IGS Analysis Center Workshop, Darmstadt, Germany, Feb. 9-11, 1998.

Position Paper #2:

ORBIT PREDICTIONS AND RAPID PRODUCTS

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Abstract

The IGS is facing ever increasing demands for more precise and more rapid (real-time!) products. The computation of the rapid orbits and especially the orbit predictions, which are available in real-time, therefore are becoming more important and deserve special attention. This position paper reviews the methods of generating the rapid and predicted products and proposes ways to improve the prediction accuracy and to reduce the turn-around time.

1. Introduction

The use of GPS techniques for near real time data processing requires fast availability of relatively precise GPS products. New fields of application require availability of GPS orbits with high precision and at short delay after the observations are taken. An example of this is the developing field of operational meteorology using GPS. The GPS derived precipitable water vapor (PWV) measurements have to be processed within hours after the observation so they can be used for weather forecast. In order to get the best observability of PWR precise predicted orbits have to be available.

The IGS have been producing orbits and eops with a 24 delay and predictions for the following day since 1996. These products are obtained as a combination of the results of a number of Analysis Centers and are currently available before 22:00 UTC (rapid products) and before 23:00 UTC (predictions for the following day).

The factors that limit the accuracy of the rapid and predicted products are the availability of a sufficient set of tracking data and the accuracy of the orbit prediction models.

The IGS community has been working to speed the delivery of the measurement data, but we have not yet achieved a satisfactory status, because many stations are still late and this is normally the case for stations outside Europe and North America. Faster or more frequent delivery of the data could also allow for more frequent (sub-daily) delivery of precise and rapid products.

Progress has been made in the accuracy of orbit prediction models, with investigations on new radiation pressure models being presented in this session, but we still have problems for some satellites and some improvement is possible. It is also very important for users of predicted orbits to have a good estimate of the accuracy of predicted orbits so they can de-weight or exclude those satellites that can not be well predicted.

2. Data availability and reduction of the turn-around time

There are two aspects in the reduction of the turn-around time, measurement data and data processing. Data from a sufficient number of well distributed stations should be available before the rapid orbits can be computed. The current deadline for data to be used in rapid orbits is 05:00 UTC, but most ACs start computing their orbits later due to the lack data from stations in the southern hemisphere. In order to obtain a good rapid orbit the criticallity is not only the number of stations but their distribution. We have studied the availability of data at CDDIS, as listed in the reports of CDDIS GPS tracking data holdings, and for the purpose of this study we have grouped the stations in six regions. The selection is of course arbitrary, the stations in the border between two regions could belong to the other region, but it is useful in order to analyze the arrival of the data. The regions that we have selected are:

- AS: Central and Eastern Asia
- EU: Europe, Asia Minor and the Canary Islands
- IN: Indian Ocean rim and Islands
- NA: North America and Greenland
- PA: South Pacific, Micronesia and Polynesia
- SA: Caribbean and South America

These regions are shown in Figure 1.

We have checked the number of stations available at the following times:

- Within two hours of tracking. This is time enough for data retrieval at the operational data center, reformatting, and transmission to the global data center.
- Within five hours of tracking. This is the theoretical Rapid Orbit deadline.
- Within twelve hours of tracking. This represents a typical AC Rapid Orbit deadline.
- Within forty-eight hours of tracking. This is the theoretical Precise Orbit deadline.

The number of stations that were available at CDDIS for the period from Nov. 29th 1997 to Jan. 27th 1998 are shown in Table 1. The two values that are shown are the minimum and maximum number of stations that were available at that time. Detailed plots for the studied period are in Figures 2 to 5.

