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Review of Advantages and Disadvantages of Magnetometer Types and Measuring Techniques to be Used for GNSS-free PNT in the Maritime Environment

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ABSTRACT: Reliable determination of position, navigation and timing (PNT) is essential for safe shipping traffic. PNT using the Earth's magnetic anomaly field, which is always globally available, is a promising alternative to satellite-based positioning which can be disturbed in case of conflicts. The aim of the review is to give an overview of the advantages and disadvantages of magnetometer technologies and data gathering methods with respect to positioning and their restrictions of the maritime environment such as specific setups, necessary accuracy and sensitivity as well as measurement frequency to obtain the high frequency components of the earth magnetic field.

1 INTRODUCTION

In recent decades, satellite-based navigation or GNSS (Global Navigation Satellite System) has become the standard in civil shipping. However, GNSS is susceptible to jamming and other sources of interference. This can lead to incorrect positioning information, which can have devastating consequences for ship and supply chain safety. In recent years, conflicts have shown that satellite-based navigation can be changed (spoofing) and/or jammed (e.g. in the Baltic Sea region), or in the event of a conflict, the spatial resolution can be reduced in certain regions. Therefore, satellite-independent navigation systems for civil shipping are essential to detect and mitigate the effects of a disruption of GNSS-based systems and to stabilize supply chains.

Accurate positioning without the use of GNSS is a difficult engineering problem. Many alternative technologies exist as summarized in Table 1, each with their own limitations and benefits. Often, these limitations restrict where and when the alternative systems may be used. Ships can determine the position via charts or external signals or determine a position relative to a starting point with inertial sensors via dead reckoning. Possible implementations of the methods are shown in Table 1. Compared to direct positioning, inertial sensors have the problem that the drift of the sensors increases errors in positioning over time. Very accurate inertial sensors have high costs and often high complexity in maintenance. Inertial sensors are advantageous in that they provide additional data for positioning compared to map-based methods. Therefore, it makes sense to use map-based methods and inertial sensors in combination. However, in this review we are concentrating on positioning via maps.

The different methods of positioning have different advantages and disadvantages. While radio-based and optical methods have passed their heyday in the maritime world due to their limited range, magnetic field and gravitational anomaly measurements are relatively new, non-interference-prone methods for which there is often not yet sufficient map material. Yet there are early adopters with maritime surveys have already paved the way in the usage of this new technology.

Table 1. Presentation of different methods for positioning and inertial sensors

	Position via maps	Dead reckoning via inertial navigation sensors (INS)
Methods	- Magnetic field (map-based) - Gravity (map-based) - Optical (e.g. distance navigation in a convoy, lighthouses) - GNSS - Radio-based - Sea depths	- Rotation Sensors - MEMS - Fibre Optical Gyroscope - Hemispherical Resonator Gyroscope - Ring Laser Gyroscope - Accelerometers (MEMS)

Navigating with the Earth's magnetic anomaly field shows potential to overcome common limitations of optical or radio-based positioning methods by always being available, world-wide. The earth magnetic field has a higher resilience to jamming than GNSS, since it would take much more energy to disrupt the earth's magnetic field. Navigation accuracies within hundreds of meters can be reached with accurate magnetic field maps. However accurate maps with sufficient sensitivity, spatial resolution and recordings of high-frequency, daily and monthly variations of magnetic field anomalies are not available for most areas at sea. Hence, adequate magnetometers are needed for both navigation and generation of more accurate maps.

There are many theoretical papers on the topic of map matching for navigation [1] [2] [3] [4] [5]. The algorithms typically either use variations of Kalman filters or particle filters or combinations of both. Most algorithms can use multi-sensor data, e.g. from the INS system and the magnetometers which improve the navigation accuracy up to some point [1]. For these algorithms to work, the errors related to positioning, velocity and tilt of the INS systems as well as the estimated temporal variation and accuracy errors of the magnetometers need to be considered. We are considering a navigational accuracy of a few hundred meters to be sufficient for civilian seafaring.

