MTi Family Reference Manual

User Manual

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Xsens MTi User Manual Repository

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Introduction

This manual gives an overview of the latest generation Xsens products (MTi 1-series, MTi-320 and MTi 600-series) and their usage. For previous generations, refer to *MTi User Manual*. The MTi product portfolio from Xsens currently has family members ranging in functionality from Inertial Measurement Units (IMU's), Vertical Reference Unit (VRU), Active Heading Trackers (AHT), Attitude and Heading Reference System (AHRS) to a fully integrated GNSS/INS (Global Navigation Satellite System/Inertial Navigation System). All products contain a 3D IMU composed of a gyroscope and an accelerometer plus a 3D magnetometer, with optionally a barometer and GNSS receiver.
The MTi product range is divided into several series; the MTi 1-series, the MTi-320, the MTi 600-series, the MTi 10-series and the MTi 100-series.

- The MTi 1-series is a low-cost Surface-Mount Devices (SMD) module.
- The MTi-320 combines the cost and performance of the MTi 1-series with the ease of integration of the MTi 600-series.
- The MTi 600-series is a cost-effective product line for easy integration.
- The MTi 10-series is Xsens' entry level model with robust accuracy.
- The MTi 100-series is Xsens' proven high end class of MEMS IMUs, orientation and position sensor modules.

The table below summarizes all available official documents for the Xsens MTi product line. It is highly recommended to review all documents applicable to your Xsens Motion Tracker.

MTi documentation overview

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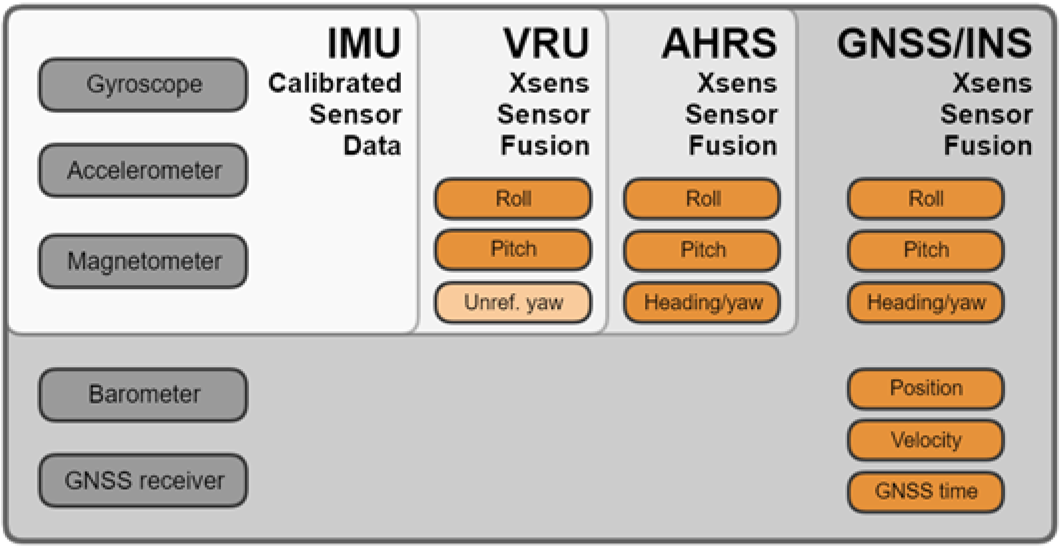
From IMU to GNSS/INS

Within each MTi series, Xsens offers several product variants. Each variant is based on a firmware version which enables different functionalities. The figure below summarizes the functionality of each variant.



From IMU to GNSS/INS

IMU

The IMU variant is an Inertial Measurement Unit that measures 3D acceleration and 3D rate of turn with the addition of 3D magnetic field data and, depending on the product, barometric pressure. It does not fuse sensor data to deliver orientation estimates. The IMU can also be configured to output data generated by the strapdown integration algorithm (orientation increments Δq and velocity increments Δv).

VRU/AHT

The Vertical Reference Unit (VRU), also referred to as Active Heading Tracker (AHT) adds the first layer of algorithms which uses gravity as a reference for roll and pitch calculations. Essentially it delivers the same data as the AHRS, except for the yaw. The yaw estimate of a VRU/AHT product is unreferenced, which means that it is computed without any geographic/magnetic reference, though still superior to just gyroscope integration (e.g., when using the gyro bias estimation techniques). All data outputs from the IMU are also available in this product version. The AHS feature is also available in this product variant (see also chapter Additional setting options and features).

AHRS

This is the full Attitude and Heading Reference System (AHRS). It provides various outputs: roll, pitch and heading (magnetic referenced yaw). In addition, all functionalities of the IMU and VRU are also available in this product variant.

GNSS/INS

The GNSS/INS variant is a product with an interface to an external or internal (RTK) GNSS receiver as well as a barometer. It provides roll, pitch, yaw/heading, as well as 3D position, 3D velocity and time data. In addition, all data outputs of the IMU, VRU/AHT and AHRS are also available in this product variant.

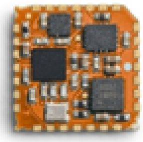
Xsens MTi hardware platforms

This section summarizes all available Xsens MTi platforms (see Table Xsens MTi portfolio overview).

MTi 1-series

The MTi 1-series is the Xsens' smallest (12.1mm x 12.1mm), lightest (<1gr) and most cost effective product suitable for SMD (Surface Mountable Device) integration. It is compatible with the JEDEC PLCC-28 standard footprint. Designed for integration in high volume applications.

Available in IMU, VRU/AHT, AHRS and GNSS/INS (with external GNSS receiver) product versions.
Please refer to the *MTi 1-series Datasheet* for more information.



MTi 1-series

MTi-320

The MTi-320 Active Heading Tracker (AHT) module is a combination of the MTi 1-series (performance and functionality-wise) and the MTi 600-series (form factor). It is a cost-effective but easy to integrate motion tracker specifically aimed at robotic ground vehicles, such as AGVs and AMRs. It features an RS232 interface.

Please refer to the *MTi-320 Datasheet* for more information.

MTi-320

MTi 600-series

The MTi 600-series (IP51) modules are designed to be lightweight, cost effective and easy to integrate. It can be integrated in two ways: either with the header facing downwards, directly mounted on a PCB, or standalone, using a flat cable for communication. The rugged (IP68) MTi-630R, MTi-670G and MTi-680G feature an aluminum housing. The MTi-670G and MTi-680G feature an integrated GNSS receiver.
The entire MTi 600-series features a CANbus interface.

Available in IMU, VRU/AHT, AHRS and GNSS/INS product versions.
Please refer to the *MTi 600-series Datasheet* for more information.

MTi 600-series

MTi 10-series

The MTi 10-series offers inertial and orientation data at an affordable price. It features a sturdy anodized aluminium housing, and robust push/pull connectors. The MTi-10 series can easily be recognized by the aluminium silver base plate.

Available in IMU, VRU/AHT and AHRS product versions.
Please refer to the *MTi User Manual* for more information.
This product is not recommended for new designs.