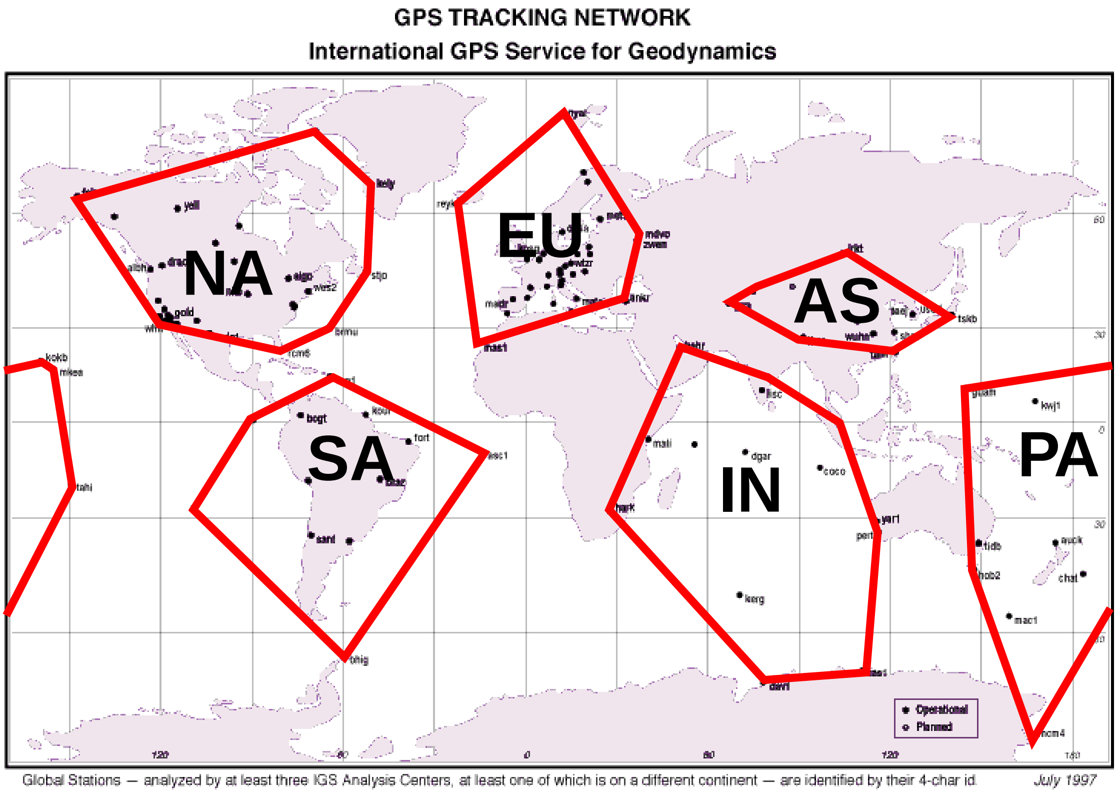

Fig. 1 Grouping of stations in order to study availability

Region \ delay	< 2 h	< 5 h	< 12 h	< 48 h
NA	2 - 18	11 - 41	20 - 50	25 - 54
EU	3 - 12	5 - 16	8 - 22	16 - 26
IN	0 - 3	2 - 9	4 - 11	5 - 12
AS	0 - 5	0 - 6	2 - 7	4 - 13
SA	0 - 3	0 - 8	1 - 11	3 - 13
PA	0 - 2	0 - 8	1 - 12	1 - 13
All	12 - 34	29 - 79	45 - 103	57 - 126

Table 1. Data available at CDDIS for the last two months

There are days for which no station is available at 12:00 UTC for some of the less covered regions (PA, SA). This means that the rapid orbits are calculated without taking in account any observations from a substantial part of the satellite orbits. This also affects the predicted orbits that will be obtained based on the rapid orbits. The ideal would be to have a minimum of 4 stations available from each of the regions at the time of the calculation of the rapid orbits. The maximum number of stations available at the different times also tells the capability of the system when everything goes well and for +5 a minimum of 6 stations are available from each of the regions when the data retrieval and transfer is at its best.

One of the ways to reduce the delay in the availability of data and to increase the probability of data being available would be to perform incremental downloads during the day. The data could be retrieved by the Operational Data Centers every 6 or 8 hours, processed and sent to the Global Data Centers where it would be available to the ACs. The current RINEX file naming convention can accommodate multiple files per day. It could be agreed that the *statdoy0.yyo* file name would correspond to a a whole day and that *statdoyi.yyo* with i>1 corresponds to a fraction of the day. Fractional files could be stored in a different directory accessible to the ACs and then combined in a whole day file for final archiving. Incremental delivery would insure that some data would be available for rapid orbits even if there were communication problems right after 00:00 UTC. It would also allow more frequent computation of rapid and predicted orbits. Reduction of the turn-around time leads to improved predictions because the predicted orbit is less "old" and therefore better. At the moment we have a 24 hour delay of the predictions, but this could easily be reduced to 12 hours.

3. Orbit models

The most characteristic features of the orbit models that are used by the ACs for rapid and predicted orbits are listed in Table 2. Special emphasis is given to the description of radiation pressure models, stochastic accelerations and the handling of eclipsing satellites. One of the points that are handled differently by every center is the prediction of eops. To make the orbits more consistent the IGS could produce a set of predicted Earth orientation parameters, based on the rapid eops and that could be used for generating and using orbit predictions.

