A Long-Term Analysis of the GPS Broadcast Orbit and Clock Error Variations

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Abstract

The computation of a navigation satellite position and clock is a general task in GPS positioning, and the data needed for this task can be obtained from broadcasted navigation messages and IGS precise ephemerides. This study analyzes broadcast orbit and clock error variations by comparing them with IGS precise ephemerides. Orbit and clock errors from 2001 to 2013 are computed for all GPS satellites as well as for the group of satellites visible in Korea. Orbit and clock errors versus GPS satellite types are also analyzed. Correlations with shadow conditions, solar activity, and geomagnetic activity are analyzed. Clock errors and signal-in-space range errors are reduced with the new generation of GPS satellites. The correlations show that orbit errors increase by 3.2% in shadows. Solar activity and orbit error have a high correlation until 2008, but have a low correlation after 2009.

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1. Introduction

The computation of a navigation satellite position and clock is a general task in global positioning system (GPS) positioning that is necessary to compute a user position. The data needed for this task can be obtained from a broadcasted navigation message. A satellite orbit can be computed by using satellite orbital elements and perturbations.

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Users should use a precise ephemeris provided by the International GNSS Service (IGS) or National Geospatial-Intelligence Agency (NGA). IGS is a voluntary federation of about 400 stations that provides GPS and GLONASS precise ephemerides [1]. IGS orbit accuracy is believed to be less than 0.05m. The IGS precise ephemeris is available in 15 minute intervals.

NGA provides GPS-based precise ephemerides, and its accuracy is also less than 0.05m. As a part of GPS modernization, 28 Block II/IIA satellites were launched between 1989 and 1997 [2]. They utilize L1 and L2 frequencies, and they were designed to have a 7.5-year lifespan. As 3rd generation satellites, Block IIR satellites were launched from 1997 to 2004. Block II/IIA and IIR satellites have been included in the GPS satellite constellation since 2005. Block IIR-M satellites were launched between 2005 and 2009. Block IIF satellites, launched from 2010, use L5 signals and have a 12-year lifespan.

Studies up until the early 2000s mainly focused on variations in broadcast ephemeris accuracy. Since the mid-2000s, they have focused on broadcast ephemeris fault detection and statistics. GPS broadcast ephemeris accuracy in 1999 and 2000 was analyzed by Langley et al. [3]. Warren and Raquet analyzed the variation of GPS broadcast ephemeris errors over a decade (1993-2002) [4]. Daily and yearly GPS and GLONASS broadcast orbit errors from 1994 to 2003 were analyzed by Starr et al. [5]. Also, broadcast ephemeris errors according to GPS blocks and shadow conditions were analyzed. The geographical variation of pseudorange error was investigated. Cohenour and Graas discussed GPS signal-in-space (SIS) fault probabilities and error distributions from 2005 to 2012 [6]. Montenbruck et al. analyzed the phase center offset (PCO) of GPS and GNSS satellites [7]. The satellite broadcast errors of 2013 were analyzed.

We analyzed the variation of orbit and clock errors by comparing the broadcast ephemerides with the IGS precise ephemerides from 2001 to 2013. The IGS precise final orbit is used as the true orbit. A power spectral density (PSD) analysis of broadcast orbit errors is also conducted. Two error statistics, those for all GPS satellites and those for a group of satellites visible in Korea, are computed to analyze a geographical effect. Orbit errors for each GPS block are analyzed, as are the correlations with satellite shadow conditions, solar activity, and geomagnetic activity.

2. Data analysis

The GPS satellite coordinates provided by the IGS represent the center-of-mass of the satellites. The broadcast ephemeris, in contrast, represents the satellite antenna phase center coordinates. The satellite antenna phase center is the mean of all satellite antenna phases, and the distance from center-of-mass to the antenna phase center is defined as the phase center offset. IGS precise ephemeris users need to correct the PCO vectors. Previous studies used different PCOs. Langley et al. used IGS recommended PCOs, which were used until November 4, 2006. The only radial-direction PCO was applied in a study by Warren and Raquet. Cohenour and Graas used PCO corrected NGA precise ephemerides. Montenbruck et al. [7] adjusted the PCO values for each type of GPS satellite.

