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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Preface

Indeed, it is often very challenging for both inexperienced and advanced users of inertial technology to make the right decision in an environment of complex marketing information about which of the various inertial measurement systems, inertial navigation systems, attitude and heading reference systems, inertial measurement units, or at least inertial sensors on the market best and most economically meets their requirements.

With this article, we aim to help the reader better understand the physics behind inertial navigation or inertial measurement systems and sensors, and to evaluate the information. We also aim to enable you to better validate the datasheets provided by suppliers, identify inconsistencies that are unfortunately often present, and find your best technical and economic solution. Only in this way can you be sure that the product you select truly meets your requirements.

> *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.*
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> *Mit diesem Artikel helfen wir dem Leser, 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, leider oft vorhandene Inkonsistenzen zu identifizieren und Ihre beste technische und wirtschaftliche Lösung zu finden. Nur so können Sie sicher sein, dass das von Ihnen ausgewählte Produkt tatsächlich Ihren Anforderungen genügt.*

Introduction into Inertial Measurement Technology:

Inertial navigation and guidance systems were initially developed for rocket guidance and control. Today, their applications span a wide range of fields, from horizontal directional drilling deep underground to spacecraft navigation. In fact, inertial technology has become an integral part of everyday life. For example, 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 conditions. Likewise, every smartphone incorporates accelerometers, gyroscopes, a GNSS receiver, and a magnetometer.

A typical Inertial Navigation System (INS) relies on gyroscopes (angular rate sensors) and accelerometers as its primary sensors. Gyroscopes are used to determine the vehicle's orientation, compensating for gravitational effects on the accelerometer data. This process involves solving a complex set of differential equations in real-time to convert the sensor measurements into estimates of velocity, position, attitude, and heading, based on a known initial position in latitude and longitude.

Modern Inertial Navigation Systems (INS) commonly utilize 'strap-down' technology, where all inertial sensors (gyroscopes and accelerometers) are rigidly mounted to the vehicle. In earlier designs, 'gimbal' technology was used, with gyroscopes mechanically stabilizing accelerometers in space. In strap-down systems, stabilization is achieved through mathematical calculations, subjecting all inertial sensors to the vehicle's full dynamic range. Despite the absence of mechanical gimbals, strap-down systems are significantly more robust operationally than gimbaled systems, although they demand higher sensor range, scale factor accuracy, and sensor durability.

All unaided inertial navigation systems experience drift over time, as small measurement errors accumulate, resulting in progressively larger errors in velocity and, especially, position due to double integration over time. The methods for compensating and correcting this drift, particularly in real-time applications, differ substantially across market solutions. Only suppliers who excel in providing unaided inertial navigation with the highest performance — especially under challenging environmental conditions, often regarded as the 'king class of inertial measurement technology' — are capable of delivering compelling solutions for aided navigation scenarios as well.

Control theory, particularly Kalman filter-based techniques, provides a framework for integrating complementary data from various sensors, a process known as sensor data fusion. Common supplementary sensors used to support INS-based systems include satellite navigation systems like GPS, GALILEO, BeiDou and GLONASS (GNSS), as well as odometers, air data sensors, magnetometers, radio positioning systems, and more. Additionally, specific techniques such as Zero Velocity Update (ZUPT) and Position Update (PUPT) can enhance accuracy for particular applications. (Link)

The **significant risks** of other signal processing methods, such as **AI-based approaches**, which are often greatly underestimated by inexperienced users, are discussed in a dedicated chapter of this paper, particularly regarding their use not only in safety-critical or reference measurement applications.

> *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* ***ungestützten*** *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, Funkortungs-systeme usw. Des weiteren erlauben besondere Methoden wie ZUPT, PUPT (Zero Velocity Update, Position Update) usw. anwendungsspezifische Genauigkeitsverbesserungen. (Link)

*Die signifikanten und von unerfahrenen Anwendern zumeist **deutlich unterschätzen Risiken** anderer Signalverarbeitungsmethoden wie **KI basierter Verfahren** für den Einsatz nicht nur in sicherheitsrelevanten oder Referenzmesstechnik-Anwendungen werden in einem eigenen Kapitel in dieser Abhandlung erörtert.*

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

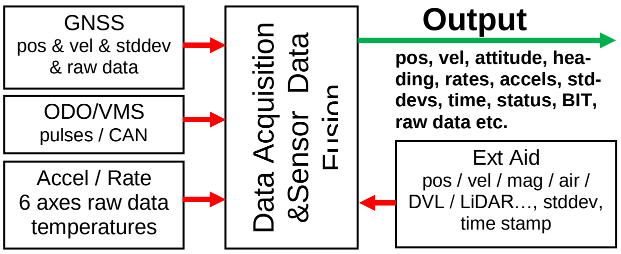
Compare the conditions of operation given in the data sheet of the system intended to be used: Is the condition well defined and will it meet your application requirements?

- 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, ...)
- Do you need accurate, reliable and available results of the system during your data sensitive or safety critical missions or anywhere, where you have to rely on the data output? Then any AI based solution might not be the right

choice even if it might be slightly cheaper in purchasing. Cost should be compared in case of a failed mission due to an unpredicted AI decision.

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 significant performance degradation due to physical reasons, caused by vibration impacts and temperature gradients as well as due to absolute temperature. As an example, most FOG based products for north seeking applications, where an accuracy of better 5 mil is required, are not able to perform a cold start at temperature < -32 °C[1] and they often do not specify the behavior at real-world temperature gradients (10 K/min).



