If you intend to use an inertial measurement system...

... which technical data you should analyze and compare before making your decision

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Keywords: inertial navigation system, inertial measurement system, inertial measurement unit, attitude heading reference system, inertial sensor, gyroscope, accelerometer, angular random walk, bias, drift, free inertial, unaided inertial navigation, GNSS denied, aided navigation, INS, IMU, IMS, AHRS

Preface

In fact, it is often very difficult for both inexperienced and advanced users of inertial technology to get the right "feel" for which of the various inertial measurement systems, inertial navigation systems, attitude heading reference systems, inertial measurement units, or at least inertial sensors offered on the market will best and most economically meet their application requirements.

With this article, we will try to assist you in better understanding the physics behind inertial navigation or inertial measurement systems and sensors. We also aim to empower you to independently validate the datasheets of the vendors and find your best technical and economical solution.

> *Tatsächlich ist es oft sehr schwierig, sowohl für unerfahrene als auch für fortgeschrittene Benutzer von Trägheitstechnologie, im Umfeld vielschichtiger Marketing-Informationen die richtige Entscheidung zu treffen, welches der verschiedenen Trägheitsmesssysteme, Trägheitsnavigationssysteme, Lage-Kurs-Referenzsysteme, Trägheitsmessgeräte oder zumindest Trägheitssensoren auf dem Markt am besten und wirtschaftlichsten ihren Anforderungen entspricht.*
>
> *Mit diesem Artikel werden wir versuchen, Ihnen zu helfen, die Physik hinter der Trägheitsnavigation oder den Trägheitsmesssystemen und Sensoren besser zu verstehen und die Informationen zu bewerten. Wir versuchen auch, Sie besser in die Lage zu versetzen, die Datenblätter der Anbieter selbst zu validieren und Ihre beste technische und wirtschaftliche Lösung zu finden.*

Introduction into Inertial Measurement Technology:

Inertial navigation and guidance systems were originally developed for rocket guidance and control. Nowadays, they find applications in various fields, ranging from horizontal directional drilling deep underground to the navigation of spacecraft. Today, everyone interacts with inertial technology on a daily basis; for instance, every modern car is equipped with at least one gyroscope and two accelerometers for the Electronic Stability Program (ESP) or airbag control, ensuring safe travel even in challenging environments. Similarly, every smartphone contains accelerometers, gyroscopes, a GNSS receiver, and a magnetometer.

A typical Inertial Navigation System (INS) utilizes gyroscopes (angular rate sensors) and accelerometers as sensors. Gyroscopes are employed to determine the orientation of the vehicle, compensating for the gravitational effects on the acceleration sensor data. This involves solving in real-time a complex set of differential equations to convert these measurements into estimates of velocities, position, attitude, and heading, starting from a known initial position in latitude and longitude.

Current implementations of Inertial Navigation Systems (INS) often use the "strap-down" technology, where all inertial sensors (gyroscopes and accelerometers) are rigidly mounted on the vehicle. In the past, systems were designed using the "gimbal" technology, where gyroscopes were used to mechanically stabilize accelerometers in space. In strap-down systems, stabilization is achieved mathematically, subjecting all inertial sensors to the full dynamics of the vehicle. Despite the lack of mechanical gimbals, strap-down systems are much more operationally robust than gimbaled systems, though they have higher requirements for sensor range, scale factor accuracy, and sensor robustness.

All unaided inertial navigation systems suffer from drift integration over time, as small errors in measurements accumulate into progressively larger errors in velocity and, especially, position due to double integration over time. The compensation and correction of this drift, particularly in real-time applications, vary significantly among solutions available in the market. Only a system supplier who excels in and can offer unaided inertial navigation with highest performance, especially in challenging environmental conditions - often deemed the "king class of inertial measurement technology" - is capable of delivering compelling solutions for aided navigation scenarios as well.

Control theory, especially Kalman filter-based approaches, provides a framework for combining complementary information from various sensors, known as sensor data fusion. Common supplementary sensors used to support INS-based systems include satellite navigation systems like GPS, GALILEO, GLONASS (GNSS), odometers, air data sensors, magnetometers, radio positioning systems, and more. Furthermore, specific methods such as ZUPT (Zero Velocity Update), PUPT (Position Update) and others allow application-specific accuracy improvements. (Link)

Trägheitsnavigations- und führungssysteme wurden ursprünglich zur Steuerung von Raketen entwickelt. Heutzutage werden sie in vielen Anwendungen eingesetzt, von der horizontalen Richtungsbohrtechnik tief unter der Erdoberfläche bis zur Navigation von Raumfahrzeugen. Heutzutage kommt jeder täglich mit Trägheitstechnologie in Kontakt: Zum Beispiel enthält jedes moderne Auto mindestens ein Gyroskop und zwei Beschleunigungssensoren für das ESP (elektronisches Stabilitätsprogramm) oder für die Airbag-Steuerung, um das Reisen auch in schwierigen Umgebungen so sicher wie möglich zu machen. Auch jedes Smartphone enthält heute Beschleunigungssensoren, Gyroskope sowie einen GNSS-Empfänger und ein Magnetometer.

Ein typisches Trägheitsnavigationssystem (INS, inertial navigation system) verwendet als Sensoren Gyroskope (Drehratensensoren) und Beschleunigungssensoren. Die Gyroskope werden dabei verwendet, um die Orientierung des Fahrzeugs zu bestimmen und insbesondere auch, um die Messdaten der Beschleunigungssensoren in Bezug auf die Schwerkraft zu kompensieren. Das bedeutet, eine große Menge an Differentialgleichungen in Echtzeit zu lösen, um diese Messwerte in Schätzungen von Geschwindigkeiten, Position, Lage und Kurs umzuwandeln, ausgehend von einer bekannten Anfangsposition in Breiten- und Längengrad.

Die heutige Implementierung von Trägheitsnavigationssystemen (INS) erfolgt in der sogenannten "strap-down"-Technologie, bei der alle Trägheitssensoren (Gyroskope und Beschleunigungssensoren) steif am Fahrzeug montiert sind. In der Vergangenheit wurden die Systeme in der sogenannten "gimbal"-Technologie entworfen, bei der die Gyroskope verwendet wurden, um die Beschleunigungssensoren mechanisch im Raum zu stabilisieren. In strap-down-Systemen erfolgt die Stabilisierung mathematisch, und daher sind alle Trägheitssensoren den vollen Fahrzeugdynamiken ausgesetzt. Aufgrund fehlender mechanischer Gimbals sind die strap-down-Systeme im Betrieb viel robuster als die gimballed Systeme, aber die Anforderungen an den Messbereich, die Skalenfaktorgenauigkeit und die Robustheit der Sensoren sind entsprechend höher.

Alle ***ungestützen*** *Trägheitsnavigationssysteme leiden aufgrund der erforderlichen mathematischen Integration von Drehraten und Beschleunigungen zur Bestimmung der Lagewinkel und Position unter einer zeitabhängigen Drift, weil kleine Fehler in den Messungen zu progressiv größeren Fehlern in Geschwindigkeit und insbesondere Position aufgrund der doppelten Integration über der Zeit führen. In der Kompensation und Korrektur dieser Drift insbesondere in Echtzeitanwendungen unterscheiden sich die am Markt angebotenen Lösungen ganz erheblich. Nur wer als Systemlieferant die ungestützte Trägheitsnavigation (free inertial navigation, unaided navigation) als „Königsklasse der Inertialmesstechnik“ in schwierigen Umgebungsbedingungen führend beherrscht und anbieten kann, der kann auch für gestützte Navigationslösungen (aided navigation) überzeugende Lösungen liefern.*

Regelungstechnik im Allgemeinen und insbesondere Kalman-Filter basierte Verfahren bieten den Rahmen für die Kombination von Informationen aus verschiedenen komplementären Sensoren

– die sogenannte Sensordatenfusion. Die hierfür am häufigsten ergänzenden Sensoren, die zur Stützung INS-basierter Systeme verwendet werden, sind Satellitennavigationssysteme wie GPS, GALILEO, GLONASS, …(GNSS), Odometer, Luftdatensensoren, Magnetometer, Funkortungssysteme usw. Desweiteren erlauben besondere Methoden wie ZUPT, PUPT (Zero Velocity Update, Position Update) usw. anwendungsspezifische Genauigkeitsverbesserungen. (Link)

The right INS for your Application: It is a big difference to operate an inertial measurement system in static lab conditions or low dynamic environment or in the "real-world". Check the performance of the IMS (IMS = **i**nertial **m**easurement **s**ystem) for the environment you want to operate the system in. Link

- Will it be used on an aircraft (transportation aircraft, helicopter, drone or fighter?),
- or on a rail vehicle (surface or underground?),
- or on a passenger car or a truck or a tank,
- or on a naval ship, a ferry or a speed boat or on an underwater surveying vehicle,
- or inside of a missile or a torpedo,
- or will it be used e.g. in a drilling application or in pipeline surveying or for machinery guidance,
- or will it be used e.g. to acquire the field of gravity with high accuracy?

