Broadcast vs. precise GPS ephemerides: a historical perspective

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Abstract The Navstar Global Positioning System (GPS) Operational Control Segment (OCS) generates predicted satellite ephemerides and clock corrections that are broadcast in the navigation message and used by receivers to estimate real-time satellite position and clock corrections for use in navigation solutions. Any errors in these ephemerides will directly impact the accuracy of GPS based positioning. This paper compares the satellite position computed using broadcast ephemeredes with the precise position provided by the International GPS Service for Geodynamics (IGS) Final Orbit solution. Similar comparisons have been undertaken in the past, but for only short periods of time. This paper presents an analysis of the GPS broadcast ephemeris position error on a daily basis over the entire operational lifetime of the GPS system. The comparison was undertaken from 14 November 1993 through to 31 December 2002. The statistics of these errors were also analyzed.

Introduction

Historical information on the day-to-day performance of the broadcast ephemeris message is only publicly available for small periods in 1993 (Zumberge and Bertiger 1996), 1996 and 1997 (Conley 1997; Malys et al. 1997a), from 1998–2000 (Jefferson and Bar-Sever 2000), and for all of 1999 onwards (Langley et al. 2000). A complete set of data would provide the GPS Joint Program Office (JPO) with an independent assessment of the impact of past OCS Kalman filter modifications and OCS system improvements. For this reason the GPS JPO asked AFIT to evaluate the broadcast ephemeris error using external publicly available data for as much of the project's history as practical. The time period chosen was from 14 November 1993 (a few weeks before the system officially achieved Initial Operational Capability status) to 31 December 2002.

Background

The generation of the navigation message starts with the OCS's use of a Kalman filter to estimate satellite position, velocity, solar radiation pressure coefficients, clock bias, clock drift and clock drift rate. These estimated parameters are then used to propagate the satellite position and clock corrections into the future. The propagated values are then fit to a set of equations and the fit coefficients are distributed as broadcast ephemerides in the navigation message.

GPS navigational errors

The accuracy of the GPS Precise Positioning Service (PPS) and Standard Positioning Service (SPS) are routinely monitored by several US Department of Defense and commercial organizations (Malys et al. 1997a).

The GPS navigation accuracy specification calls for a 16-m 50% Spherical Error Probable (SEP) and a 100-m 95% 2drms, for the PPS and SPS systems, respectively. These specifications were developed through operational experience gained from the USN TIMATION program, the USAF 621B Project, the USN NNSS project, and through simulations.

The above GPS real time user accuracy specifications are comprised of 'Signal-In-Space' (SIS) and User-Equipment (UE) error components. The SIS Range Error (SISRE) is a measure of the fidelity of the navigation messages broadcast by the GPS satellites, and its accuracy is the responsibility of the GPS OCS (Malys et al. 1997a).

The UE Range Error (UERE) is comprised of receiver noise, tropospheric refraction, uncompensated

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ionospheric effects, multipath effects, and any other errors induced by a user's local environment. UERE is completely dependent upon the receiver design and the environment in which a receiver is used. In contrast, the Signal In Space Range Error (SISRE) is a measure of the fidelity of the broadcast navigation message, including ephemeris and satellite clock errors.

The User Navigation Error (UNE) can be approximated by

$$UNE(1\sigma) = GDOP\sqrt{SISRE^2 + UERE^2} \qquad (1)$$

where *SISRE* is the RMS of many individual SISRE values approximated using Malys et al. (1997a)

$$SISRE = \sqrt{(R - CLK)^2 + \left(\frac{1}{49}\right)(A^2 + C^2)} \qquad (2)$$

where

R = radial ephemeris error

A = along track ephemeris error

C = crosstrack ephemeris error

CLK = SV clock phase error (wrt GPS time)

$UERE$ = composite of all UE range errors

$GDOP$ = *Geometric Dilution Of Precision*

Error analysis

Historically, GPS orbit accuracy has been analyzed using a variety of operational and a posterior analysis methods. For operational analysis, the OCS monitors three performance measures every 15 min to track the quality of the navigational message, Observed Range Deviations (ORDs), Estimated Range Deviations (ERDs) and NAVigational SOLutions (NAVSOLs). The OCS also monitors the Kalman Filter Estimates every 24 h by executing a tool called Smoothed Measurement RESidual Generator (SMRES). These operational methods provide a useful real-time analysis of satellite and OCS performance.