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)

With over 30 years of experience in sensor data fusion and integration, iMAR incorporates all state-of-the-art gyro technologies and performance classes in its systems, ranging from MEMS to FOG, RLG, and HRG, depending on the application requirements. The company utilizes a robust real-time sensor data fusion process with more than 40 states to estimate and compensate for most residual errors and even the aging effects of inertial sensors. Link

Additional complementary sensors can also be integrated into the sensor data fusion process, such as GNSS (single and dual antenna), wheel sensor data (odometer, VMS), DVL (Doppler Velocity Log), EM-Log, magnetometer data (magnetic heading — though caution is advised with these sensors, as they are highly sensitive to environmental influences that cannot be compensated for if they change during the mission), air data sensors, and more.Link

The physics underlying the mathematics of inertial navigation is, among other things, described by Newton's axioms. While the fundamental mathematical framework and

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[1] Excerpt for FOG based systems provided fort he defence market with announced heading accuracy < 5 mils sec lat, which do not allow a cold start at ϑ < -32 °C (i.e. typically not suitable for defence application environment): PETRA 1000 and PETRA 2000 by Honeywell / Civitanavi (datasheet 2024/11), or e.g. all devices of ADVANS system family (INS for defence applications) by iXblue / Exail (datasheet 2024/10)

solutions to navigation equations have been well known for many decades, the real challenge lies in implementing these solutions in a robust, efficient, highly reliable, and readily available manner. Achieving this requires a vast amount of experiential knowledge, which the iMAR team has accumulated over more than 30 years across hundreds of different applications.

In the absence of such expertise, less experienced providers of PNT solutions may find it tempting to turn to so-called artificial intelligence (AI) methods, as these can quickly demonstrate promising results in a well-trained environment. AI techniques are well-established in fields like image, speech, and video processing, particularly where the physical modeling of phenomena remains challenging for engineers and scientists. However, because the learning processes of AI agents are only sporadically verifiable, there is a consensus among experienced users and experts that AI-based systems should not be employed in mission-critical or safety-relevant applications. The real behavior of these systems cannot be entirely predicted, posing a significant risk to the mission.

At iMAR, we firmly believe that only physics has to determine the behavior of our measurement systems. Our deterministic real-time results arise from the intelligent signal processing conducted by our experienced engineers and scientists, **not from opaque AI**. Our customers choose our systems because they value the exceptional reliability, availability, and accuracy of our solutions, even in critical missions during daily operations. We achieve this through **our mathematically and physically precise algorithms** — and intentionally not through AI (artificial intelligence) interpreted so-called “measurement results”.

AI methods are utilized in our work only in areas where they can contribute, such as object detection or classification, and do not have any safety-critical implications.

> Die Physik, der die Mathematik der Inertialnavigation folgt, wird u.a. durch die Newton’schen Axiome beschrieben. Während die grundsätzliche mathematische Beschreibung und Lösung der Navigationsgleichungen seit vielen Jahrzehnten allgemein bekannt ist, liegt die besondere Herausforderung darin, die Lösung robust, effizient, hochgradig zuverlässig und verfügbar zu realisieren. Hierzu bedarf es eines enormen Erfahrungswissens, welches sich das iMAR-Team in über 30 Jahren in hunderten verschiedener Anwendungen erarbeitet hat und täglich weltweit demonstriert.
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> Kann man auf ein solches Wissen nicht aufsetzen, erscheint es für einen Anbieter von PNT-Lösungen auf den erste Blick sehr attraktiv, auf **Metoden der sog. künstlichen Intelligenz (KI)** zu ersetzen, denn hiermit kann er im trainierten Umfeld recht schnell passable Lösungen vorzeigen. KI-Verfahren sind bestens in Bereichen der Bild-, Sprach- und Videomanipulation etabliert und insb. dort, wo eine physikalische Beschreibung von Sachverhalten den Anwendern heute noch schwer fällt. Da der Lernprozess solcher KI-Agenten jedoch nur sporadisch prüfbar ist, ist es in erfahrenen Anwenderkreisen Konsenz, dass auf KI-Methoden basierte Systeme nicht in Daten- oder sicherheitsrelevanten Anwendungen zum Einsatz kommen, da das reale Verhalten derartiger Systeme nicht hinreichend voraussagbar ist, womit ein enormes Sicherheitsrisiko gegeben sein kann.
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> Deshalb gilt bei iMAR: **Nur die Physik bestimmt das Verhalten unserer Messsysteme.** Unsere deterministischen Echtzeitergebnisse entstehen durch die intelligente Signalverareitung unserer projekterfahrenen Ingenieure und Wissenschaftler, und **nicht durch intransparente KI**. Unsere Kunden verwenden unsere Systeme, denn sie schätzen die außerordentliche Zuverlässigkeit, Verfügbarkeit und Genauigkeit unserer Lösungen auch in kritischen Missionen im täglichen Einsatz. Dies erreichen wir durch unsere mathematisch-physikalisch präzisen Algorithmen - und ganz bewusst nicht durch AI (artificial inteligence) interpretierte sogenanten "Messergebnissen".

AI-Methoden kommen bei uns nur dort zum Einsatz, wo diese z.B. bei Objekterkennung oder Klassifizierung einen Beitrag liefern können abr keinen sicherheitsrelevanten Einfluss haben.

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[2]. 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 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).