To support your needs as best as possible, you can send us the Inquiry Form from our web site, filled with your application related information:

https://www.imar-navigation.de/downloads/faq/enquiry_imar.docx **or**

https://www.imar-navigation.de/downloads/faq/enquiry_imar.pdf

Compare the conditions of operation given in the data sheet of the system intended to be used: Is the condition well defined and will it meet your application requirements?

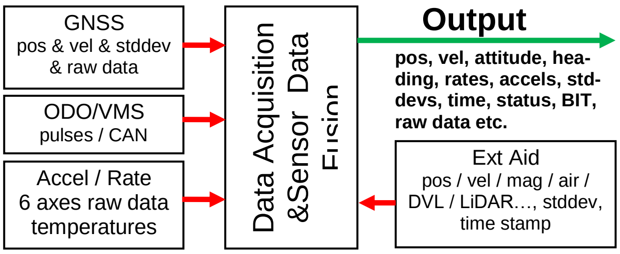
- Will GNSS be available in your application in the way as it is assumed inside the data sheets of the systems you are investigating?
- Do you require operation also in GNSS denied environment, e.g. under jamming or spoofing impacts? Is the solution, described in the datasheet, able to handle operation in such GNSS denied environment?
- What is the behavior of the system under coning motion, under vibration and under temperature gradients?
- What operation mode is required for your application and is the advertised solution able to comply? See the next chapters of this paper regarding free inertial navigation, pure inertial navigation, aided navigation, surveying, ZUPT and PUPT aiding, ...)

Sensor Technology Selection and Sensor Data Fusion: Each inertial sensor technology has its specific advantages and drawbacks which have to be considered regarding the foreseen application and desired accuracy. Some sensor technologies come e.g. with a very high stability of sensor performance (e.g. ring laser gyros) while others are for instance optimized for very light weight or low cost, but being affected by possible accuracy aging effects (like MEMS based sensors).

Inertial Sensors: Take into consideration that MEMS based gyros (working on Coriolis law using vibratory excitation) as well as spinning dynamical tuned gyros (DTG) show a so-called g-dependent drift, i.e. they produce a drift (angular rate offset) dependent on linear and quadratic acceleration and environmental vibration impacts. High performance ring laser gyros (RLG = ring laser gyros) and hemispherical resonator gyroscopes (HRG) as well as mid performance fiber optical gyros (FOG) do not show such g-dependent drift, while higher performance fiber optical gyros (FOG) also show performance degradation due to physical reasons, caused by vibration impacts and temperature gradients.

Sensor Data Fusion: The signal processing on system level ("sensor data fusion") has to take care for all sensor errors. Therefore the iMAR sensor data fusion is able e.g. not only to estimate the common inertial sensor offsets, but also estimates and compensates the scale factor drifts, misalignments and other effects in real-time (more than 40 states are estimated, compared to the classical and most common implementations of competitors with only 15 states). (Link)

iMAR has more than 30 years experience in sensor data fusion and sensor integration and uses inside their systems all state of the art gyro technologies and performance classes from MEMS over FOG and RLG up to HRG, dependent from the application requirements, operating a robust and real-time sensor data fusion with more than 40 states to estimate and compensate most of the residual errors and even aging effects of the inertial sensors. Link



Also further complementary sensors can be processed within the sensor data fusion, like GNSS (single and dual antenna), wheel sensor information (odometer, VMS), DVL (Doppler Velocity Log), magnetometer data (magnetic heading – be careful with these sensors as they are strongly dependent on environmental impacts, which cannot be compensated due to physical reasons, if they are changing during the mission), air data sensor information etc. Link

Gyro Bias:

If the inertial system operates unaided (without odometer/velocity or GNSS or magnetometer aiding or similar), the gyro bias indicates the increase of the angular error over time (in deg/h or deg/s). If the system is aided with speed information (e.g. odometer / wheel sensor or Doppler log), the roll and pitch gyro drift can be compensated in the measurement system by sensor data fusion and the gyro drift mainly affects the heading accuracy over time. If the system consists of low drift gyros, also the true heading can be estimated using gravity and earth rate information (so-called north-seeking or gyro compassing).

If the system is aided with position information (e.g. GPS or GALILEO or GLONASS or LiDAR etc.), also the heading drift can be corrected and true heading can be obtained (even with medium grade performance gyros), if the applied motion dynamics is sufficient, i.e. if the heading state is observable in the Kalman filter[1]. But of course the smaller the gyro drift the better all possible angular corrections and the longer the allowed time where the aiding information may be not present (e.g. GPS in urban canyons)!

If the system is operated in free inertial navigation mode, the gyro bias is responsible for the position and velocity error over time (so-called Schuler oscillation).

Gyro Scale Factor Error:

This is an indication of the angular error which occurs during rotation. E.g. with 300 ppm scale factor error (=0.03%) the angular error is in the area of 0.1 degree after a one revolution turn. With a ring laser gyro or hemispherical

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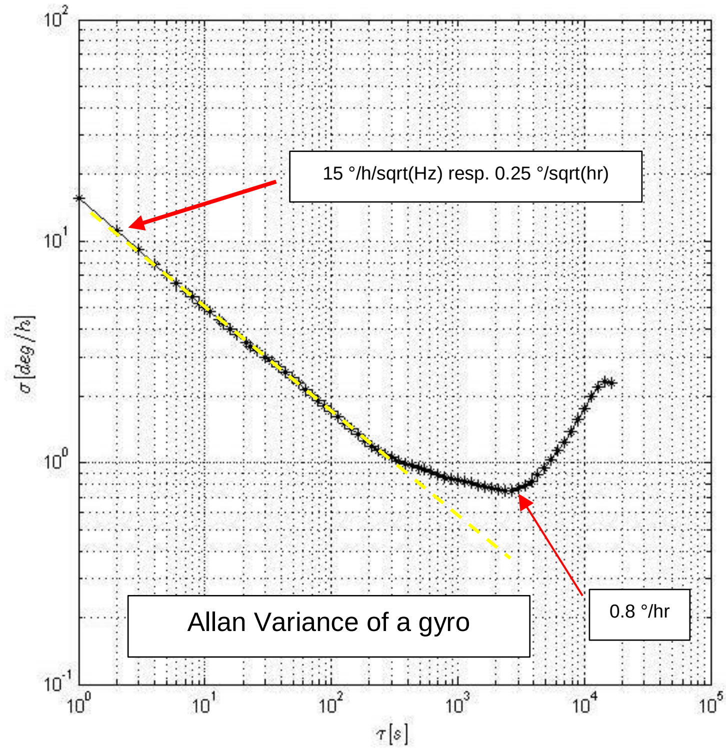
[1] Observability means, that the sensor data fusion has enough information available to estimate certain states like gyro bias or heading. Example: If an aircraft flies always straight forward at constant speed, it is impossible to estimate vertical gyro bias or heading using a single antenna GNSS aiding, because due to the mentioned motion no significant acceleration or angular rate will be measured.

resonator gyro system with < 10 ppm scale factor error the angular error is less than 1 arcsec (0.0003 deg) if the rotation angle is 30 deg.

Misalignment: A misalignment between the gyro axes (or accelerometer axes) causes a cross-coupling between the measurement axes. A misalignment of 0.1 mrad inside of the system (e.g. residual calibration mismatch) leads to a roll error of 0.036 degree during a one revolution turn around the yaw axis (if the system is unaided). The smaller the required misalignment, the higher the requirements to sensor performance and calibration equipment (e.g. iMAR's multi-axes turn-tables).

Accelerometer Offset: An offset on an accelerometer leads to an error during alignment, i.e. determination of initial roll and pitch angle, because it has an direct impact on the accuracy of measuring the gravity g (approx. 9.81 m/s^2) . An offset of 0.1 mg leads therefore to approx. 0.006 degree angular error in pitch or roll (0.1 mg = g x sin (0.006 deg)). The sensor offsets can be estimated during operation by the system due to the integrated Kalman filter data fusion, using GPS or DGPS or RTK data or ZUPT (zero velocity update procedure) if sufficient motion dynamics is available.



Bandwidth: In general the dynamic performance of an inertial measurement system is as better as higher the internal sampling rate and the bandwidth of the inertial sensors is. Also the proper internal data synchronization (time stamping) is very important for accurate signal processing, not only if the IMS is operated under difficult dynamical environment. A high precision internal time reference and hardware based time stamping of all data therefore is crucial for an INS with good performance reliability. Additionally a low latency of the data output is mandatory to use an INS for the trajectory or attitude control, e.g. of autonomous vehicles.