A posterior analysis techniques enable comparison of the GPS satellite orbits against a precise reference standard. This allows the OCS to characterize improvements and system performance.

A posterior analysis

The primary method used for a posterior analysis is a comparison of the OCS Kalman filter orbit and clock estimates to a set of more accurate post-fit ephemeris and clock estimates. The National Imagery and Mapping Agency (NIMA) GPS Precise orbit and clock estimates are often used, since they are developed from data collected by multiple PPS stations and therefore provide precise ephemeris and clock estimates.

The advantages of this method of a posterior analysis include:

- allows isolation of ephemeris from clock components in total SISRE;
- facilitates characterization of SISRE as a function of prediction span;
- isolates SISRE from total URE;
- editing of corrupt data from precise orbits is generally not necessary; and
- can be projected along lines of sight to a specific location or user trajectory, resulting in a more accurate representation than the approximation in Eq. (2).

The results of this a posterior analysis are usually quoted as RMS SISRE, and they assume that the NIMA data is a truth source. The satellite clock differences and the along-track, cross-track and radial (ACR) orbit differences at any given epoch are combined to obtain an individual SISRE for each satellite.

Equation (2) is generally used for calculating SISRE; however, it does vary between studies due to organizational legacies (Malys et al. 1997a). The RMS value is calculated for each individual satellite over a selected period or for the entire constellation.

IGS orbits are sometimes used to calculate SISRE. The IGS uses an order of magnitude more stations than NIMA and therefore provides more accurate precise ephemeris and clock estimates. However since most IGS stations comprise SPS receivers, they include the effects of Selective Availability (SA) prior to May 2000 (when SA was set to zero). While each individual IGS station is corrupted by the effects of SA, the advanced estimation techniques (comparable to differential positioning techniques) employed by the IGS allow removal of SA effects from the IGS orbit estimates. IGS clock states, however, cannot be directly compared to NIMA PPS clock states; therefore, CLK in Eq. (2) is normally set to zero and the SISRE is classified as 'orbit-only' (Malys et al. 1997a).

Broadcast ephemeris analysis and results

Precise orbit

Precise orbits were obtained from the IGS website managed by the Jet Propulsion Laboratory of the California Institute of Technology (IGS 2003a). The IGS website maintains precise orbit records from GPS week 649 (1992) through to the present. Data is stored in SP3 format as compressed (zip) files. The IGS final orbit was used for the comparison, since it had the highest accuracy of any publicly available orbit. The accuracy of precise IGS final orbit has steadily improved between 1992 and 2002. The IGS orbit accuracy in 2002 is believed to be on the order of <0.05 m (IGS 2003b).

The precise orbit was determined by loading all available ephemeris records (which provided epochs each 15 minutes). The positions provided by the IGS are in the International Terrestrial Reference Frame (ITRF), which is consistent with the WGS-84 frame to a few centimeters (Malys et al. 1997b). For this reason a transformation was not considered necessary for the purposes of this analysis.

Broadcast ephemeris

Broadcast ephemerides were obtained from the Crustal Dynamics Data Information System (CDDIS) website located at National Aeronautics and Space Administration

(NASA) Goddard Space Flight Centre in Greenbelt, Maryland (CDDIS 2003). The CDDIS website maintains broadcast ephemeris records from GPS week 0570 (1991) through to the present. Data is stored in RINEX format as compressed (zip) files.

The broadcast orbits were determined from the broadcast ephemeris using the method described in ICD-GPS-200C Table 20-IV. The ephemeris data are normally uploaded daily and are valid for a period 2 h either side of the time of ephemeris (TOE) broadcast as part of the GPS navigational message (GPS Navstar Joint Program Office 2003). The position of each satellite was determined using the broadcast ephemeris at 15-min intervals that coincide with the IGS orbit epochs.

