vehicle frame.

For the DMI sensor, a specific alignment procedure has to be performed so that LANDINS can estimate the DMI sensor misalignment. Once this procedure is achieved, velocity data is entered into LANDINS with reference to the DMI Sensor frame. This is also the case during DMI Sensor calibration.

DMI to LANDINS heading misalignment angle is determined during installation procedure. Roll and pitch misalignments should be set to zero.

VI.8 Lever Arms: Definition and Conventions

Inertial products are able to calculate the motion of several external monitoring points. External monitoring points are defined by their "Lever Arm" to the center of measurement P of the iXBlue inertial product. P position is defined in your *Product user manual*.

The lever arm (of the main Monitoring Point, of the three secondary ones, of the external sensor, and of the Center of gravity of the vehicle) is represented by three lengths LV1, LV2, LV3 defining the position of external monitoring point M in the (XV_1, XV_2, XV_3) vehicle's axis (see Figure 30).

To define the lever arm of an external sensor, refer to the sensor documentation to know the exact point of measurement of the sensor.

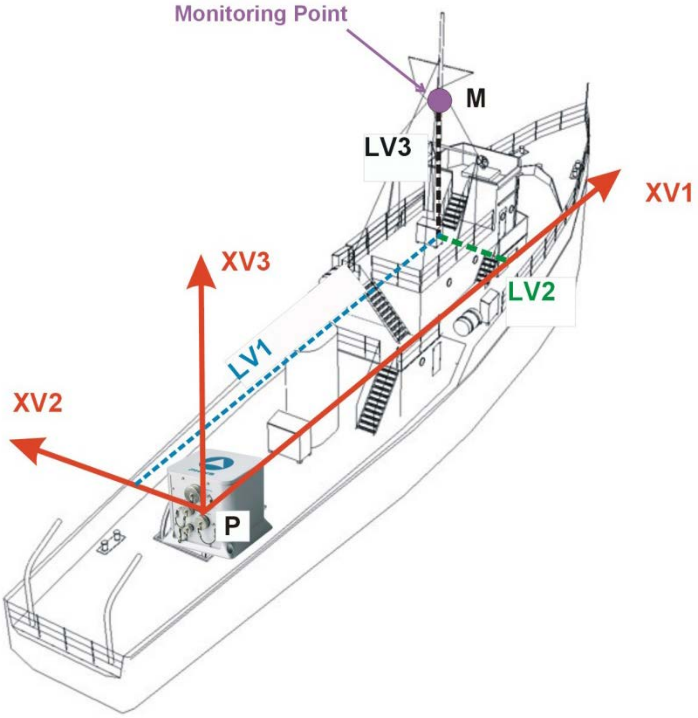


Figure 30 - Definition of Lever Arm

Four types of lever arms are considered (some products do not use all these lever arms):

- Inertial product lever arm or Primary lever arm is the lever arm from the product center of measurement P to the main monitoring point. All output data is computed on this primary lever arm (position, motion, speeds and accelerations). The iXBlue MMI only displays primary lever arm data.
- Secondary lever arms: The secondary lever arms are used to compute the heave and position for the output protocols that provide it. To define the secondary lever arms refer to the document corresponding to your product:
  - ❑ For AHRS unit: Configuration & Operation with the Web-based User Interface (Ref.: MU-AHRS-AN-001)
  - ❑ For INS unit, Marine applications – Web-based Interface User guide (Ref.:MU-INSIII-AN-021)

- For INS unit, Land & Air applications – Web-based Interface User guide (Ref.: MU-INSIII-AN-022)

  You can define up to three secondary lever arms.

  Only position and motion (heave, surge and sway) are computed on secondary lever arms. Speeds and accelerations are not computed at these secondary monitoring points.

- External sensor lever arm is the distance from the product center of measurement P to the center of measurement of the external sensor (refer to the external sensor User Manual to locate this point).
- Center Of Gravity (COG) lever arms. This lever arm is useful for marine vehicles because a way to avoid the effect of transient vehicle movement is to indicate the COG position by entering levers arms between the unit (AHRS/INS) and the COG of the vehicle. Refer to the document *Inertial Products – Application Note - Installation and Configuration of AHRS and INS for Seabed Mapping Measurements (Ref.: MU-HEAVAPN-AN-001)* to get more details.

VI.9 Accounting for Misalignments and Lever Arms

Inertial product automatically compensates for any misalignment or lever arm, once these have been set. External sensor data is then entered directly into the inertial product without any pre-compensation by the user. For a Log or a DMI sensor (if any), a specific alignment procedure has to be performed so that the inertial product can estimate the Log sensor misalignment. Once this procedure is achieved, velocity data is entered into the inertial product with reference to the Log Sensor frame. This is also the case during Log Sensor calibration.

