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Performance analysis of Real Time PPP for transit of Mercury

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ABSTRACT

In recent years, Precise Point Positioning (PPP) techniques, which are alternative to relative positioning techniques, have begun to be widely used in Global Navigation Satellite System (GNSS) positioning applications. The PPP technique offers an effective solution to obtain coordinates at high accuracy with a single receiver. Real-time PPP (RT-PPP) solutions can also be provided with real-time correction data and products (ephemerides, satellite clock, bias, etc.) provided by different organizations (International GNSS Service (IGS), European Reference Frame (EUREF), Bundesamt für Kartographie und Geodäsie (BKG), European Space Agency (ESA), German Research Centre for Geosciences (GFZ), etc.). In this regard, RT-PPP applications are getting widespread day by day. Considering this situation in this study, the positional accuracy of RT-PPP was analyzed during the transit of Mercury which was determined to be about 7 h on May 9th, 2016. Two GNSS stations, POVE and BUCU that are in the global IGS network, were chosen. The RT-PPP solutions were performed with BKG Ntrip Client (BNC v2.11.2) software. In the analysis, "RTCM3EPH as the broadcast ephemeris stream and "CLK10" as the combined orbit/clock product of IGS were used. The results of the RT-PPP solutions were compared with the results of the Post-Process (PP) solutions of the 24-hour data of the same day by using the web-based online AUSPOS service. According to the results, it can be concluded that the positioning accuracies for the RT-PPP approach at the different phases of the transit of Mercury have different characters.

1. Introduction

Relative positioning has still been used effectively in Global Positioning System (GPS)/Global Navigation Satellite System (GNSS) applications (geodetic and geodynamic studies, deformation analysis, etc.) where precise positioning is required. As known, this method allows to compute the position of a new point depending on the point with well-known coordinates and the accuracy of the observations can vary in accordance with baseline length and observation duration [1–3]. Also, the spatial correlation of the physical effects especially orbit and atmospheric effects in relative positioning model is decreased when baseline length is increased [4,5]. Some error sources have effects on the GPS/GNSS positioning applications. In Table 1, the main GPS/GNSS error sources and the amount of them can be found.

In Precise Point Positioning (PPP) technique, observation with a single receiver on the absolute positioning principle is sufficient to compute the unknown point coordinates. PPP is an alternative technique to the traditional relative technique in terms of using particularly precise satellite orbit/clock corrections and the other error/correction models and many studies have been focused on the theory and applications of the PPP technique such as geodynamics, determination of tropospheric delay, computation of the coordinates of permanent GPS stations, health monitoring of the engineering structure, real time applications, assessment of precipitable water vapor [6–20]. Nowadays, especially the Real Time PPP (RT-PPP) applications are very popular for the integration of GPS/GNSS with other low-cost sensors such as self-driving cars, smartphones and unmanned aerial vehicles (UAV) [21].

In PPP, there are also some particular error sources that should be taken into consideration, which affect the positioning accuracy. These error sources can be listed as satellite errors (satellite antenna offset, phase wind-up correction), site displacement effects (solid earth tide, ocean loading, and earth rotation parameters) and relativistic effects (sagnac delay) [6,22]. When considering either relative or PPP technique in GPS/GNSS positioning, the three of major error sources are listed as orbital, ionospheric and tropospheric errors. Especially the ionospheric effect has a big impact (see, Table 1) in GPS/GNSS positioning with a great amount. Especially for the RT-PPP, these sources are very effective on the coordinate estimation. The celestial event may also affect the atmosphere; that's why the performance of the RT-PPP may be affected as well. One of these celestial events is the transit of Mercury. The differences may be seen on the layers of the atmosphere due to the magnetic effects of the transit of Mercury. Thus, the effect

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Table 1
The main GPS/GNSS error sources and average error values [6].

Error Sources	Amount of Error (m)
Satellite Clock and Signal Bias	~0.3–4.0
Orbital Errors	~0.8
Ionospheric Delay	~7.0
Tropospheric Delay	~0.2
Antenna Phase Center Variations	~0.01–0.02 (horizontal)/~0.1 (vertical)
Multipath Signal	~0.1–3 C/A code/~0.05 Carrier-Phase

especially seen in the atmosphere caused by this transition that rarely seen and occurred in different years is significant in GPS/GNSS positioning. The accuracies on positioning vary during this transition. Therefore, this study investigates the performance of the RT-PPP technique considered as to be used effectively worldwide in the future, during the transit of Mercury dated May 9th, 2016 completed approximately in seven hours. Especially during the transit of the Mercury between the Sun and the Earth, the variation of the atmospheric effect shows how the positioning accuracies in RT-PPP change.