MTi 10-series

MTi 100-series

The MTi-100 series is the high-performance product range of the MTi product portfolio, with accuracies surpassing conventional MEMS motion trackers, because of the use of superior gyroscopes and a new optimization filter, going beyond standard Extended Kalman Filter implementations. In addition, the factory calibration is more accurate, repeatable and robust.
The MTi 100-series can be recognized by the dark-grey/black base plate and the small barometer holes on one side of the casing. The MTi-G-710 has an extra SMA connector to allow a GNSS antenna to be attached.

Available in IMU, VRU/AHT, AHRS and GNSS/INS (with internal GNSS receiver) product versions.
Please refer to the *MTi User Manual* for more information.

MTi 100-series including the MTi-G-710

Xsens MTi portfolio overview

	MTi 1-series	MTi-320	MTi 600-series	MTi 10-series	MTi 100-series
IMU	MTi-1	-	MTi-610	MTi-10	MTi-100
VRU/AHT	MTi-2	MTi-320	MTi-620	MTi-20	MTi-200
AHRS	MTi-3	-	MTi-630 MTi-630R	MTi-30	MTi-300
GNSS/INS	MTi-7	-	MTi-670 MTi-670G	-	MTi-G-710
GNSS/INS (RTK)	MTi-8 RTK	-	MTi-680 MTi-680G	-	-

The Family Reference Manual focusses mainly on the MTi 1-series, MTi-320 and MTi 600-series. For more information on the MTi 10-series and MTi 100-series, please refer to the Introduction of the MTi 10-series and MTi 100-series.

Getting started with the MTi

Overview MTi Development Kit

The MTi development kit is a very easy to use starter's kit that allows for fast and easy integration of the MTi in any user scenario. The figure below shows a typical Development Kit, containing an MTi. All software and installation instructions are available online via http://www.xsens.com/setup.

MTi Development Kit

Depending on the model of MTi you have purchased, the Development Kit can contain any of the following items:

Description of hardware components of Development Kit

Component	Description
An MTi Motion Tracker	
Development board	A tool for prototyping and validation
(micro) USB (converter) cable or dongle	A cable or dongle to connect the MTi device to a USB port
multi-purpose (flat) cable	A cable which exposes all physical lines to a MTi device

Component	Description
GNSS daughter card	An accessory which fits the MTi 1-series and MTi 600-series development board which contains a GNSS receiver (click-board™ compatible)
GNSS antenna	
Test and Calibration certificate	

Description of software components of Development Kit

Component	Description
MT Software Suite (MTSS)	available for download via http://www.xsens.com/setup
Xsens MTi USB driver	Part of the MTSS
MT Manager for Linux and Windows	Part of the MTSS
MT Software Development Kit (MT SDK) for multiple OS	Part of the MTSS, containing the following components: • XDA public source files (C, C++ wrapper ; any OS) • Example source code and examples - C++ - C# - Python - MATLAB - Robotic Operating System (ROS) - Embedded examples (ST Nucleo)
Magnetic Field Mapper – MFM (Windows and Linux)	Part of the MTSS, containing the following component: • MFM SDK (Windows and Linux)
Firmware Updater	Separate component design to update MTi device firmware
Documentation	Part of the MTSS, PDFs are available online, containing the following components: • Links to online manuals • Xsens Device API library

Component	Description
MFM SDK Library	Library for the Magnetic Field Mapper

NOTE: the most recent version of the software, firmware updater, source code and documentation can always be downloaded on www.xsens.com/software-downloads.

Getting Started with MT Manager software

The easiest way to get started with your MTi is to use MT Manager. MT Manager is a software tool to easy get to know and to demonstrate the capabilities of the MTi and to configure the device to suit your needs.

Additionally, MT Manager allows you to:

- record data and playback/review data;
- view orientation, position and velocity in real-time;
- view inertial and magnetic sensor data in real time;
- view low-level communication and XDA communication via message terminals;
- export log files to ASCII and KMZ (format viewable in Google Earth);
- change and/or view various device settings and properties;
- reprocess recorded data with different settings.

Please refer to the *MT Manager User Manual* for more information on MT Manager.

MT Software Development Kit (MT SDK)

The Xsens Device API (XDA) serves as a starting point for system integrators interested in assessing the basics of the SDK. The main objective of the SDK is to facilitate the development of user-specific host applications based on Xsens motion trackers.
The MT Software Development Kit (MT SDK), part of the MT Software Suite installation, provides examples based on XDA for multiple programming languages. These programming examples can be used as a starting point for further software development.

The MT SDK (and the MT Software Suite) is designed for the MTi 1-series, MTi 600-series, MTi 10-series and MTi 100-series. See also: Introduction to the MT SDK programming examples for MTi devices

Low-level Communication

The low-level communication protocol (named Xbus protocol) offers full control and functionality. It is essential on platforms that do not support the Xsens Device API, such as custom embedded computers and microcontrollers.

The low-level communication is extensively described in the *MT Low-Level Communication Protocol Documentation***.** Next to that, source code is delivered to make driver development and Xbus message parsing for the MTi as easy and quick as possible.

Firmware updates

New firmware versions for MTi products are released several times per year. A release notification will be included in the Xsens newsletter, including all changes made with respect to the previous firmware version. A complete history of firmware releases is available on our Knowledge Base: MTi Release Notes and Changelogs

Public firmware versions can be divided into two categories:

1. **Stable firmware** versions are fully tested prior to release, including automated functionality tests as well as performance tests. This is the firmware version which is loaded into the MTi in the factory. It is strongly recommended to update all MTi products to the latest stable firmware in order to take advantage of the latest new features and bug fixes, and to ensure compatibility with the latest MT Software Suite. MT Manager will automatically display a notification in case an MTi is connected for which a newer stable firmware version is available.
2. **Beta firmware** versions are subject to rigorous (automated) tests prior to release, but to a lower extent than stable firmware versions. Beta firmware versions are in principle release candidates for stable versions and often contain new features or settings but are not loaded into the MTi in the factory. Feel free to test and validate in your application. Beta firmware versions may contain bugs or performance issues, which will be fixed in a later stable firmware release. Beta firmware versions are therefore released together with a disclaimer that can be found in the table below.

Firmware disclaimer

Component	Disclaimer
Beta firmware	**Caution!** This in-development version of software and/or firmware may be unstable and contain bugs. Your valuable feedback will help us to create the best software possible. Before you start using the software and/or firmware, please be aware that: • Xsens is not liable for any loss or damage, whether such loss or damage is direct, indirect, special or consequential, arising out of the use of or inability to use the software and/or firmware of the Beta Release. • As a Beta version is not an official stable release by Xsens, this version may contain errors or inaccuracies and may result in data loss or cause system reliability issues. If such a problem arises, you may need to use the latest stable release to resume normal operations. • Users acknowledge and agree that Xsens offers this software and/or firmware “as is” without any express or implied warranty of any kind. Xsens shall have no obligation to maintain, correct, update, change, modify or otherwise support the software and/or firmware in beta testing. • By downloading and/or using beta software and/or firmware from Xsens, you are considered to have read this Beta disclaimer and agreed to its terms.