VI.10 Definitions and Conventions for Navigation Data

The navigation data provided by the inertial product are summarized in *the Interface Library document (Ref.: MU-AHRS-AN-003 for AHRS, or MU-INSIII-AN-001 for INS)*.

VI.11 Conventions for Position Data

For AHRS products, only latitude convention is used.

For the INS products, position is given both in usual latitude/longitude/altitude or latitude/longitude/depth format and in UTM (Universal Transverse Mercator) format. The earth model used is WGS-84 (ellipsoid).

VI.11.1 LATITUDE, LONGITUDE AND ALTITUDE

The conventions are:

Latitude Convention

- For latitude (degrees):
  - Northern hemisphere latitudes are positive (0 to 90 degrees)
  - Southern hemisphere latitudes are negative (–90 to 0 degrees)

Longitude Convention

- For longitude (degrees):
  - Longitude ranges from 0 to 360 degrees. Longitude zero is the Greenwich meridian and longitude is positive going eastwards.
  - Longitude can be entered manually into the inertial product interface, either from 0 to 360 degrees or from –180 to +180 degrees. Whatever the format of the manually entered longitude, it will be displayed in the Web-based User Interface windows as a positive number from 0 (Greenwich meridian) to 360 degrees. For instance, if a longitude of –30 degrees is entered manually, it will be displayed as 330 degrees in the Web-based User Interface.

Altitude / Depth Convention

- For Altitude / Depth (meters): Conventions depend on the inertial product, on the output protocol settings, and selected altitude mode. Refer to the modes described in the document corresponding to your product:
  - For INS unit, Marine applications – Web-based Interface User guide (Ref.:MU-INSIII-AN-021)
  - For INS unit, Land & Air applications – Web-based Interface User guide (Ref.: MU-INSIII-AN-022)

VI.11.2 THE UTM COORDINATE SYSTEM

Applicable only to INS products.

The UTM coordinate system is made up of 60 vertical (north/south) zones starting at 180 degree longitude meridian and wrapping around the earth towards East. Each zone is 6 degree wide and is numbered from 1 to 60. The system is further divided into 20 horizontal (east/west) bands starting at -80 degrees south latitude with band labeled 'C" and ending north at + 84 degrees latitude with band "X" (the letters "I" and "O" are not used to avoid confusion with numbers).

Inside each UTM zone, the coordinates of a point on the earth are expressed by two values in meters: UTM Northing and UTM Easting. These coordinates are obtained by local projection of the earth on a cylinder. This kind of projection ensures that the deformation due to plane projection is minimized. The UTM Northing and Easting coordinates are always positive.

VI.12 Convention for Speeds

By default, the linear speeds of inertial products are displayed in the MMI in geographic coordinates (North, East and Up), unit is meter per second. Depending on the output protocol used to obtain data from the inertial product, the speeds can also be obtained in different geographic coordinates, or in body coordinates (coordinates linked to the product).

Maximum linear speed is limited to comply with export regulations (see document *Inertial Products - General Information (Ref.: MU-INS&AHRS-AN-007)* for details).

The heave, surge and sway speeds are measured along the same axis as heave, surge and sway (refer to section VI.4).

For AHRS, refer to section V.2.1 for more information.

VII DEFINITION & CONVENTIONS FOR STANDARD DEVIATION DATA

The standard deviation data provided by the inertial product are summarized at the end of the *Product Interface Library* document *(Ref.: MU-AHRS-AN-03 for AHRS, or MU-INSIII-AN-001 for INS)*.

The standard deviation data are estimations of the possible errors on the data provided by the inertial product. The standard deviation data readable from the inertial product include:

- Estimated possible position error
- Estimated possible speeds errors
- Estimated possible Attitude and Heading errors.

These error estimates are based on theoretical error models of accelerometers and gyrometers associated with external sensor errors estimates. They can be used to monitor the quality of the mission but are not accurate physical measurements of actual errors.

VIII CONVENTIONS FOR THE EXTERNAL SENSOR DATA

The data of all external sensors connected to an inertial product can also be displayed and repeated, unmodified, through the user interface and/or output protocols. This feature helps to monitoring of external sensor (e.g. quality, performances …), especially in cases they are exclusively connected to the Inertial Product.

The list of external sensor data readable from the inertial product is summarized at the end of the document *Product Interface Library (Ref.: MU-AHRS-AN-003 for AHRS, or MU-INSIII-AN-001 for INS).*