ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (2017) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Spacecraft orbit propagator integration with GNSS in a simulated scenario

Shuai Jing [a], Xingqun Zhan [a,*], Zhenghong Zhu [b]

[a] School of Aeronautics and Astronautics, Shanghai Jiao Tong University, No. 800 Dongchuan Road, Shanghai 200240, China
[b] Department of Mechanical Engineering, York University, 4700 Keele Street, Toronto, Ontario M3J 1P3, Canada

Received 5 January 2017; received in revised form 29 April 2017; accepted 29 May 2017

Abstract

When space vehicles operate above the Global Navigation Satellite System (GNSS) constellation or even above geosynchronous orbit, it is common that the traditional GNSS single–epoch solution can't meet the requirement of orbit determination (OD). To provide the required OD accuracy continuously, a new designed spacecraft orbit propagator (OP) is combined with the GNSS observations in a deep integration mode. Taking both the computational complexity and positioning accuracy into consideration, the orbit propagator is optimized based on a simplified fourth order Runge-Kutta integral aided with empirical acceleration model. A simulation scenario containing a typical Highly-inclined Elliptical Orbit (HEO) user and GPS constellation is established on a HwaCreat™ GNSS signal simulator to testify the performance of the design. The numerical test results show that the maximum propagation error of the optimized orbit propagator does not exceed 1000 m within a day, which is superior to conventional OPs. If the new OP is deeply integrated with GNSS in our proposed scheme, the 95% SEP for the OD accuracy is 10.0005 m, and the time to first fix (TTFF) values under cold and warm start conditions are reduced by at least 7 s and 2 s respectively, which proves its advantage over loose integration and tight integration.

Keywords: GNSS; Orbit propagator; Deep integration; Highly-inclined Elliptical Orbit; Orbit determination; Time to first fix

1. Introduction

Recently, the GNSS extension applications have drawn increasing attention. To maximize the potential of GNSS and optimize resource utilization, the GNSS service range is broadened from terrestrial segment to space segment, which results in the emergence of GNSS SSV (Bauer et al., 2006). Operating at an altitude above 8000 km or even above 36,000 km, the SSV users can hardly receive any signals from the zenith direction. Worse still, the signals from the nadir direction traverse the limb of the Earth and become even weaker to be acquired by the space-borne receiver. Without a doubt, the domain of SSV is the most challenging environment that fusing all signal processing difficulties, namely, high dynamics, high sensitivity, high reliability, high integrity and signal propagation interferences (such as occultation and atmospheric effects).

Plenty of evidences have proved that it is feasible to utilize GNSS signals in medium and high orbit. In terms of engineering applications, the experiment conducted on Equator-S showed that the tracking of GPS main lobe and side lobe signals above the GPS orbits is possible in 1998 (Balbach et al., 1998). In 2014, the Chinese lunar probe, Chang'e 5T1, successfully completed GNSS signal in-orbit test at an altitude around 50,000 km (Liu et al., 2017). In terms of theoretical research, the initial

* Corresponding author.
E-mail addresses: lightning95@sjtu.edu.cn (S. Jing), xqzhan@sjtu.edu.cn (X. Zhan), gzhu@yorku.ca (Z. Zhu).

http://dx.doi.org/10.1016/j.asr.2017.05.041
0273-1177/

Please cite this article in press as: Jing, S., et al. Spacecraft orbit propagator integration with GNSS in a simulated scenario. Adv. Space Res. (2017), http://dx.doi.org/10.1016/j.asr.2017.05.041

assessment of SSV characteristics showed the potential of GNSS for medium and high orbit navigation (Jing et al., 2015). The contribution of (Capuano et al., 2015) demonstrated that GNSS signals can be acquired up to the Moon's surface.

When there are four or more GNSS satellites available, the single point geometric solution is employed to determine the 3D position and time of the user receiver. Referring to the published GPS SSV performance (Bauer et al., 2006), the upper SSV users, generally named as HEO/GEO SSV, only have a probability of less than 6.5% to receive four or more GNSS signals simultaneously. Even if four or more signals are tracked, the Geometric Dilution of Precision (GDOP) is very likely greater than 20 due to their poor distribution, which significantly deteriorate the positioning accuracy. These facts indicate that the single point geometric solution is almost impossible to achieve the OD accuracy on the order of 10 m (Bamford et al., 2006) for upper SSV (HEO/GEO SSV) users.

