Precision Analysis of CNAV Broadcast Ephemeris and Its Impact on the User Positioning

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Abstract GPS broadcast ephemeris error is an important factor affecting the real-time positioning accuracy. Since April 2014, the IGS provided two new broadcast ephemeris products, namely LNAV (Legacy Navigation Message) and CNAV (Civil Navigation Message). Compared with LNAV, CNAV was broadcasted only on Block IIR-M and IIF satellites. This paper introduces the parameters of satellite orbit calculation in CNAV, and algorithm of satellite orbits calculation is introduced by using CNAV broadcast ephemeris. CNAV satellite orbits and clocks of one year are calculated and evaluated by using the IGS precise products as reference. Results show that mean and RMS of CNAV orbits error is less than 0.4 and 2 m for all three components, respectively; RMS of 3D orbits error is about 3 m. RMS of CNAV satellite clock error is about 1.5 ns. CNAV SISRE is around 0.6 m. User pseudo-range positioning using CNAV shows similar performance as the LNAV.

Keywords CNAV broadcast ephemeris · LNAV broadcast ephemeris · Precise ephemeris · 3D orbit errors · Clock bias · SISRE · User positioning

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1 Introduction

The GPS broadcast ephemeris is the basic of satellite navigation and positioning, its orbit errors and clock bias will directly affect the final stand-alone positioning. At present, the common ephemeris products have two kinds: one is the precise ephemeris by the IGS (International GNSS Service), the other is GPS (Global Positioning System) broadcast ephemeris, which is widely used in stand-alone real-time positioning. Though its precision is lower than former, it has the characteristics of real-time and easy to obtain. Several researches from 2002 to 2013 [1–4] have been conducted for the in-depth analysis of NAV (Navigation Message) ephemeris precision. With the implementation of the L-AII (Legacy Accuracy Improvement Initiative) program, the global station increases and the improvement of dynamic model in orbit prediction. The current precision of NAV broadcast ephemeris is less than 1.5 m, clock bias is about 8 ns, and its overall precision is increasing year by year.

The need for more flexibility and higher precision of the transmitted data fostered the development of a new CNAV (Civil Navigation Message) broadcast ephemeris from 28 April 2014, its broadcast time at intervals of two hours from 01:30:00 to 23:30:00, each ephemeris group contains 32 parameters. An initial CNAV test campaign was conducted from 15 to 29 June 2013, and [5] found RMS of 3D orbit errors is 88 cm for a few hour data set of three satellites. Steigenberger et al. [6] have conducted analysis of CNAV broadcast ephemeris precision from 2014 to 2015, its SISRE (signal-in-space range error) is about 0.6 m. This paper will introduce an algorithm of satellite orbits calculation using CNAV broadcast ephemeris, and CNAV satellite orbits and clocks of one year are calculated and evaluated by using the IGS precise products as reference. Finally, the performance of CNAV on user positioning is analyzed.

2 Analysis Strategy of CNAV Broadcast Ephemeris Error

2.1 CNAV Parameters

Daily CNAV + LNAV (Legacy Navigation Message) broadcast ephemeris are recorded in RINEX 3 navigation format and provided at ftp://cddis.gsfc.nasa.gov/gnss/data/campaign/mgex/daily/rinex3/20yy/cnav/brdxddd0.yyx, where ddd and yy denotes the day of year and two-digit year respectively [6]. Each group of CNAV broadcast ephemeris contains 32 parameters, satellite orbits and clocks are calculated using 20 parameters in Table 1.