Gyro Random Walk: This value, given in deg/sqrt(hr), shows the noise of the used gyro. The larger the value the more noise is measured on the angular rates and on the angles. Some manufacturers also specify it as the noise density in deg/h/sqrt(Hz). Both values are equivalent for white noise gyro output - if the second value is divided by 60, you get it in deg/sqrt(hr). An angular random walk of 0.003 deg/sqrt(hr) indicates, that the angular error (uncertainty) due to random walk is e.g. 0.001 deg after 6 minutes (unaided) or 0.0004 deg after 1 minute (all values one sigma). The angular random walk is very important for the accuracy of north seeking, because if the random walk decreases times 2 then the needed duration for north seeking decreases by times four (if the resolution of the gyro is high enough).

The example plot of the Allan Variance of a mid performance gyro shows the square-root ARW of a MEMS gyro graphically (take the value at 1 sec and divide it by sixty to obtain the ARW in [deg/sqrt(hr)]).

At 1 sec the value of the square-root of the Allan Variance is 15 deg/hr. This leads to a value of the Angular Random Walk (ARW) of 15/60 deg/sqrt(hr) = 0.25 deg/sqrt(hr) = 0.0042 deg/s/sqrt(Hz) = 15 deg/hr/sqrt(Hz) [white gyro noise assumed]. The bias stability (minimum point of the graph) is 0.8 deg/hr at a correlation time of 3'000 seconds. So it is really quite a good MEMS gyro which we have in use.

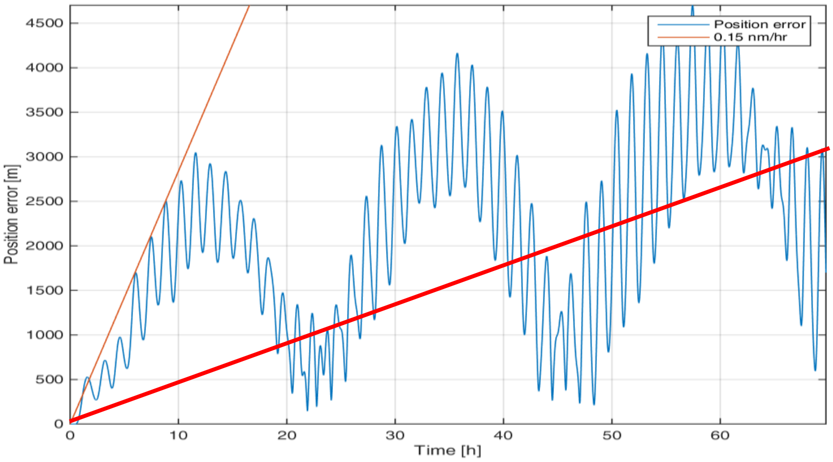
Position error of an *unaided*, *free inertial* INS:

We have to distinguish between short-time accuracy and long-time accuracy of an **i**nertial **n**avigation **s**ystem (INS). Furthermore we have to distinguish between arbitrary moving objects (like aircrafts or ships or spacecrafts) and land based vehicle which are moving on the road, i.e. applications with so-called motion constraints.

Long-time accuracy of an arbitrary moving, unaided, free inertial INS:

Definition: An arbitrary moving unaided free inertial INS means, that the INS is in free inertial operation mode (no external aiding, i.e. no GNSS, no magnetometer, no air data, no Doppler log, no LiDAR, no RF positioning, no ZUPT, …..) and the INS can move without any limitation (inside the measurement range of the inertial sensors).

In this case, the system shows a position error which is called Schuler oscillation. The position error (typically given in nm/hr i.e. nautical miles per hour) gives the global position error of the free inertial operated INS due to the residual accelerometer gyro errors. The position error oscillates with a period duration of approx. 84 minutes as well as with a period of 24 hours. The amplitude of oscillation depends on the accelerometer offset and the "shift" (average of position drift) depends on gyro drift (simple model assumption for easy explanation within this paper; details can be seen from the inertial differential equations!).



The figure shows such long time behavior of a free inertial navigation (example: data obtained from iNAT-RQT over more than 3 days): Link

This Schuler Oscillation plot is given in meters and the time in hours. As an example, the free inertial running INS shows a position error of 3 km after 70 hours (i.e. 0.02 nm/hr).

As you can see from the plot, it is important to define how to derive the value of “free inertial drift”. Due to the 24 hrs oscillation here you recognize that the position error after 11 hrs is the same as after 70 hrs. Also the pre-condition of the data acquisition is important: This plot has been acquired with only 10 minutes initial alignment.

What is the background, that some competitors advertise much lower free inertial drifts?

If you aid the INS upfront of the drift determination (e.g. operation of the INS with significant motion dynamics and external aiding by GNSS or other aiding sources), it is easy to achieve drift values of lower than 1 nm / 100 (!) hours or even 300 hours. **Attention:** In this case we do not speak about “pure inertial, unaided” operation, because the INS requires a proper aiding for a significant duration (e.g. 12 hours) to be able to provide such unaided results. In most datasheets, however this requirement is not explained as well as the fact, that such systems habe to be temperature controlled and need significant time for power-up.

Short-time accuracy of an arbitrary moved unaided INS (free inertial navigation):

Definition: A free inertial operating INS without any aiding means, that the INS is in free inertial operation mode (no external aiding, i.e. no GNSS, no magnetometer, no air data, no Doppler log, no LiDAR, no RF positioning, …..). Short term operation means, that the duration of operation is significantly shorter than the Schuler period of 84 minutes (see above).

In this operational mode the values (given in m or m/s) are relevant for measuring over durations less than approx. 20...40 minutes, because Schuler oscillation is not really relevant for short time measurements. An accelerometer offset leads to an position error increasing quadratically over time

delta_s = 0.5 x delta_a x T^2 [m] (a)

with delta_a = accelerometer offset [m/s^2] and T = measuring time [s].

Example for a medium accurate system:
delta_a = 1 mg ≈ 0.01 m/s^2, T = 100 sec ➔ delta_s = 50 m

The gyro drift delta_omega affects the position error corresponding to the equation

delta_s = g/6 x delta_omega x T^3 [m] (b)

with delta_omega in [rad/s] and g = 9.81 m/s^2 .

An attitude (roll/pitch) error of e.g. delta_attitude affects the position error due to a wrong compensation of the gravity on the horizontal IMS axes:

delta_s = 0.5 x g x sin (delta_attitude) x T^2 [m] (c)

Example, how you can validate manufacturer’s statements (with data from a vendor’s datasheet):

If someone promotes an IMS with 0.005 deg roll/pitch accuracy and advertises a horizontal position error of 0.7 m (and a vertical position error of only 0.5 m) after 300 seconds in free inertial navigation mode (i.e. without odometer aiding, without ZUPT; without internal vibration isolators), you can just check and calculate two things with the simple thumb rule equations given above:

- Position error due to 0.005 deg roll or pitch error after 300 sec (free inertial):
  0.5 x 9.81 m/s^2 x sin(0.005°) x $(300\ \text{sec})^2$ = 38 m (from equation (c))

- What must be the accelerometer accuracy to achieve 0.7 m after 300 sec (free inertial)?
  0.7 m / (0.5 x $(300\ \text{sec})^2$) = 1.5 µg (!!) absolute accuracy over 300 sec (from equ. (a))

The easy calculation shows the mismatch of the announced performance data (i.e. position error must be much worse or attitude error must be much smaller to achieve the advertised performance). For information: An absolute accuracy of accelerometer bias of 1.5 µg is close to gravimeter accuracy but not reliable available in industrial or military land navigation systems. Consider, that already the gravity by itself changes by about 0.3 µg per height meter !

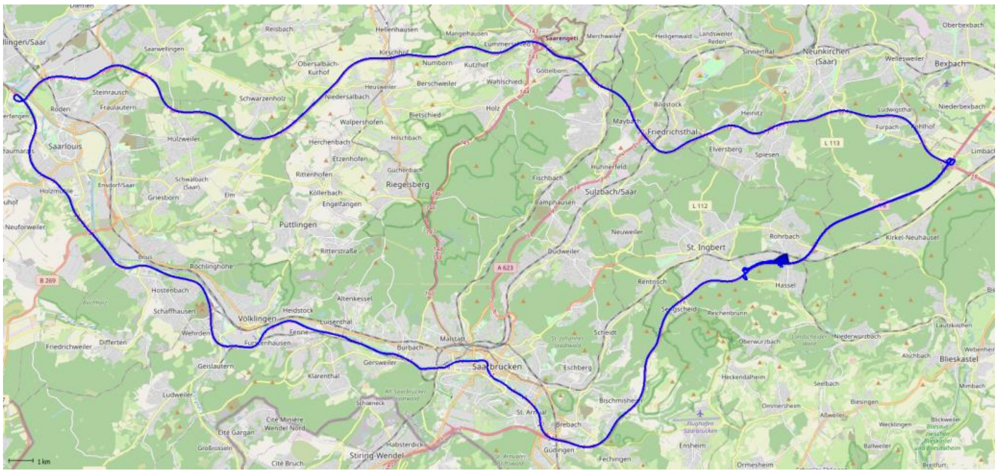
Position error of an ***unaided,*** **pure inertial** INS on road vehicles (taking only into account motion specific constraints):

Long-time accuracy of an pure inertial INS without ZUPT aiding:

Definition: The INS is operated on a land vehicle driving on a road or off-road. The vehicle has no capability to fly or to swim – this we call "motion constraints". The vehicle has sufficient grip on the surface. No external aiding is available, i.e. **no GNSS, no wheel sensor (odometer)**, no magnetometer, no LiDAR, no RF positioning etc. Over long duration and distance **no ZUPT or PUPT** shall be required.