In this study, the IGS precise ephemerides and PCO values of Montenbruck et al. [7] are used. Orbit errors represented in the ECEF frame are converted to radial (R), transverse (T), and normal (N) frames. Radial denotes the vector from Earth-center to satellite, and transverse denotes the satellite’s direction of motion. Normal denotes the perpendicular direction to radial and transverse. The clock error cannot be compared directly because of differences in the realization of the GPS system time scales [7]. To correct the clock, an ensemble clock error should be computed and applied to the clock errors of each satellite. In this paper, the ensemble clock error correction is not conducted. In order to convert ECEF to a RTN frame, Warren [4] and Cohenour [6] used an ECEF→RTN direction cosine matrix (DCM), but Langley [3] and Montenbruck [7] used ECEF→Earth centered inertia (ECI)→RTN DCM. In this paper, ECEF→ECI→RTN DCM is used. Signal-in-space range error (SISRE) represents the pseudorange errors caused by a weighted orbit and clock error. The weight factors depend on the satellite altitude [7]. This is unity for the radial direction, about 1/7 for medium Earth orbit (MEO) satellites, and about 1/11 for geosynchronous orbit (GEO) satellites. In the case of the GPS satellites, the weight factor for the radial direction and clock error is 0.98, and the factor for the transverse and normal direction error is 1/7.

For the correlation analysis on the shadow condition, orbit errors are classified into shadow and sunlight conditions. The orbit errors can be increased in the shadow condition due to solar radiation incident variation. In this study, both umbra and penumbra conditions are considered as a shadow condition.

Orbit and clock errors can be increased via a broadcast ephemeris fault due to a corrupted individual ephemeris
and bad health status. The health status is set to bad during satellite orbit control or satellite status checking. In this paper, all of the GPS satellite health statuses are checked. If the health status value is more than 1, the corresponding data is excluded for processing. Also, the data outside 3σ of the SISRE is excluded.

3. Orbit and clock error analysis

The R, T, and N orbit and clock errors of PRN 12 on October 14, 2013 are shown in Fig. 1(a). R, T, and N orbit and clock RMS errors are 0.22m, 1.51m, 0.45m, and 1.72m, respectively. The radial direction error is less than the other direction errors because the GPS pseudorange is more sensitive to the changes in the radial component than changes in other components. The 3D orbit error and SISRE are shown in Fig. 1(b). The SISRE variation is similar to the radial and clock error variation because it is sensitive to the change of the radial and clock errors. The PSDs of the orbit errors are computed for all PRNs from October 14 to 23, 2013. The PSD value peaks at $2.3 \times 10^{-5}$ Hz, and it corresponds to a GPS orbital period of 12 hours. Also, another PSD peak at $7 \times 10^{-5}$ Hz corresponds to one-third of a GPS orbital period.

Orbit and clock errors for different GPS blocks are shown in Table 1. Clock error differences between 2nd (Block II and IIA) and 3rd (Block IIR) generations are from 11% to 20%. Block II/IIA satellites have two Cesium and two Rubidium atomic clocks. In contrast, Block IIR satellites only have Rubidium atomic clocks. The error statistics prove that the Block IIR Rubidium clocks have greater frequency accuracy than Block II/IIA clocks [8]. SISRE decreases with the new generation of GPS satellites.

Orbit, clock errors, and SISRE are computed for all GPS satellites and for the group of satellites visible in Korea. To compute the local orbit error, the elevation mask angle in Korea is set to 5°. SISRE is computed for 30 user positions, which are allocated with 40° latitude and 60° longitude intervals. Computed global and local SISRE are 1.96m and 1.94m, respectively. Table 2 shows that global orbit errors are slightly higher than those for Korea. R, T, and N orbit and clock error differences are 0.2%, 1.7%, 0.3%, 0.4%, respectively. It is possible that GPS orbit determination accuracy improves due to the four monitoring stations in Korea. Fig. 2(a) shows daily global RTN orbit errors from 2001 to 2013. The orbit errors decrease until 2008 as the number of 3rd generation GPS satellites (Block IIR) increases. Fig. 2(b) shows daily 3D orbit and clock error variations. The 3D orbit and clock RMS errors

![Graph showing orbit and clock errors](image)

Fig. 1. Broadcast orbit and clock errors of PRN 12 on October 14, 2013: (a) RTN orbit and clock errors; (b) 3D orbit error and SISRE.

