Chapter 16
Modeling and Application of COMPASS Satellite Orbits and Clocks Predicted Correction

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Abstract To evaluate the satellite orbit and clock errors of COMPASS, we compare the difference between broadcast ephemeris and precise orbits and clocks. Results show that the orbit errors present certain periodicity for GEO and IGSO satellites. The SISRE of COMPASS is larger than GPS and GLONASS overall. However, the broadcast ephemeris of COMPASS appears regular changes in short time. Based on this, we establish different rapid correction models for COMPASS satellite orbits and clocks error. Analysis proves that the result performs well when the length of the arc for the model is shorter than 30 min, and the linear model is best for satellite clock corrections. By using this model, we predict the corrections of the satellite orbits and clocks, which is used for pseudo-range and carrier phase positioning. Results show that the positioning accuracy is on the same level with precise products for pseudo-range and carrier phase, while the convergence time is longer. This research provides an important basis for the realization of sub-meter wide area augmentation of COMPASS.

Keywords Broadcast ephemeris error · Space-in-space range error (SISRE) · Predicted model · Single point positioning

16.1 Introduction

Broadcast ephemeris error including satellite orbits and clock errors is a very important factor for user positioning. A lot of researches have been focusing on the precision of broadcast ephemeris for GPS and GLONASS [1–5]. Many years'

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results show that the precision of GPS broadcast ephemeris has been improving over the years. For GPS broadcast ephemeris, the error on radius is smaller than that on track and normal direction, while the errors in three directions are below 2 m. For GLONASS, the precision is about 3–4 m. Yang [6] studies the GPS broadcast ephemeris error and its effect on positioning, and results show that the GPS broadcast ephemeris error has a great effect on GPS single point positioning, and little effect on relative positioning. Huang [7] analyzes the spectral characteristic of GPS broadcast ephemeris by using spectral analysis model, the results demonstrate that the GPS broadcast ephemeris has a periodical error wave form. After compensation, the precision of ephemeris was at the level of 0.5 m.

The COMPASS Navigation Satellite System, also named Beidou-2, was taken into formal operation on Dec. 27th, 2012. The interface control document is also released at that time [8].

To compensate the lack of basic GNSS navigation service, many countries are developing their own GPS or GLONASS augmentation system. For COMPASS, to achieve a better augmentation result, how to correct the errors on broadcast ephemeris and broadcast in an appropriate way is an important issue.

Based on the above background, we analyze the error of COMPASS broadcast ephemeris. On the basis of the regularity of COMPASS broadcast ephemeris error, we establish fast correction models to predict the errors. By broadcasting the parameters of the correction model, this model can be used to correct the error of broadcast ephemeris to improve positioning accuracy.

16.2 Strategic Analysis

To analyze the error of COMPASS broadcast ephemeris, we take the precise orbits and clocks as 'true' value, and compare it with broadcast ephemeris so that to get the satellite orbits and clocks error ($\Delta X\ \Delta \mathrm{Y}\ \Delta Z\ \Delta Clk$) in CGCS2000 coordinate system.

To describe the orbit error correctly, we usually transfer the orbit error into radius, along-track and across-track direction, namely satellite orbit coordinate system. According to the state vector of satellites at the epoch, we can calculate the rotation matrix $G_{3\times 3}$ to convert orbit error from ECEF to satellite orbit coordinate system:

$$[\Delta R\ \Delta T\ \Delta N\ \Delta Clk] = \begin{bmatrix} G_{3\times 3} & 0_{3\times 1} \\ 0_{1\times 3} & 1 \end{bmatrix} (\Delta X\ \Delta \mathrm{Y}\ \Delta Z\ \Delta Clk) \tag{16.1}$$

where ΔR, ΔT, ΔN denote components in radial, along-track, across-track direction respectively, and ΔClk represents the satellite clock error.

As the broadcast error consist of satellite orbits and clocks, error we use the SISRE (Signal-In-Space Range Error) to evaluate the precision of broadcast ephemeris, and the RMS reflects the total precision. The expression of SISRE can be written as follow:

$$SISRE = \sqrt{(\Delta R - \Delta Clk)^2 + \frac{1}{49}(\Delta T^2 + \Delta N^2)}. \quad (16.2)$$

SHA analysis centre is now focusing on GPS/GLONASS/COMPASS multi-system orbit determination and positioning [10]. User can download GPS and GLONASS precise products through the internet freely [11].