Unaided Road and Outdoor Navigation:
Condition: No GNSS, no odometer, no RF aiding, no magnetometer aiding - but using advanced iMR proprietary algorithms which take generalized motion specific constraints of the vehicle into account.

Even without odometer and without GNSS or any other external aiding sources, in road based applications a very high position accuracy can be achieved. The operational sensor mode we call "pure inertial". We are using iMAR proprietary algorithms regarding specific motion constraints based on our more than 30 years knowledge and experience on the motion behavior of road vehicles (cars and trucks). With this experience, which covers both, light weight vehicles as well as heavy trucks, **we can keep the unaided position accuracy within a few meters during performing a 100 km trip within a duration of e.g. 1 hour (typically 0.03 % CEP50 of distance travelled in horizontal accuracy and 0.02 % DT PE50 in vertical accuracy), and this without any ZUPT or PUPT and any odometer aiding**[2]. These proprietary algorithms are applicable in both, in real-time as well as in post-processing.



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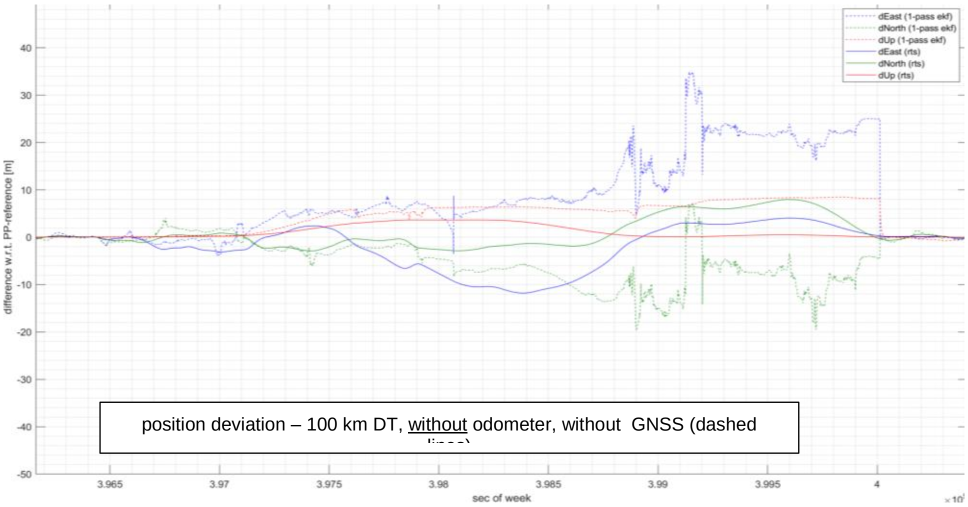
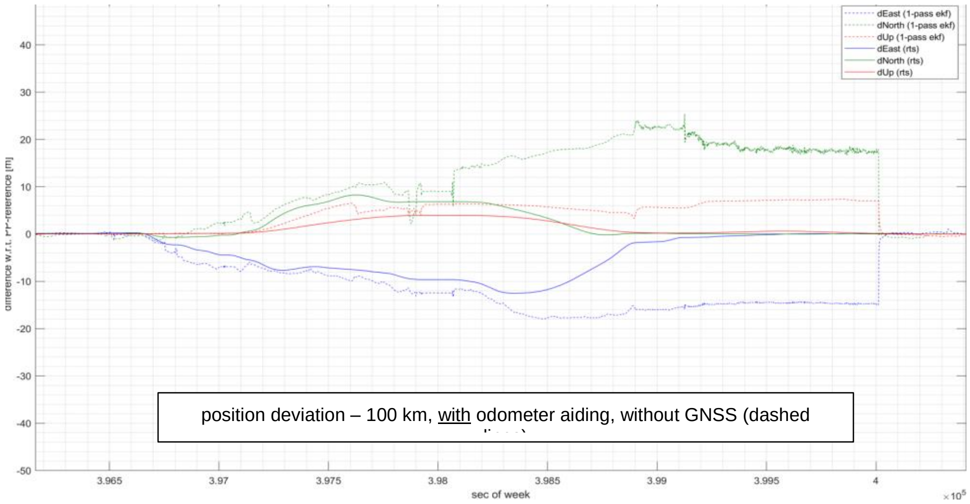
[2] Have in mind, that datasheet of conventional high performance INS for military applications, provided by competitors, annunce values of about 0.11 % horizontal and 0.1 % vertical, but with (!) odometer (VMS – vehicle motion sensor, wheel sensor) aiding, while the iMAR solution provides the above given accuracy also without any VMS (and without GNSS).

This allows fully autonomous navigation or at least to survive extremely long GNSS outages **("GNSS denied environment")** in real-time with a very high accuracy, if we compare the "pure inertial" result to "free inertial" results. Link. Our specific algorithms using such knowledge are the result of advanced algorithm design with decades of experience in all areas of inertial navigation and localization.

It can be seen from the above plots, that the odometer aiding (VMS) will not improve the position performance for the above mentioned conditions significantly. This may safe cost of installation at the integrator. The motion of the vehicle should, as usual, contain sufficient motion dynamics and changes in heading to achieve this performance.

A benefit of the VMS is an advanced motion / standstill detection, which is fully supported by the iMAR agorithms too. Due to the used motion constraints we list this method under "pure inertial, with constraints".





If a vendor claims that his system achieves a position accuracy in real-world (!) environment of 0.01 % DT without GNSS, it is advised that the user performes extensive tests to validate this promised data in his application. Lab conditions are often far away from real world conditions. See also footnote [4]

Long-time accuracy of an pure inertial INS with ZUPT aiding:

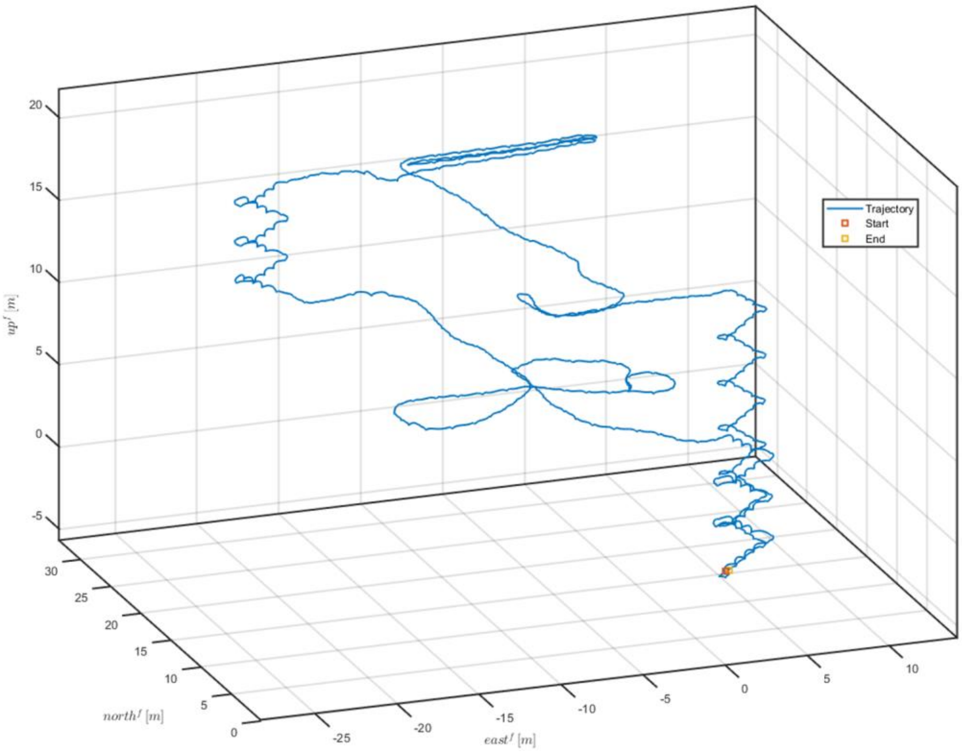
Definition: A free inertial operating INS with periodical ZUPT aiding means, that the INS is in free inertial operation mode (no external aiding, i.e. no GNSS, no magnetometer, no air data, no Doppler log, no LiDAR, no RF positioning, …..) and the INS can be operated at zero velocity condition (ZUPT) periodically, i.e. all 10 minutes. This operational mode can be applied to land based vehicles (driving on the road) but not to aircrafts or ships.