Table 1 CNAV broadcast ephemeris parameters

a_{f_0}	clock bias (seconds)	i_0	i0 (radians)
a_{f_1}	clock drift (sec/sec)	ω	omega (radians)
a_{f_2}	clock drift rate (sec/sec^2)	$\dot{\Omega}$	OMEGA DOT (radians/sec)
$\sqrt{A}$	sqrt(A) [sqrt(m)]	$iDot$	IDOT (radians/sec)
ΔA	aDot (meters/sec)	C_{rc}	Crc (meters)
Δn	Delta n (radians/sec)	C_{rs}	Crs (meters)
t_{op}	Time of ephemeris prediction (secs of week)	C_{uc}	Cuc (radians)
M_0	M0 (radians)	C_{us}	Cus (radians)
e	e Eccentricity	C_{ic}	Cic (radians)
Ω_0	OMEGA0 (radians)	C_{is}	Cis (radians)

2.2 Algorithm of Satellite Orbits and Clocks Calculation

The algorithm of satellite orbits and clocks calculation using CNAV broadcast ephemeris is described in the Ref. [5, 7]. Compared to LNAV, CNAV provides an extended orbit parameterization including a change rate for the semi-major axis and the mean motion as well as improved precision of the orbital elements. Different from the previous studies, we do not consider the change rate of mean motion. Detailed calculation procedure is shown in Table 2.

2.3 Evaluation Methods

IGS provide precise ephemeris at 15 min intervals,its orbit and clock precision is less than 2.5 cm and 0.075 ns respectively [8] and thus can be regarded as reference, the precise ephemeris of IGS is under the ITRF framework, which provided by IERS, while the CNAV uses the WGS-84 coordinate system. The deviation between the two systems is about 1–2 cm [2], compared with CNAV broadcast ephemeris error is much smaller and it can be neglected in comparison. Empirically derived satellite antenna z-offsets given in the Ref. [9] are applied in the comparison, as the IGS products refer to the center of mass of the satellites whereas the CNAV broadcast ephemeris refer to the mean antenna phase center [9]. Detailed satellite antenna offset correction algorithm in the Ref. [1]. The median of all satellite clock bias as a time benchmark is used to access accuracy of clock errors.

The data sampling of orbits and clocks comparison is 15 min. Satellite orbit errors, clock bias and SISRE are all calculated, the mean difference and RMS are calculated as follows:

Table 2 Algorithm of satellite orbits and clock bias

Calculation formula	Meaning
$t_{oe} = week\_in\_\sec(y, mon, d, h, \min, \sec)$	Time of reference epoch (week in seconds)
$t_k = t - t_{oe}$	Time difference
$A = (\sqrt{A})^2 + \Delta A^* t_k$	Semi-major axis
$n = \sqrt{GM/A^3} + \Delta n$	Mean angular velocity GM is Earth's gravitational constant
$M_k = M_0 + n \cdot t_k$	Mean anomaly
$E_k = M_k + e \cdot \sin E_k$	Eccentric anomaly
$\cos v_k = \frac{\cos E_k - e}{1 - e \cdot \cos E_k}$ $\sin v_k = \frac{\sqrt{1 - e^2} \cdot \sin E_k}{1 - e \cdot \cos E_k}$	True anomaly
$\phi_k = v_k + \omega$	Latitude parameter
$\delta u_k = C_{us} \sin(2\phi_k) + C_{uc} \cos(2\phi_k)$ $\delta r_k = C_{rs} \sin(2\phi_k) + C_{rc} \cos(2\phi_k)$ $\delta i_k = C_{is} \sin(2\phi_k) + C_{ic} \cos(2\phi_k)$	Perturbation correction
$u_k = \phi_k + \delta u_k$	Corrected latitude parameter
$r_k = A(1 - e \cos E_k) + \delta r_k$	Corrected radius
$i_k = i_0 + \delta i_k + iDot \cdot t_k$	Corrected orbit inclination
$\Omega_k = \Omega_0 + (\dot{\Omega} - \dot{\Omega}_e) t_k - \dot{\Omega}_e t_{oe}$	Corrected longitude of ascending node
$x = r_k \cos(u_k)$ $y = r_k \sin(u_k)$	Coordinates in the orbit plane
$X_k = x \cdot \cos(\Omega_k) - y \cdot \cos(i_k) \cdot \sin(\Omega_k)$ $Y_k = x \cdot \sin(\Omega_k) + y \cdot \cos(i_k) \cdot \cos(\Omega_k)$ $Z_k = y_k \cdot \sin(i_k)$	Coordinates in the WGS-84
$dts = a_{f0} + a_{f1} \cdot t_k + a_{f2} \cdot t_k^2$	Clock bias

