Acta Astronautica 123 (2016) 350–362

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

Low-Earth Orbit Determination from Gravity Gradient Measurements

Xiucong Sun [a,b], Pei Chen [a], Christophe Macabiau [b], Chao Han [a,*]

[a] School of Astronautics, Beihang University, Beijing 100191, China
[b] TELECOM Lab, Ecole Nationale de l'Aviation Civile (ENAC), Toulouse 31055, France

ARTICLE INFO

Article history:
Received 27 September 2015
Received in revised form
13 February 2016
Accepted 14 March 2016
Available online 30 March 2016

Keywords:
Gravity gradient
Gravity gradiometry
LEO orbit determination
Adaptive hybrid least squares
GOCE

ABSTRACT

An innovative orbit determination method which makes use of gravity gradients for Low-Earth-Orbiting satellites is proposed. The measurement principle of gravity gradiometry is briefly reviewed and the sources of measurement error are analyzed. An adaptive hybrid least squares batch filter based on linearization of the orbital equation and unscented transformation of the measurement equation is developed to estimate the orbital states and the measurement biases. The algorithm is tested with the actual flight data from the European Space Agency's Gravity field and steady-state Ocean Circulation Explorer (GOCE). The orbit determination results are compared with the GPS-derived orbits. The radial and cross-track position errors are on the order of tens of meters, whereas the along-track position error is over one order of magnitude larger. The gravity gradient based orbit determination method is promising for potential use in GPS-denied spacecraft navigation.

1. Introduction

Satellite orbit determination usually relies on geometric measurements. Two typical examples are the ground-based radar tracking and the Global Positioning System (GPS), both utilizing electromagnetic wave propagation to measure relative distance and direction. Current GPS technology achieves centimeter-level accuracy for Low Earth Orbiting (LEO) satellites with dual-frequency carrier phases [1,2]. An alternative method to the geometry-based orbit determination is the geophysical navigation, which derives position from local geophysical data. One representative is the magnetometer-based autonomous navigation. Orbital position errors ranging from a few to a hundred kilometers have been achieved with real flight data from several LEO satellites [3–6]. Despite the low accuracy, the geophysical navigation does not need any support from ground stations or any other satellites and is thus suitable for autonomous spacecraft operation in GPS-denied environments.

Besides the magnetic field, the gravity is another kind of geophysical information that can be exploited for orbit determination. The gravity field of the Earth is more stable than the magnetic field. The effects of the gravity field on satellites include two aspects. Firstly, the gravitational attraction is the main driving force of the orbital motion. The modeling of the gravity field is of crucial importance to precise orbit prediction. Secondly, the gravity gradients vary as functions of position and orientation and can be measured by a spaceborne gradiometer [7,8]. With a known gravity model as well as the satellite orientation information, the orbit could be estimated from the gravity gradient observations.

According to the gravitational potential theory, the gravity filed is usually described in terms of multipoles, which provide integral characteristics of the matter distribution inside an astronomical body. The multipolar expansion of gravity has been proven to be useful in celestial mechanics. For example, the long-term effects on satellite orbital motion due to lower-order zonal harmonics are well investigated for an arbitrary orientation of the rotation axis of the body [9–11]. The multipoles are crucial also in several satellite tests of fundamental physics such as the LARES/LAGEOS frame-dragging experiment [12–14].

Nowadays, the accuracy of the Earth's gravity model has been improved dramatically since the development of modern space-geodetic techniques such as GPS, VLBI (Very Long Baseline Interferometry), and SLR (Satellite Laser Ranging). The new developed Earth Gravitational Model 2008 (EGM2008) is complete to degree 2190 and order 2159 by combination of satellite geodetic data and high-resolution surface gravimetry [15]. More recently, general relativity has entered the field of geodesy towards better interpretation of high-precision geodetic measurements with a post-Newtonian formalism [16–18]. The endeavor has led to the adoption of a series of resolutions on relativistic reference systems and time scales by the International Astronomical Union (IAU). Vice versa, the space-geodetic measurements can also be used to explore the relativistic effects. Orbiting superconducting gravity

* Corresponding author. Tel.: +86 10 82339583.
E-mail address: hanchao@buaa.edu.cn (C. Han).

http://dx.doi.org/10.1016/j.actaastro.2016.03.012
0094-5765/

gradiometers have been recently proposed to detect the gravitomagnetic field, which causes the “frame-dragging effect” or “Lense-Thirring effect” [19,20].

The application of gravity gradiometry for navigation has been studied since the 1960s. One of the main research interests is to incorporate a gradiometer into an airborne or shipborne inertial navigation system (INS) for real-time compensation of gravity model uncertainties [21–24]. Metzger and Jircitano [25] presented an early form of map-matching technique by cross-correlating the sensed gravity gradients with previously mapped values. The premise was to let a vehicle travel a course twice and to compute the state lag from gravity gradient measurements on both passes. Affleck and Jircitano [26] later developed a passive gravity gradiometer navigation system in which the gravity gradient map was not provided by a first flight but generated from the terrain elevation data base. An optimal filter was designed to update positions and to correct instrument errors. During the following twenty years, further contributions were made on this topic, including the Fast Fourier Transformation based rapid map generation [27], extended application to a hypersonic cruise [28], and feasibility investigation using a modern gradiometer, which is defined as a gravity gradiometer projected to be available within the next 10 years [29]. By contrast, little research has been conducted on the applications of gradiometry for spacecraft navigation. The major difference between the inertial navigation aiding and the application for spacecraft navigation lies in the fact that high-precision attitude information could be easily obtained onboard a satellite by star trackers. This decouples position estimation from attitude estimation. In addition, the higher frequency terrain contributions are dramatically attenuated at the height of a spacecraft. A truncated spherical harmonic gravity model will be accurate enough for space users.