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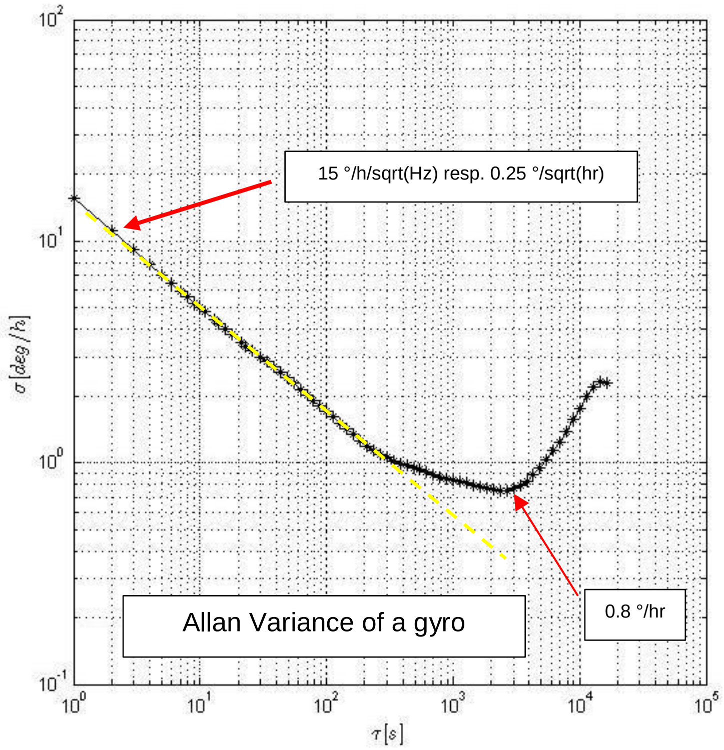
[2] Observability means, that the sensor data fusion has enough information available to estimate certain states like gyro bias or heading. Example: If an aircraft flies always straight forward at constant speed, it is impossible to estimate vertical gyro bias or heading using a single antenna GNSS aiding,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



Accelerometer Offset: An offset in an accelerometer introduces an error during alignment, specifically in the determination of the initial roll and pitch angles, as it directly affects the accuracy of measuring gravity (approximately 9.81 m/s²). For instance, an offset of 0.1 mg results in an angular error of about 0.006 degrees in either pitch or roll (0.1 mg = g × sin(0.006 deg)). These sensor offsets can be estimated during operation through the system's integrated Kalman filter data fusion, utilizing GPS, DGPS, RTK data, or the Zero Velocity Update Procedure (ZUPT), provided there is sufficient motion dynamics.

Bandwidth: In general, the dynamic performance of an inertial measurement system (IMS) improves with higher internal sampling rate and bandwidth of the inertial sensors. Proper internal data synchronization (time stamping) is also essential for accurate signal processing, especially when the IMS operates in challenging dynamic environments. A high-precision internal time reference and hardware-based time stamping for all data are crucial for ensuring reliable performance in an INS. Furthermore, low latency in data output is mandatory for utilizing an INS in trajectory or attitude control applications, such as those involving autonomous vehicles.

Gyro Random Walk: This value, expressed in deg/sqrt(hr), represents the noise of the gyro used. A larger value indicates more noise in the measured angular rates and angles. Some manufacturers also specify this as noise density in deg/h/sqrt(Hz). Both values are equivalent for white noise gyro output; dividing the second value by 60 converts it to deg/sqrt(hr). An angular random walk (ARW) of 0.003 deg/sqrt(hr) suggests that the angular error (uncertainty) due to random walk is approximately 0.001 deg after 6 minutes (unaided) or 0.0004 deg after 1 minute (all values reported as one sigma). The angular random walk is crucial for the accuracy of north-seeking, as halving the random walk reduces the time required for north-seeking by a factor of four, provided the gyro's resolution is sufficiently high.

The accompanying plot of the Allan Variance for a mid-performance gyro graphically illustrates the square-root ARW of a MEMS gyro (to obtain the ARW in [deg/sqrt(hr)], take the value at 1 second and divide it by sixty). At 1 second, the square-root of the Allan Variance is 15 deg/hr. This yields an 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) (assuming white gyro noise). The bias stability, indicated by the minimum point of the graph, is 0.8 deg/hr at a correlation time of 3,000 seconds. Overall, this demonstrates that we are utilizing a relatively high-quality MEMS gyro.

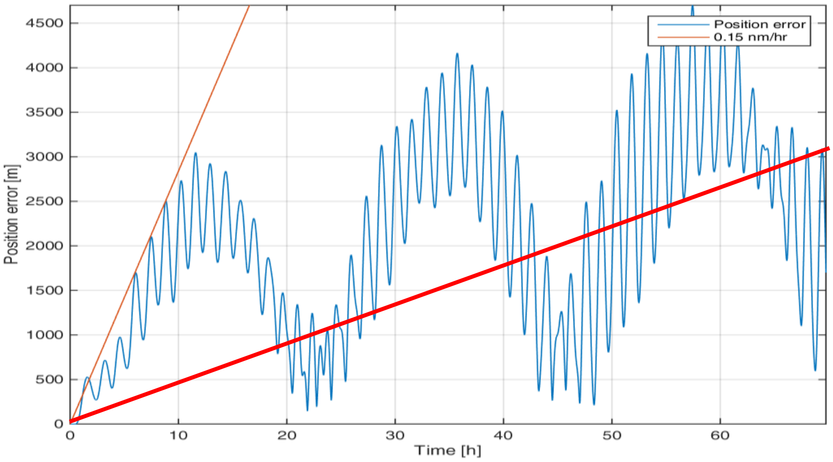
Position error of an *unaided, free inertial* INS:

We must distinguish between short-term accuracy and long-term accuracy in an inertial navigation system (INS). Additionally, it's important to differentiate between arbitrary moving objects, such as aircraft, ships, or spacecraft, and land-based vehicles that travel on roads — applications characterized by specific motion constraints.