Table 1. Broadcast orbit and clock RMS errors, and SISRE RMS for GPS block types (2001-2013)

<table>
<thead>
<tr>
<th>Errors</th>
<th>II</th>
<th>II-A</th>
<th>II-B</th>
<th>II-M</th>
<th>IIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (m)</td>
<td>1.31</td>
<td>0.58</td>
<td>0.22</td>
<td>0.33</td>
<td>0.16</td>
</tr>
<tr>
<td>T (m)</td>
<td>6.06</td>
<td>2.68</td>
<td>1.63</td>
<td>1.36</td>
<td>1.26</td>
</tr>
<tr>
<td>N (m)</td>
<td>1.80</td>
<td>1.32</td>
<td>0.88</td>
<td>0.67</td>
<td>0.51</td>
</tr>
<tr>
<td>Clock (m)</td>
<td>2.78</td>
<td>2.67</td>
<td>2.56</td>
<td>2.56</td>
<td>2.52</td>
</tr>
<tr>
<td>3D (m)</td>
<td>6.46</td>
<td>3.04</td>
<td>1.87</td>
<td>1.56</td>
<td>1.37</td>
</tr>
<tr>
<td>SISRE (m)</td>
<td>2.98</td>
<td>2.69</td>
<td>2.38</td>
<td>2.57</td>
<td>2.53</td>
</tr>
</tbody>
</table>
Table 2. Global and local broadcast orbit and clock RMS errors as well as RMS SISRE (2001-2013)

<table>
<thead>
<tr>
<th>Errors</th>
<th>Global</th>
<th>Korea</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (m)</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>T (m)</td>
<td>2.40</td>
<td>2.36</td>
</tr>
<tr>
<td>N (m)</td>
<td>1.10</td>
<td>1.10</td>
</tr>
<tr>
<td>Clock (m)</td>
<td>2.53</td>
<td>2.52</td>
</tr>
<tr>
<td>3D (m)</td>
<td>2.68</td>
<td>2.66</td>
</tr>
<tr>
<td>SISRE (m)</td>
<td>2.56</td>
<td>2.55</td>
</tr>
</tbody>
</table>

are 2.68m and 2.53m, respectively. Clock error distribution increases after 2004. One of the possible causes of the increase is the end of the designed lifespan of the Block II/IIA atomic clocks. Also, the ensemble clock correction is not applied in this paper. The daily RMS SISREs of all PRNs are shown in Fig. 3. Because of the large clock error variation, SISRE is similar to the clock errors. Orbit and clock RMS errors for each PRN are shown in Fig. 4. It appears that the clock errors are biased for each PRN because the ensemble clock correction is not applied.

4. Correlation analysis

3D orbit errors versus shadow conditions are analyzed. GPS satellites in umbra and penumbra are considered as being a shadow condition. The shadow condition period is 1.3% of the entire period. The 3D orbit error in a shadow is 3.2% higher than that in sunlight. 3D orbit errors from 2001 to 2013 are also computed with the Solar index F10.7
and geomagnetic index Ap. F10.7 is the solar radio flux per unit frequency at a wavelength of 10.7 cm. Ap is a daily mean of Kp that makes up the geomagnetic activity index. The F10.7 and Ap time series were obtained from the National Oceanic and Atmospheric Administration (NOAA). Fig. 5 shows the 3D orbit errors versus F10.7. 3D orbit errors are divided into two groups; one from 2001 to 2008 and the other from 2009 to 2013. The 3D orbit errors up to 2008 increased along with F10.7. However, the error level after 2008 is almost constant regardless of the increasing F10.7. One possible cause is that the 3rd generation of Block IIR and IIF satellites have been included in the GPS satellite constellation since 2009. The correlation coefficients are 0.81 from 2001 to 2008 and -0.17 from 2009 to 2013. The correlation coefficients of the 3D orbit error versus Ap are 0.16 from 2001 to 2008 and -0.05 from 2009 to 2013. It appears that there is a low correlation between the 3D orbit error and geomagnetic index.

5. Conclusion

By using the IGS precise final orbit as a true orbit, long-term orbit and clock variations are analyzed. Orbit and clock errors are computed for all GPS satellites and for the group of satellites visible in Korea. Orbit and clock errors versus GPS satellite types are also analyzed. The orbit error variation period coincides with the GPS orbital period. The radial orbit errors of the 2nd generation satellites are approximately two times greater than those of the 3rd generation satellites. The clock errors and SISRE decrease with the new generation of GPS satellites. The 3D orbit error difference between global and Korea-only is 0.02m. The correlation analysis shows that the 3D orbit errors in shadow are 3.2% higher than those in sunlight. Solar activity and orbit error have a high correlation until 2008, but they have a low correlation after 2009.

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References