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ScienceDirect

Advances in Space Research xxx (2017) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

VLBI observations to the APOD satellite

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Received 3 May 2017; received in revised form 20 October 2017; accepted 28 October 2017

Abstract

The APOD (Atmospheric density detection and Precise Orbit Determination) is the first LEO (Low Earth Orbit) satellite in orbit co-located with a dual-frequency GNSS (GPS/BD) receiver, an SLR reflector, and a VLBI X/S dual band beacon. From the overlap statistics between consecutive solution arcs and the independent validation by SLR measurements, the orbit position deviation was below 10 cm before the on-board GNSS receiver got partially operational. In this paper, the focus is on the VLBI observations to the LEO satellite from multiple geodetic VLBI radio telescopes, since this is the first implementation of a dedicated VLBI transmitter in low Earth orbit. The practical problems of tracking a fast moving spacecraft with current VLBI ground infrastructure were solved and strong interferometric fringes were obtained by cross-correlation of APOD carrier and DOR (Differential One-way Ranging) signals. The precision in X-band time delay derived from 0.1 s integration time of the correlator output is on the level of 0.1 ns. The APOD observations demonstrate encouraging prospects of co-location of multiple space geodetic techniques in space, as a first prototype.

Keywords: APOD; VLBI; GNSS; SLR; Space ties

1. Introduction

The VLBI technique has been used successfully and extensively for tracking a number of deep-space missions since the second half of the 1980s. Another application of VLBI is to track Earth orbiting satellites, like the highly elliptical orbit satellite TanCe-1, Earth synchronous orbit satellites (80°E and 140°E) (Shu et al., 2003), and GNSS ones (Tornatore et al., 2014; Plank et al., 2015a, 2017). The APOD (Atmospheric density detection and Precise Orbit Determination) is the first LEO (Low Earth Orbit) satellite that was observed with GNSS, SLR, and VLBI. Observing the APOD satellite is challenging since the mutual visibility depends on the altitude of the satellite and the separation of the radio telescopes (Hase, 1999). The APOD satellite travels through the horizon to horizon

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https://doi.org/10.1016/j.asr.2017.10.046
0273-1177/

Please cite this article in press as: Sun, J., et al. VLBI observations to the APOD satellite. Adv. Space Res. (2017), https://doi.org/10.1016/j.asr.2017.10.046

on the observing stations for tens of seconds, and there are only 2–3 passages through the zone of mutual visibility per day. Observations to the APOD satellite are promising in the area of space ties, combining all techniques by the installation of adequate technique-specific sensors on a single satellite platform, e.g. with the proposed GRASP mission (Geodetic Reference Antenna in Space) (Bar-Sever et al., 2011) or the European E-GRASP/Eratosthenes mission (Biancale, 2016).

We will describe the APOD mission and GNSS/SLR observations in Section 2. In Section 3 the VLBI observations to the APOD satellite and data processing are investigated, in particular focusing on the VLBI observations with geodetic VLBI radio telescopes. The designed cross-correlation algorithms for this LEO satellite and preliminary results are provided in Section 4, considering the low accuracy of the APOD orbit. Finally in Section 5, discussions on present results and further developments are presented.

2. APOD mission

2.1. General descriptions

On Sept. 20, 2015, 20 satellites were launched successfully by a Chinese CZ-6 rocket from TaiYuan Satellite Launch Center, and then operated in a circular, near-polar orbit with an altitude of 520 km. Among these satellites, a set of four CubSats, named APOD, are projected for measurement of atmospheric density by in situ sensors and by analyzing the orbit evolution (Tang et al., 2016). The precise orbit prediction for LEO spacecraft is very important for space debris collision avoidance (Liou, 2006), orbit manoeuvres of LEO spacecraft, as well as rendezvous and docking at space stations. The major challenge for accurate orbit prediction of LEO satellites is inaccuracy of atmospheric density model at high altitudes. Improving the accuracy of atmospheric density models needs high quality observations of mass density (direct or indirect) with sufficient spatial and temporal resolutions and coverage. From the 1960s, many techniques have been developed to measure high altitudes atmospheric mass density and composition, including drag-derived means by orbit of spacecraft, in situ measurement by neutral mass spectrometers, ultraviolet remote sensing and other techniques by rockets payload or from ground base (Emmert, 2015). Still, more extensive spatial and temporary coverage would be needed to improve the accuracy of atmospheric density models because of the complex variation of atmosphere. And the cost to meet this requirement is huge. But the development of low cost CubSats provides a very good opportunity to detect atmospheric density in a more extensive spatial coverage. Thus BACC/AFDL (Beijing Aerospace Control Center/Aerospace Flight Dynamic Laboratory) proposed the APOD project to study the technology of in situ detection by payload instruments and derivation by precise orbits. The APOD satellites were manufactured by DFH Co., the ground segment is controlled by BACC/AFDL including payload operation as well as science data receiving, processing, archiving and distribution. The APOD mission aims to detect atmospheric density below 520 km.

The APOD family includes a nano satellite (named APOD-A) and three pico satellites (named APOD-B, APOD-C, APOD-D). All four satellites are flying in a circular, near polar-orbit with an inclination at about 97 degrees and all four satellites were located at 520 km altitude after being launched. Then APOD-A was descended to a 470 km altitude orbit two weeks later. In order to obtain atmospheric density by an in situ detector and by deriving density from precise orbits, payloads used for precise orbit determination and density detection are mounted on the APOD-A satellite (see Fig. 1), which include the atmospheric density detector, a dual-frequency GNSS (GPS/BD) receiver, an SLR reflector and a VLBI X/S dual band beacon. The payloads of multiple observations on the APOD-A satellite are listed in Table 1. The mass of APOD-A is 25.88 kg and its size is 391 mm × 398 mm × 398 mm. It should be mentioned that it takes great efforts to integrate these instruments in such a miniature satellite. APOD-A is a three-axis stabilized satellite, and its attitude stability is maintained by gyros, magnetometer, and sun sensor. The in-orbit commissioning of the platform and payloads was finished in December 2015 and APOD has been in ordinary operation since then. The satellite guaranteed lifetime is 12 months, but the APOD satellites are still working as of September 2017, except that the GNSS receiver is not providing pseudorange and carrier phase raw data any more.

2.2. GNSS observations

The POD (Precise Orbit Determination) is performed by GPS L1/L2 double differences carrier phase data and pseudorange data. BACC/AFDL generates precise orbit solution using its own proprietary software. The geophysical models and estimated parameters are summarized in Table 2. The orbit has been verified by the XiAn Satellite Control Center (XSCC) using the Bernese software (Dach et al., 2015) (personal communications with Jun Zhu). To evaluate orbit precision, we produced orbit overlaps by comparing the differences of two consecutive orbit solutions (arcs) spanning 10 h and computed independently. We evaluated the RMS (Root Mean Square) differences for the radial, along-track and cross-track components during arc common time period. The averaged RMS are 5, 7, and 3 cm for these three components of the overlap respectively. The left plot in Fig. 2 depicts the post-fit residuals of the GPS L1/L2 POD solution of APOD-A. The RMS of pseudorange residuals and carrier phase residuals are 1.95 m and 1.58 cm, respectively.

On Jan. 21, 2016, the GNSS receiver on APOD-A partially ceased functioning. There are no carrier phase and pseudorange raw data recorded from that time on, only

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