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

Definition: An arbitrary moving unaided free inertial INS operates in a mode devoid of any external aids, meaning there is no GNSS, magnetometer, air data, Doppler log, LiDAR, RF positioning, or ZUPT. In this mode, the INS can move without limitations, provided it remains within the measurement range of the inertial sensors.

In this context, the system experiences a position error known as Schuler oscillation. This position error, typically measured in nautical miles per hour (nm/hr), reflects the global position error of the free inertial INS due to residual accelerometer and gyro errors. The oscillation occurs with a period of approximately 84 minutes, as well as with a 24-hour cycle. The amplitude of the oscillation is influenced by the accelerometer offset, while the average position drift, or 'shift,' is affected by gyro drift. This is a simplified model for explanatory purposes; further details can be derived 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 displays position error in meters and time in hours. For example, the free inertial INS shows a position error of 3 km after 70 hours (equivalent to 0.02 nm/hr)

As illustrated in the plot, it is crucial to clarify how the value of 'free inertial drift' is derived. Due to the 24-hour oscillation, you can observe that the position error after 11 hours is identical to that after 70 hours. The conditions of data acquisition also play a significant role: this plot was generated following only 10 minutes of initial alignment.

Why do some vendors claim much lower free inertial drifts?

If the INS is aided prior to drift determination (for instance, by operating it with significant motion dynamics and external aids like GNSS), and if the system is aided by an EM-log (example: naval vessels, submarines), it is possible to achieve drift values below 1 nm per 100 hours, or even over 360 hours. However, it is essential to note that this scenario does not represent 'pure inertial, unaided' operation, as the INS requires adequate position aiding for a substantial duration (e.g., 12 hours) and at least periodical velocity aiding to provide such results. Many datasheets, however, do not adequately explain this requirement, nor do they mention that these systems need to be temperature-controlled and require significant time for power-up.

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

Definition: A free inertial operating INS functions in a mode devoid of any external aidings, meaning no GNSS, magnetometer, air data, Doppler log, LiDAR, RF positioning, or other assistance. Short-term operation refers to a duration that is significantly shorter than the Schuler period of 84 minutes (as previously mentioned).

In this operational mode, the values (expressed in meters or meters per second) are relevant for measurements lasting less than approximately 20 to 40 minutes, as Schuler oscillation is not significant for short-term measurements. An accelerometer offset results in a position error that increases quadratically over time.

$$\text{delta\_s} = 0.5 \text{ x } \text{delta\_a} \text{ x } T^2 \qquad [\text{m}] \qquad \text{(a)}$$

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

$$\text{delta\_s} = g/6 \text{ x } \text{delta\_omega} \text{ x } T^3 \qquad [\text{m}] \qquad \text{(b)}$$

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:

$$\text{delta\_s} = 0.5 \text{ x } g \text{ x } \sin(\text{delta\_attitude}) \text{ x } T^2 \qquad [\text{m}] \qquad \text{(c)}$$

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

If a provider promotes an inertial measurement system (IMS) with a roll/pitch accuracy of 0.005 degrees and claims 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—without odometer aiding, without ZUPT, and without internal vibration isolators—you can easily verify and calculate two key factors using the simple thumb rule equations provided 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 simple calculations reveal a discrepancy in the reported performance data; either the position error must be significantly worse, or the attitude error must be much smaller to achieve the advertised specifications. For context, an absolute accuracy of 1.5 µg in accelerometer bias approaches gravimeter accuracy, yet such reliability is typically not available in industrial or military land navigation systems. It's important to note that gravity itself changes by approximately 0.3 µg for every meter of elevation!

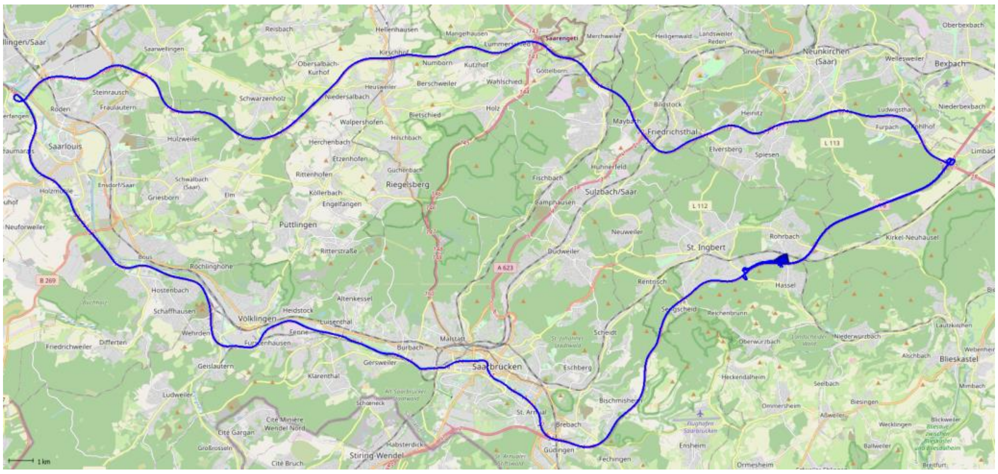
Position error of an *unaided,* pure inertial INS on road vehicles (taking only into account motion specific constraints):

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**[3]. These proprietary algorithms are applicable in both, in real-time as well as in post-processing.