The firmware of MTi products can be updated (or downgraded to an older version) using the Firmware Updater, which can be downloaded from the Xsens website: https://www.xsens.com/software-downloads.
An embedded firmware updater is available specifically for MTi 1-series devices that have been designed-in without the possibility to connect with a PC. It can be found in the MT SDK folder of your MT Software Suite.

Terms of use of MT Software Suite

The installer of the MT Software Suite can install 4 components: MT Manager, MT SDK, Magnetic Field Mapper (MFM) and MFM SDK. The Firmware Updater is a separate installer. The MT Software Suite has a Restricted License Agreement that you need to accept. In the table below, the conditions for use of each component are summarized.

Conditions for the use of the MT Software Suite

Component	Conditions
MT Manager	For use with Xsens products only Not allowed to re-distribute Not allowed to reverse engineer Not allowed to modify
MT SDK	For use with Xsens products only Allowed to re-distribute “as is” or embed in programs Not allowed to reverse engineer Allowed to execute, reproduce, modify and compile (modified) source code to use with Xsens products only Not allowed to modify DLL Include License Agreement with distribution
MFM	For use with Xsens products only Allowed to re-distribute “as is” Not allowed to reverse engineer Not allowed to modify Include License Agreement with distribution

Component	Conditions
MFM SDK	For use with Xsens products only Allowed to re-distribute “as is” or embed in programs Not allowed to reverse engineer Allowed to execute, reproduce, modify and compile (modified) source code to use with Xsens products only Not allowed to modify DLL Include License Agreement with distribution
FWU	For use with Xsens products only Allowed to re-distribute “as is” Not allowed to reverse engineer Not allowed to modify Include License Agreement with distribution

MTi System Overview

Test and Calibration

A correct calibration of the sensor components inside the MTi is essential for an accurate output. The quality and importance of the calibration are of highest priority. Each Xsens' MTi is calibrated and tested by subjecting each device to a wide range of motions and temperatures.

The individual calibration parameters are used to convert the sensor component readout (digitized voltages) to physical quantities as accurately as possible, compensating for a wide range of deterministic errors. Additionally, the calibration values are used in Xsens sensor fusion algorithms, as discussed later in this document.

Each MTi contains individual test and calibration data in its eMTS (electronic Motion Tracker Settings). It is digitally signed by a Test Person and states the calibration values determined during the calibration of the MTi at Xsens' calibration facilities. The values can be seen by connecting the MTi to MT Manager and navigating to Device Settings   Modelling Parameters.

Next to the calibration values shown in MT Manager, each device is calibrated according to more complicated models to ensure accuracy (e.g. non-linear temperature effect, cross coupling between acceleration and angular rate[1]).

Physical sensor model

This section explains the basics of the individual calibration parameters of each MTi.

The physical sensors inside the MTi (accelerometers, gyroscopes and magnetometers)[6] are all calibrated according to a physical model of the response of the sensors to various physical quantities, e.g. temperature. The basic model is linear and according to the following relationship:

$$s=K_T^{-1}(u-b_T)$$

During factory calibration, a unique gain matrix, $\boldsymbol{K}_T$ and the bias vector, $\boldsymbol{b}_T$, are assigned to each MTi. This calibration data is used to relate the sampled digital voltages, $\boldsymbol{u}$, from the sensors to the respective physical quantity, $\boldsymbol{s}$.

The gain matrix is split into a misalignment matrix, $\boldsymbol{A}$, and a gain matrix, $\boldsymbol{G}$. The misalignment specifies the directions of the sensitive axes with respect to the ribs of the sensor-fixed coordinate system (S_{xyz}) housing. E.g. the first accelerometer misalignment matrix element $\boldsymbol{a}_{1,x}$ describes the sensitive direction of the accelerometer on channel one. The three sensitive directions are used to form the misalignment matrix:

$$\boldsymbol{A} = \begin{bmatrix} a_{1,x} & a_{1,y} & a_{1,z} \\ a_{2,x} & a_{2,y} & a_{2,z} \\ a_{3,x} & a_{3,y} & a_{3,z} \end{bmatrix}$$

$$\boldsymbol{G} = \begin{bmatrix} G_1 & 0 & 0 \\ 0 & G_2 & 0 \\ 0 & 0 & G_3 \end{bmatrix}$$

$$\boldsymbol{K_T} = \begin{bmatrix} G_1 & 0 & 0 \\ 0 & G_2 & 0 \\ 0 & 0 & G_3 \end{bmatrix} \begin{bmatrix} a_{1,x} & a_{1,y} & a_{1,z} \\ a_{2,x} & a_{2,y} & a_{2,z} \\ a_{3,x} & a_{3,y} & a_{3,z} \end{bmatrix} + \boldsymbol{O}$$

With $\boldsymbol{O}$ representing higher order models, temperature modelling, g-sensitivity corrections, etc.

Each individual MTi is modeled for temperature dependence of both gain and bias for all sensors and other effects. This modeling is not represented by the simple model in the above equations but is implemented in the firmware with the temperature coefficient being determined individually for each MTi device during the calibration process. The basic indicative parameters in the above model of your individual MTi can be found in MT Manager (Device Settings dialog).

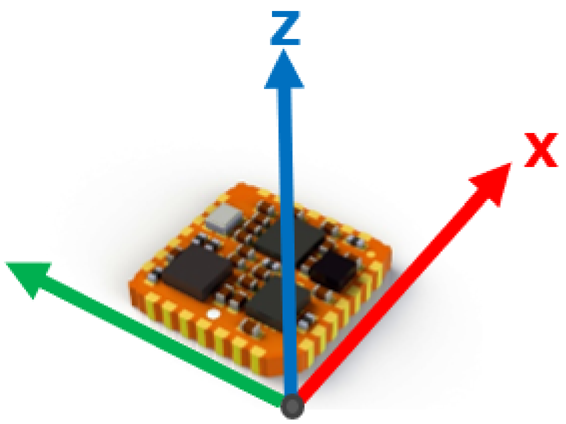
Coordinate systems

Data from the MTi is represented in various coordinate systems, which are explained below.