Satellite antenna phase centre offset

The broadcast orbits are determined relative to the spacecraft's antenna phase center, but the IGS orbits are determined relative to the spacecraft's center of mass. An approximate radial correction was applied to the broadcast orbit to correct for the offset between each GPS satellite's antenna phase center and its center of mass. (The correction is approximate, because satellite attitude data were not used, so the small nonradial component of the antenna/center of mass offset is not properly accounted for.) The correction applied was 1.023 m for block II/IIA satellites and 0.0 m for block IIR satellites. These correction values are consistent with those used by four of the IGS regional processing centers (NRCan, the European Space Agency, GeoForschungsZentrum Potsdam, and the US Naval Observatory) (National Resources Canada 2002; European Space Agency 2002; GeoForschungsZentrum Potsdam 2001; Centre for Orbit Determination in Europe 2001).

Analysis technique

The difference between the precise and broadcast orbits was determined at 15-min intervals for the entire study interval. This difference was initially calculated in Earth-Centered Earth-Fixed (ECEF) coordinates, but at each epoch it was converted to an orbital reference frame comprised of along-track (satellite's direction of motion), cross-track (tangential to along-track and radial) and radial (vector from center of Earth to satellite) components. Because the precise orbits are generally more accurate than the broadcast orbits by almost two orders of magnitude, the precise orbits were considered to be the truth, and any difference between the two is attributed to broadcast orbit error. A number of data integrity checks were performed to make sure that the data used for generating the results of this study were valid.

First of all, the health bit was checked for all satellites at all analyzed epochs, and only satellites with a valid health bit were used in this analysis. This should eliminate errors due to satellite maneuvers or satellite tests, in which the satellites were not intended to be used by receivers. Also, errors were calculated only if there was valid precise ephemeris data. If the accuracy of the precise ephemeris data on any given day was unknown (indicated by an accuracy flag of 0 in the header of the sp3 file), no comparisons were generated for that satellite on that day. Even after checking the health bits and accuracy flags, initial testing showed occasional extreme position error values (outliers) on the order of several kilometers or more, due to errors within the broadcast ephemeris. These errors are generated by individual ephemeris terms, and occur in only a few epochs in each of the affected broadcast ephemeris files.

Initially a mean ±1 sigma filter was proposed, but it removed excessive numbers of data points. Over the entire study period, all along-track, cross-track and radial errors were either less than 50 m or were extremely large outliers (kilometer or greater error). Therefore, an outlier filter was used to remove individual satellite epochs that exceeded the 50 m limit in any one of the along-track, cross-track and radial coordinate axis. Approximately 0.1% of the data points were removed through this process.

Broadcast orbit position error

Figures 1 and 2 are representative samples plots of ACR broadcast orbit position error (for PRN 22 for 1 November 97 and 1 November 00 respectively). Both graphs show a periodic trend that is consistent with the GPS constellations 12-h orbit. The graphs shown for PRN 22 are consistent across other satellites within the GPS constellation. By studying various ACR plots it was determined that the along-track and cross-track components tend to have similar magnitudes, which are approximately twice the amplitude of the radial component. Previous studies determined that the uncertainty in the radial component is three to four times better than the along-track and cross-track components (Roulston et al. 2000). This difference is due to the GPS pseudorange being more sensitive to changes in the radial direction than in other directions, and also due to the fact that orbit revolution time is very accurately determinable, and that gives through the Kepler