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.

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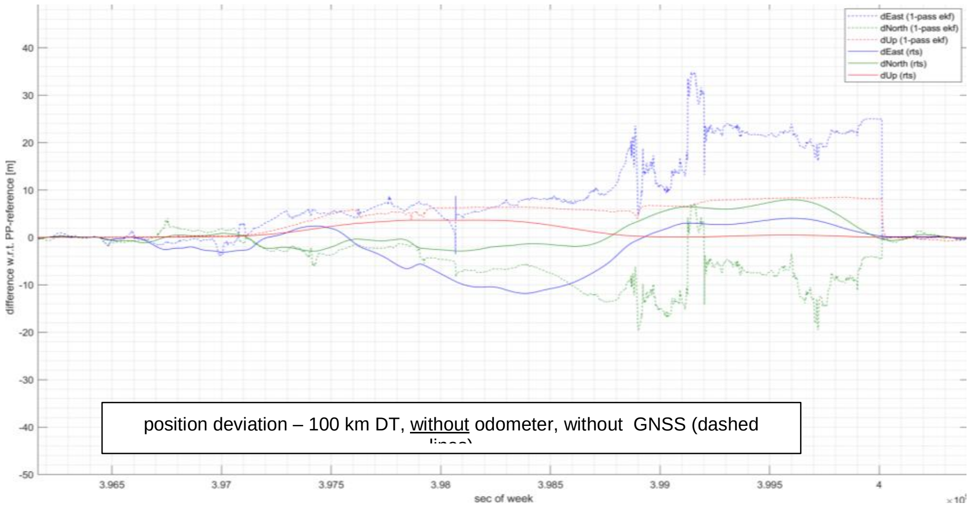
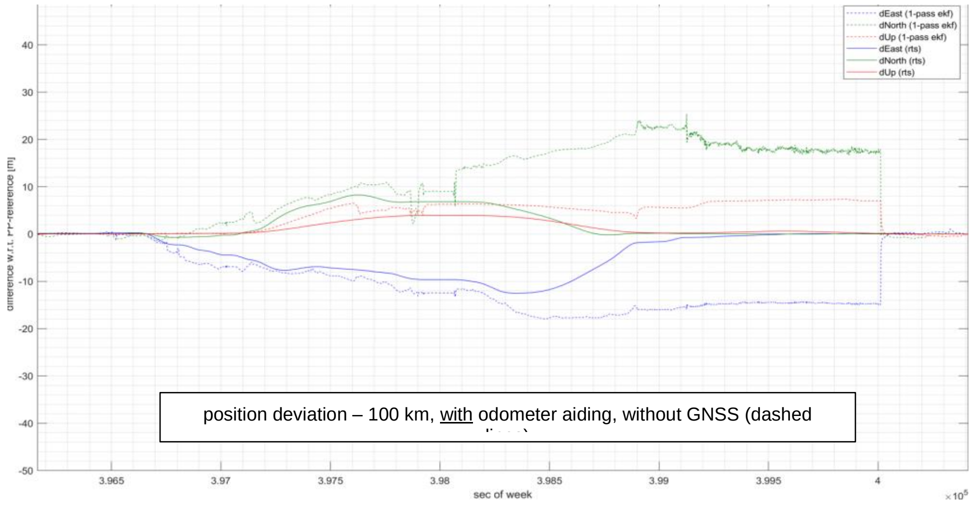
[3] Have in mind, that datasheet of conventional high performance INS for military applications, provided by competitors, annunce values of about 0.11 % horizontal and 0.1 % vertical, but with (!) odometer (VMS – vehicle motion sensor, wheel sensor) aiding, while the iMAR solution provides the above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

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”.



position deviation – 100 km DT, without odometer, without GNSS (dashed



position deviation – 100 km, with odometer aiding, without GNSS (dashed

If a vendor claims a much better position accuracy in real-world (!) environment, it is advised that the user performes extensive tests to validate such promised data in his application. Lab conditions are often far away from real world conditions – and e.g. defining a “closed loop” test track and only comparing the test results at the end of the mission does not reflect the truth. iMAR has specially designed a verification method to qualify the performance of INS systems in GNSS denied environment. It has been published in 2024-10-23 at the international IEEE conference DGON ISA 2024 (link).