2 MAPS OF THE EARTH MAGNETIC FIELD

Any physical observables outside controlled laboratory situations are dependent on influences from their surroundings which need to be considered. This holds for the earth's magnetic field which has anomalies which cannot be modelled purely mathematically. Concerning positioning with the earth magnetic field, this has advantages and disadvantages. On one hand these anomalies provide maps with enough features to be able to navigate, on the other hand some features cannot be modelled and contribute to systematic background noise.

There exists a set of magnetic field maps which are based on mathematical models as well as data from satellites, observatories and surveys around the world describing different components of the magnetic field. Usually, these maps are used in combination with each other to extract the exact value at a certain position. E.g., the International Geomagnetic Reference Field (IGRF) [1] is a standard mathematical description of the Earth's main magnetic field. It is used widely in studies of the Earth's deep interior, crust, ionosphere, and magnetosphere, but does not consider anomalies which arise from geological features. The earth magnetic field anomalies are compiled in the EMAG2 map which considers data from satellite, ship and airborne magnetic measurements [8]. The EMAG2 map has a spatial resolution of 2-arcminutes. To reduce navigation accuracies stemming from the low spatial resolution, new measurements, e.g. from ships carrying magnetometers can be used to incorporate these data into the maps and therefore generate a self-building map with a higher resolution. Thus, magnetometers ca n be used for both positioning and map building, at the same time.

To generate a self-building magnetic field map one can use existing models of magnetic fields. The modeling of magnetic anomaly fields is well understood in the field of geophysics where magnetic anomaly fields are routinely modeled for geological studies and for oil and mineral exploration. This type of modeling can be seen as an inverse problem, in which a set of observations is used to solve a magnetic source distribution to model the observed field. Several methods with different advantages and disadvantages can be used. E.g. the equivalent source dipole inversion method [9] that represents the combined effect of a set of magnetic dipoles or least-square collocation can be used. While the first method is mathematically instable, least-square collocation is often used for map building [10]. Least square collocation calculates the magnetic field value at a given point as the weighted average of nearby observations. Least square collocation often does not take physical effects into account, however there are methods which use the Maxwell equations and therefore are more representative of reality [11]. However, these methods need a vector field which typically is not available. For aviation it has been shown that there is potential for a huge improvement for existing magnetic field maps when adding additional data taken in test flights [9].

To find the limits of sensitivity necessary in magnetometers we have studied the gradients of the magnetic field in the Baltic Sea area with the help of the EMAG2 map. As can be seen in Figure 1 the gradients are around 4-21nT between a nautical mile at a latitude of 55.3 degree a longitude between 14.6 and 14.8 degrees in the Baltic Sea. Similar data can be taken at other locations in the Baltic Sea. It is not possible to get a better resolution due to the resolution of the map. To get to a navigation accuracy of a few hundred meters, we estimate that a sensitivity of the magnetometers a few nT or even below is necessary if one uses the magnet field map without considering information from the INS or in case of measuring gradients between two magnetometers which are located a few hundred meters away from each other.

The maps have certain characteristics and limitations for positioning: E.g. in the EMAG2 map distinct patterns and magnetic signatures can be seen in the oceans. They are attributed to the formation and destruction of oceanic crusts and the alternating polarity of the geomagnetic field. Figure 2 shows such characteristic changes in the earth's anomaly field at the edge of tectonic plates.

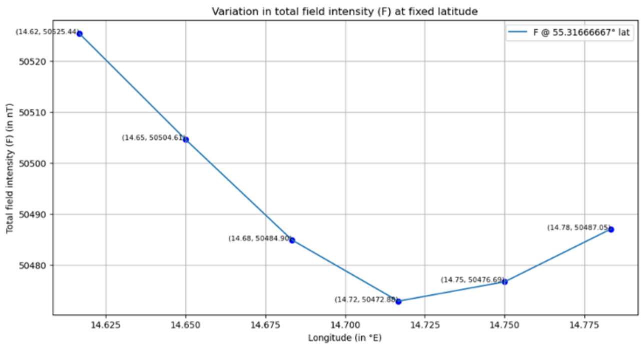

Figure 1. Variation in total field intensity (F) at fixed latitude of 55.3 degrees and longitude between 14.6 degrees to 14.8 degrees from IGRF-14 plus EMAGv3 data. The data has been taken at an altitude of 4km.