16.3 COMPASS Broadcast Ephemeris Correction

When comparing broadcast ephemeris and precise products for GPS and GLONASS, the consistency of the coordinate time system and the correction of antenna phase centre should be taken into account [12]. The COMAPSS broadcast ephemeris is based on CGCS2000 reference frame, and the time is aligned to BTD, which has a difference of 14 s with GPST. The satellite coordinates are referred to the antenna phase centre [8]. The precise orbits and clocks provided by SHA is consistence with broadcast ephemeris, so there is no need to consider the time and orbits inconsistency.

In this paper, we use the COMPASS broadcast ephemeris from June 27th to June 30th, 2012. We compared the healthy satellite orbits and clocks with that provided by SHA. The orbit errors are then transferred to satellite RTN direction according to Eq. (16.1). Figure 16.1 show the orbit and clock errors for one GEO (C01), one IGSO (C08) and one MEO (C11), respectively.

From Fig. 16.1 we can see that the orbit errors present certain periodicity for GEO and IGSO satellites, especially in the normal direction. While for MEO satellites, the periodicity is not obvious. This may be due to that the tracking stations of COMPASS are not world-wide distributed, and the MEO satellite has the phenomenon of satellite arising and descending. For GEO, IGSO or MEO satellites, the error in radius is much smaller, this is because that the observations of the ground tracking stations is more sensitive than the other two directions, and the force model in normal and track direction is still inadequate. These make the precision in radius better than normal and track direction, similar to GPS and GLONASS [4, 5]. However, the broadcast ephemeris precision is worse than GPS or GLONASS.

From Fig. 16.1 we can also notice an phenomenon that error jumps exists in all directions, for that the COMPASS broadcast ephemeris provide a series of orbit parameters every one hour, and the adjacent two ephemeris is not consistent. However, in the same ephemeris, the orbit and clock error appears a regular change.

We also make a four-day SISRE statistics for all healthy satellites, the mean value and RMS distribution are shown in Fig. 16.2. From Fig. 16.2 we can see that the SISRE of COMPASS is between 3 and 10 m. The result is worse than GPS or GLONASS, resulting from the error of COMPASS broadcast ephemeris, which will affect the precision of user positioning.

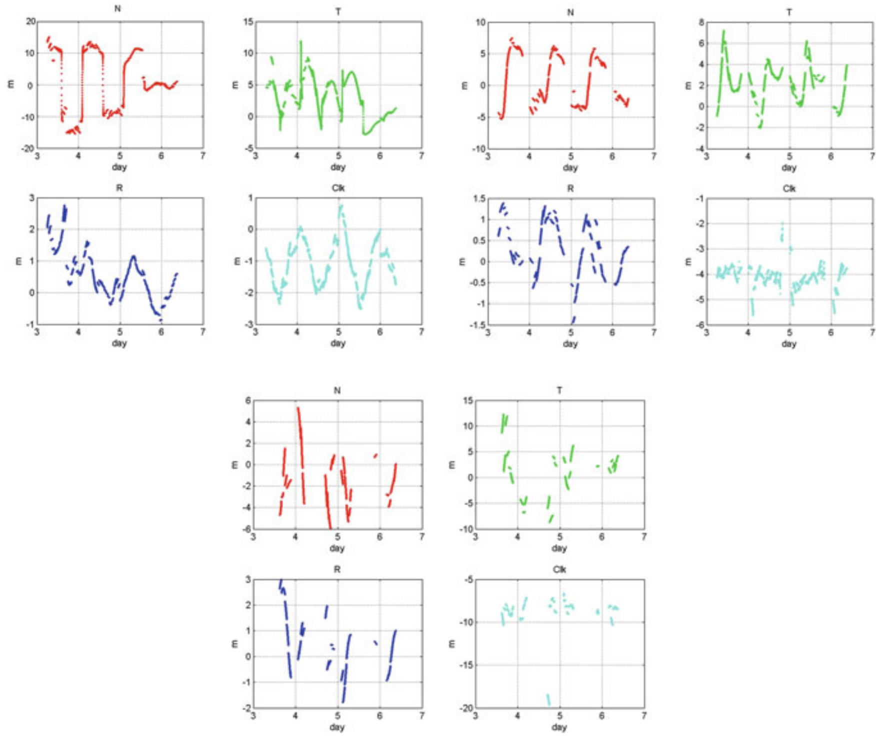
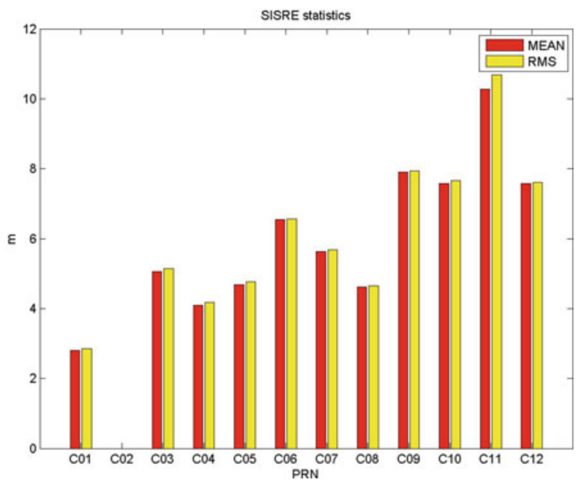


