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Identification of the orbit semi-major axis using frequency properties of onboard magnetic field measurements

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ABSTRACT

In this paper a novel algorithm for estimating the satellite's semi-major axis is presented. The procedure makes solely use of measurements of the magnitude of the magnetic field and it is therefore independent of the satellite's attitude. Relying on the fact that the orbital motion is nearly periodic in nature and that the Earth's magnetic field has a spherical harmonic behavior, the magnetic signal measured on board is analyzed in the frequency domain. The identification procedure calculates characteristic frequencies of the satellite motion from the magnetic spectrum and relates them to the orbit semi-major axis. Simulations, hardware-in-the loop and real data analyses have been performed. They prove that the algorithm is capable of estimating the semi-major axis well within 1 km for a broad range of orbits. Considering the tiny requirements in terms of measurement and computational burdens, the procedure looks appealing especially for very small satellites.

1. Introduction

Autonomous onboard determination of the satellite's orbit is a challenging task for spacecraft of a very small size. Nowadays, specialized space-rated GPS receivers may yield extraordinarily accurate onboard estimates of the satellite's position and velocity in Low Earth Orbit (LEO). Moreover, GPS technology provides a compact equipment suited to any satellite of medium and large size. However, although in the last decade very small and light space GPS receivers have been developed [1] and successfully applied to nanosatellites [2], tight requirements in terms of power and mass combined with economical factors make this solution generally problematic for satellites with mass of a few kilograms or less. Thus, some researches have focused on the problem of onboard identification of a spacecraft's position using small and power efficient sensors. Most of these works proposed the utilization of the Kalman filter for correcting model predictions with onboard measurements of the magnetic field [3–6] complemented with measurements from Sun sensor [7], horizon sensor [8] or gyro [9,10]. All cited works yield estimates of the actual position of a spacecraft by operating in the time-domain.

The intuition behind this study is that the spherical harmonic behavior of the Earth's magnetic field and the periodic motion of the orbiting body promote the analysis of onboard magnetic measurements in the frequency-domain for gaining information about the orbital motion of a satellite. Thus, this paper illustrates a novel method that estimates the semi-major axis of the orbit of a spacecraft based only on the spectral analysis of magnetic measurements. The proposed procedure is characterized by a small computational burden because it does not require any evaluation of orbital or magnetic field models. Indeed, orbital information are extracted by processing a magnetic signal with length of several orbits. It results in semi-major axis estimates that represent average values over the signal timespan and gives the method robustness against sensor noise or calibration errors. Moreover, the procedure needs only the knowledge of the magnetic field strength. It is therefore independent of the satellite's attitude. Finally, the procedure does not require an absolute time information, which allows one to apply the method even when the onboard clock is not synchronized. However, the procedure evidences a moderate sensitivity to the onboard clock drift, which may require special care while designing the time measurement unit.

The presented procedure, validated through numerical laboratory and flight data, represents a significant enhancement of the original work presented in [11,12]. It now yields semi-major axis estimates with errors generally far below 1 km. This work intends

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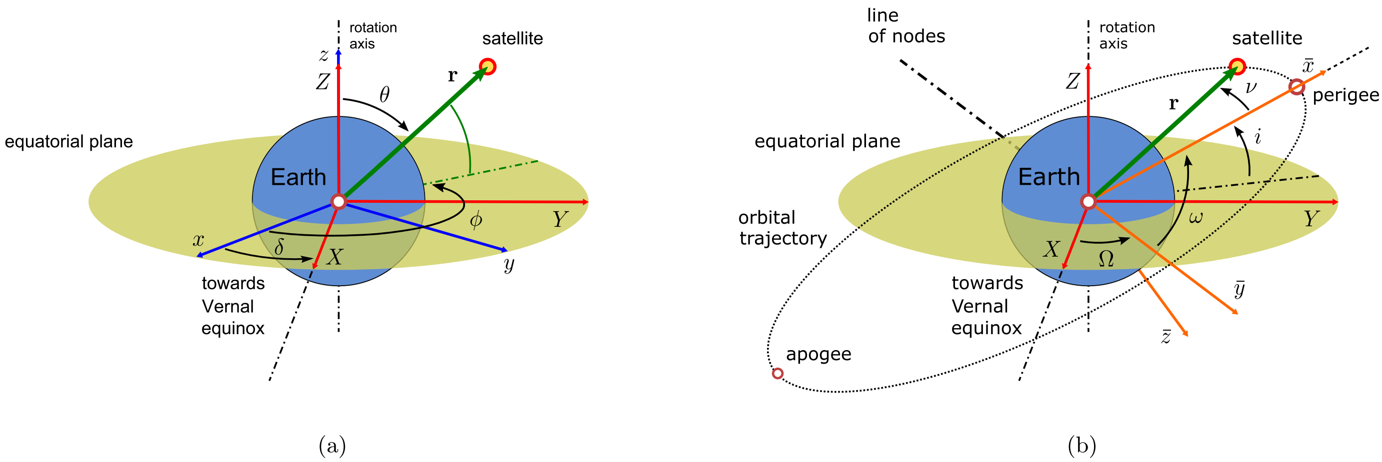

Fig. 1. Representation of (a) the spherical coordinates and of (b) the Keplerian orbital parameters used to describe the satellite position. The Keplerian orbital elements are defined with respect to ECI while the spherical coordinates with respect to ECR.

to be a first step toward the development of an extended algorithm that attempts at estimating all six orbital elements from the spectral analysis of the magnetic signal. Nonetheless, it is believed that the results obtained so far already have some potential applications. For instance, the procedure could be used for the initialization of Kalman filter-based methods. It could also be exploited when many small satellites of a cluster are released at the same time, which poses the problem of object identification by the operator [13].