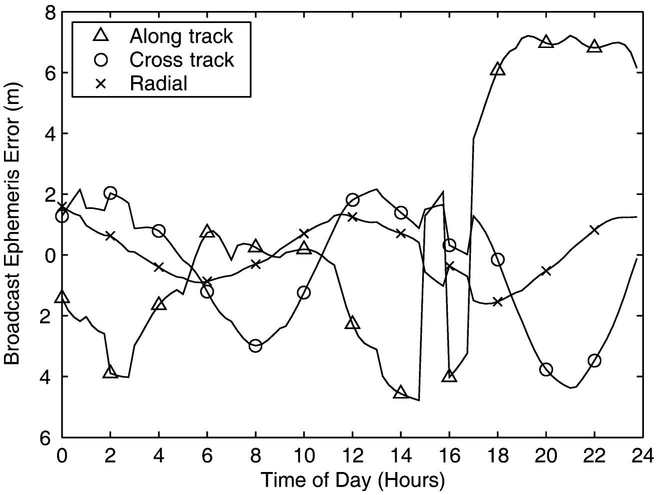

Fig. 1
ACR broadcast orbit position error with respect to IGS final orbit 1 November 97, PRN 22

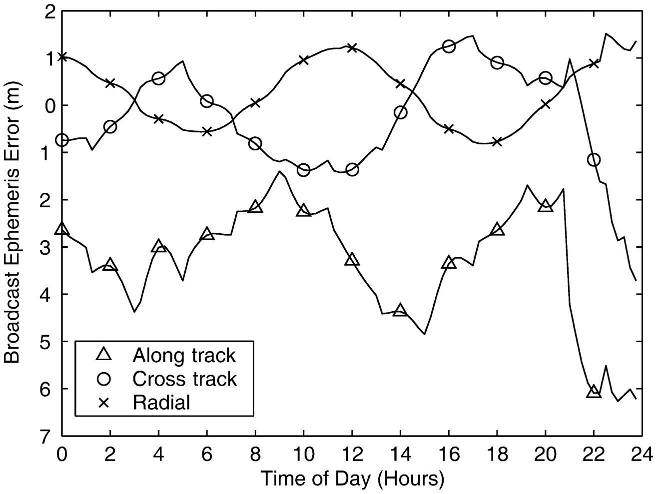

Fig. 2
ACR broadcast orbit position error with respect to IGS final orbit 1 November 00, PRN 22

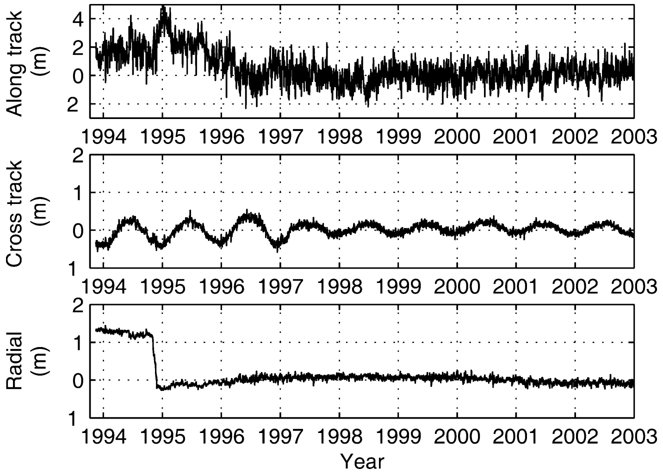

Fig. 3
Daily mean of broadcast orbit position error with respect to IGS final orbit

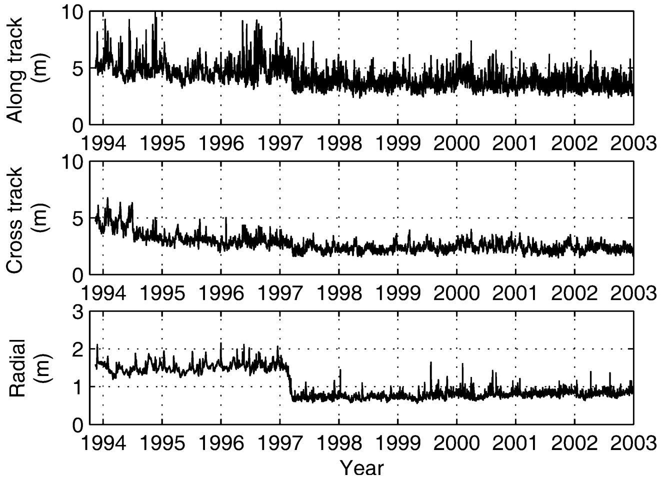

Fig. 4
Daily standard deviation of broadcast orbit position error with respect to IGS final orbit

law a good estimate for the semi-major axis (which corresponds to the radial component) (Zumberge and Bertiger 1996).