Fig. 16.1 Broadcast ephemeris errors for C01, C08 and C11

Fig. 16.2 SISRE statistics for each satellite



16.4 COMPASS Broadcast Ephemeris Corrections Model

According to Sect. 16.3, the error of COMPASS broadcast ephemeris varies much with a certain periodicity. However, the error appears a regular change in short time (such as in 1 h). So we can fast model the error of COMPASS broadcast ephemeris, and then predict the error of satellite orbits and clocks according to the model.

16.4.1 The Establishment of the Correction Model

Owning to the byte limit of broadcast ephemeris, the predict model should be simple but not reduce the predict accuracy. Huang used the combined model of spectral analysis model and AR model, and the precision was at 0.5 m level [7]. However, the model is too complex and not conductive for broadcasting.

Figure 16.1 shows that the error of broadcast ephemeris has a regular change in the same ephemeris. So we can use a linear or quadratic model to fit the errors. In order to find a best fitting model and fitting length, we use the linear and quadratic model to fit the error of broadcast ephemeris with a data length of 30 and 60-min. The fitting residuals for C04 on RTN direction and clocks are presented in Fig. 16.3, and Table 16.1 gives the statistics of fitting residuals for different fitting models and fitting length.

From Fig. 16.3 and Table 16.1 we can see that for each fitting model and different fitting length, the precision of fitting residuals is at centimeter-level or higher, which is due to the high precise orbits and clocks. While the fitting precision of clocks varies not much, this is because that the satellite orbit applies to the law of movement of dynamics. As for different fitting model and length, the quadratic model is better than linear model; the shorter the fitting length, the better fitting result we get. However, with the byte limitation of broadcast ephemeris, the bytes used in quadratic model are more than linear model; the shorter the fitting length, the more bytes should used. So how to choose a best fitting model and fitting length is a weigh issue.

16.4.2 Precision of Prediction Model

Having got the fitting model, the next issue is using it for prediction to correct the error of COMPASS broadcast ephemeris. Take C04 as example, Fig. 16.4 presents the satellite orbits and clocks predicting residuals by using the fitting model for prediction. The model here we choose is quadratic model, the fitting length and predicting length are both 60-min. Figure 16.4 demonstrates that the predicting error increases when predicting length extends, but all are less than 1 m in 1 h.