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

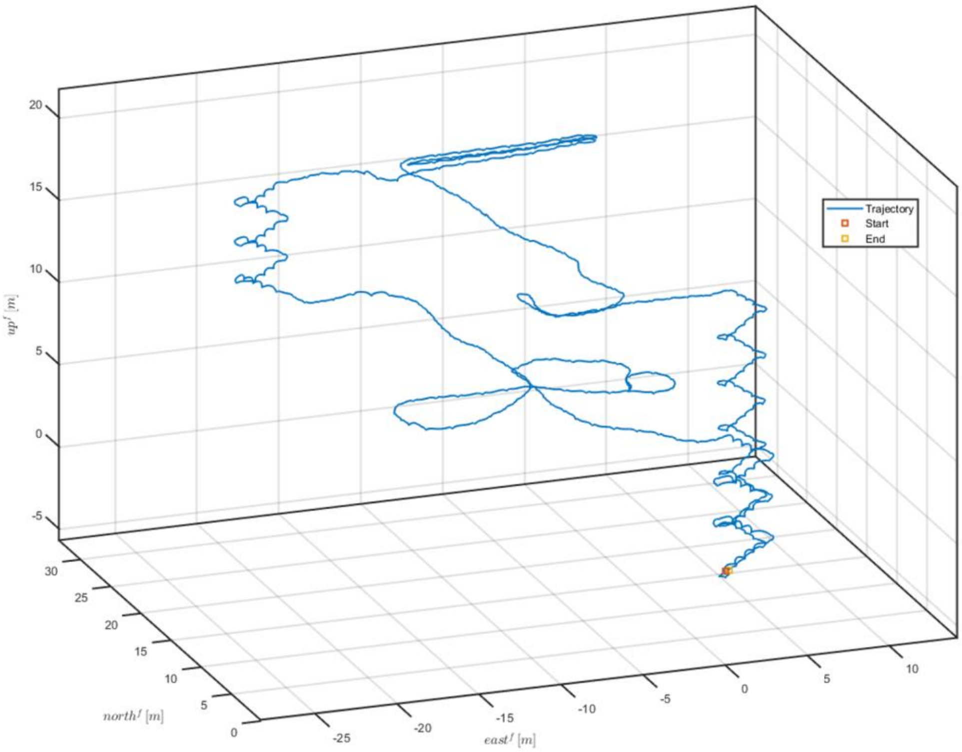
Definition: A free inertial operating INS with periodical ZUPT aiding means, that the INS is in free inertial operation mode (no external aiding, i.e. no GNSS, no magnetometer, no air data, no Doppler log, no LiDAR, no RF positioning, …..) and the INS can be operated at zero velocity condition (ZUPT) 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 builduing: Distance 338 m, final position error 0.5 m

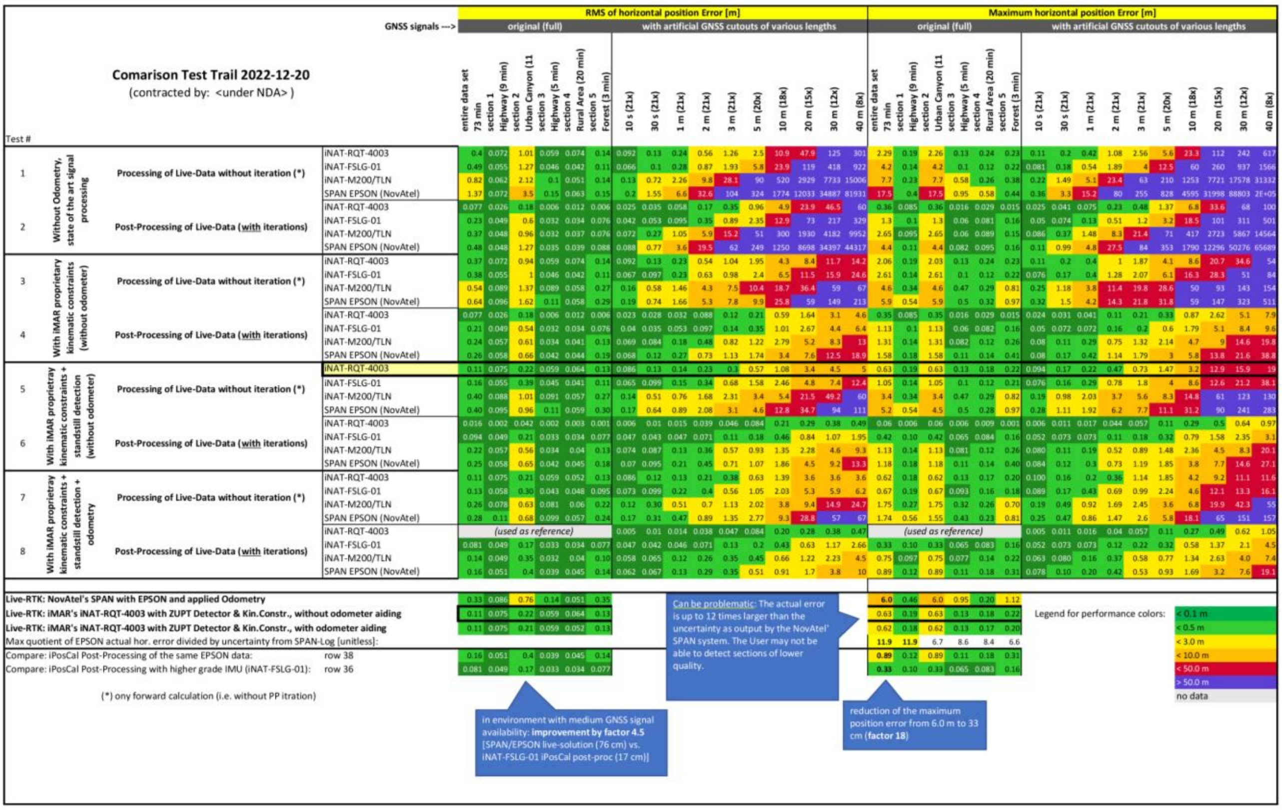
The specific constraint allow that the position error will increase in good approximation only with the walked distance. And the INS which is used weighs only a few grams. Ask iMAR Sales engineers for details about iTHESEUS, the best of class autonomous pedestrian localization system (Link).