The GPS OCS Performance Analysis and Reporting (GO-SPAR) project showed that the 12-h period terms are not due to longitude or latitude variations (Conley 1997). User position error does vary somewhat with longitude, due to the ephemeris upload pattern employed by the OCS, which is dictated by fixed ground stations (Conley 1997) and dilution of precision (DOP) values which are not constant at any given time around the globe. Weiss stated that Kalman filter residual errors could generate the 12-h periodic terms, especially a consistent error in the orbit eccentricity (Centre for Orbit Determination in Europe 2001).

Daily statistics

For each day during the 9+ year analysis period, a mean error and error standard deviation were calculated in each axis for the entire constellation (across all satellites and all comparison time epochs). These daily mean and standard deviation values are shown in Figs. 3 and 4.

Several observations can be made from these figures. Figure 3 shows that the mean along-track error has been fairly consistent over the analysis period, although it did start with a positive bias for the first two years or so. (Note the variation in scale between the along-track and the cross-track and radial errors). The mean cross-track error has a fairly consistent periodic trend, with a 1-year period. This sort of yearly periodicity might implicate eclipse periods as a cause. However, all of the points shown in Fig. 4 are daily averages across the entire satellite constellation, so the effect of eclipses should be reduced, because at any given time only some of the orbital planes would be experiencing eclipse periods. Also, note that the magnitude of the trend was reduced at the beginning of 1997, for reasons that will be discussed later. The mean radial error has been very consistently close to zero since 1995. Prior to 1995, the radial error was around 1.2 m, which is very close to the magnitude of center of gravity/antenna phase center lever arm correction. It is possible that this lever arm was handled differently prior to 1995 in either the IGS data or the broadcast ephemeris data.

The plot of the daily standard deviations (Fig. 4) also indicates a significantly more precise radial error than the along-track or cross-track errors (note differences in scale). Also, improvement over time is evident. Of particular interest is a drop in the standard deviations in all three axes in early 1997 (most notable in the radial case), at the same time as the reduction in the magnitude of the periodic cross-track error from Fig. 3. This coincides with the 2SOPS implementation of the Ephemeris Enhancement Endeavor (EEE) (Crum et al. 1997), and it demonstrates the significant impact that this improvement in the control segment had on broadcast ephemeris accuracy.

Orbit-only SISRE analysis

As stated in the introduction, the signal-in-space range error (SISRE) is often used as an overall measure of the

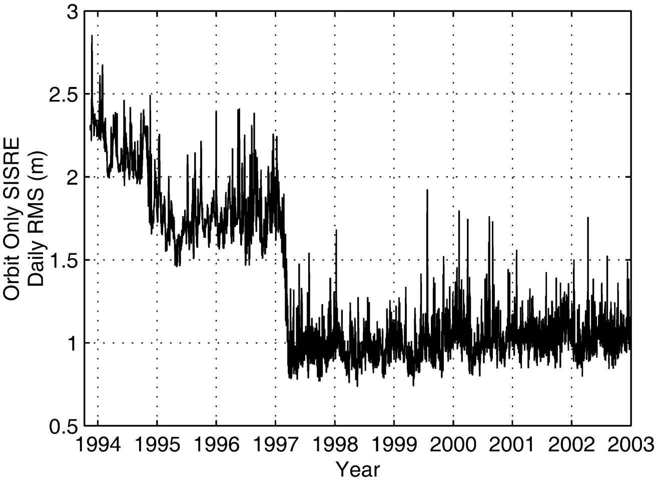

Fig. 5
Orbit only SISRE history—daily RMS values across all satellites and time epochs