To improve the long-time performance of position determination without aiding (no GNSS, no odometer!), the system can be set to zero-velocity all x minutes (ZUPT, zero velocity update). During this stand-still period, which may take 10 seconds all 10 minutes (example), the internal Kalman filter is able to estimate the internal residuals of the gyros and accelerometers and can improve the position performance dramatically (e.g. position error over 70 km distance with iNAT-RQT has been shown to be approx. 5 meters as an example).

Position error of an ***unaided,*** **pure inertial** INS for Pedestrian Navigation in GNSS denied environment:

Definition: The INS is operated on the foot of a pedestrian. The pedestrian is allowed to move arbitrarily – walking, running, crawling, climbing ladders etc. No aiding (no RF / WiFi, no magnetometer, no GNSS) is required.

With specific hardware, algorithms and constraints about a walking person it is possible to determine the position of a walking person in real-time without any external aiding information within an accuracy of better than 1 % distance walked, nearly whatever the motion is (walking, running, jumping, crawling, ….).



The Plot shows the walk of a firefighter within a buildung: Distance 338 m, final position error 0.5 m

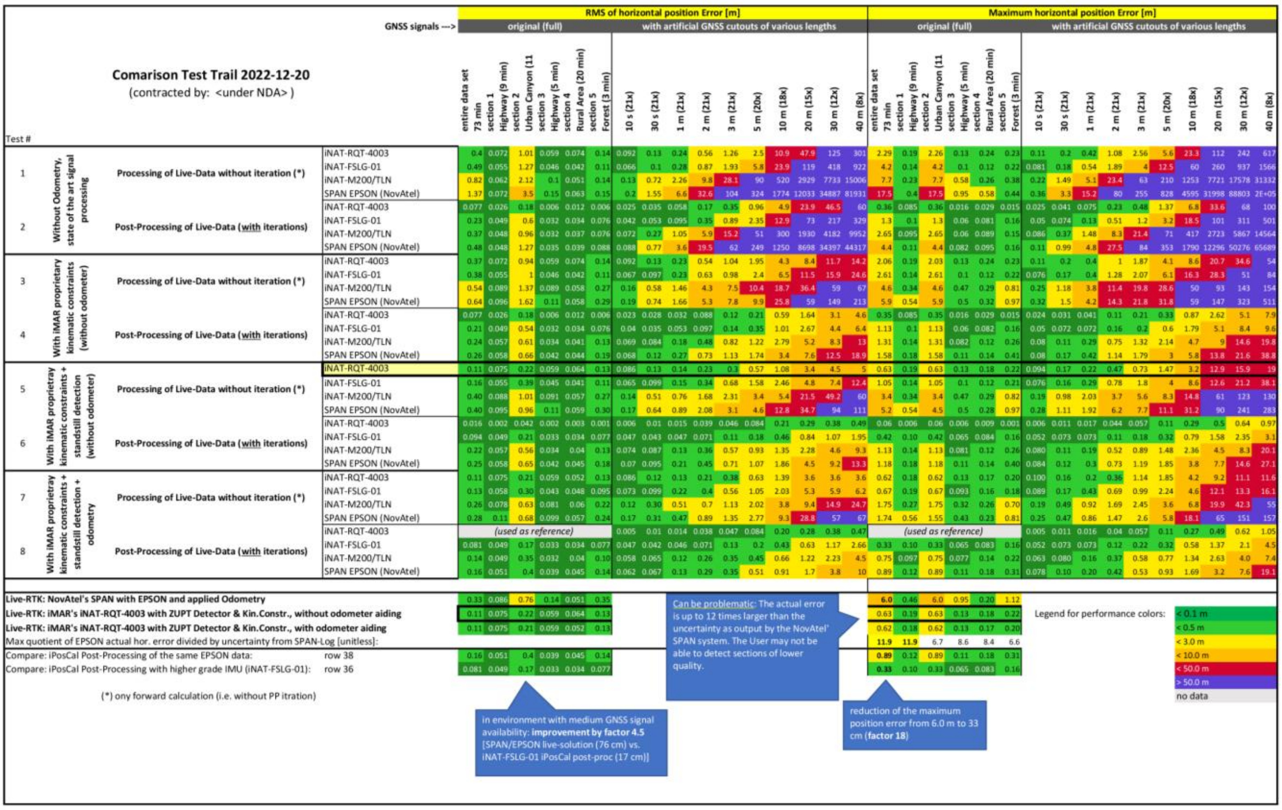
The specific constraint allow that the position error will increase in good approximation only with the walked distance. And the INS which is used weighs only a few grams. Ask iMAR Sales engineers for details about iTHESEUS, the best of class autonomous pedestrian localization system (Link).

Position error of an ***aided*** INS under arbitrary motion:

If the INS is aided, we have to distinguish between position aiding (e.g. by GNSS) and velocity aiding (e.g. by odometer/wheel sensor/VMS or GNSS Doppler velocity or Doppler log).

Position aiding:
The INS provides high accuracy during short time periods while it shows significant position drift over long-time measurements. GNSS e.g. provides position information with high noise and low data rate, but the position error does not increase over measuring time. We talk about complementary performance features of INS and GNSS.

Therefore, using the Kalman filter for sensor data fusion, the short-term accurate INS can be coupled with a long time accurate (complementary) position / velocity localization system (e.g. GNSS). iMAR's Kalman filter has typically not to be adapted to specific applications, but iMAR's architecture allows this, if required (e.g. to add additional states for additional sensors, constraints, parametrization of covariances, stability analysis etc.). In such applications of INS/GNSS coupling, while the inertial sensors provide an excellent short term position and velocity accuracy with unmatched high neighborhood accuracy, the total accuracy of the global position can never be better than the global position error of the position aiding system (e.g. GNSS). E.g. if GNSS shows a constant position error over a longer duration, also the INS/GNSS solution will follow those position error. Of course, short term deviations of the GNSS accuracy (e.g. short term spoofing) or slippage of the odometer are detected and isolated by iMAR's sensor data fusion algorithms. Using dissimilar sources of aiding (GNSS, ZUPT, odometer) the total position error are further minimized.



Comarison Test Trail 2022-12-20
(contracted by: <under NDA>)