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

When the INS is aided, it's important to distinguish between position aiding (e.g., via GNSS) and velocity aiding (e.g., through an odometer, wheel sensor, VMS, EM-log or GNSS Doppler velocity).

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>)

RMS of horizontal position Error [m]

Test #			GNSS signals --->	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)
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
			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
			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
			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
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
			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
			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
			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
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
			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
			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
			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
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
			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
			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
			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
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
			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
			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
			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
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
			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
			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
			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
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
			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
			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
			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
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
			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
			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
			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

Maximum horizontal position Error [m]

Test #			GNSS signals --->	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)
1	Without Odometry, state of the art signal processing	Processing of Live-Data without iteration (*)	iNAT-RQT-4003	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	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	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)	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	0.36	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	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	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)	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	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	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	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)	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	0.35	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	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	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)	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	0.63	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	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	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)	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	0.06	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	0.42	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	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)	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	0.62	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	0.67	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	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)	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	0.011	0.016	0.04	0.057	0.11	0.27	0.49	0.62	1.05
			iNAT-FSLG-01	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	0.75	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)	0.89	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 of horizontal position Error [m]						Maximum horizontal position Error [m]					
		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)	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:

Every inertial measurement system requires an initial position and orientation for optimal operation. The initial position can be obtained through user input (such as waypoint or landmark input from a map), GNSS, or other sources. The initial orientation can be determined using various methods, with implementations varying significantly depending on the performance of the core inertial sensors. Typically, the alignment process consists of three stages of signal processing: leveling (either dynamic or static), coarse alignment, and fine alignment. We distinguish between static alignment (when the system is at a standstill) and dynamic alignment (during motion):

- 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[4] 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.
        - 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

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[4] 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.

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. There are several methods to obtain "true heading" – but do not mix them with "Course over Ground"!

a) If the INS contains high performance gyroscopes like ring laser or fiber optical gyros or hemispherical resonator 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.

b) 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.

c) 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.

d) 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[5], 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) [see case b)], it is feasible to determine true heading, 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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[5] 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

Caution:

Some vendors promise impossible performance: One of them e.g. claims to achieve a true heading (pure inertial, i.e. without GNSS or other aidings) of **0.1 deg** sec lat, but in the same datasheet he also confirms a gyro bias day-to-day drift of 0.05 deg/hr (remember: the "bias instability" parameter is not relevant for free inertial gyro compassing!). A quick calculation regarding earth rate shows, that the best you can achieve by physics with 0.05 deg/hr is a true heading of

$$\Delta\psi = \text{atan}\,(0.05 \text{ deg/hr} / 15.04 \text{ deg/hr}) = \mathbf{0.19 \text{ deg}} \text{ sec lat (and not 0.1 deg)}$$

We typically do not publish datasheet from other vendors, but we decided todo so in this case, because we have many questions from customers regarding this issue:

From Datasheet downloaded in 2024-10-25 from the vendor's web site (BOREAS D70):

SPECIFICATIONS

NAVIGATION

Roll and Pitch Accuracy	0.01 °
Heading Accuracy (Dual GNSS 1 m separation)	0.01 °
Heading Accuracy (without GNSS)	0.1 ° secant latitude RMS
Gyrocompassing Alignment	2 minutes coarse

GNSS

Model	Advanced Navigation Aries
Supported Navigation Systems	GPS L1, L2 GLONASS L1, L2 GALILEO E1, E5b BeiDou B1, B2

SENSORS

SENSOR	ACCELEROMETERS	GYROSCOPES	PRESSURE
Range	± 15 g	± 490 °/s	10 to 130 kPa
Bias Instability	7 µg	0.01 °/hr	8 Pa
Initial Bias	< 100 ug	< 0.05 °/hr	< 50 Pa
Initial Scaling Error	340 ppm	100 ppm	-
Scale Factor Stability	150 ppm	20 ppm	-
Non-linearity	150 ppm	10 ppm	-
Cross-axis Alignment Error	< 0.001 °	< 0.001 °	-
Noise Density	40 ug/√Hz	0.3 °/hr/√Hz	0.4 Pa/√Hz
Random Walk	23 mm/sec/√hr VRW	0.005 °/√h ARW	-
Bandwidth	300 Hz	400 Hz	50 Hz

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Time Stamping / Synchronization / Latency / Jitter: Especially when an inertial measurement system (IMS) is used for control tasks or surveying applications, precise time stamping of inertial data, odometer data, and all other aiding information (such as GNSS and machine vision) is essential. For this reason, iMAR's measurement systems, equipped with the proprietary iNAT architecture, offer high-performance time stamping capabilities.

For example, if a target is moving at 100 m/s, a timing error of just 1 millisecond would result in a position error of 10 cm. Given that RTK aiding can achieve about 1 cm accuracy, it's clear why a synchronization accuracy of at least 25 µs is essential, along with high internal clock performance. Additionally, inertial navigation systems (INS) designed for advanced applications can provide NTP data for time synchronization.

In some cases, integrating a semiconductor-based atomic clock may be beneficial for prolonged operation in GNSS-denied environments.