2. Transit of Mercury

The transits of the inner planets have historically provided the calibrations needed to convert Kepler's relative scale of distances in the Solar System to absolute ones e.g. [23–28]. It was the famous astronomer Johannes Kepler who, in 1607, realized that transits of the inner planets, Mercury and Venus, were possible [29]. The first transit of Mercury was seen in 1631 by Gallendi and provided early confirmation of the accuracy of Kepler's tables. In the 21st century, there have been transits of Mercury in 2003, 2006, 2016, and after the next, on Nov. 11, 2019, there will be 10 more [30]. Mercury completes each orbit around the Sun every 88 days and passes between the Earth and Sun every 116 days (one-third of Earth year), which means Mercury has at least three passes during one year. During a transit, Mercury appears as a tiny black dot moving across the Sun's disk. Due to the orbital movements of the Earth and Mercury, the pass between the Sun and the Earth is called as Transit of Mercury [31]. Since Mercury's orbit is inclined seven degrees to Earth, Mercury's appearance does not intersect with the Sun's Disk. It intersects the ecliptic at two points or nodes, which cross the Sun each year and these nodes line up with the Sun from Earth twice per year on November and May. So, Mercury passes occur in November or May. If Mercury passes through inferior conjunction at that time, a transit will occur. The conjunction of Mercury's and the Earth's orbits on the solar system, namely the transit of Mercury is a rare event occurring about 13 times per century at varying intervals. In Table 2, the dates of the transits of Mercury can be seen for the 21st century.

Table 2
Transits of Mercury: 2000–2100 [31].

Date	Universal Time	Separation
2003 May 07	07:52 am	708″
2006 Nov 08	09:41 pm	423″
2016 May 09	02:57 pm	319″
2019 Nov 11	03:20 pm	76″
2032 Nov 13	08:54 am	572″
2039 Nov 07	08:46 am	822″
2049 May 07	02:24 pm	512″
2052 Nov 09	02:30 am	319″
2062 May 10	09:37 pm	521″
2065 Nov 11	08:07 pm	181″
2078 Nov 14	01:42 pm	674″
2085 Nov 07	01:36 pm	718″
2095 May 08	09:08 pm	310″
2098 Nov 10	07:18 am	215″

Table 3
Geocentric Phases of the 2016 Transit of Mercury [31].

Event	Universal time	Position angle
Contact I	11:12:19 am	83.2°
Contact II	11:15:31 am	83.5°
Greatest Transit	02:57:26 pm	153.8°
Contact III	06:39:14 pm	224.1°
Contact IV	06:42:26 pm	224.4°

In principle, that orbital transition may also be considered the same as the solar eclipse. Table 3 represents the beginning and the ending time of transit of Mercury in Universal Time on May 9, 2016, around the Earth. Here, Contact I shows the beginning of the transition, where the Mercury's disk is externally tangent to the Sun. At Contact II, the Mercury is internally tangent to the Sun, where the transition can be tracked on the solar disk. Greatest Transit is the instant when Mercury passes closest to the Sun's center that reflects the transition clearly. At Contact III, the Mercury accesses to the opposite side of the solar disk and second time it internally tangents to the Sun. On the last phase, at Contact IV, the transition ends. Fig. 1 shows the path of Mercury with the position at any instant during the transition [31].

This transition completed approximately in seven hours was tracked from the several sides of the Earth including America, the Atlantic and Pacific Oceans, Europe, Africa and much of Asia (see Fig. 2) [31].

3. PPP model

The relationship between GPS and PPP was introduced in Zumberge et al. [7]. In that study, PPP was modelled by the un-differenced and ionosphere-free combinations using code and carrier phase observations with a single dual-frequency receiver. This enables to reach from decimeter to centimeter-level positioning accuracy in absolute observations [6,7,22,32,33]. PPP and RT-PPP play key roles in scientific papers and engineering applications in GPS/GNSS [34–39].

In the traditional PPP technique, dual-frequency GPS observation models are used to reduce the impact of ionospheric errors. Here, ionosphere-free code and carrier phase observations are converted into the ionosphere-free combination, namely L3. So, refraction bias of GPS signal at ionosphere layer can mostly be eliminated [6,22].

The simplified mathematical equations of the PPP functional observation equations model combinations are shown in Eqs. (1) and (2) using parameters of position, clock, troposphere, and integer ambiguity as provided in Kouba and Heroux [22].

$$\ell_p = \rho + c(dT - dt) + T_r + \varepsilon_p \quad (1)$$

$$\ell_\Phi = \rho + c(dT - dt) + Tr + N\lambda + \varepsilon_\Phi \quad (2)$$

Here ℓ_p (P3) is the ionosphere-free combinations of P1 and P2 code observations, (P3) = (2.546P1-1.546P2), ℓ_Φ (L3) is the ionosphere-free combinations of L1 and L2 carrier phase observations, (L3) = (2.546 λ1 Φ1 − 1.546 λ2 Φ2), ρ is the geometric distance between satellite and receiver, c is the speed of light in meters per second, dT is the receiver clock offset according to GPS time, dt is the satellite clock offset according to GPS time Tr is the signal delay in atmosphere (prior tropospheric delay) in meters, N are the carrier-phase ambiguities on L1 and L2 frequencies in cycles, respectively. λ1, λ2, λ are the carrier-phase wavelengths on L1, L2 frequencies and combined L3 (10.7 cm) carrier phases, respectively and ε_P, ε_Φ are the components of related survey noises including multipath and un-modeled errors.

However, in order to increase accuracy in this technique, many other correction types are needed together with precise orbit/clock information. In this perspective, error sources and correction models in