

Using distributed magnetometry in navigation of heavy launchers and space vehicles

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Abstract

Recently, a new technique has emerged to address the general problem of reconstructing the inertial velocity of a rigid body moving in a magnetically disturbed region. The contribution of this paper is to apply the developed method, in a prospective spirit, to a case of space navigation in view of estimating the performance improvement that could be obtained using state-of-the-art magnetometer technology onboard heavy launchers and other space vehicles.

The main underlying idea of the approach is to estimate the inertial velocity by readings of the magnetic field at spatially distributed (known) locations on the rigid body. Mathematically, through a chain-rule differentiation involving variables commonly appearing in classic inertial navigation, an estimate of this velocity can be obtained.

In this paper, we show the potential of this method in the field of navigation of heavy launchers passing through particular regions of the Earth magnetosphere as considered, e.g., for upcoming Galileo missions. Numerical results based on the specifications of candidate embedded magnetic sensors stress the relevance of the approach.

The presented methodology is patent pending and was financed by the French space agency.

1. Introduction

The overall life expectation of a spacecraft is strongly related to the amount of fuel that is available on-board. Interestingly, the flight phase of injection into orbit of the payload is a critical phase with respect to this factor. The main reason for this is that the spacecraft may have to use a vast amount of its propellant to compensate for launchers position offsets. To minimize the undesired usage of propellants during this phase, a new generation of Ariane 5 launcher (Ariane 5 ME – Midlife Evolution) will be equipped with a re-ignitable engine: the Vinci rocket engine which can be used for the injection task. In this context, a new standard mission appears as very promising: the GTO+. It is a new version of the usual Geosynchronous Transfer Orbit (GTO) which is the historical mission of Ariane 5. The GTO apogee equals the altitude of the geosynchronous orbit, while its perigee lies between 200 km and 250 km of altitude. The GTO+ has the same apogee, but its perigee is significantly higher (approx. 6000 km). To reach this new orbit, the launcher trajectory includes a long ballistic phase lasting approximately 5.5 hours. This very long phase is inconsistent with the accuracy of current inertial navigation systems, whose drift are proportional to the

total flight time. Importantly, navigation devices are critical for the success of the mission as they are needed to estimate the (generalized) position of the launcher with respect to an inertial frame of reference. To maintain a good level of accuracy during such long-lasting launch missions, hybridizing the inertial measures with other sources of positioning information seems necessary. Unfortunately, classic technologies such as Global Navigation Satellite Systems (GNSS) or GPS are discarded because they are easily blurred. Lately, CNES and SYSSNAV have proposed a new paradigm of navigation exploiting the Earth magnetic field to address this problem. This technique, referred to as “magneto-inertial navigation” and its application to the field of space navigation is the subject of this article. The paper is organized as follows. In Section 2, we expose the principles of the magneto-inertial navigation technique for near-Earth application and report a state-of-the-art on the useable magnetometers. In Section 3, we give a brief overview of the geomagnetic field model used to evaluate the spatial derivatives (gradient) of the magnetic field, which is one of the key factors for magneto-inertial navigation. In Section 4, we evaluate the potential gain of the magneto-inertial navigation for a launcher during a GTO+ mission, and we sketch a method of hybridization.

2. Magnetic navigation

2.1 Notation and reference frames

We consider the following frames of reference:

- The inertial Earth frame (index IF) which has its origin at the center of the Earth. Its axes are not rotating with the Earth. The Oz_{IF} axis coincides with the Earth's polar axis (which is assumed to have a constant direction).
- The Earth rotating frame (index EF) which has its origin at the center of the Earth. Its axes are attached to the Earth. The Oz_{EF} axis coincides with the Earth's polar axis.
- The body frame (index BF) which is fixed to the body under consideration (vehicle). The orthogonal axes are aligned with the roll, pitch and yaw axes of the vehicle, respectively.

Notations are reported in Table 1.

2.1 Basic equations of magneto-inertial navigation

Magneto-inertial navigation is a newly introduced technique to evaluate the velocity of a rigid body in a spatially disturbed and time-invariant magnetic field ([R1, R6]). It has been introduced for navigation applications on the ground (for pedestrians [R7] and automotive vehicles [R8], mostly). Interestingly, it can be generalized to space vehicles, at the expense of more sophisticated equations modelling the Earth magnetic field as rotating with the Earth. As will be discussed, magneto-inertial navigation uses inertial measurements to evaluate some parameters. Therefore, the body we study is assumed to be equipped with an Inertial Measurement Unit (IMU).