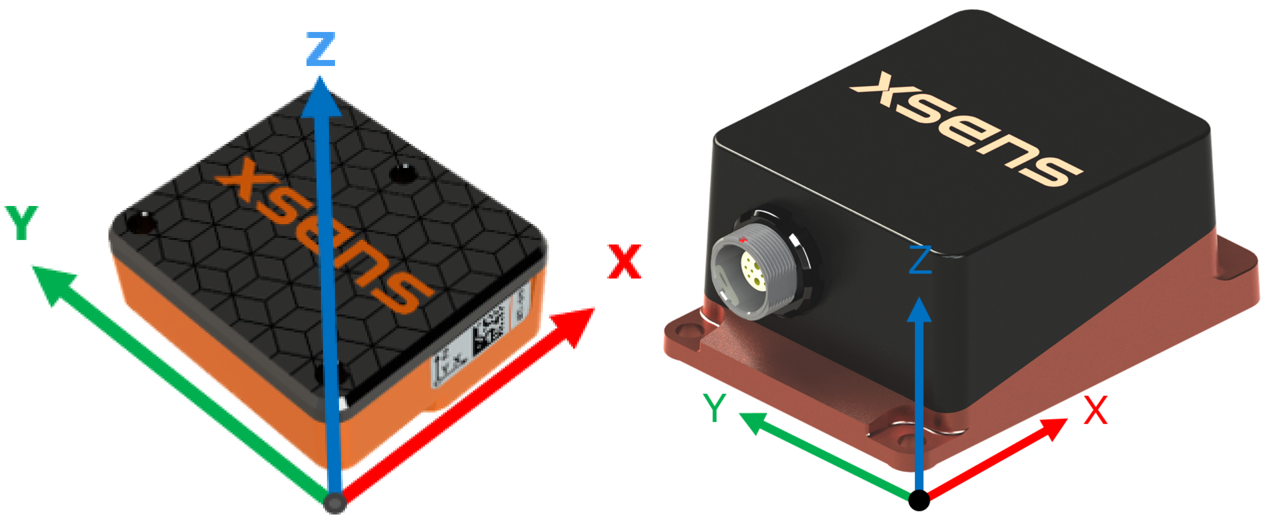
Calibrated inertial data and magnetic field data

The default sensor-fixed frame (S_{xyz}) is a right-handed Cartesian coordinate system that is fixed to the device. When the sensor is rigidly attached to another object or vehicle but not aligned, it may be convenient to rotate the sensor coordinate system S_{xyz} to an object coordinate system (O_{xyz}).
Refer to BASE: MTi reference co-ordinate systems for more information on the available orientation resets.

S_{xyz} or O_{xyz} are the coordinate frames used to express the rate of turn, acceleration and magnetic field outputs. The encased version of the MTi shows S_{xyz} on the sticker. Figure Default coordinate system of MTi 1-series and Figure Default coordinate system of MTi 600-series depict the sensor coordinate system on the MTi 600-series and MTi 1-series. Later in this document, small x, y and z are the axes labels for S_{xyz} and O_{xyz}. Capital X, Y and Z stand for the local-earth fixed coordinate system (L_{XYZ}).



Default coordinate system of MTi 1-series



Default coordinate system of MTi 600-series

The housing and PCB of the MTi 600-series are carefully aligned with the output coordinate system during the individual factory calibration. The non-orthogonality between the axes of S_{xyz} is <0.05°. This also means that the output of 3D linear acceleration, 3D rate of turn and 3D magnetic field data all will have orthogonal xyz readings within <0.05°.

Some of the commonly used data outputs and their reference coordinate systems are listed in the table below.

Data outputs with reference coordinate systems

Data	Reference coordinate system	Details
Acceleration	Sensor-fixed frame (S_{xyz}) or O_{xyz}	Calibrated inertial data and magnetic field data
Rate of turn	Sensor-fixed frame (S_{xyz}) or O_{xyz}	Calibrated inertial data and magnetic field data
Magnetic field	Sensor-fixed frame (S_{xyz}) or O_{xyz}	Calibrated inertial data and magnetic field data
Velocity increment	Sensor-fixed frame (S_{xyz}) or O_{xyz}	Orientation increment and Velocity increment (dq and dv)
Orientation increment	Sensor-fixed frame (S_{xyz}) or O_{xyz}	Orientation increment and Velocity increment (dq and dv)
Free acceleration	Local earth-fixed frame (L_{XYZ}), default ENU	Free acceleration
Orientation	Defined as the difference between Sensor-fixed frame ((S_{xyz}) or O_{xyz}) and local earth-fixed frame (L_{XYZ}), default ENU	Orientation data
Velocity	Local earth-fixed frame (L_{XYZ}), default ENU	Velocity data
Position	Local earth-fixed frame (L_{XYZ}), default ENU	Position data

Orientation increment and Velocity increment (dq and dv)

The Strap Down Integration (SDI) output of the MTi contains orientation increments (dq) and velocity increments (dv). These values represent the orientation change and velocity change during a certain interval based on the output rate. The output rate is selectable up to 100 Hz or 400 Hz depending on the product. The dq and dv values are always represented in the same coordinate system as calibrated inertial data and magnetic field data, which can be S_{xyz} or O_{xyz}.

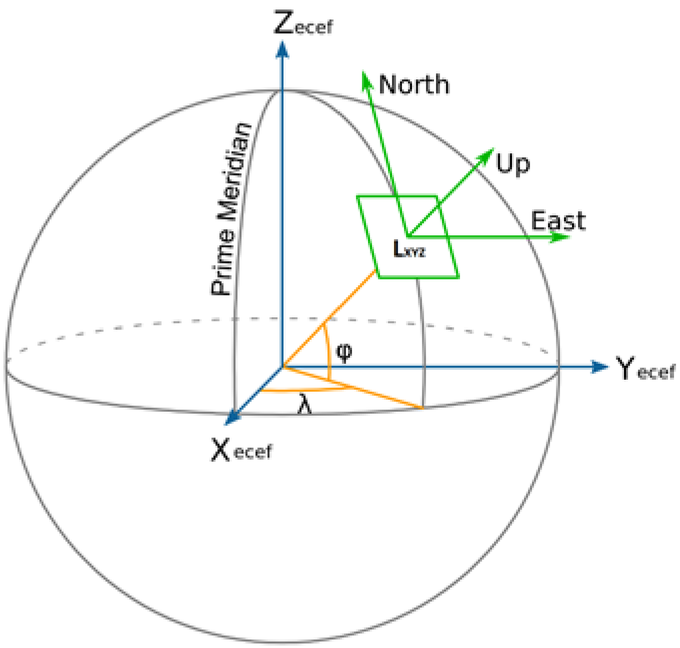
Orientation data

By default, the local earth-fixed reference coordinate system L_{XYZ} is defined as a right-handed Cartesian coordinate system with[2]:

- X positive to the East (E).
- Y positive to the North (N).

- Z positive when pointing up (U).

This coordinate system is known as ENU (East-North-Up) and is the standard in inertial navigation for aviation and geodetic applications. See the figure below for a visualization. Note that it is possible to change L_{XYZ} into a different convention, like NWU (North-West-Up) or NED (North-East-Down), by changing an alignment matrix or applying an orientation reset. Refer to BASE: MTi reference co-ordinate systems for more information on the available orientation resets.



Visualization of the local earth-fixed coordinate system (L_{XYZ}) and Position representation systems WGS84 (φ, λ) and ECEF (X_{ecef}, Y_{ecef}, Z_{ecef})

The 3D orientation output is defined as the orientation between the body-fixed coordinate system, S_{xyz} or O_{xyz}, and the local earth-fixed co-ordinate system, L_{XYZ}.

Orientation output modes

The output orientation can be presented in different equivalent representations:

- Unit Quaternions;
- Euler angles[3]: roll, pitch, yaw (XYZ Earth fixed type) are output following the aerospace sequence (Z-Y'-X");
- Rotation Matrix (directional cosine matrix).

A positive rotation is always “right-handed”, i.e. defined according to the right-hand rule (corkscrew rule), see Figure Right hand rule. This means a positive rotation is defined as clockwise in the direction of the axis of rotation.