$$Mean = \frac{\sum V_i}{n}, \quad RMS = \sqrt{\frac{\sum V_i^2}{n}}$$

where n is the total number of epoch, V_i is the CNAV broadcast ephemeris error, $i = 1, 2, 3, \ldots, n$.

3 Analysis of CNAV Broadcast Ephemeris Error

All Block IIR-M and IIF satellites transmitting CNAV messages are specified in Table 3. Where the total numbers keep increased from 11 to 19 satellites with the modernization of the GPS system since 28 April 2014.

Table 3 Satellite capable of providing CNAV

CNAV start	PRN
2014-04-28	01, 05, 07, 12, 15, 17, 24, 25, 27, 29, 31
2014-05-30	30
2014-07-30	06
2015-02-23	03, 09
2015-09-17	08, 26
2016-05-05	10, 32

All CNAV broadcast ephemeris error is calculated from DOY(day of year) d001 to d310 in 2016, except for PRN 10 and PRN 32 satellites, which began to transmit CNAV from DOY 126. Outliers in orbit errors and clock bias exceeding a limit of 15 m and 30 ns respectively have been rejected in the following analysis. And the 'clean' ephemeris errors to evaluate CNAV broadcast ephemeris precision.

3.1 Analysis Precision of Orbit Errors

Using PRN09 satellite as an example, the orbit error curve of the CNAV broadcast ephemeris is present in Fig. 1, where X, Y and Z components are represent in red, green and blue respectively; the horizontal and vertical axis represents epoch numbers and errors (m) respectively. CNAV orbit error of the other 18 satellites basically fits this error curve.

All 19 satellites orbit errors are calculated for the whole year, except for PRN10 and PRN32, including mean and RMS errors in X, Y and Z components. The horizontal and vertical axis represents PRN and errors (m) respectively in Fig. 2. Results show that all satellites orbit errors is less than 0.4 m, the minimum mean orbit error is about 1 cm for the Z component of PRN09 and Y component of PRN15. The maximum orbit error is −0.37 m, appears in the Z component of PRN08. All RMSs of satellites orbit errors are less than 2 m. The minimum RMS orbit error is 1.43 m for the Z component of PRN09.

3D orbit errors are calculated by considering its errors in X, Y and Z components using the formula $\sigma = \sqrt{V_x^2 + V_y^2 + V_z^2}$. Mean and RMS of 3D orbit errors for all

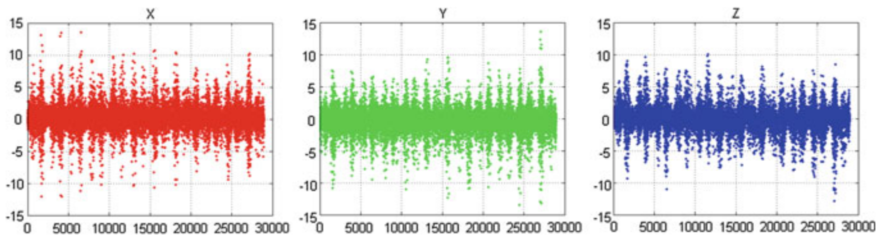

Fig. 1 Orbit error curve of the CNAV broadcast ephemeris of satellite PRN09 in a year