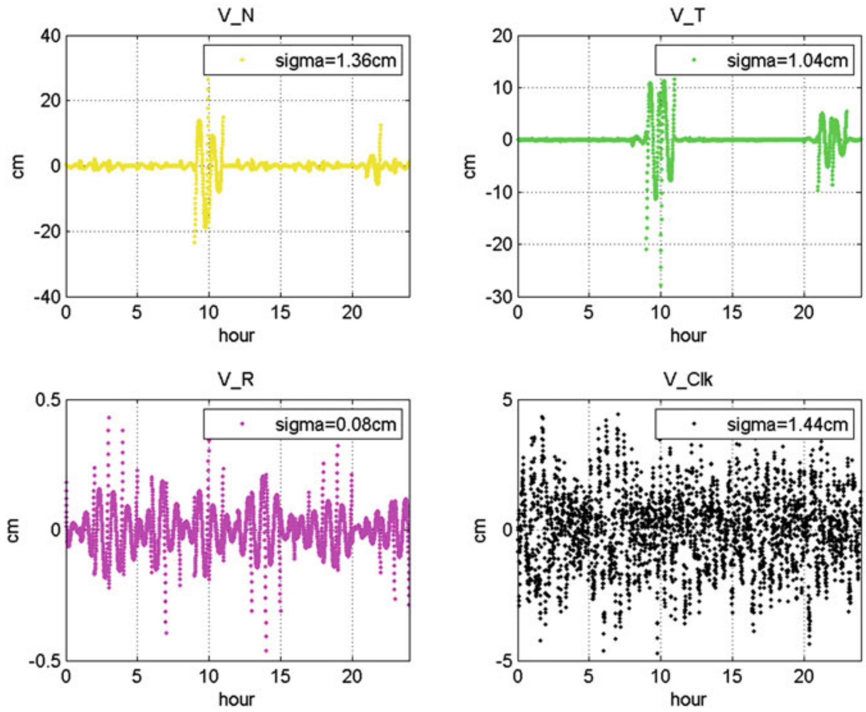


Fig. 16.3 Fitting residuals for C04 (quadratic + 60 min)

Table 16.1 Fitting residuals of different models and arc length for C04

Fitting model and fitting length	N/cm	T/cm	R/cm	Clk/cm
Linear + 60 min	3.98	4.69	0.75	1.81
Linear + 30 min	1.19	1.14	0.17	1.29
Quadratic + 60 min	1.36	1.04	0.08	1.44
Quadratic + 30 min	0.16	0.22	0.02	1.01

Table 16.2 lists the statistics of predicting residuals for orbits and clocks using different fitting models and predicting length. From the table we can see that the prediction precision of 30-min is much better than that of 60-min. As for clock prediction, a linear model is more suitable. This conclusion also applies to other satellites.

Figure 16.5 gives the statistics of SISRE after model prediction correction. Compared with Fig. 16.2, we can see that after broadcast ephemeris correction, the SISRE is at the level of 0.1–0.3 m, about 1/30 of that before correction.