The main equation used is the differentiation of the magnetic field

$$\frac{d\vec{B}}{dt} = \frac{\partial \vec{B}}{\partial t} + \left[\frac{\partial \vec{B}}{\partial X} \right] \frac{d\vec{X}}{dt} \quad (1)$$

Let us now detail each term in equation (1):

- $d\vec{B}/dt$ can be measured with a 3-axes magnetometer attached to the body. The measure is $d\vec{B}/dt|_{BF}$.
- $\partial \vec{B}/\partial t$ can not be easily measured. We make the following assumption: at the vicinity of the Earth (<800km), the magnetic field is rotating with the Earth. Therefore, $\partial \vec{B}/\partial t|_{EF} = \vec{0}$.
- $[\partial \vec{B}/\partial X]$ is the magnetic field gradient. This quantity can be estimated from measurements obtained with an array of 3-axes magnetometers located at known distinct locations in the body.
- $d\vec{X}/dt$ is the body velocity with respect to IF. To use this variable in the navigation algorithms one needs to consider $d\vec{X}/dt|_{IF}$.

Table 1: Nomenclature and notations

Symbol	Quantity	Unit
$\vec{B}(M, t)$	Magnetic field vector	T or G
$\vec{X}(M, t)$	Position of the body	m
$\left[\frac{\partial B}{\partial X} \right]$	Spatial derivatives (gradient) of the magnetic field	T/m or G/m
$M_{IF \rightarrow BF}$	Matrix transformation from inertial frame to body frame	–
$\vec{\Omega}_{IF \rightarrow BF}$	Angular speed from inertial frame to body frame	rad/s
\vec{A}^{BF}	Vector A written in the body frame axis set	$ A $
$\left. \frac{d\vec{A}}{dt} \right _{BF}$	Time derivative of the vector A in the body frame	$ A /s$
$\left. \frac{d\vec{A}^{IF}}{dt} \right _{BF}$	Time derivative of the vector A in the body frame, expressed in the inertial frame axis set	$ A /s$
$\Delta \vec{A}$	First order error on the component of A	$ A $
$V(R, \theta, \phi)$	Magnetic potential (IGRF model)	$T \cdot m$ or $G \cdot m$
a	Mean Earth's radius (IGRF model)	m
R	Radius	m
θ	Co-latitude (IGRF model)	rad
ϕ	Longitude (IGRF model)	rad
$g_{n,m}, h_{n,m}$	IGRF-2011 Coefficient	
$P_{n,m}$	Legendre polynomials	

Considering the above measurement principles, we express the vector equation (1) in the Earth frame EF

$$\left. \frac{d\vec{B}}{dt} \right|_{EF} = \left. \frac{\partial \vec{B}}{\partial t} \right|_{EF} + \left[\frac{\partial B}{\partial X} \right] \left. \frac{d\vec{X}}{dt} \right|_{EF} \quad (2)$$

This equation can be transformed under the form to make the velocity with respect to the inertial frame IF appear

$$\left. \frac{d\vec{B}}{dt} \right|_{EF} = \left. \frac{\partial \vec{B}}{\partial t} \right|_{EF} + \left[\frac{\partial B}{\partial X} \right] \left(\left. \frac{d\vec{X}}{dt} \right|_{IF} + \vec{\Omega}_{IF \rightarrow EF} \otimes \vec{X} \right) \quad (3)$$

As one can measure $\left. \frac{d\vec{B}}{dt} \right|_{BF}$ we use the following transformation

$$\left. \frac{d\vec{B}}{dt} \right|_{EF} = \left. \frac{d\vec{B}}{dt} \right|_{BF} + \vec{\Omega}_{BF \rightarrow EF} \otimes \vec{B} \quad (4)$$

in equation (3), and we finally obtain

$$\left. \frac{d\vec{B}}{dt} \right|_{BF} = -\vec{\Omega}_{BF \rightarrow EF} \otimes \vec{B} + \left[\frac{\partial B}{\partial X} \right] \left(\left. \frac{d\vec{X}}{dt} \right|_{IF} + \vec{\Omega}_{IF \rightarrow EF} \otimes \vec{X} \right) \quad (5)$$

Let us now discuss each term appearing in equation (5):

- $\vec{\Omega}_{BF \rightarrow EF}$ is the sum of : $\vec{\Omega}_{BF \rightarrow IF}$ which is the angular velocity of the body with respect to IF (measured with a 3-axes gyrometer) and $\vec{\Omega}_{IF \rightarrow EF}$ which is the angular velocity of the Earth with respect to IF.
- \vec{X} is the position of the body and can be determined by integrating the acceleration (measured by the IMU) or the velocity.