Right hand rule

Refer to BASE by Xsens to find more information on how quaternions, Euler angles and the rotation matrix relate to each other.

Interpretation of yaw as heading

With the default ENU L_{XYZ} coordinate system, the MTi's yaw output is defined as the angle between East (X) and the horizontal projection of the sensor roll axis (x), positive about the local vertical axis (Z) following the right-hand rule [4]. The table below shows the different yaw values corresponding to the different local coordinate systems that are available for the MTi.

Yaw in different coordinate systems (applies only to AHRS and GNSS/INS product types). The MTi is assumed to be mounted with its roll-axis (X) aligned with the roll-axis of the vehicle (front of the vehicle).

Local coordinate system (output)	Roll-axis of the vehicle	Yaw value
East-North-Up (ENU, default)	Pointing North	90 deg
East-North-Up (ENU, default)	Pointing East	0 deg
North-West-Up (NWU)	Pointing North	0 deg
North-East-Down (NED)	Pointing North	0 deg

When using the ENU convention (default), the yaw output is 0º when the vehicle (x-axis of the MTi) is pointing East (X axis of L_{XYZ}). When it is required that the yaw output is 0º when the x-axis of the MTi is pointing north, it is recommended to select NWU or NED as the local coordinate system. In article Changing or resetting the MTi reference co-ordinate systems the various alignment resets are described.

When using the GNSS/INS products in an automotive application, as best practice, pay proper attention to mounting of the MTi on the automotive platform/vehicle. It is recommended to always mount the MTi with the x-axis pointing to the front of the vehicle irrespective of the local coordinate frame used for the output data.

True North vs. Magnetic North

As defined above, the output coordinate system of the MTi is with respect to local Magnetic North. The deviation between Magnetic North and True North (known as the magnetic declination) varies depending on the location on earth and can be roughly obtained from the latest World Magnetic Model[5] of the earth's magnetic field as a function of latitude and longitude. The MTi accepts a setting of the declination value. This is done by setting the position in the MT Manager, SDK or by low-level communication. The yaw/heading will then be corrected for the declination calculated internally and thus referenced to "local" True North. The GNSS/INS products automatically set the current position when a GNSS-position fix is available. Therefore, the user does not have to insert it.

Velocity data

Velocity data, calculated by the sensor fusion algorithm, is provided in the same coordinate system as the orientation data (L_{XYZ}), and thus adopts orientation resets as well (if any is applied). The velocity output is available in all GNSS/INS products (MTi-G-710, MTi-7, MTi-8, MTi-670(G) and MTi-680(G)).

Note that the velocity data coming directly from the PVT (Position Velocity Time) data retrieved from any GNSS receiver provided with any Xsens development kit is represented in the NED reference frame. Different GNSS receivers may represent the velocity in different coordinate frames.

Position data

Position data, calculated by the sensor fusion algorithm, is represented in Latitude, Longitude and Altitude as in the WGS84 datum. The position output is available in all GNSS/INS products (MTi-G-710, MTi-7, MTi-8, MTi-670(G) and MTi-680(G)).

It is possible to retrieve position data calculated by the sensor fusion algorithm in Earth Centered – Earth Fixed (ECEF) format. See figure Visualization of the local earth-fixed coordinate system and Position representation systems WGS84 for a visualization and the *MT*

Low Level Communication Protocol Documentation for more information.

Calibrated Δq and Δv outputs

The calibrated Δq (delta_q) and Δv (delta_v) outputs are the coning and sculling compensated strapdown integrated data in the sensor-fixed coordinate system (S_{xyz}) or (O_{xyz}). Note that the value of the output depends on the output frequency, as the values are integrated over the sample time. Delta_q can also be noted as dq, delta_angle, del_q or OriInc. Delta_v can also be noted as dv, delta_velocity, del_v or VelInc.

Output specifications Δq and Δv outputs

Output	Unit
Delta_q (DataID 0x8030)	a.u. (quaternion values)
Delta_v (DataID 0x4010)	m/s

It is possible to multiply consecutive delta_q values to find the total orientation change over a specific period. Note that this data is not drift free, it still contains the sensor bias, as it has not been processed by the sensor fusion algorithm. Use the orientation output for drift free orientation.

Calibrated inertial and magnetic data outputs

Output of calibrated 3D linear acceleration, 3D rate of turn and 3D magnetic field data is in the sensor-fixed coordinate system (S_{xyz}) or (O_{xyz}). The units of the calibrated data output are as shown in the table Output specifications inertial and magnetometer data outputs.

Output specifications inertial and magnetometer data outputs

Vector	Unit
Acceleration (DataID 0x4020)	m/s^2
Angular velocity (RateOfTurn) (DataID 0x8020)	rad/s
Magnetic field (DataID 0xC020)	a.u. (arbitrary units; normalized to earth field strength at the location the MFM is performed)

High-rate (HR) inertial data outputs

High-rate calibrated 3D acceleration (accelerometer) and 3D rate of turn (gyroscope) are outputted in the sensor-fixed coordinate system (S_{xyz}) or (O_{xyz}). The units of the calibrated data output are as shown in the table Output specifications high rate calibrated inertial data outputs. HR calibrated data is available at a higher rate than regular calibrated inertial data outputs. It is outputted as a separate data packet next to the other data outputs. The maximum output rate, degree of signal processing, and calibration applied depends on the device type.
Refer to *MT Low Level Communication Protocol Documentation* for more details.

Output specifications high rate calibrated inertial data outputs

Vector	Unit
AccelerationHR (DataID 0x4040)	m/s^2
RateOfTurnHR (DataID 0x8040)	rad/s

Free acceleration

Free acceleration (Data ID 0x4030) is the acceleration in the local frame (L_{XYZ}) from which the local gravity is deducted. The output is in m/s^2.

Xsens Sensor Fusion Algorithms

The orientation and position output of the VRU/AHT, AHRS and GNSS/INS are computed by Xsens’ proprietary sensor fusion algorithm. It uses signals from the rate gyroscopes, accelerometers, magnetometers and optionally a GNSS receiver and barometer to compute a statistical optimal 3D orientation and position estimates of high accuracy without drift for both static and dynamic movements.

The design of a typical algorithm can be summarized as a sensor fusion algorithm where the measurement of gravity (by the 3D accelerometers) and Earth's magnetic north (by the 3D magnetometers) compensate for otherwise slowly, but unlimited, increasing (drift) errors from the integration of rate of turn data (angular velocity from the rate gyroscope). This type of drift compensation is often called attitude and heading referencing and such a system is referred to as an Attitude and Heading Reference System (AHRS).

In products where a GNSS receiver is available, GNSS data is continuously used to aid the estimation of the device’s roll, pitch and heading next to position and velocity. An additional benefit is that short term GNSS outages can be coped with, through dead-reckoning, ensuring continuous data output. Such a system is referred to as GNSS/INS.

Internal Sensor Bias Estimation

The Xsens algorithm continuously estimates the gyroscope bias. For the rate of turn around the x-axis and the y-axis (roll and pitch axes), the gyroscope bias is estimated using gravity (accelerometers). In a homogenous magnetic field and with filter profiles using the magnetometer, the gyroscope bias around the z-axis will also successfully be estimated.