The paper is structured as follows. Section 2 provides the theoretical background behind the proposed method. Section 3 illustrates the algorithm used for the identification of the semi-major axis. In Section 4 several application cases validating the procedure are presented. They involve numerical simulations, laboratory experiments and actual flight data analyses. Conclusions and future work are given in Section 5.

2. Theoretical background

This section intends to give a rationale of the method from a mathematical perspective. We firstly recall mathematical properties of the model used to describe the Earth's magnetic field in LEO. Then, the periodic properties of the satellite's motion are examined for different orbital models. Investigating the effect of spectral features of the orbital motion on the magnetic field model allows us to explain the spectral behavior of the onboard magnetic field measurement. A Keplerian orbit model is initially examined because this simplified framework offers a better understanding of basic principles of the method. Equipped with this knowledge the analysis moves toward a model including most important perturbation effects. The case of more sophisticated models and real scenario are addressed at the end of the section.

The position of a satellite can be described through the position vector $\mathbf{r}$ applied to the Earth's center. This vector can be represented in the Earth-Centered Inertial (ECI) frame with axes X, Y and Z or in the Earth-Centered Rotating (ECR) frame with axes x, y and z. The two frames are rotated to each-other along the common $z \equiv Z$ axis by an angle δ variable with the time. In the ECR frame the position vector can be expressed in spherical coordinates that are the radius r, the longitude ϕ and the co-latitude θ. Alternatively, the satellite's motion can be examined through a set of Keplerian orbital elements. These elements define the shape of the orbit, the position of the orbit with respect to ECI and the position of the satellite in the orbit. The six orbital elements we use in this work are the semi-major axis, a, the inclination, i, the eccentricity, e, the right ascension of ascending node, Ω, the argument of periapsis, ω and the true anomaly, ν. These elements may be clearly visualized by introducing a perifocal frame with axes $\bar{x}$, $\bar{y}$ and $\bar{z}$. All parameters introduced in this paragraph are depicted in Fig. 1.

2.1. Earth's magnetic field model

An accurate description of the Earth's magnetic field in LEO is given by the spherical harmonic model proposed by the International Association of Geomagnetism and Aeronomy (IAGA) [14] called the International Geomagnetic Reference Field (IGRF) model. It takes the following expression

$$V(r,\phi,\theta) = R\sum_{u=1}^{k}\left(\frac{R}{r}\right)^{u+1}\sum_{\nu=0}^{u}\left(g_u^\nu \cos\nu\phi + h_u^\nu \sin\nu\phi\right)P_u^\nu(\cos\theta)\,, \tag{1}$$

where V is the magnetic potential, k the order of the approximation and R the reference Earth's radius. $P_u^\nu(\cos\theta)$ terms are the Schmidt quasi-normalized associated Legendre functions. The model is parametrized by the g_u^ν and h_u^ν coefficients that slightly change over time and undergo major update every 5 years by IAGA. In our analysis we consider g_u^ν and h_u^ν constant with the time. The magnetic field vector B can be derived from the scalar potential as follows [15]:

$$B_r = -\frac{\partial V}{\partial r} = \sum_{u=1}^{k}\left(\frac{R}{r}\right)^{u+2}(u+1)\sum_{\nu=0}^{u}\left(g_u^\nu \cos\nu\phi + h_u^\nu \sin\nu\phi\right)P_u^\nu(\cos\theta) \tag{2}$$

$$B_\theta = -\frac{1}{r}\frac{\partial V}{\partial\theta} = \sum_{u=1}^{k}\left(\frac{R}{r}\right)^{u+2}\sum_{\nu=0}^{u}\left(g_u^\nu \cos\nu\phi + h_u^\nu \sin\nu\phi\right)\frac{\partial P_u^\nu(\cos\theta)}{\partial\theta} \tag{3}$$

$$B_\phi = -\frac{1}{r\sin\theta}\frac{\partial V}{\partial\phi} = \frac{-1}{\sin\theta}\sum_{u=1}^{k}\left(\frac{R}{r}\right)^{u+2}\sum_{\nu=0}^{u}\nu\left(-g_u^\nu \cos\nu\phi + h_u^\nu \sin\nu\phi\right)P_u^\nu(\cos\theta)\,, \tag{4}$$

where B_r, B_θ and B_ϕ are the B components in the North–East Down reference frame at the satellite's location. Expanding, for in-