Because all the magnetic measurements are performed in the body frame BF, we now express equation (5) in this reference frame

$$\begin{aligned} \left. \frac{d\vec{B}^{BF}}{dt} \right|_{BF} &= -\vec{\Omega}_{BF \rightarrow IF}^{BF} \otimes \vec{B}^{BF} - \left(M_{IF \rightarrow BF} \vec{\Omega}_{BF \rightarrow EF}^{IF} \right) \otimes \vec{B}^{BF} \\ &+ \left[\frac{\partial B}{\partial X} \right]^{BF} M_{IF \rightarrow BF} \left. \frac{d\vec{X}^{IF}}{dt} \right|_{IF} \\ &+ \left[\frac{\partial B}{\partial X} \right]^{BF} M_{IF \rightarrow BF} \left(\vec{\Omega}_{IF \rightarrow EF}^{IF} \otimes \vec{X}^{IF} \right) \end{aligned} \quad (6)$$

To evaluate the potential accuracy improvement obtained by hybridization of the inertial navigation and the magneto-inertial technique, we detail the accuracy of the standard IMU and the accuracy of embeddable magnetic sensors. We use data from the Ariane 5 IMU and analyse their impact through equation (6). Preliminary to this analysis, we present a state-of-the-art of magnetometers in the following section.

2.3 Magnetometers state-of-the-art

Various sensing technologies could be embedded onboard a heavy launcher such as Ariane 5. Because we need to evaluate the three coordinates of the magnetic field, only vector magnetometer are considered in the study. Table 2 reports a list of the main technologies along with their respective advantages and drawbacks.

Table 2: Magnetometers state-of-the-art

Technology	Advantages	Drawbacks	Accuracy (nT)
Fluxgate*	<ul style="list-style-type: none"> • Good accuracy • Most exploited technology in space 	<ul style="list-style-type: none"> • creates a magnetic field 	$10^{-2} - 10^7$
GMR sensors	<ul style="list-style-type: none"> • Small size 	<ul style="list-style-type: none"> • poor accuracy 	$10^1 - 10^8$
Magnetoelectric sensors	<ul style="list-style-type: none"> • Good accuracy • Small size 	<ul style="list-style-type: none"> • nonlinearity for measuring small magnetic field 	$10^{-3} - 10^8$
MTJ sensors	<ul style="list-style-type: none"> • Small size 	<ul style="list-style-type: none"> • poor accuracy 	$10^1 - 10^8$
Search-Coil*	<ul style="list-style-type: none"> • Very good accuracy 	<ul style="list-style-type: none"> • time dependent magnetic field 	$10^{-5} - 10^8$
SQUID sensors	<ul style="list-style-type: none"> • Best accuracy • Low noise 	<ul style="list-style-type: none"> • low working temperature 	$10^{-6} - 10^0$

(*) already used in space applications

As will appear, SQUID sensors seem to be the only available technology measuring the magnetic field with enough accuracy to exploit the principles of magneto-inertial navigation in space applications.

To evaluate the magnetic field gradient, an array of 3-axes magnetometers is used. Two configurations can be considered:

- A tight network of magnetometers will ensure a thermal stability and an increased knowledge of the mechanical properties (distance between the magnetometers, orientation, limited mechanical deformation...). On the other hand, the sensitivity of this arrangement is greatly reduced.

- A spread-out network of magnetometers will ensure a greater sensitivity, but thermal and mechanical fluctuations may reveal much larger than in the compact network.

3. Model of Earth magnetic field and evaluation of its gradient

There exist numerous models of the Earth magnetic field (e.g. [3], [9] and [10]). Earlier, we have formulated the assumption of a time-invariant magnetic field in the Earth frame at low altitudes. An internal-source field model is consistent with the hypothesis. Among such models is the IGRF-2011 ([3]). This model describes the geomagnetic internal field, and its secular variations, as being the gradient of a scalar potential V that is expressed through a spherical harmonic expansion with respect to spherical geocentric coordinates:

$$V(R, \theta, \phi) = a \sum_{n=1}^N \sum_{m=0}^n \left(\frac{a}{R} \right)^{n+1} (g_{n,m} \cos(m\phi) + h_{n,m} \sin(m\phi)) P_{n,m}(\cos(\theta)) \quad (7)$$

Notations are given in Table 1.