In some situations, the heading cannot be referenced to the Earth's magnetic field. This is the case when the magnetic field is not used (for example for VRU/AHT devices) or when the magnetic field is distorted. There are several ways to mitigate the drift in yaw (rotation around the z-axis):

1. When the MTi has sufficient movement in roll and pitch (>30 degrees for more than 10 seconds), the gyroscope bias will be estimated for the z-gyroscope. When rotating the MTi back to roll and pitch around 0 degrees, the yaw will be more stable than before the roll/pitch movements.
2. The yaw drift can also be stabilized by using Active Heading Stabilization (AHS). Refer to section Additional setting options and features of this document for more details.
3. It is also possible to estimate the gyroscope bias using the manual gyro bias estimation feature when the MTi does not rotate (also called No Rotation Update). More information about the Manual Gyro Bias Estimation feature can be found on BASE. For the MTi-680(G), an automated (non-user-initiated) version is available: the Continuous Zero Rotation Update (CZRU).

Roll and Pitch estimation

The Xsens sensor fusion algorithm stabilizes the inclination (i.e. roll and pitch combined) using the accelerometer signals. An accelerometer measures the specific force that is composed of the gravitational acceleration plus the linear acceleration due to the movement of the object with respect to its surroundings. The algorithm uses the assumption that on average the acceleration due to the movement is zero. Using this assumption, the direction of the gravity can be observed and used to stabilize the attitude. The orientation of the MTi in the gravity field is accounted for such that centripetal accelerations or asymmetrical movements cannot cause a degraded orientation estimate performance. The key here is the amount of time over which the acceleration must be averaged for the assumption to hold. During this time, the gyroscopes must be able to track the orientation to a high degree of accuracy. In practice, this limits the amount of time over which the assumption holds true.

However, for some applications, this assumption does not hold. For example, an accelerating automobile may generate significant permanent accelerations for time periods lasting longer than the maximum duration the MT's rate gyroscopes can reliably keep track of the orientation. This may degrade the accuracy of the orientation estimates because the application does not match the assumptions made in the algorithm. Note, however, that as soon as the movement again matches the assumptions made, the algorithm will recover and stabilize. The recovery to optimal accuracy can take some time.

NOTE: To be able to accurately measure orientations as well as position in applications which can encounter long-term accelerations, we offer solutions that use aiding data from a GNSS receiver: the GNSS/INS products.

Heading/yaw estimation

By default, yaw is referenced by using the local (earth) magnetic field (e.g. in the AHRS product versions). In other words, the measured magnetic field is used as a compass. If the local Earth magnetic field is temporarily disturbed, the algorithm will track this disturbance instead of incorrectly assuming there is no disturbance. However, in the case of structural magnetic disturbance (>10 to 30 seconds, depending on the filter profile settings) the computed heading will slowly converge to a solution using the 'new' local magnetic north. Note that the magnetic field has no direct effect on the inclination estimate.

The filter profile 'Fixed Mag Ref' will assume a magnetic reference upon startup and keep that reference regardless of new magnetic environments (available only on MTi 600-series, see *MTi 600-series Datasheet*).

In the special case the MTi is rigidly strapped to an object containing ferromagnetic materials, structural magnetic disturbances will be present. In that case, Xsens offers an easy-to-use solution to recalibrate the magnetometers based on those structural magnetic disturbances (refer to chapter *Magnetic materials and magnets* of this document).

Next to the solutions described in the article Estimating Yaw in magnetically disturbed environments to mitigate effects of magnetic disturbances, the sensor fusion algorithm in a GNSS/INS device makes use of data from the GNSS receiver. This means that the GNSS/INS device has an increased resistance towards magnetic disturbances. It is for example possible to estimate the heading based on comparison between accelerometer data and the GNSS acceleration. For GNSS/INS devices, the magnetometer data is only actively used in the GeneralMag filter profile, the other filter profiles are completely independent of the magnetic field.

Velocity and Position estimation

Transient accelerations

The GNSS/INS algorithm adds robustness to its orientation and position estimates by combining measurements and estimates from the inertial sensors and GNSS receiver in order to compensate for transient accelerations. It results in improved estimates of roll, pitch, yaw, position and velocity.

Loss of GNSS

When the GNSS/INS device has limited/mediocre GNSS reception or even no GNSS reception at all, the sensor fusion algorithm seamlessly adjusts the filter settings in such a way that the highest possible accuracy is maintained. The GNSS/INS MTi will continue to output position, velocity and orientation estimates, although the accuracy is likely to degrade over time as the filters will have to rely on dead-reckoning. The GNSS status will be monitored continuously such that the filter can take GNSS data into account again when available and sufficiently trustworthy. In case the loss of GNSS lasts longer than a specific period (depending on product type, e.g. 45 seconds), the device will enter a state in which it stops outputting position and velocity estimates, and no longer uses velocity estimates in its sensor fusion algorithms until GNSS reception is re-established.

Initialization

The Xsens sensor fusion algorithms do not only estimate orientation, but also keeps track of variables such as sensor biases or properties of the local magnetic field. For this reason, the orientation output may need some time to stabilize once the MTi is put into measurement mode. Time to obtain optimal stable output depends on a number of factors. An important factor determining stabilizing time is determined by the time to correct for small errors in the bias of the gyroscopes. The bias of the gyroscope may slowly change due to different effects such as temperature change or exposure to impact.
For the MTi-670(G)/680(G), it is highly recommended to set the initial heading (Yaw) of the device after power-up. Refer to the *MTi 600-series Datasheet* or the SetInitialHeading command in the *MT Low-Level Communication Protocol Document* for more information.

Filter Profile options

As described above, the algorithm uses assumptions about the acceleration and the magnetic field to obtain orientation. Because the characteristics of the acceleration or magnetic field differ for different applications, the Xsens algorithm makes use of filter profiles to be able to use the correct assumptions given the application. This way, it can be optimized for different types of movement. For optimal performance in a given application, the correct filter profile must be set by the user. Each product offers different filter profile options. Refer to the specific documentation to know more about the filter profiles[7].

Additional settings, options and features

The table below summarizes the additional options offered to adapt and optimize the algorithm to cover more scenarios and possible corner cases.