Test #			GNSS signals --->	RMS of horizontal position Error [m]																Maximum horizontal position Error [m]															
				original (full)						with artificial GNSS cutouts of various lengths										original (full)						with artificial GNSS cutouts of various lengths									
				entire data set 73 min	section 1 Highway (9 min)	section 2 Urban Canyon (11	section 3 Highway (5 min)	section 4 Rural Area (20 min)	section 5 Forest (3 min)	10 s (21x)	30 s (21x)	1 m (21x)	2 m (21x)	3 m (21x)	5 m (20x)	10 m (18x)	20 m (15x)	30 m (12x)	40 m (8x)	entire data set 73 min	section 1 Highway (9 min)	section 2 Urban Canyon (11	section 3 Highway (5 min)	section 4 Rural Area (20 min)	section 5 Forest (3 min)	10 s (21x)	30 s (21x)	1 m (21x)	2 m (21x)	3 m (21x)	5 m (20x)	10 m (18x)	20 m (15x)	30 m (12x)	40 m (8x)
1	Without Odometry, state of the art signal processing	Processing of Live-Data without iteration (*)	iNAT-RQT-4003	0.4	0.072	1.01	0.059	0.074	0.14	0.092	0.13	0.24	0.56	1.26	2.5	10.9	47.9	125	301	2.29	0.19	2.26	0.13	0.24	0.23	0.11	0.2	0.42	1.08	2.56	5.6	23.3	112	242	617
			iNAT-FSLG-01	0.49	0.055	1.27	0.046	0.042	0.11	0.066	0.1	0.28	0.87	1.93	5.8	23.9	119	418	922	4.2	0.14	4.2	0.1	0.12	0.22	0.081	0.18	0.54	1.89	4	12.5	60	260	937	1566
			iNAT-M200/TLN	0.82	0.062	2.12	0.1	0.051	0.14	0.13	0.72	2.26	9.8	28.1	90	520	2929	7733	15006	7.7	0.23	7.7	0.58	0.26	0.38	0.22	1.49	5.1	23.4	63	210	1253	7721	17578	31332
			SPAN EPSON (NovAtel)	1.37	0.072	3.5	0.15	0.063	0.15	0.2	1.55	6.6	32.6	104	324	1774	12033	34887	81931	17.5	0.4	17.5	0.95	0.58	0.44	0.36	3.3	15.2	80	255	828	4595	31998	88803	2E+05
2		Post-Processing of Live-Data (with iterations)	iNAT-RQT-4003	0.077	0.026	0.18	0.006	0.012	0.006	0.025	0.035	0.058	0.17	0.35	0.96	4.9	23.9	46.5	60	0.36	0.085	0.36	0.016	0.029	0.015	0.025	0.041	0.075	0.23	0.48	1.37	6.8	33.6	68	100
			iNAT-FSLG-01	0.23	0.049	0.6	0.032	0.034	0.076	0.042	0.053	0.095	0.35	0.89	2.35	12.9	73	217	329	1.3	0.1	1.3	0.06	0.081	0.16	0.05	0.074	0.13	0.51	1.2	3.2	18.5	101	311	501
			iNAT-M200/TLN	0.37	0.048	0.96	0.032	0.037	0.076	0.072	0.27	1.05	5.9	15.2	51	300	1930	4182	9952	2.65	0.095	2.65	0.06	0.089	0.15	0.086	0.37	1.48	8.3	21.4	71	417	2723	5867	14564
			SPAN EPSON (NovAtel)	0.48	0.048	1.27	0.035	0.039	0.088	0.088	0.77	3.6	19.5	62	249	1250	8698	34397	44317	4.4	0.11	4.4	0.082	0.095	0.16	0.11	0.99	4.8	27.5	84	353	1790	12296	50276	65689
3	With iMAR proprietary kinematic constraints (without odometer)	Processing of Live-Data without iteration (*)	iNAT-RQT-4003	0.37	0.072	0.94	0.059	0.074	0.14	0.092	0.13	0.23	0.54	1.04	1.95	4.3	8.4	11.7	14.2	2.06	0.19	2.03	0.13	0.24	0.23	0.11	0.2	0.4	1	1.87	4.1	8.6	20.7	34.6	54
			iNAT-FSLG-01	0.38	0.055	1	0.046	0.042	0.11	0.067	0.097	0.23	0.63	0.98	2.4	6.5	11.5	15.9	24.6	2.61	0.14	2.61	0.1	0.12	0.22	0.076	0.17	0.4	1.28	2.07	6.1	16.3	28.3	51	84
			iNAT-M200/TLN	0.54	0.089	1.37	0.089	0.058	0.27	0.16	0.58	1.46	4.3	7.5	10.4	18.7	36.4	59	67	4.6	0.34	4.6	0.47	0.29	0.81	0.25	1.18	3.8	11.4	19.8	28.6	50	93	143	154
			SPAN EPSON (NovAtel)	0.64	0.096	1.62	0.11	0.058	0.29	0.19	0.74	1.66	5.3	7.8	9.9	25.8	59	149	213	5.9	0.54	5.9	0.5	0.32	0.97	0.32	1.5	4.2	14.3	21.8	31.8	59	147	323	511
4		Post-Processing of Live-Data (with iterations)	iNAT-RQT-4003	0.077	0.026	0.18	0.006	0.012	0.006	0.023	0.028	0.032	0.088	0.12	0.21	0.59	1.64	3.1	4.6	0.35	0.085	0.35	0.016	0.029	0.015	0.024	0.031	0.041	0.11	0.21	0.33	0.87	2.62	5.1	7.9
			iNAT-FSLG-01	0.21	0.049	0.54	0.032	0.034	0.076	0.04	0.035	0.053	0.097	0.14	0.35	1.01	2.67	4.4	6.4	1.13	0.1	1.13	0.06	0.082	0.16	0.05	0.072	0.072	0.16	0.2	0.6	1.79	5.1	8.4	9.6
			iNAT-M200/TLN	0.24	0.057	0.61	0.034	0.041	0.13	0.069	0.084	0.18	0.48	0.82	1.22	2.79	5.2	8.3	13	1.31	0.14	1.31	0.082	0.12	0.26	0.08	0.11	0.29	0.75	1.32	2.14	4.7	9	14.6	19.8
			SPAN EPSON (NovAtel)	0.26	0.058	0.66	0.042	0.044	0.19	0.068	0.12	0.27	0.73	1.13	1.74	3.4	7.6	12.5	18.9	1.58	0.18	1.58	0.11	0.14	0.41	0.08	0.17	0.42	1.14	1.79	3	5.8	13.8	21.6	38.8
5	With iMAR proprietray kinematic constraints + standstill detection (without odometer)	Processing of Live-Data without iteration (*)	iNAT-RQT-4003	0.11	0.075	0.22	0.059	0.064	0.13	0.086	0.13	0.14	0.23	0.3	0.57	1.08	3.4	4.5	5	0.63	0.19	0.63	0.13	0.18	0.22	0.094	0.17	0.22	0.47	0.73	1.47	3.2	12.9	15.9	19
			iNAT-FSLG-01	0.16	0.055	0.39	0.045	0.041	0.11	0.065	0.099	0.15	0.34	0.68	1.58	2.46	4.8	7.4	12.4	1.05	0.14	1.05	0.1	0.12	0.21	0.076	0.16	0.29	0.78	1.8	4	8.6	12.6	21.2	38.1
			iNAT-M200/TLN	0.40	0.088	1.01	0.091	0.057	0.27	0.14	0.51	0.76	1.68	2.31	3.4	5.4	21.5	49.2	60	3.4	0.34	3.4	0.47	0.29	0.82	0.19	0.98	2.03	3.7	5.6	8.3	14.8	61	123	130
			SPAN EPSON (NovAtel)	0.40	0.095	0.96	0.11	0.059	0.30	0.17	0.64	0.89	2.08	3.1	4.6	12.8	34.7	94	111	5.2	0.54	4.5	0.5	0.28	0.97	0.28	1.11	1.92	6.2	7.7	11.1	31.2	90	241	283
6		Post-Processing of Live-Data (with iterations)	iNAT-RQT-4003	0.016	0.002	0.042	0.002	0.003	0.001	0.006	0.01	0.015	0.039	0.046	0.084	0.21	0.29	0.38	0.49	0.06	0.006	0.06	0.006	0.009	0.001	0.006	0.011	0.017	0.044	0.057	0.11	0.29	0.5	0.64	0.97
			iNAT-FSLG-01	0.094	0.049	0.21	0.033	0.034	0.077	0.047	0.043	0.047	0.071	0.11	0.18	0.46	0.84	1.07	1.95	0.42	0.10	0.42	0.065	0.084	0.16	0.052	0.073	0.073	0.11	0.18	0.32	0.79	1.58	2.35	3.1
			iNAT-M200/TLN	0.22	0.057	0.56	0.034	0.04	0.13	0.074	0.087	0.13	0.36	0.57	0.93	1.35	2.28	4.6	9.3	1.13	0.14	1.13	0.081	0.12	0.26	0.080	0.11	0.19	0.52	0.89	1.48	2.36	4.5	8.3	20.1
			SPAN EPSON (NovAtel)	0.25	0.058	0.65	0.042	0.045	0.18	0.07	0.095	0.21	0.45	0.71	1.07	1.86	4.5	9.2	13.3	1.18	0.18	1.18	0.11	0.14	0.40	0.084	0.12	0.3	0.73	1.19	1.85	3.8	7.7	14.6	27.1
7	With iMAR proprietray kinematic constraints + standstill detection + odometry	Processing of Live-Data without iteration (*)	iNAT-RQT-4003	0.11	0.075	0.21	0.059	0.052	0.13	0.086	0.12	0.13	0.21	0.38	0.63	1.39	3.6	3.6	3.6	0.62	0.18	0.62	0.13	0.17	0.20	0.100	0.16	0.2	0.36	1.14	1.85	4.2	9.2	11.1	11.6
			iNAT-FSLG-01	0.13	0.058	0.30	0.043	0.048	0.095	0.073	0.099	0.22	0.4	0.56	1.05	2.03	5.3	5.9	6.2	0.67	0.19	0.67	0.093	0.16	0.18	0.089	0.17	0.43	0.69	0.99	2.24	4.6	12.1	13.3	16.1
			iNAT-M200/TLN	0.26	0.078	0.63	0.081	0.06	0.22	0.12	0.30	0.51	0.7	1.13	2.02	3.8	9.4	14.9	24.7	1.75	0.27	1.75	0.32	0.26	0.70	0.19	0.49	0.92	1.69	2.45	3.6	6.8	19.9	42.3	55
			SPAN EPSON (NovAtel)	0.28	0.11	0.68	0.099	0.057	0.24	0.17	0.31	0.47	0.89	1.35	2.77	9.3	28.8	57	67	1.74	0.56	1.55	0.43	0.23	0.81	0.25	0.47	0.86	1.47	2.6	5.8	18.1	65	151	157
8		Post-Processing of Live-Data (with iterations)	iNAT-RQT-4003	(used as reference)						0.005	0.01	0.014	0.038	0.047	0.084	0.20	0.28	0.38	0.47	(used as reference)						0.005	0.011	0.016	0.04	0.057	0.11	0.27	0.49	0.62	1.05
			iNAT-FSLG-01	0.081	0.049	0.17	0.033	0.034	0.077	0.047	0.042	0.046	0.071	0.13	0.2	0.43	0.63	1.17	2.66	0.33	0.10	0.33	0.065	0.083	0.16	0.052	0.073	0.073	0.12	0.22	0.32	0.58	1.37	2.1	4.5
			iNAT-M200/TLN	0.14	0.049	0.35	0.032	0.04	0.10	0.058	0.065	0.12	0.26	0.35	0.45	0.66	1.22	2.23	4.5	0.75	0.097	0.75	0.077	0.14	0.22	0.063	0.080	0.16	0.37	0.58	0.77	1.34	2.63	4.0	7.4
			SPAN EPSON (NovAtel)	0.16	0.051	0.4	0.039	0.045	0.14	0.062	0.067	0.13	0.29	0.35	0.51	0.91	1.7	3.8	10	0.89	0.12	0.89	0.11	0.18	0.31	0.078	0.10	0.20	0.42	0.53	0.93	1.69	3.2	7.6	19.1