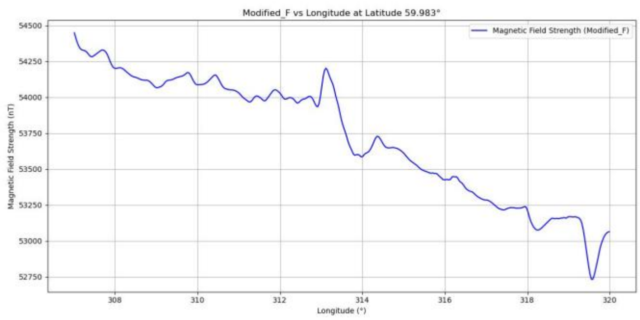

Figure 2. Variation of magnetic field strength close to tectonic plate edges (latitude 69 degrees and longitude between 306 and 320 degrees) from IGRF and EMAGv3 data.

3 TEMPORAL VARIATION OF THE EARTH MAGNETIC FIELD

In addition to the limitations depending on the magnitude of the anomalies, additional factors limit the navigational accuracy. One limiting factor is the temporal variation, where the yearly and monthly variation can be modelled quite well, but the daily variations are stochastic. A good way to suppress the daily variations is with the help of a stationary reference magnetometer. Values of the reference stations are valid for a radius of about 100km depending on the frequency of the magnetic field variations [10]. The higher the frequency, the shorter the propagation of the variations. There is data available from a worldwide network of magnetometers (e.g. the Intermagnet or the SuperMagnet network). The existing stationary reference stations are mainly located ashore or on islands. However, especially in Europe there is a high density of magnetometers to be found, so that there is good coverage of the Baltic Sea. For high-sea areas there is no sufficient coverage of the existing reference stations. Figure 3 shows the daily variations in November 2020 at the InterMagnet magnetometer in Wingst (near Hamburg). When modelling the daily variation, one gets a variance in the order of a few nT. Thus, lower accuracies of the magnetometers only make sense when using real time values from the reference stations which can consider the stochastic changes or when measuring the gradients between two magnetometers which are a few hundred meters away from each other.

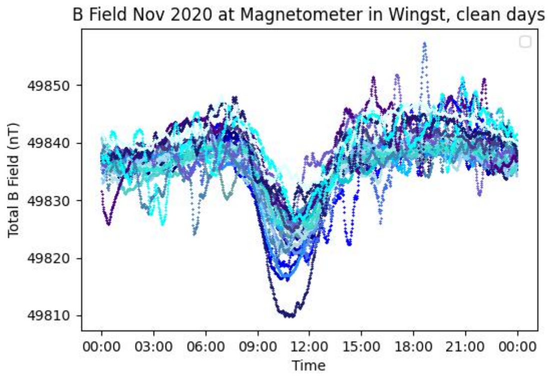

Figure 3. Daily variation of the InterMagnet magnetometer in Wingst (near Hamburg) for several days in November 2020 from the InterMagnet dataset. Days which have a k index [9], a parameter which measures the influence of the solar activity on the earth magnetic field, lower than 3, have been selected.

4 EFFECT OF THE VESSEL AND SEA WATER

To reduce the effects of the vessel on the earth's magnetic field one can envisage either to install the magnetometer in a water-tight tow fish which is towed behind the vessel or to carry the magnetometer on ship as far away from electrical sources as possible and compensate the effects of the vessel. For marine surveys, often boats with small magnetic signatures have been used. In such settings an error of a few nT in total intensity and about 0.1 degree in declination and inclination are reported for a carbon fiber vessel [2]). However, when using steel vessels with a strong associated magnetic signal such calibration techniques break down and yield much higher errors [3]. One can mitigate some effects by sophisticated calibration algorithms such as Tolles-Lawson which holds if the permanent, induced and eddy current terms can be approximated linearly [4]. Continuous calibration routines can be carried out throughout the voyage to reduce the calibration error.