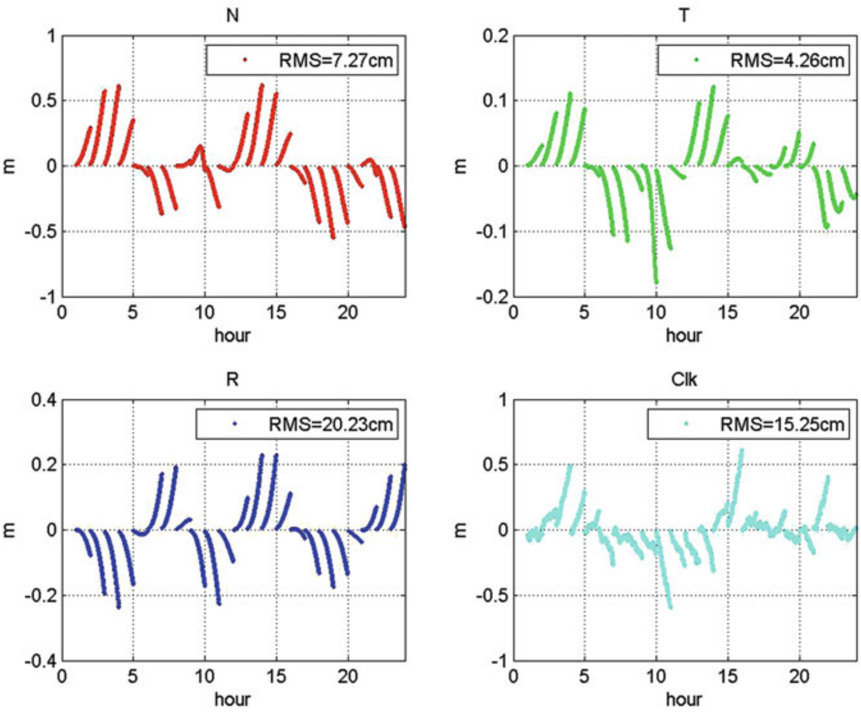


Fig. 16.4 Prediction residuals for C04

Table 16.2 Predict precision of different model and length for C04

Prediction model and length	N/cm	T/cm	R/cm	Clk/cm
Linear + 60 min	33.61	9.01	3.27	7.66
Linear + 30 min	8.25	2.54	2.48	5.53
Quadratic + 60 min	20.23	4.26	7.27	15.25
Quadratic + 30 min	4.76	1.17	0.43	12.85

16.5 The Application of Prediction Model

For users, the most important issue is positioning precision. After having the predicted model on broadcast ephemeris correction, the system can broadcast the parameter of the model to users via GEO. Thus user can correct the broadcast ephemeris and improve the positioning precision.

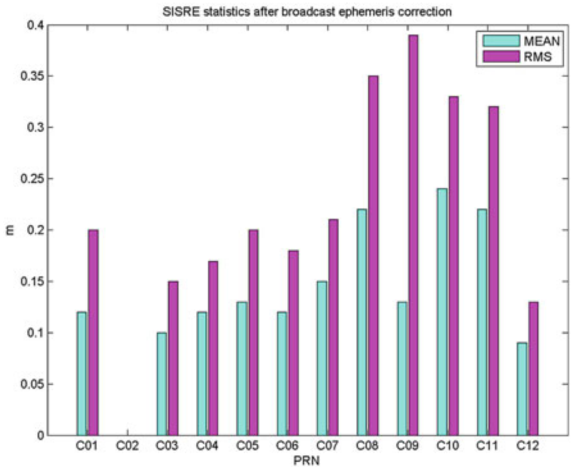


Fig. 16.5 SISRE statistics for each satellite after broadcast ephemeris correction

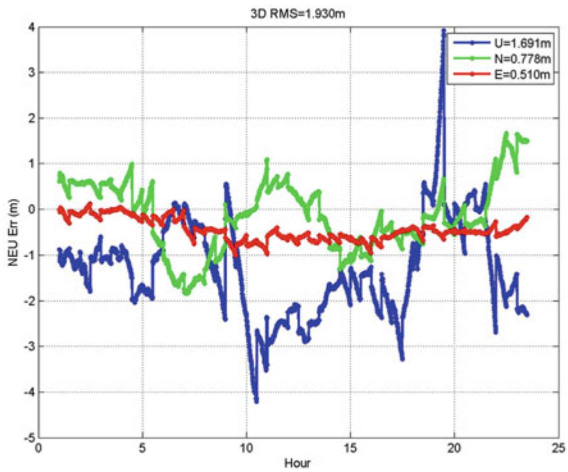


Fig. 16.6 Single point positioning using broadcast ephemeris after correction

16.5.1 Single Point Positioning

After receiving the correction model, one can correct the broadcast orbits and clocks for real-time pseudo-range positioning.

Figure 16.6 gives the COMPASS single point positioning result using the predicted model, the correction model is quadratic for orbits and linear model for satellite clocks, the length of fitting and prediction are both 30-min. Table 16.3 gives the result compared with precise orbits and clocks, and raw broadcast ephemeris.

From Fig. 16.6 and Table 16.3 we can conclude that the single point positioning result improves much after the correction of broadcast ephemeris. The precision is similar to precise orbits and clocks, which is due to the precision of prediction model.