		RMS: entire data set 73 min	section 1 Highway (9 min)	section 2 Urban Canyon (11	section 3 Highway (5 min)	section 4 Rural Area (20 min)	section 5 Forest (3 min)	Maximum: entire data set 73 min	section 1 Highway (9 min)	section 2 Urban Canyon (11	section 3 Highway (5 min)	section 4 Rural Area (20 min)	section 5 Forest (3 min)
Live-RTK: NovAtel's SPAN with EPSON and applied Odometry		0.33	0.086	0.76	0.14	0.051	0.35	6.0	0.46	6.0	0.95	0.20	1.12
Live-RTK: iMAR's iNAT-RQT-4003 with ZUPT Detector & Kin.Constr., without odometer aiding		0.11	0.075	0.22	0.059	0.064	0.13	0.63	0.19	0.63	0.13	0.18	0.22
Live-RTK: iMAR's iNAT-RQT-4003 with ZUPT Detector & Kin.Constr., with odometer aiding		0.11	0.075	0.21	0.059	0.052	0.13	0.62	0.18	0.62	0.13	0.17	0.20
Max quotient of EPSON actual hor. error divided by uncertainty from SPAN-Log [unitless]:								11.9	11.9	6.7	8.6	8.4	6.6
Compare: iPosCal Post-Processing of the same EPSON data:	row 38	0.16	0.051	0.4	0.039	0.045	0.14	0.89	0.12	0.89	0.11	0.18	0.31
Compare: iPosCal Post-Processing with higher grade IMU (iNAT-FSLG-01):	row 36	0.081	0.049	0.17	0.033	0.034	0.077	0.33	0.10	0.33	0.065	0.083	0.16

(*) ony forward calculation (i.e. without PP itration)

Can be problematic: The actual error is up to 12 times larger than the uncertainty as output by the NovAtel' SPAN system. The User may not be able to detect sections of lower quality.

In environment with medium GNSS signal availability: **improvement by factor 4.5** [SPAN/EPSON live-solution (76 cm) vs. iNAT-FSLG-01 iPosCal post-proc (17 cm)]

reduction of the maximum position error from 6.0 m to 33 cm (**factor 18**)

Legend for performance colors:
- < 0.1 m
- < 0.5 m
- < 3.0 m
- < 10.0 m
- < 50.0 m
- > 50.0 m
- no data

Typical performance of an INS/GNSS coupled system with RTK (real time kinematic) GNSS perforace is about 1…2 centimeters. Strong differences in the performance of different systems of known manufacturers can be seen in the case of signal degradation of GNSS like multi-path and during GNSS outages in urban canyons or similar environment. The datasheet of the providers sometimes provide so-called performance tables, which give some standard deviations of position and velocity errors , but they are usually not comparable because the test methods are often quite different. E.g. if a test drive contains 20 % urban canyon and 80 % highway, the obtained position standard deviation may look nice despite there might be strong position outliers over a short (but significant) duration (Link). iMAR uses highest performance

INS/GNSS/ODO reference systems as well as its proprietary mult-pass post-processing to validate the performance of real-time solutions against a most accurate ground truth. The following figure shows such analysis.

Velocity aiding / Dead Reckoning:
If velocity is provided for aiding (e.g. from a wheel sensor / odometer or from Doppler velocity log) instead of position, the position error of the Kalman filter based sensor data fusion will grow mainly with the scale factor error of the velocity aiding sensor. If GNSS aiding is present for a certain time before it will be interrupted (e.g. before the vehicle enters a longer tunnel), the GNSS data will be used together with the IMS and the odometer data to estimate the scale factor of the odometer precisely and automatically, together with some other installation parameters like mounting misalignment errors. This also allows to determine the position of the vehicle during very long outages of the GNSS signal with high precision. As an example, using an iNAT-M300/SLN (MEMS based IMS) with wheel sensor, GNSS aiding and integrated sensor data fusion, the position error after 10 km GNSS outage had been demonstrated to be typically about 8 m (i.e. < 0.1 %).

Alignment:

Each inertial measurement system needs an initial position and orientation for proper operation. The initial position can be obtained from a user input (so-called waypoint or landmark input from a map) or from GNSS or from any other source. The initial orientation can be obtained via several methods and here the implementation of several systems may be quite different, also depending on the sensor performance of the core inertial sensors. Typically the alignment contains three pases of signal processing: The leveling (dynamic or static), the coarse alignment and the fine alignment. e distinguish between staic (at standstill) and dynamic (under motion) alignment:

- Statc Alignment: The INS is at standstill
    - Determination of roll and pitch: Roll and pitch can be obtained by using the integrated accelerometers inside the field of gravity, if their performance is good enough. If a vendor claims a day-to-day accuracy of the integrated acceerometers of 1 mg and at the same time **a roll and pitch accuracy** after static alignment of 0.02° (0.5 mrad), check the validity (thumb rule: static roll/pitch accuracy [°] cannot be better than accel_bias [mg] x 180/PI.
    - Determination of yaw (true heading) is possible via four different methods:
        - **Gyro Compassing**: If the day-to-day bias[3] of the gyros (also called gyro drift) is good enough. Thumb rule: If the gyro bias is 0.015 deg (day-to-day), the very best achievable value of true heading (no motion, static alignment) is 1 mrad, sec Lat i.e. 0.057° sec Lat (i.e. atan2(0.015 °/h / 15.05 °/h).
        - by **Stored Heading**, i.e. if the haeding had been stored at last power down and if the vehicle has not moved between power-on and last power down. A myriad of procedures are used, not all of them are satisfying in real-world applications.
        - by using dual-antenna GNSS: Here GNSS is used to determine the heading from a local RTK solution between two GNSS antennas. See chapter **True Heading** for details.
- Dynamic Alignment: The INS is in motion
        - under dynamic conditions the determination of roll and pitch is more complex and requires additional information like GNSS or VMS / odometer / Doppler Log etc. or periodical ZUPTs.

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[3] Do not confuse „bias drift“ (day-to-day) with „bias instability“ (sometimes also named „bias stability“). Typically the bias instability is about 10…100 times smaller than the bias drift, but it is not relevant for gyro compassing, because during gyro compassing the earth rate hase to be measured independent on the motion of the vehicle.

- The classical dynamic alignment requires sufficient motion excitation and availability of some position or velocity aiding. Using the integrated sensor data fusion attitude, heading and all other initial data are determined. This procedure also works wel lfor systems, which are not capable to perform a gyro compassing or which do not contain a dual-antenna GNSS receiver, i.e. all systems with a gyro bias of about > 0.1 deg/hr. Dynamic alignment is also suitable to improve the performance of higher performance inertial systems.

Once the static or dynamic alignment has been finished, the inertial system enters the navigational mode.

True Heading: The "true heading" performance of an INS is always an important parameter. If the INS contains high performance gyroscopes like ring laser or fiber optical gyros (drift < 0.1 deg/hr), it can perform an **autonomous gyro compassing**, i.e. it measures the earth rotation rate, determines the levelling by measuring the gravity vector and calculates from these data the true north (heading) beside of roll, pitch and other values. See chapter **Alignment** for some thumb rules.

If the INS does not contain such high performance gyroscopes, it can obtain the true heading only from a combination of a position aiding (e.g. GNSS) and the inertial sensors, assuming sufficient motion dynamics will be present.

Using only GNSS (without inertial sensors), a so-called "track over ground" can be determined, which is obtained from the GNSS velocity in East and North direction, i.e. atan2(v_{east}/v_{north}). Of course, this information shows only the direction of the motion of the GNSS antenna over ground, but it says nothing about the true heading of the vehicle (i.e. the direction of the vehicle's "nose")! Hence with a single GNSS antenna and without additional inertial sensors and without sufficient motion dynamics it is not (!) possible to determine the true heading.