Since seawater is a weak electrical conductor, motional induction of sea water moving in the earth magnetic field causes magnetic signals. These can be tidal effects or ocean swells. Tidal effects play a role in Europe in areas such as the Northern Sea. Due to their periodic nature these effects can be modeled in a similar way to daily variations of the earth's magnetic field. Ocean swells have been studied since 1965 [5]. As both experimentally and theoretically shown, the period of the ocean swell and of the magnetic field is the same. In case of [6] the ocean swell has a period of about 13s with a sharp spectral peak and a magnetic signal of about 1.6 nT for every meter of wave motion. Such sharp spectral peaks can be filtered in marine magnetic measurements. The swell signal decays exponentially with height which means that if the magnetometers are mounted on board big ships the effects of ocean swell are typically negligible.

5 OVERVIEW OVER DIFFERENT MAGNETOMETERS

5.1 *Definition of sensitivity and accuracy*

Concerning magnetometer technology parameters such as the necessary accuracy and sensitivity, power requirements, additional requirements (e.g. cryogenics), dimensions of the setup and operating frequencies, bandwidth and drift need to be considered for the use case. The dynamic range of the magnetometers needs to be sufficient to measure the earth's magnetic field which ranges between approximately 22 and 67 μT. In this review we are focusing on the necessary accuracy for positioning in the civil maritime sector.

Sensitivity and accuracy are two important properties of magnetometer sensors. Sensitivity, i.e. the larger value of either sensor noise or sensor resolution, is typically given in units of nT/sqrt(Hertz) RMS. This means that a measurement rate of one microsecond decreases the sensitivity by a factor of one thousand. As a rule, higher frequency variations of the earth magnetic field tend to have lower amplitudes [2]. From a navigation standpoint this is beneficial, as the larger temporal variations will vary more slowly with time. If the sampling frequency is at least twice the highest frequency (Nyquist frequence), information about such high-frequency signals can be analyzed and bandpass filters applied to suppress the errors.

The accuracy, i.e. the precision with which the total magnetic field can be measured, is a tricky specification to describe in the context of measuring the earth's magnetic anomaly field. The actual instruments have a certain absolute accuracy, but they measure the total field, including the vessel's magnetic field, which can never be totally removed. The actual sensor's absolute accuracy may be well under 1nT for e.g. an optically pumped magnetometer, but if the vessel's field cannot be removed to that extent, it will be the vessel compensation system which is driving the accuracy of the sensor with respect to measuring the earth's magnetic field.

5.2 *Scalar magnetometers*

Scalar magnetometers have been used since the sixties in aerial surveys and are well-proven instruments. Optical pumping alkali vapor magnetometers with high sampling rate and high sensitivity are generally used aboard airframes whereas proton precession magnetometers (including Overhauser) are favoured at sea. There are several types of nuclear resonance magnetometers including proton-precession, optically pumped magnetometers and Overhauser magnetometers. Proton precision and Overhauser magnetometers are a mature technology while there has been a lot of development for optically pumped [8] magnetometers concerning miniaturisation and the need of cryogenic cooling. Optically pumped magnetometers still have a small dynamic range, so that they can be deployed in the earth's magnetic field, but they cannot be objected to too high magnetic fields. The nuclear resonance magnetometers are small, lightweight, stand-alone instruments which can digitally provide an extremely sensitive (typically smaller than 0.04nT/sqrt(Hz)) and accurate (smaller than 3nT) magnetic field measurement [8]. A good way to measure the sensor accuracy is to watch how a gradient measurement drifts in a constant field. Because the gradient measurement is subtracting out the common field between each instrument, any drift is likely due to inaccuracies. Novel magnetometers such as optomechanical magnetometers [10] [11] promise sensitivities ranging from several nT/sqrt(Hz) down to tens of pT/sqrt(Hz). However, these platforms are novel and will need some further research and engineering before allowing to use them in operation.

5.3 *Gradient magnetometers*

Gradient magnetometers have been deployed since the eighties. They are typically towed behind a ship with a distance between the two sensors of a few 100m. Summing up the differences between the field values of the two sensors along the line reconstructs the spatial variations that are due to the main field of the Earth and the crustal magnetic sources. It also allows the recognition and removal of time varying field variations. The effect of vessel on the earth's magnetic field is negligible at long tow distances. Some papers [2] report towing distances of more than 700 m, where the ship's magnetic field is well below one nT and can be assumed constant along a line with constant course. However, a very long cable is required to maintain the distance between the ship and the magnetometer which could lead to potential positional inaccuracies.