Supplementary features and settings

Active Heading Stabilization (AHS)	Active Heading Stabilization (AHS) is a software component within the sensor fusion engine designed to give a low-drift unreferenced (not North-referenced) yaw solution even in a disturbed magnetic environment. It is aimed to tackle magnetic distortions that do not move with the sensor, i.e. temporary or spatial distortions. AHS is not tuned for nor intended to be used with GNSS/INS devices. Therefore, Xsens discourages the use of this feature for GNSS/INS devices. For the MTi 600-series, the AHS feature is embedded in the filter profiles. For more information on the activation and use of AHS, refer to the BASE-article: BASE by Xsens - AHS tutorial

Orientation Smoother	The Orientation Smoother is a software component within the sensor fusion engine that is currently only available for the MTi-670(G), MTi-680(G) and MTi-G-710. This feature aims to reduce any sudden jumps in the Orientation outputs that may arise when fusing low-rate GNSS receiver messages with high-rate inertial sensor data. The Orientation Smoother can be enabled from the Device Settings window in MT Manager, or by using the *setOptionFlags* low-level command (see *MT Low Level Communication Protocol Documentation*).
Position / velocity Smoother	The Position/velocity Smoother is a software component within the sensor fusion engine that is currently only available for the MTi-680(G). This feature aims to reduce any sudden jumps in the position outputs that may arise when fusing low-rate GNSS receiver messages with high-rate inertial sensor data. The Position/velocitySmoother can be enabled from the Device Settings window in MT Manager, or by using the *setOptionFlags* low-level command (see *MT Low Level Communication Protocol Documentation*).
GNSS Platform	u-blox GNSS receivers support different dynamic platform models in order to adjust the navigation engine to the expected application environment. The GNSS/INS products can be configured to communicate a desired platform model upon start-up. This enables the user to adjust the u-blox receiver platform to match the dynamics of the application. The setting influences the estimates of Position and Velocity and, therefore, it affects the behavior of the Xsens filter output. The platform model can be configured using MT Manager or low-level communication by providing the GNSS Platform ID. For more details on the low-level commands used to set the GNSS Platform (*SetGnssPlatform* for the MTi-7/8 and *SetGnssReceiverSettings* for the MTi-670/680(G)), refer to the *MT Low Level Communication Protocol Document.* For more details on GNSS platform settings, refer to the *u-blox Receiver Description Manual*. Alternatively, when interfacing with a GNSS receiver through other communication protocols than UBX (u-blox), the position data is used ‘as is’, independent of the GNSS platform setting.

In-run Compass Calibration (ICC)	In-run Compass Calibration (ICC) provides a solution to calibrate the sensor for magnetic distortions caused by objects that move with the MTi. Examples are the cases where the MTi is attached to a car, aircraft, ship or other platforms that can distort the magnetic field. It also handles situations in which the sensor has become magnetized. ICC is an alternative to the offline MFM (Magnetic Field Mapper). It results in a solution that can run embedded on different industrial platforms (leaving out the need for a host processor like a PC) and relies less on specific user input. ICC is currently a feature in beta. For more information, refer to the BASE-article on ICC: BASE by Xsens - ICC Tutorial.
Continuous Zero Rotation Update (CRZU)	The Continuous Zero Rotation Update (CZRU) is a feature that is currently only available for the MTi-680(G). The purpose of the CZRU is to reduce the undesired effects of gyroscope bias, such as drift of the orientation output. Although all MTi products are individually calibrated for various parameters, including sensor bias, the aging and use of Motion Trackers in industrial environments can cause sensor biases to change during the product's lifetime. Because of that, the filters of the MTi are continuously re-restimating calibration parameters such as sensor bias while they are powered up. If enabled, the Continuous Zero Rotation Update will execute a background algorithm that will automatically initiate a gyroscope bias estimation sequence whenever the Motion Tracker is motionless. The Continuous Zero Rotation Update can be enabled through the Device Settings window in MT Manager, or through the SetOptionFlags low-level command (see *MT Low Level Communication Protocol Document*).

MTi series interface options

The MTi series product lines are able to communicate and output data via many different interfaces. The table below provides a convenient overview for the MTi 1-series and 600-series. Details on the interfaces for each product are available in the respective datasheets or hardware integration manuals.

Overview of interface options in MTi portfolio

Interface	MTi 1-series	MTi-320	MTi 600-series modules	MTi-630R, MTi-670G, MTi-680G
I²C	•			
SPI	•			
UART	•		•	
USB	Development Board	Via cable and USB converter	Development Board or UART2USB Converter	Via cable and USB converter
RS232		•	•	•
RS485				
RS422			Dev. Board	
CAN			•	•

Timing and synchronization

The MTi products support multiple features for synchronizing data with external devices and timing. Please refer to the respective datasheets or manuals for more information.

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[1] Also known as “g-sensitivity”.
[2] The default reference coordinate system L_{XYZ} only applies to the MTi in Normal (Xbus) or CAN output mode. Refer to the Low Level Communication Protocol Documentation for detailed orientation output specifications when using the ASCII (NMEA) output mode.
[3] Please note that, due to the definition of Euler angles, there is a mathematical singularity (gimbal lock) when the sensor-fixed x-axis is pointing up or down in the earth-fixed reference frame (i.e. pitch approaches ±90°). In practice, this means roll and pitch is not defined as such when pitch is close to ±90 deg. This singularity is in ***no way*** present in the quaternion or rotation matrix output mode.
[4] IEEE Std 1559™-2009: IEEE Standard for Inertial Systems Terminology
[5] Xsens releases a firmware update when a new WMM version is available
[6] The barometer and GNSS receiver do not require additional calibration.
[7] Datasheet for the MTi 1-series and MTi 600-series. MTi User Manual for the other Xsens MTi

products

Input and Output Specification

In this chapter, the various output modes of the MTi are described. The MTi's have several output options. It is possible to select a different output frequency and/or output format (e.g. float or double) per output or group of outputs. A full overview of the output options can be found in the *MT Low Level Communication Protocol Documentation*.

Performance specifications on orientation, position and sensor data can be found in the specific datasheets of each MTi series.

Overview of data output protocols

The MTi supports different data protocols: the binary (hexadecimal) XBus protocol, NMEA (ASCII) messages and CAN 2.0. Refer to *MT Low Level Communication Protocol Documentation* and *MT CAN Protocol Documentation* to learn more about the structure of the protocols and how to switch between them.

NOTE: The MTi 1-series only supports the binary Xbus protocol.

Overview of data inputs

GNSS input

The MTi-7, MTi-8, MTi-670 and MTi-680 require data from an externally connected GNSS receiver to provide a full GNSS/INS solution. Depending on the MTi and its firmware version, this can be achieved by using the u-blox (UBX), NMEA, Septentrio (SBF) or Trimble (GSOF) protocol. For more information on how to setup your device to communicate with its external GNSS receiver, please refer to your product's (MTi 1-series or MTi 600-series) datasheet.

RTCM

RTCM messages contain position correction data which is required by the MTi-680G to achieve cm-level positioning. The protocol which is supported by the MTi-680G is RTCMv3 with a standard 1 Hz frequency.

Built-in self-test

All MTi's feature a built-in self-test (BIT). The self-test actuates the mechanical structures in the MEMS accelerometer and gyroscope by inducing an electric signal. This allows checking the proper functioning of the mechanical structures in the MEMS inertial sensors as well as the signal processing circuitry. For the magnetometer, the self-test checks the integrity of the sensor component.

A passed self-test will result in a valid self-test flag in the status byte. Because the self-test influences the sensor data, the self-test is only available in Config mode. For more information, look for *RunSelftest* in *MT Low Level Communication Protocol Documentation.*

Timestamp and packet counter output

Each data message can be accompanied by a packet counter and/or timestamp. Refer to *MT Low Level Communication Protocol Documentation* detailed information on the various time outputs.