Using a **dual antenna GNSS** system (like iNAT-M300/SLN-DA) as stand-alone solution, true heading can be determined as long as both antennas can observe the same (!) GNSS satellites. As a thumb rule have in mind, that a dual-antenna system is limited by physics to an accuracy of about 0.17° heading accuracy per 1 meter antenna baseline, which corresponds to 3 mm position accuracy at 1 m baseline (i.e. atan2(0.003 m / 1 m). So, if a vendor specifies a pure dual-antenna absolute accuracy (not standard deviation!) of 0.006° at 1 meter baseline[4], check the validity. GNSS outages can be bridged by the gyros – i.e. the better the gyro performance, the longer the duration of acceptable GNSS outages. Link

Conclusion: If the IMS contains inertial sensors with drift > 0.1 deg/hr and only a single antenna GNSS receiver (standard setup), it is easily possible to determine true heading with iMAR's real-time signal processing, but this requires two constraints (subject of physical laws):

a) The vehicle has to be under motion, and

b) The vehicle has to perform sufficient changes in heading to provide enough observability to the Kalman filter based data fusion to be able to estimate true heading with sufficient accuracy

An IMS without gyro compassing capability and without dual-antenna GNSS aiding is not able to determine true heading of its carrying vehicle, if the vehicle is moving only on a straight line without changes of direction (this feature is called as "lack of observability"). As soon as a change of heading occurs, the observability is given and the system can provide the desired information. It is very important to take this into

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[4] found on the web site, on the datasheet and inside the reference Manual of an Australian vendor of „advanced navigation" systems for defence and industrial applications [01/2024]

account when selecting the right IMS/GNSS solution for the foreseen application (therefore it had been explained in this document extensively). Link

Time Stamping / Synchronization / Latency / Jitter:

Especially if an IMS shall be used for control tasks or for surveying applications, a superior time stamping of the inertial data, odometer data and all other aiding information (GNSS, machine vision) is mandatory. Therefore iMAR's measurement systems, containing the proprietary iNAT architecture, provide time stamping with very high performance.

Example: If a target is moving with 100 m/s, a timing error of 1 milli second would already lead to a position error of 10 cm. Consider an RTK aiding with about 1 cm accuracy and you may immediately imagine why a synchronization accuracy with at least 25 µsec is mandatory together with a very high internal clock performance. Optionally INS being designed for advanced applications can provide NTP data for time synchronization and sometimes the integration of an semiconductor based atomic clock might be helpful when operating long time in GNSS denied environment.

Using an INS for control tasks, like autonomous vehicle guidance or platform stabilization, a small latency and a small jitter of the acquired data as well of the data output is mandatory. The architecture e.g. of iMAR's iNAT / iPRENA / iCOMBANA / iSULONA / iTraceRT-MVT / iATTHEMO, iIPST systems also guarantee here best-in-market values. (Link)

EMI / EMC Protection:

Inertial measurement systems for military or aviation use come with high EMI/EMC protection levels.

The systems being manufactured by iMAR are designed for the markets with challenging EMI/EMC requirements, as of surveying, vehicle testing, aerial laser scanning, pipeline inspection, vehicle and camera stabilization, drilling, aircraft guidance & control etc. Due to the wide application area and strong reliability needs, iMAR systems are protected and qualified according to strong standards like MIL-STD 461 and MIL-STD 704 or DO160 (beside of the environmental qualification according to MIL-STD 810 or DO160). This prevents the system from unexpected electro-magnetic interferences and related performance degradation. Due to our high qualification level, about 50 % of all originally for the industrial market designed iMAR systems are also used within advanced military applications. **Link** to our own EMI/EMC lab Spezial-EMV GmbH in St. Ingbert / Germany, which offers EMI/EMC qualification and certification for their customers worldwide. Spezial-EMV GmbH is a 100 % daughter company of iMAR Navigation and located also at the iMAR Campus in St. Ingbert / Germany.

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EMI / EMC TESTLAB & SOLUTIONS

Check the protection level of the system, which you want to apply, against these requirements too. Especially inertial measurement systems being offered by competiors for commercial or surveying applications, sometimes do not provide a sufficient EMI/EMC protection level and this may lead to operational problems in real world's environment.

MTBF:

The reliability of an INS is most important for critical applications. Typically high performance inertial sensor assemblies show a calculated mean time between failure of about 100'000 hrs. Using field experience data, also higher values are acquired, but be careful to compare these data: Typically the base of an MTBF acquired from data in the field do not contain the full environmental impact as it is used within the model estimated calculation values.

So be cautious if you read a value of e.g. 500'000 hrs MTBF of an INS.

- For which environment it has been calculated? See the categories in MIL-STD 810H or DO160G for details and a better understanding.

- May be this is only fielded data, typically not covering the full environmental impacts of vibration and temperature?
- Have in mind, that typically even the calculated MTBF of the electronics of a powerful electronics with advanced EMI/EMC and over-voltage protection together with the MIL connectors (without sensors) is lower than 1 M hrs

Open Interfaces: Open interfaces are very important for the user to have highest flexibility in using the system. Interfaces are user-interfaces as well as interfaces to external sensors like optional GNSS engines, odometer, depth/altitude sensor, visual odometry, DVL etc. The system's architecture should also provide custom specific interfaces if required. See iMAR's proprietary iXCOM protocol for details. Link

GUI / Wizard: Users, which are new in the are of operating an inertial measurement system, sometimes need assistance to implement the system in the best way. For this typically a GUI is provided to configure the IMS on the vehicle.
Beside of configuration assistance such GUI should also allow a visualization of the acquired data in real-time as well as in playback mode.
Additionally an installation wizard is helpful to support the operator surveying the lever arms between GNSS antenna, odometer, camera etc. and the inertial measurement unit. Last but not least such GUI should provide some maintenance features to allow even a fast system analysis in the field.
As an example you can see the recommended features of such GUI here: iXCOM-CMD

Surveying Applications, Post-Processing: For surveying applications results may be required in real-time as well as in post-processing. For real-time applications the before explained solutions are available, up to INS/GNSS-RTK solutions, optionally aided via LiDAR etc. Link

For post-processing several solutions are available on the market, which differ significantly in the used methods and algorithms. The post-processing allows a forward / backward calculation to eliminate most of the modelled sensor errors. Have in mind, that due to the post-processing approach the position and velocity errors at the beginning and at the end of the measurement period appear to be zero. Link

Gravimetry: Airborne gravimetry or gradiometry is the art to determine the gravity disturbance from a moving aircraft. For this very special algorithms as well as ultra accurate inertial sensors are required. The result is obtained in post-processing. The phsical challenge is to determine the gravity within an accuracy of 1 µg (= 1 mGal) within an aircraft or ship which is moving with up to 1 g motion dynamics.
Link

Customized Solutions: Many applications require cusomized solutions of and with inertial sensor systems. iMAR's more than 30 years lasting expertise allows the prvision of dedicated solutions from the prototype up to production batches of several thousand devices. Do not hesitate to ask our Technical Sales for a detail led analysis of your needs – our skilled engineers will join the meeting and will provide you the technical and commercal best fitting solution for your application.

Also a lot of other features have important influence on the performance of an inertial measurement system. If you have additional questions please do not hesitate to contact us for further information.

Easy-to-Use Interfaces: iMAR’s inertial measurement solutions provide easy-to-use communication and data interfaces, proven and evolved during more than 30 years experience on all kind of applications, commercial, industrial, automotive and military. This covers interfaces like Ethernet / TCP/IP / UDP, EtherCAT, UART RS422/RS232, CAN, NMEA183, ARINC429, HDLC, SDLC etc. as well as customized interfaces (hardware and software).

iMAR supports the inegrators and users also providing ROS 2 nodes, Python scripts, SDK for C++ and WireShark dissector.

Customer Support: Specifying and purchasing an inertial measurement system is one thing - integrating it and configuring it optimally for use is a technically demanding task for many users. Therefore, our team at iMAR Navigation offers you comprehensive support from selection to integration of your measurement system, in both German and English, and if necessary, anywhere in the world.

With over 30 years of extensive experience in almost all applications of inertial measurement technology, our support team is always available to assist you!

Ein Inertialmesssystem zu spezifizieren und zu kaufen ist die eine Sache - es zu integrieren und für den Einsatz optimal zu konfigurieren ist für viele Anwender eine technisch anspruchsvlle Aufgabe. Daher bieten wir, iMAR Navigation, Ihnen eine Rundum-Unterstützung von der Auswahl bis zur Integration Ihres Messsystems an, in deutscher und englischer Sprache und bei Bedarf gerne an jedem Ort der Erde.

Mit über 30 Jahren umfassender Erfahrung in nahezu allen Anwendungen der inertialen Messtechnik steht Ihnen unser Support-Team jederzeit gerne zur Verfügung!

Please don’t hesitate to contact our support and sales engineers for any further questions!
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Additional information can be found on our download site at www.imar-navigation.de

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