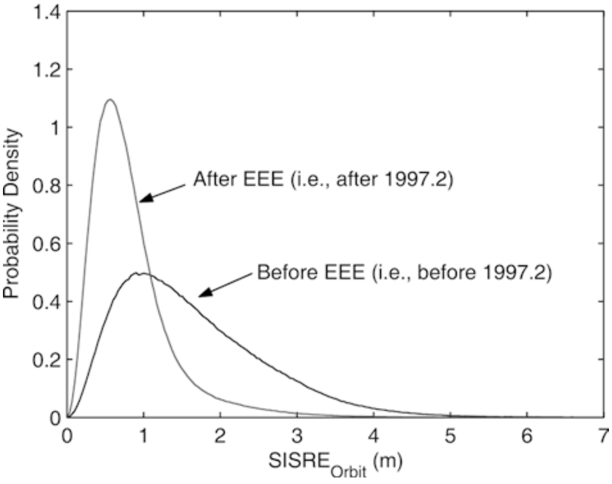

Fig. 6
Data-derived probability density function for SISRE before and after ephemeris enhancement endeavor

satellite errors (including clock errors). The “orbit only” SISRE, which does not include the clock error, is given by

$$SISRE_{Orbit} = \sqrt{R^2 + \left(\frac{1}{49}\right)(A^2 + C^2)} \qquad (3)$$

where A, C, and R are the along-track, cross-track, and radial orbital errors. An orbit-only SISRE was calculated for every satellite at every analysis epoch. Then, the root-mean-square error of the $SISRE_{Orbit}$ errors across all satellites and all measurement epochs for every day of the analysis period. (Because the SISRE is itself a root-sum-square value, it is more appropriate to use a root-mean-square value to represent a “typical” SISRE value than to use the mean value.) The resulting daily RMS $SISRE_{Orbit}$ values are shown in Fig. 5.

This orbit-only SISRE plot shows the combined effect of a reduction in mean error and a reduction in error standard deviation (with the highest emphasis on the radial error, which has the most impact to a user on Earth). Once again, the effects of the Ephemeris Enhancement Endeavor in early 1997 can be clearly seen. It is interesting to note, however, that there appears to be a very slight increase in the orbit only SISRE between 1997 and 2003 (on the order of a few centimeters).

While Fig. 5 shows a good summary of the $SISRE_{Orbit}$ error over time, it only gives single daily RMS values, so it cannot fully capture the full distribution of the $SISRE_{Orbit}$ errors. Figure 6 shows the probability density functions of the $SISRE_{Orbit}$ error before and after implementation of the Ephemeris Enhancement Endeavor, derived from each individual satellite/time combination. The “Before EEE” plot represents the probability density of the set of all individual $SISRE_{Orbit}$ errors (for each satellite at each analysis epoch) prior to year 1997.2 (a total of over 2.9×10^6 data points). Likewise, the “After EEE” plot was generated from data after the year 1997.2 (over 5.4×10^6 data points). These pdf plots again show that the $SISRE_{Orbit}$ errors tend to be significantly lower after 1997.