In 2009, ESA’s Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite was launched into a sun-synchronous LEO orbit to determine the Earth’s gravity field [30]. The satellite carried an Electrostatic Gravity Gradiometer (EGG) and measured gravity gradients from an unprecedented low altitude of about 260 km in space. Post flight analysis showed that a noise density level of 0.01 $E/\sqrt{Hz}$ was achieved within the measurement bandwidth (MBW) from $5 \times 10\text{-}3$ to 0.1 Hz [8]. The satellite was also equipped with three advanced star trackers and two dual-frequency GPS receivers. These conditions make GOCE an ideal testbed for the research of gravity gradient based space navigation. Sun et al. [31] introduced an idea of using full-tensor gravity gradients combined with high-precision attitudes to determine a spacecraft’s position. A least squares searching algorithm was developed and a mean positioning error of 620 m was achieved with real GOCE data. An eigendecomposition method using the J2 gravity model was presented in Chen et al. [32] and position errors ranging from 421 to 2690 m were achieved.

In the previous studies mentioned above, the gravity gradient observation errors are modeled as low-level white noise only. In fact, the gradiometer measurements contain significant biases and low-frequency noises. The present work deals with the biases and the drifts in the actual measurements. The noise characteristics are investigated and a simplified observation error model is formulated. An adaptive hybrid least squares batch filter is developed to estimate the orbital states and the biases. The filter combines the advantages of the linear approximation of the orbital equation and the unscented transformation of gravity gradient observations to achieve fast and accurate orbit determination. The measurement time span at each iteration step is adaptively adjusted to restrict the linearization errors and thus to guarantee convergence. An augmented state iterated least squares filter is implemented thereafter to further estimate the drifts. The algorithms are tested with real GOCE data and the orbit determination results are compared with the Precise Science Orbit (PSO) solutions derived from the GPS system.

The remainder of this paper is organized as follows. Section 2 briefly reviews the measurement principle of GOCE gravity gradiometry and investigates the sources of measurement error in gravity gradient retrieval. Section 3 presents the orbital dynamic model, the gravity gradient observation model, and the measurement error model for orbit determination. Section 4 summarizes the iterated least squares filter and the unscented least squares filter for nonlinear estimation and presents the algorithm of the adaptive hybrid least squares filter. Section 5 presents the orbit determination results obtained with real GOCE data. Conclusions are drawn in Section 6.

2. GOCE gravity gradiometry

A differential accelerometry technique was employed by GOCE to measure gravity gradients. The gradiometer was placed close to the spacecraft's center of mass (CoM) and consisted of three orthogonal pairs of capacitive accelerometers. Each accelerometer had two ultra-sensitive axes and one less-sensitive axis. The three pairs of accelerometers were mounted at the ends of three baselines having an approximate length of 0.5 m. The gradiometer reference frame (GRF) is materialized by the three orthogonal baselines with the X axis in the flight direction, the Y axis normal to the orbit plane, and the Z axis radially downwards, as depicted in Fig. 1. Inside each accelerometer, a platinum-rhodium proof mass was electrostatically levitated at the center of a cage, leading to control voltages that were representative of the sum of the non-gravitational accelerations at the location of the proof mass [33]. The gravity gradients were contained in the accelerometer differences.

2.1. Measurement principle

To describe the measurement process, an ideal gradiometer is considered by assuming that:

(1) The centers of the three baselines are coincident;
(2) The baselines are mutually perpendicular and perfectly aligned with the three axes of GRF;

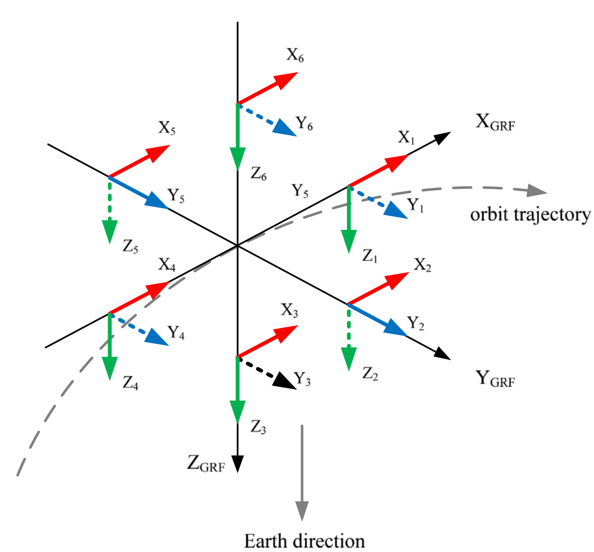

Fig. 1. The arrangement of the six accelerometers inside GOCE gradiometer and the orientation of the GRF reference frame. The solid arrows at each accelerometer show the ultra-sensitive axes and the dashed arrows show the less sensitive axes.