Status word

The status word includes information about the status of the MTi, its sensors, the filter and user inputs.
Information contained within the status word is, for example:

- Selftest
- Filter valid
- GNSS fix
- No rotation update status
- Representative motion
- Clip flags of all axis gyroscopes, accelerometers and magnetometers
- SyncIn / SyncOut
- Filter modes

Refer to *MT Low Level Communication Protocol Documentation* for detailed information on the Status Word output.

- Transient accelerations
- Vibrations
- Magnetic materials and magnets
- GNSS antenna

Transient accelerations

The 3D linear accelerometers in the MTi are primarily used to estimate the direction of gravity to obtain a reference for attitude (pitch/roll). During long periods (more than tens of seconds) of transient "free" accelerations (i.e. 2nd derivative of position), the observation of gravity cannot be made. The sensor fusion algorithms can mitigate these effects to a certain extent, but nonetheless, it is impossible to estimate the true vertical without additional information.

The impact of transient accelerations can be minimized when you take into account a few things when positioning the device when installing it in the object you want to track/navigate/stabilize or control.

If you want to use the MTi to measure the dynamics of a moving vehicle, it is best to position the measurement device at a position close to the centre of rotation (CR) of the vehicle/craft. Any rotations around the centre of rotation translate into centripetal accelerations at any point outside the centre of rotation. For a GNSS/INS device with a valid GNSS-fix, the detrimental effect of transient accelerations on orientation estimates is overcome by integrating GNSS measurements in the sensor fusion engine.

Vibrations

The MTi samples IMU signals at high frequency per channel, processing them using a strapdown integration algorithm with coning/sculling compensation. Proper coning/sculling compensation already mitigates errors that poorly designed signal processing pipelines introduce when the device is under vibration. For best results, however, it is recommended that the MTi be mechanically isolated from vibrations as much as possible: since vibrations are measured directly by the accelerometers, the following two conditions can make the readings from the accelerometers invalid;

1. The magnitude of the vibration is larger than the measurement range of the accelerometer. This will cause the accelerometer to saturate, which may be observed as a "drift" in the zero-level of the accelerometer. This will show up as an erroneous roll/pitch.
2. The frequency of the vibration is higher than the bandwidth of the accelerometer. In theory,

such vibrations are rejected, but in practice they can still give rise to aliasing, especially if close to the bandwidth limit. This can be observed as a low frequency oscillation. Further, high frequency vibrations often tend to have large acceleration amplitudes (see item 1).

There is an effect on the gyroscopes as well and, especially when the vibrations include high-frequent coning motion, the gyroscope readings may become invalid.

Xsens has tested a set of vibration dampeners on the MTi. Vibration dampeners are low-profile rubber cylinders that allow the MTi to be mounted on an object without a direct metal to metal connection that transduces vibrations from the object to the MTi. The vibration dampeners have been tested with frequencies up to 1200 Hz that caused aliasing when the MTi was mounted directly on the vibration table had no effect with the vibration dampeners fitted. The dampeners tested are manufactured by Norelem and have part number 26102-00800855, www.norelem.com

Magnetic materials and magnets

When an MTi is placed close to or on an object that is either magnetic or contains ferromagnetic materials, the measured magnetic field is distorted (warped) and causes an error in the computed heading. The earth's magnetic field is altered by the presence of ferromagnetic materials, permanent magnets or power lines with strong currents (several amperes) in the vicinity of the device. The distance to the object and the amount of ferromagnetic material determines the magnitude of disturbance introduced. Errors in estimated yaw due to such distortions can be quite large, since the earth's magnetic field is very weak in comparison to the magnitude of the sources of distortion.

By default, the AHRS and the GNSS/INS versions (when using the GeneralMag filter profile) stabilize heading using the local Earth's magnetic field. In other words, the measured magnetic field is used as a compass. In addition, the gyroscope biases are continuously estimated by the MTi's on-board filter. For the rate of turn around the x-axis and the y-axis (roll and pitch axes), the gyroscope bias is estimated using gravity (i.e. by using the accelerometers). In a homogeneous magnetic field, the gyroscope bias around the z-axis can be successfully estimated as well by monitoring the direction of the magnetic field.

The magnetic field can be distorted by the presence of ferromagnetic materials, permanent magnets or power lines with strong currents (several amperes) in the vicinity of the device. The distance to the object and the amount of ferromagnetic material determines the magnitude of disturbance introduced. If the local Earth magnetic field is temporarily disturbed, the on-board filters will initially track this disturbance instead of incorrectly assuming that the device has rotated. However, in case of continuous magnetic disturbances (>10 to 30 s, depending on the filter settings), the computed heading will slowly converge to a new solution using the 'new' local magnetic north. Note that the magnetic field has no direct effect on the inclination estimate.

In the special case that the MTi is rigidly strapped to an object containing ferromagnetic materials, constant magnetic disturbances will be present. Using a so-called 'magnetic field mapping' (MFM, i.e. a 3D calibration for soft and hard iron effects), these magnetic disturbances can be completely calibrated for, allowing the MTi to be used as if it would not be secured to the object containing ferromagnetic materials.

For more information please review the *Magnetic Calibration Manual.*

GNSS antenna

Xsens GNSS/INS Development/Starter Kits include a GNSS patch antenna. In contrast to other antenna types such as helix antennas, patch antennas require a ground plane underneath them to operate properly. A ground plane will reduce errors due to multipathing effects, by blocking signals that can normally reach the GNSS antenna from low or sub-horizon elevations.
Adding a ground plane is not necessary when mounting the antenna directly onto a flat metal surface, such as the roof of a car. Otherwise, we recommend mounting the antenna on top of a metal plate (thickness irrelevant) with a minimum diameter of 10 cm.
For best practices or tailor-made ground planes, we recommend contacting the original manufacturer of the used GNSS antenna. Antennas that are sold by Xsens, as well as their product code and original manufacturer, are listed in this BASE article. For Tallysman patch antennas, best practices were discussed here.
In addition to creating a proper ground plane, avoid mounting the antenna underneath or in close proximity of other metal structures and electronics in order to ensure the best GNSS signal reception.

For the MTi’s with RTK enabled GNSS receivers, the antenna placement becomes more critical. Because RTK enabled GNSS receivers can measure the position down to centimetre level, the used antenna must be properly fixed with respect to the MTi. An accurate measurement of the lever-arms from the MTi’s origin of measurements to the antenna’s phase centre should be made. Note that an antenna’s phase centre is not always the physical centre of the antenna. Also, an antenna with low phase centre variation should be used. Further details on the GNSS lever arm (i.e. the relative distance of the antenna with respect to the MTi) can be found on

BASE: The GNSS lever arm (antenna offset) and its role in the GNSS/INS sensor fusion algorithm.

A normal (code phase) GNSS receiver needs at least 4 satellites to get a three-dimensional position fix. However, RTK (carrier phase) initialization demands that at least 5 common satellites must be tracked at base and rover sites. Furthermore, carrier phase data must be tracked on the 5 common satellites for successful RTK initialization. Once initialization has been gained, a minimum of 4 continuously tracked satellites must be maintained to produce an RTK solution. Therefore, it is even more critical for an RTK GNSS antenna to have a clear view of the sky to receive data from as many satellites as possible.