Table 16.3 Positioning error using different orbits and satellites

	N/m	E/m	U/m	3D/m
BRD (raw)	3.016	1.893	3.585	5.039
BRD (prediction model)	0.778	0.510	1.691	1.930
Precise orbits and clocks	0.486	0.778	1.385	1.662

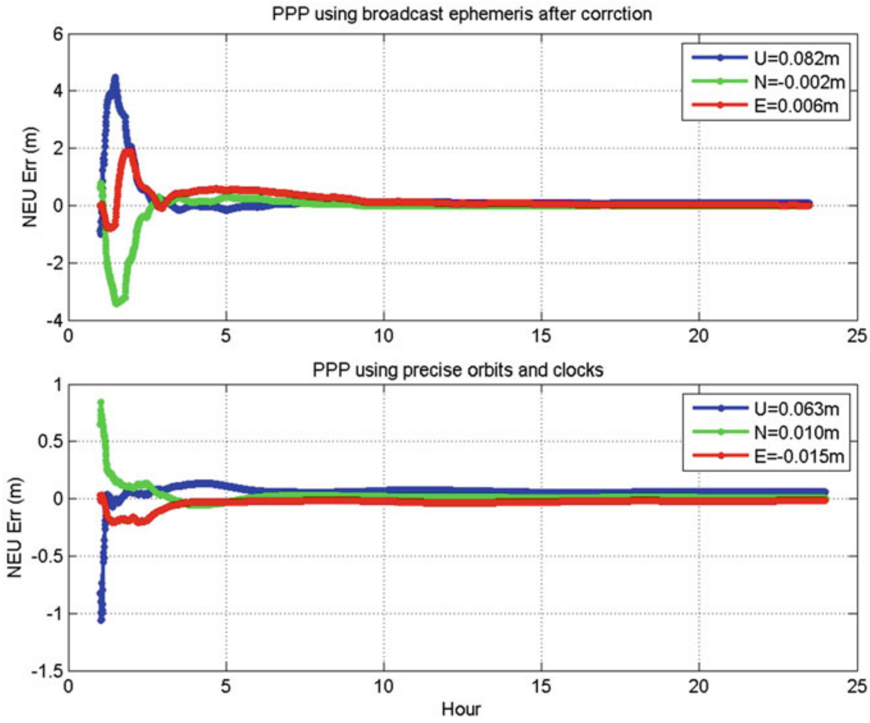


Fig. 16.7 Precise point positioning using broadcast ephemeris after correction

16.5.2 Precision Point Positioning

Due to the precision of broadcast ephemeris, the ambiguity can't convergence correctly for carrier phase positioning. According to the previous sub-section, the broadcast ephemeris can be corrected well by using the prediction model, and it is almost at the same level as precise products. So we can use the corrected broadcast ephemeris for carrier phase positioning.

Figure 16.7 shows the precise point positioning result for COMPASS users, the upper plot is the positioning result using the broadcast ephemeris after prediction model correction. The correction model is quadratic for orbits and linear model for satellite clocks, the fitting and prediction length are both 30-min. The lower plot is the PPP result using the COMPASS precise orbits and clocks. By comparing the two plots, the convergence time is longer for modeled correction on broadcast ephemeris. However, the positioning precision is at the same level with precise orbits and clocks after convergence, and the final positioning error is (0.2, 0.6, 8.2) cm and (1.0, 1.5, 6.3) cm. This proves that this method can be used in precise point positioning.

16.6 Conclusion

In this paper, the COMPASS broadcast ephemeris error is analyzed by the comparison with the COMPASS precise ephemeris from SHA. On this basis, the broadcast ephemeris error model is established to predict the error correction and build the prediction model. The broadcast ephemeris errors can be corrected with this prediction model, thereby improving the users' real-time positioning accuracy. Some useful conclusions are as follows.

(1) There are certain periodicities in the GEO and IGSO orbit errors from COMPASS broadcast ephemeris, especially in their N direction, whereas the periodicity of MEO orbit errors is less obvious. Overall, the SISRE of COMPASS broadcast ephemeris is higher than the GPS and GLONASS.
(2) In a short time, regularities exist in COMPASS broadcast ephemeris error. Linear model or quadratic model can be used to fit the short time broadcast ephemeris errors. When the fitting arc length is 30–60 min, the fitting residuals are centimeter level.
(3) COMPASS broadcast ephemeris error can be predicted by the fitting model. The comparison results demonstrate that the longer time predicted, the larger prediction residuals produced. Better forecast results will be obtained in 30 min or less time. Linear model are recommended in the satellite clock error fitting and forecasting.
(4) User pseudo-range and carrier phase positioning accuracy can be greatly improved due to the broadcast ephemeris prediction model.

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