Because gradiometers are towed behind the ship and therefore do not get additional errors due to the magnetic field of the vessel, they provide the most accurate data of gradients and are very well suited for map building of magnetic anomaly fields as well as measuring the gradients of the earth magnetic fields for navigation purposes.

5.4 *Vector magnetometers*

Vector magnetometers can be an important tool at the poles and equatorial regions where the vector components of the earth magnetic field differ greatly. Here scalar magnetometers reach their limits. While in the pole region the horizontal component of the magnetic field is large, and the total magnetic field is low, close to the equator the vertical component of the magnetic field is about doubled to the total field. Here vector magnetometer can be used to model the anomalies by fitting the enhanced vertical component together with the magnetic field [2].

When considering vector magnetometers, the roll and pitch of vessels needs to be considered to transform the strap-down vector magnetometer data into a world reference frame. Attitude sensors typically do not have the necessary resolution. To allow for a resolution of 1 nT in the earth magnetic field, which is on average about 50 000 nT strong, an attitude accuracy of atan(1/50 000)=30.6 arcsec or 0.001 degree is necessary. Such requirement is almost impossible. If the attitude sensor and the magnetometer were 10 cm away from each other, the relative orientation between attitude sensor and magnetometer would be below one micrometre. Values around 0.01 degree orientation error are reachable with modern attitude sensors and result in a systematic error of the magnetic field of about 15 nT. However, there exist algorithmic methods to correct for the attitude in operation and can provide data with the necessary accuracy [23].

The existing vector magnetometers have quite different specifications: e.g. SQUID magnetometers [10] [11] [12] have (size, weight and power) requirements which are difficult to achieve in the maritime environment, but which have been implemented [2] despite these difficulties. Novel quantum sensors based on the Zeeman effect such as nitrogen-vacancy centers (NV) in diamond [17] [18] [19] have low power, size and weight requirements. These magnetometers have a high accuracy [2] and do not need to be calibrated. Due to their novelty these magnetometers have not been used in magnetic field surveys often.

Nowadays flux-gate sensors are most often used. They measure the relative magnetic field with respect to some uncalibrated baseline. The most accurate fluxgate magnetometers [15] are accurate to within about +/- 100nT.

Due to all the above difficulties (attitude accuracy, accuracy of the vector magnetometers), no high-resolution magnetic vector maps exist. This lack of high-resolution vector data stands in stark contrast to the widespread availability of scalar magnetic data. Thus, for navigational purposes vector maps need to be created. These can be measured with a lot of effort or analytically derived from the scalar maps using the declination and inclination angle that is known from the IGRF and World Magnetic Map (WMM) data [33]. It is yet to be proven if such maps are a good approximation to reality. As stated in [5] the position accuracy between using vector magnetometers plus INS or using scalar magnetometers plus INS is expected to be quite small for commercial scale INS, but becomes more significant when using more precise INS.

5.5 *Tensor gradiometers*

Tensor gradiometers which are setup by using two vector magnetometers with a certain towing distance, measure the gradients of vector components. Like scalar gradiometers they are relatively immune to noise sources from the vessel and temporal variations. The spatial gradients form a tensor with nine components. In a conductive medium, such as seawater, conduction currents are present, and the curl of the magnetic field is non-zero. The gradient tensor is asymmetric with eight independent components [6]. However, since vector magnetometers are in an insulating instrument capsule one can assume that the magnetic gradient tensor in the cavity is symmetric and traceless.

Tensor gradiometers have a high sensitivity and are in use for the detection of magnetic underwater objects. Concerning positioning with the help of tensor gradiometers there is clearly no map of magnetic field tensors available, and it might be difficult to construct one with the help of existing data. Therefore, positioning with tensor gradiometers remains an open topic for future research.