When utilizing an inertial navigation system (INS) for control tasks, such as autonomous vehicle guidance or platform stabilization, minimal latency and jitter in both the acquired data and output are essential. The architecture of iMAR's systems—such as iNAT, iPRENA, iCOMBANA, iSULONA, iTraceRT-MVT, and iATTHEMO—ensures best-in-market performance in this regard. (Link)

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

The systems manufactured by iMAR are specifically designed for markets with demanding EMI/EMC requirements, including surveying, vehicle testing, aerial laser scanning, pipeline inspection, vehicle and camera stabilization, drilling, and aircraft guidance and control. Given the wide range of applications and the need for high reliability, iMAR systems are protected and qualified according to stringent standards such as MIL-STD 461, MIL-STD 704, and DO-160, in addition to environmental qualifications per MIL-STD 810 or DO-160. These measures help prevent unexpected electromagnetic interference and related performance degradation. Due to our high qualification standards, approximately 50% of all iMAR systems originally designed for the industrial market are also utilized in advanced military applications. Here is a **link** to our EMI/EMC lab, Spezial-EMV GmbH, located in St. Ingbert, Germany. This facility offers EMI/EMC qualification and certification services for customers worldwide. Spezial-EMV GmbH is a wholly-owned subsidiary of iMAR Navigation and is situated on the iMAR Campus in St. Ingbert, Germany.

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EMI / EMC TESTLAB & SOLUTIONS

Ensure that the protection level of the system you intend to use meets these requirements as well. In particular, inertial measurement systems offered by competitors for commercial or surveying applications often lack adequate EMI/EMC protection. This deficiency can result in operational problems in real-world environments.

MTBF: The reliability of an Inertial Navigation System (INS) is crucial for critical applications. Typically, high-performance inertial sensor assemblies exhibit a calculated mean time between failure (MTBF) of approximately 100,000 hours. Field experience data may indicate even higher values; however, caution should be exercised when comparing these figures. The MTBF derived from field data often does not account for the full range of environmental factors considered in model-based calculations.

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

- In which environment was the MTBF calculated? Refer to the categories in MIL-STD 810H or DO-160G for details and a better understanding.
- Is this data solely based on field conditions, which may not fully account for the complete range of environmental impacts, such as vibration and temperature?
- Keep in mind that the calculated MTBF for high-performance electronics, even with advanced EMI/EMC and over-voltage protection and integrated GNSS engine, along with MIL connectors (excluding inertial sensors), is typically by far less than 200'000 hours.

Open Interfaces: Open interfaces are essential for users to achieve maximum flexibility when utilizing the system. These interfaces include user interfaces as well as connections to external sensors, such as optional GNSS engines, odometers, depth/altitude sensors, visual odometry, and DVL, among others. Additionally, the system architecture should support custom-specific interfaces as needed. For more details, please refer to iMAR's proprietary but published iXCOM protocol. Link

GUI / Wizard: Users who are new to operating an inertial measurement system may require assistance to implement it effectively. Typically, a graphical user interface (GUI) is provided to facilitate the configuration of the IMS on the vehicle.
In addition to configuration support, the GUI should allow for real-time visualization of acquired data as well as playback mode. An installation wizard is also beneficial for helping operators survey the lever arms between the GNSS antenna, odometer, camera, and the inertial measurement unit. Finally, the GUI should include maintenance features to enable quick 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 needed both in real-time and during post-processing. For real-time use, the aforementioned solutions are available, including INS/GNSS-RTK options, with optional support from LiDAR and other aids. Link

For post-processing, various solutions are available on the market, each differing significantly in their methods and algorithms. Post-processing enables forward and backward calculations to correct for most modeled sensor errors. Keep in mind that, due to the nature of post-processing, the position and velocity errors at the start and end of the measurement period will appear to be zero. Link

Gravimetry: Airborne gravimetry or gradiometry involves measuring gravity disturbances from a moving aircraft. This requires highly specialized algorithms and ultra-precise inertial sensors, with results obtained through post-processing. The physical challenge lies in achieving a gravity measurement accuracy of 1 µg (1 mGal) aboard an aircraft or ship experiencing motion dynamics of up to 1 g. iMAR has been offering the world's leading system for airborne gravimetry for several years. Link

Customized Solutions: Many applications demand customized solutions involving inertial sensor systems. With over 30 years of expertise, iMAR is equipped to deliver tailored solutions, from prototypes to production batches of several thousand units. Feel free to contact our Technical Sales team for a detailed analysis of your requirements — our skilled engineers and scientists will participate in the meeting to provide the best technical and commercial solution for your application.

Many other factors also significantly influence the performance of an inertial measurement system. If you have any additional questions, please feel free to contact us for further information.

Easy-to-Use Interfaces: iMAR's inertial measurement solutions feature user-friendly communication and data interfaces, refined over more than 30 years of experience across a wide range of applications, including commercial, industrial, automotive, and military sectors. Supported interfaces include Ethernet/TCP/IP/UDP, EtherCAT, UART RS422/RS232, CAN, NMEA183, ARINC429, HDLC, SDLC, NTP, and more, as well as custom hardware and software interfaces.

To further support integrators and users, iMAR also provides ROS 2 nodes, Python scripts, an SDK for C++, and a 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. That's why our team at iMAR Navigation provides comprehensive support, from system selection to integration, available in both German and English, and if needed, anywhere in the world.

With over 30 years of extensive experience across nearly all applications of inertial measurement technology, our support team is always ready to assist you!

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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 anspruchsvolle 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 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!

Feel free to reach out to our support and sales engineers with 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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