To get out of this predicament, the dynamic solution method has been adopted recent years. In the dynamic method, space vehicle's dynamic force models are used to provide trajectory tracking and bridge the navigation service outage when geometric method is unavailable. Basile et al. (2015) presented an orbital filter by filtering GPS observations with a dynamic force model. The GPS observations and the dynamic model can be configured in 'loose integration' or 'tight integration'. Considering the 'tight integration' is superior to the loose form, we wonder whether the performance of 'deep integration' performs the best. Therefore, we introduce the implementation of the deeply coupled integration navigation filter and make some comparisons in the following text.

It is obvious that the capability of the dynamic force model is of great importance while the GNSS observations are integrated with the dynamic model in the orbit propagator. Compared to the dynamic model of Unmanned Aerial Vehicle (UAV) (Crocoll et al., 2013), the forces a SSV spacecraft suffered is much simpler unless the spacecraft is making orbital maneuvers. Excluded the thrust generated by the vehicle itself, the main forces acting on the spacecraft are Earth gravity and various perturbations. According to (Subirana and Hernandez-Pajares, 2013), the perturbations include non-spherical and non-homogenous effects, solar/lunar gravity, solar radiation pressure (SRP) and atmospheric drag. Note that all of the perturbations disturb the accelerations of the spacecraft, but their impacts appear very slight for an instant. But if they propagate over a long period of time, their accumulated effect can produce significant changes in the users' orbit. Meanwhile, the perturbations are so complicated to be accurately modeled. Even though the perturbing models are built as precise as possible, it is still difficult to achieve real-time data processing in view of the onboard computing capability. Therefore, the most accurate model is not the most appropriate. A dynamic model, that makes a good balance between computation complexity and propagation accuracy, is usually preferred.

Actually, the dynamic model is only taken as an auxiliary mean in the deeply coupled integration scheme, which plays two major roles. First, the dynamic model is used to improve the process of weak signal acquiring and tracking, thus it is beneficial to shorten the time to first fix (Holmes et al., 2006). Second, the dynamic model assists the integration navigation filter in producing the positioning results, whose precision partially depend on the ranging accuracy. Obviously, it is unnecessary to build too precise dynamic model. So research in this area focuses on how to simplify the perturbing models. There are a large variety of simplification approaches, i.e., mathematical interpolation, analytical method, numerical integration, etc. Mathematical interpolation is not the point we are interested in, because its estimation results easily deviate from the true position according to (Gebhardt et al., 2004). Hence, the paper emphasizes the evaluations of analytical method and numerical integration. Both of J2 perturbation propagator (Bevilacqua and Romano, 2008) and J4 perturbation propagator (Vtipil and Newman, 2012) are representatives of analytical method. The Runge-Kutta-Fehlberg (RKF) (Simos, 1998) method, which can adjust its step size adaptively, is the most typical numerical integration method. To further save computation cost, the paper proposes an improved method substantially without any loss of accuracy. It is developed from 4th order Runge-Kutta (RK4) integrator while introducing empirical acceleration compensation. Because of its simpler operation compared to traditional RKF 4(5), it is named as Simplified Runge-Kutta (SRK). On the one hand, the empirical accelerations are used to compensate the error of dynamic force models, which makes the OP on longer a pure dynamic model; on the other hand, they can relieve the computational load of sophisticated orbit position calculation.

In the numerical simulation, a HEO scenario covers all the altitude of lower and upper SSV is established. Compared with LEO (Low Earth Orbit), MEO (Medium Earth Orbit) and GEO (Geosynchronous Earth Orbit) missions, HEO mission has the largest variation ranges of signal power and dynamic stress (Jing and Zhan, 2016). Besides, the periodic characteristic of HEO mission is convenient to execute repeated tests for discovering conclusive argument.

Depending on the orbit types and altitudes of different spacecrafts, there is no uniform OD accuracy standard in the SSV. Through counting the accuracy requirements of current SSV missions, we find that a 95% SEP (Spherical Error Probable) on the order of 10 m can meet the OD accuracy requirements of majority SSV users. On such bases, the OD reliability and integrity need to be further improved as much as possible. To this end, the paper presents two innovations. The first innovation focuses on the proposed configuration of GNSS/OP deep integration in Section 2, which is recommended for weak signal