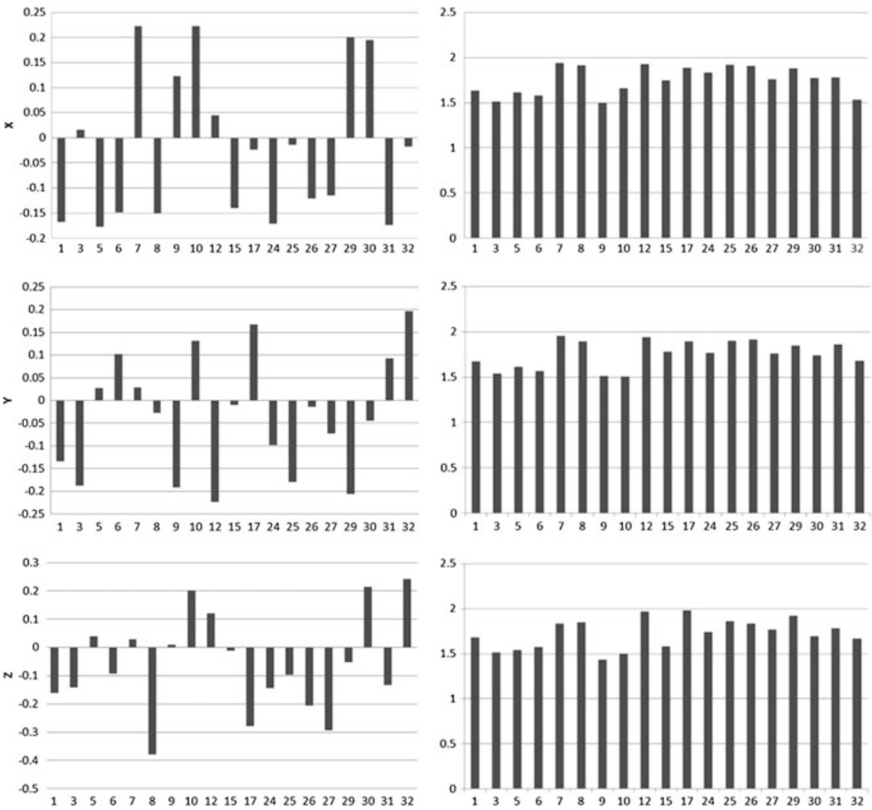

Fig. 2 Mean and RMS error of the CNAV broadcast ephemeris of 19 satellites in X, Y and Z components

satellites are present in Fig. 3. Red and blue represents mean and RMS respectively; the horizontal and vertical axis represents PRN and errors (m) respectively. In Fig. 3 the maximum and minimum mean value is 2.39 m of PRN12 and 1.79 m of PRN09, respectively. For the RMS statistics, the maximum and minimum RMS is 3.37 m of PRN12 and 2.57 m of PRN09.

3.2 *Analysis Precision of Clock Bias*

Satellites PRN06 and PRN17 are used as examples for the analysis of clock biases, Fig. 4 presents the clock bias curve of the CNAV broadcast ephemeris, where the horizontal and vertical axis represents epoch number and clock bias (ns) respectively. In Fig. 4 we see that the clock bias variation of PRN17 is larger, between −10 to 15 ns, while PRN06 satellite clock bias variation is between −3 to 4 ns. Most other satellites is similar to PRN06, the variation range of clock bias is less than 10 ns.