5.6 *Advantages and Disadvantages of the different magnetometer types*

The advantages and disadvantages of the different magnetometer types and implementations are summarised in Table 2. Concerning the sensitivity of magnetometers and the irreducible noise and errors from temporal variations, the effects of the vessel and the effects of seawater, it seems that towed gradiometers are the best choice for the measurement of the earth's magnetic field anomalies in the maritime environment despite the positioning inaccuracies that occur with this setup but which are well below the targeted positioning accuracy of a few hundred meters.

Table 2. High-level overview over the advantages and disadvantages of different magnetometer types and implementations

Magnetometer Type	Main Implementations	Advantages	Disadvantages
Scalar	Proton precession including Overhauser and optically pumped	High accuracy, most maps are built from scalar measurements, well-proven	Drift of magnetometers over time
Gradient	At least 2 scalar magnetometers which are towed in line	Cancels out temporal variations of earth's magnetic field and reduced effect of vessel due to towing	Deployment in tow fish requires more effort and adds to positioning inaccuracies
Vector	Fluxgate, SQUID, nitrogen-vacancy centers (NV) in diamond	SQUID and diamond high accuracy, more information, positioning at poles and near equator possible	No vector maps, issues with the attitude, flux gate only with relative measurement
Tensor	At least 2 vector magnetometers which are towed in a line	Gives more information of the magnetic field tensor	Difficult to setup, tow fish adds to positioning inaccuracies

Existing magnetometer platforms (such as fluxgate, proton precision, Overhauser, SQUID) have proven utility and will continue to be used in the future [6]. However, they have limitations. E.g. fluxgates suffer from drifting scale factors and voltage offsets with both time and temperature requiring periodic recalibration. Proton-precision magnetometers have an excellent sensitivity, accuracy and dynamic range, but they have considerable mass and power requirements as well as a large size. SQUID (Superconducting Quantum Interference Device) require a cryonic environment.

There is currently a surge of novel magnetometer platforms that use optical readout, including optically pumped magnetometers, magnetometers based on quantum defects in diamond and optomechanical magnetometers. These novel magnetometers offer a combination of field sensitivity, size, weight, and power consumption that allows them to reach performance regimes that are inaccessible with existing techniques. While each of these kinds of magnetometer have quite different characteristics, in general, a key attraction has been that they offer exquisite sensitivity. In recent years, they have also experienced rapid miniaturization and reduction in power consumption which is likely to continue. Therefore, these novel types of magnetometers become more important in future for maritime operations.

6 CONCLUSIONS

Concerning map-based positioning methods, using the earth's magnetic anomaly field is a good approach either stand-alone or complementing other positioning methods in case of GNSS free navigation. The gradient of the magnetic field is high enough to allow for navigation accuracies in the order of a few hundred meters. Adequate magnetometers are needed both to generate maps with a higher resolution and to navigate with the help of more accurate maps. To estimate the necessary sensitivity and accuracy of the magnetometers, temporal variations, tidal effects and effects of the vessel on the earth's magnetic field need to be considered as the main error source. These error sources limit the desired accuracy and sensitivity to 1nT for the magnetometers. Several magnetometer technologies exist which deliver either scalar or vector information of the magnetic field with a sensitivity and a dynamic range compatible with the earth's magnetic field. These can be combined to deliver gradient or tensor information. Scalar magnetometers (such as proton precession or optically pumped magnetometer) have a high accuracy and are well proven. They can be combined as gradient magnetometers (i.e. at least two scalar magnetometers towed in a line) allow to cancel out temporal variations of the earth's magnetic field. Vector magnetometers (fluxgate, SQUID, novel sensors such as diamond sensors) have very different challenges. While fluxgates have low accuracy, SQUIDs are difficult to setup and there is not much data available for diamond sensors. However, SQUID and diamond sensors have a high accuracy and vector magnetometers allow positioning close to the poles. Tensor magnetometers (i.e. at least two vector magnetometers towed in a line) give a lot of information about the magnetic field tensor for which no maps exist yet but are difficult to set up and therefore more apt for specific surveys rather than general positioning. We recommend using gradient information by setting up magnetometers in a tow fish to reduce the effect of the vessel on the accuracy of the magnetometers and to cancel out most of the temporal variations.

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