The potential model (7) can be used to evaluate the spatial derivatives of the magnetic field at any point. In Figure 1, the variations of the components of the magnetic field gradient are reported for altitude variations typical of a launch vehicle performing a GTO mission (from liftoff to GEO altitude). A typical value of 10^{-2} to 10^{-3} nT/m is observed for altitudes below 800 km. Such values can be effectively measured with an embedded network of SQUID sensors located at 1m from each other, because their theoretical sensitivity is 10^{-6} nT/m. Interestingly, thanks to this high sensitivity, the measure of the magnetic field gradient could also be achieved at GEO altitude. However, at this altitude, the assumption of a stationarity of the magnetic field in the Earth frame may prove untrue for multiple reasons, e.g. solar activity.

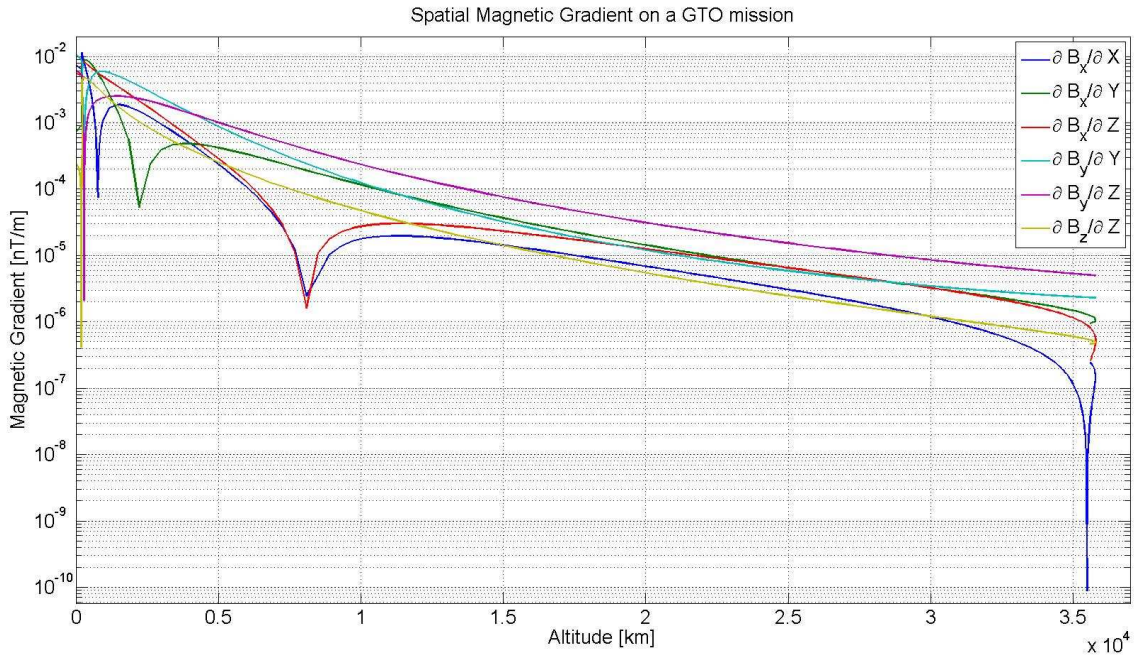


Figure 1: Variations of the magnetic field gradient along a GTO launch mission.

4. Performance of magneto-inertial navigation during a GTO mission

4.1 Accuracy

Equation (6) is the projection of equation (5) in the body frame axes set. We now wish to estimate the propagation of errors (uncertainties) in this equation. Using a current Ariane 5 IMU, the orientation error is small ($\approx 10^{-8}$ rad at 1500s). Developing equation (5) at first order gives:

$$\begin{aligned}
\Delta \left. \frac{d\vec{B}}{dt} \right|_{BF} &= -\Delta \vec{\Omega}_{BF \rightarrow IF} \otimes \vec{B} - \vec{\Omega}_{BF \rightarrow IF} \otimes \Delta \vec{B} - \vec{\Omega}_{IF \rightarrow EF} \otimes \Delta \vec{B} \\
&+ \Delta \left[\frac{\partial B}{\partial X} \right] \left(\left. \frac{d\vec{X}}{dt} \right|_{IF} + \vec{\Omega}_{IF \rightarrow EF} \otimes \vec{X} \right) \\
&+ \left[\frac{\partial B}{\partial X} \right] \left(\Delta \left. \frac{d\vec{X}}{dt} \right|_{IF} + \vec{\Omega}_{IF \rightarrow EF} \otimes \Delta \vec{X} \right)
\end{aligned} \tag{8}$$

An estimation of the accuracy for an injection at a GTO injection point (≈ 700 km from Earth) is given in Table 3, using equation (8) and the sensors accuracies. The current Ariane 5 injection accuracy [4] is 30 to 10 m/s. Considering the data reported in Table 3, one can conclude that magneto-inertial navigation techniques have the potential to improve the injection accuracy by a factor of 10 to 100.