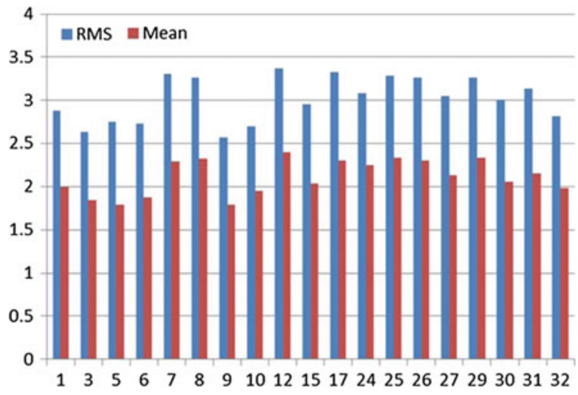

Fig. 3 3D orbit error of the CNAV broadcast ephemeris of 19 satellites

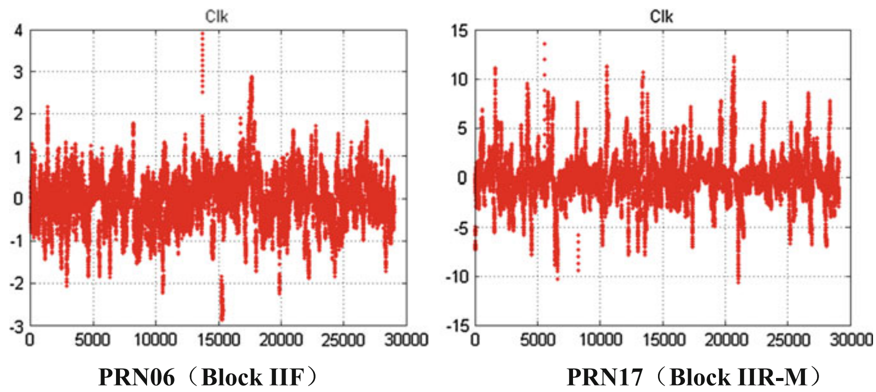

Fig. 4 Clock bias curve of the CNAV broadcast ephemeris of satellite PRN06 and PRN17 in a year

Figure 5 shows the mean and RMS of clock bias for all satellites, where we see that they are less than 0.6 and 2 ns respectively for most satellites. PRN08, PRN17, PRN24, PRN29 and PRN31 satellite clock bias have poor accuracy; Largest RMS is 4.3 ns of satellite PRN24.

3.3 *SISRE Analysis*

In order to calculate the CNAV SISRE, CNAV orbit errors in ECEF (Earth Centered Earth Fixed) are transformed into orbit coordinate system, and clock errors is converted to range by multiplying the speed of light. The detail algorithm of SISRE calculation is described in the Ref. [9]. All 19 satellites SISRE and SISRE