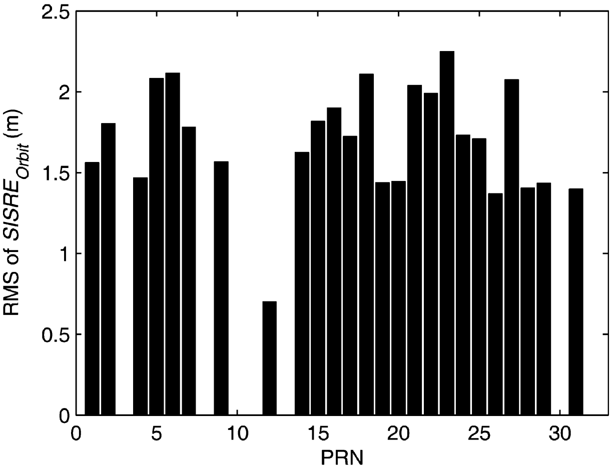

Fig. 7
RMS of $SISRE_{Orbit}$ error for each individual satellite—1995

Satellite-by-satellite SISRE analysis

In order to evaluate the differences in broadcast ephemeris error between satellites, the root-mean-square $SISRE_{Orbit}$ error was calculated on a satellite-by-satellite basis, across all data points in the years 1995, 2000, and 2001 (Figs. 7, 8, and 9, respectively). Once again, the effect of the Ephemeris Enhancement Endeavor can be seen. It is also interesting to note that there is a significant amount of variation between satellites. It is evident from Figs. 8 and 9 that the satellite errors are generally consistent from year to year, indicating that they are truly satellite-dependent, and not just random variations. The satellites that had the larger errors in the 2000–2001 timeframe (PRNs 6, 15, 17, 21, 23) were all 10 or more years old (with the exception of PRN 6, which was 6 years old). A growth in ephemeris error is consistent with component aging. For example, in 2000, PRN 15 was known to have problems with its reaction wheel during eclipse; this could be the source of the increased error relative to 1995 (Roulston et al. 2000).

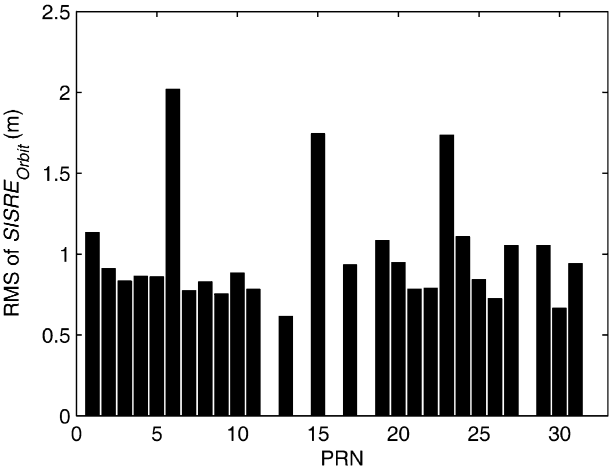

Fig. 8
RMS of $SISRE_{Orbit}$ error for each individual satellite—2000

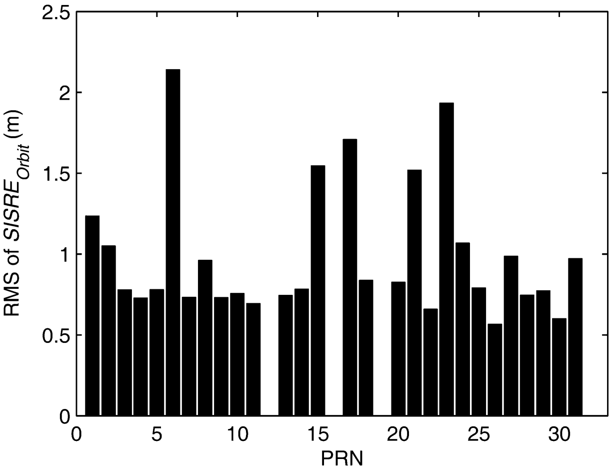

Fig. 9
RMS of $SISRE_{Orbit}$ error for each individual satellite—2001

Conclusions

The position error between the broadcast orbit and the IGS final orbit was determined for the period 14 November 1993 to 31 December 2002 in both yearly segments and for the entire time period. The evaluation shows that the broadcast orbit has nearly zero mean errors in each coordinate axis toward the end of the study period, with a small yearly periodic fluctuation in the cross-track component. In general, the error standard deviations have dropped over time, although there seems to be a slight increasing trend in the radial error standard deviation over the past few years. The constellation 'orbit-only' SISRE, calculated on a daily basis was around 1.7 m until early in 1997 when it dropped to around 1.1 m. This coincided with the 2SOPS implementation of the Ephemeris Enhancement Endeavor. Further improvements are expected when the Accuracy Improvement Initiative is implemented.

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