Table 3: Accuracy of magnetic navigation at an actual injection point

Parameter	Order of Magnitude	Unit
$\Delta \left. \frac{d\vec{B}}{dt} \right _{BF}$	10^{-6}	nT/s
$\Delta \vec{B}$	10^{-6}	nT
$\Delta \left[\frac{\partial B}{\partial X} \right]$	10^{-6}	nT/m
$\Delta \vec{\Omega}_{BF \rightarrow IF}$	10^{-8} (*)	rad/s
$\Delta \vec{X}$	10^3 (**)	m
\vec{B}	10^4	nT
$\left[\frac{\partial B}{\partial X} \right]$	$10^{-2} - 10^{-3}$	nT/m
$\left. \frac{d\vec{X}}{dt} \right _{IF}$	10^3	m/s
$\vec{\Omega}_{BF \rightarrow IF}$	10^{-2}	rad/s
$\vec{\Omega}_{IF \rightarrow EF}$	10^{-5}	rad/s
\vec{X}	10^6	m
$\Delta \left. \frac{d\vec{X}}{dt} \right _{IF}$	$10^0 - 10^{-1}$	m/s

(*) IMU parameter taken from [4]

(**) injection accuracy taken from [5]

4.2 Typical use of magneto-inertial navigation in launch vehicle and other spacecraft

By contrast to pure inertial systems, magneto-inertial navigation devices can provide an absolute estimate of velocity (which may be uncertain but does not drift as it is not the result of an integration over time). As long as the orders of magnitude of the various parameters remain unchanged, the accuracy on the estimated velocity is constant. Yet, during the launch mission, the magnetic field gradient decreases as discussed earlier and reported in Figure 1. Then, the obtained velocity estimate becomes less and less accurate. With respect to the preceding discussion, one can

define a 3 phases navigation strategy for a launch mission. This strategy is illustrated in Figure 2. It combines traditional inertial navigation and magneto-inertial techniques:

- The first phase consists in using the inertial navigation estimates to calibrate the magneto-inertial navigation system. During this phase, the inertial navigation is accurate as the drift is small.
- After some time, due to the inertial navigation drift, the magneto-inertial navigation technique provides a better estimate of the velocity than the inertial system. Hybridization of the inertial and magneto-inertial information yields an improvement of the flight parameter estimates.
- As the altitude rises, the magneto-inertial navigation velocity estimates loses accuracy. Then, the inertial navigation technique, whose error has been kept small during the previous phase (second phase), is used for the rest of the mission.

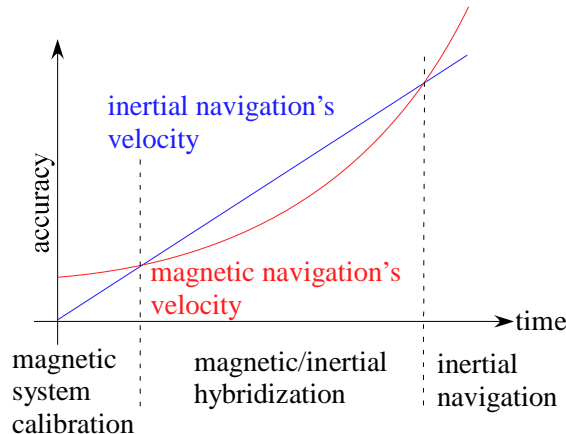


Figure 2: Typical inertial and magnetic navigation on a space launch.

5. Conclusion

Information about absolute and Earth's relative velocity is critical for numerous space applications including putting payloads into orbit. The magneto-inertial navigation technique presented in this paper brings a new solution for this problem. Considering the theoretical performance of SQUID magnetometers, we have shown that this technology has the potential of improving the current launch vehicle navigation accuracy (and thus the injection accuracy) by a factor of 10 to 100.

The potential gain is related to i) the magnitude of the magnetic field gradient observed along the trajectory ii) the accuracy of the employed magnetometers. This preliminary study and its promising results call for further investigations. Information on the real near-Earth magnetic gradient, and the impact of the space vehicle electric environment onto the magnetometers sensors array are critical to evaluate the actually obtainable performance of the system.

Finally, it is interesting to note that other potential applications for magnetic navigation can be found in the domain of interplanetary space probe navigation. As magneto-inertial navigation takes advantage of the disturbances of the magnetic field, every celestial body with a sufficiently strong and stationary magnetic field and a known motion could allow us to compensate the drift of classic inertial navigation systems.

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