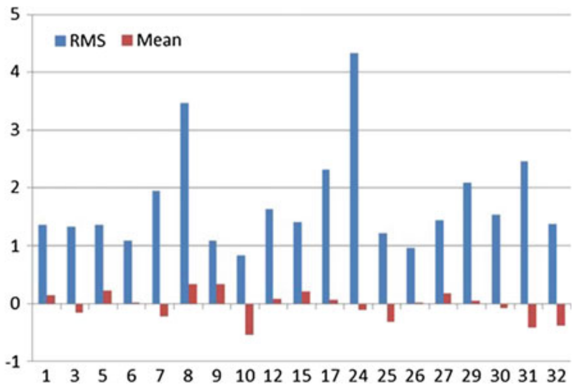

Fig. 5 Mean and RMS clock bias of the CNAV broadcast ephemeris of 19 satellites

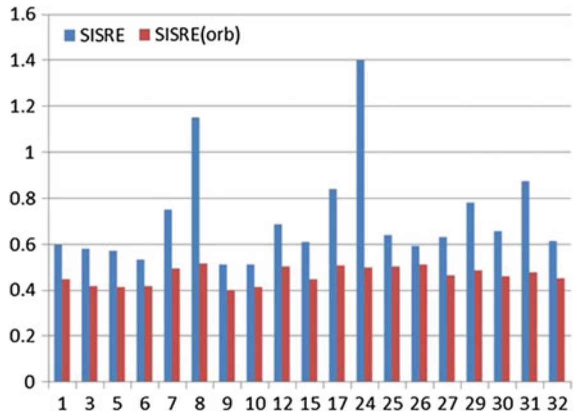

Fig. 6 SISRE and SISRE (orb) of the CNAV broadcast ephemeris of 19 satellites

(orb) are calculated for the whole year and present in Fig. 6, Red and blue represents SISRE (orb) and SISRE respectively; the horizontal and vertical axis represents PRN and SISRE values (m) respectively. In Fig. 6 we see that all satellites CNAV SISRE (orb) is about 0.4–0.5 m, while CNAV SISRE is between 0.5 and 1.4 m. The difference of CNAV SISRE for all satellites is mainly affected by the accuracy of clock bias. PRN08, PRN17, PRN 24, PRN 29 and PRN 31 satellites CNAV SISRE is about 0.8–1.4 m and significantly larger than other satellites. Most satellites CNAV SISRE is around 0.6 m.

4 Performance of CNAV Broadcast Ephemeris on User Positioning

PPP (precision point positioning) software developed by the Shanghai Astronomical Observatory is modified to add solution module for CNAV broadcast ephemeris. Specific corrections are as follows: dual frequency ionospheric-free,

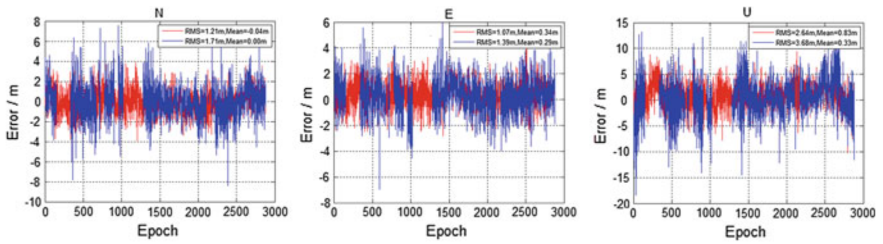

Fig. 7 Coordinate error curve

Table 4 Mean and RMS of coordinate error

Component	Mean_CNAV/m	Mean_LNAV/m	RMS_CNAV/m	RMS_LNAV/m
N	0.00	0.02	1.71	1.68
E	0.29	0.31	1.39	1.35
U	0.33	0.59	3.68	3.60

SAAS tropospheric model, relativity, earth rotation, antenna phase center and solid tide. CNAV and LNAV broadcast ephemeris are used to calculate user pseudo-range based positioning.

The data of the IGS station SHAO at shanghai with sampling of 30 s is used for coordinate calculation using LNAV and CNAV broadcast ephemeris for DOY 288 in 2016. Figure 7 compares the two solutions. Red and blue represents LNAV and CNAV respectively; the horizontal and vertical axis represents epoch numbers and errors (m) respectively.

The coordinate error curve based on two broadcast ephemeris are similar. The total number of CNAV results is less than LNAV, this is due to the fact that the CNAV is available on 19 satellites and less than 4 satellites could be tracked for some epoch. CNAV and LNAV uses 19 identical satellites to calculate user pseudo-range based positioning. Mean and RMS of coordinate error in N, E and U components is calculated in Table 4. CNAV shows similar performance as the LNAV.

5 Conclusions

CNAV satellite orbits and clocks of one year are calculated and evaluated by using the IGS precise products as reference, and the performance of CNAV on user positioning is analyzed in this paper. We have found the following conclusion:

(1) Orbit errors for all three components using CNAV show similar performance as the LNAV, its mean and RMS is less than 0.4 and 2 m respectively. For 3D orbit errors, the mean and RMS is about 2.4 m and 3.5 m respectively.

(2) Mean and RMS of clock bias of most CNAV satellites are about 0.6 and 1.5 ns respectively. PRN08, PRN17, PRN24, PRN29 and PRN31 satellite clock bias variation range is larger and less stable.
(3) CNAV SISRE (orb) for all satellites is about 0.4–0.5 m, and most satellites CNAV SISRE is around 0.6 m.
(4) User kinematic pseudo-range positioning using CNAV shows similar performance as the LNAV, but the solution fails in some epochs when less than 4 satellites could be simultaneously tracked.

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