As can be seen in the Figure 6 the IGS rapid orbits are very close to the final orbits and it is believed that the best way to improve them would be through the increase in data that is available to the Analysis Centers, more data from remote regions and more recent data. Data from the same day could be used to improved the rapid orbits, if an incremental delivery system for the data from the IGS stations is implemented.

The situation for the predicted orbits is not so good, see Figure 7, even when the comparison wrms with the rapid orbits sometimes goes down to under 50 cm, other times it is much worst. In Figures 8 to 11 it can also be seen the rms for individual satellites, both for the predicted orbits and for the broadcast orbits and for non-eclipsing and eclipsing satellites. It can be seen that there are problematic satellites (PRN#23) and that the rms for eclipsing satellites is higher that for others. In general the predicted orbits are much better than the broadcast orbits but this is not always true.

Orbit models could be improved to improve the prediction accuracy for those satellites that are not problematic and especially to improve the prediction of eclipsing satellites.

	CODE	EMR	ESA	GFZ	JPL
RAPID ORBITS					
Started at (hours)	+8 to +12	+13	+14	+11	+8 to +11
Duration (hours)	3.5	3.0	4.0	2.5	10.0
ROCK 4 T	yes	yes	yes	yes	yes
CODE orbit model	yes	-	-	-	-
stochastic DVs	along track per rev	-	3 comp. at eclipse exit	3 comp. at 12:00	-
stochastic accel.	-	-	-	-	yes
cycle per rev. acc.	-	-	radial (c+s)	-	-
est. orb. par. per arc	6+5	6+3	6+2+2	6 + 2	6+2
est. orb. par. per rev.	1	-	(3)	3/2	-
est. orb. par. per step	-	-	-	-	3
yaw rate estimated	-	-	-	yes	yes
PREDICTIONS					
IGR days fitted	-	4	4 or 1	3 or 1	4
ACR days fitted	3	-	(1)	1	(1)
eops	CODE	IGR/Bull. A	IGR	GFZ	JPL
ROCK 4 T	-	-	yes	yes	yes
CODE orbit model	all	all	-	all	ax, ayc
cycle per rev. acc.	-	-	all (c+s)	-	-
est. orb. par.	6+9	6+9	6+2+6	6+9	6+2+4
standard sat.	rms of fit	rms of fit	ae = 9	?	rms of fit
bad fit sat.	rms of fit	rms of fit	ae = 13	100 cm	rms of fit
eclipsing sat.	rms of fit	rms of fit	ae = 16	200 cm	rms of fit
maneuvering sat.	-	-	excluded	-	-

Table 2. Rapid and predicted processing at the Analysis Centers

The largest non gravitational effect on the GPS satellite orbits is the Solar radiation pressure (RPR). Table 3 shows the effect different perturbations have on the GPS satellites. The values in Table 2 were computed by integrating a given set of osculating Keplerian elements over a time period of one day (24 hours) with the respective parameters turned on or off. Given is the RMS of the orbit differences over the full 24 hour arc-length over all satellites (using the full satellite constellation of 1-1-1998).

Perturbation	**Magnitude (m)**			
	Radial	**Along**	**Cross**	**Total**
Earth oblateness	1335	12902	6101	14334
Moon (gravitation)	191	1317	361	1379
Sun (gravitation)	83	649	145	670
C(2,2), S(2,2)	32	175	9	178
Solar Radiation Pressure	29	87	3	92
C(n,m), S(n,m) (n,m=3..8)	6	46	4	46

Table 3. Effect of different perturbations on the GPS satellites over 24 hours

As can be seen the size of the perturbation caused by the Solar radiation pressure is only exceeded by the effects of the Earth oblateness, the gravitational effects from Sun and Moon and the lower harmonics (C(2,2) and S(2,2)) of the Earth gravity field. Clearly an accurate Solar radiation pressure model is as important as an accurate gravity model of the Earth.

The basis of the RPR-models currently used was furnished by Rockwell International, the spacecraft contractor for Blocks I and II [Fliegel et al., 1992]. The computer programs that embody this model became known for Block I as ROCK4, [Fliegel et al., 1985] and for Block II as ROCK42, [Fliegel and Gallini, 1989] although they are also known as the Porter models.

The ROCK models are expressed in the satellite fixed coordinate system. This system has its origin in the center of mass of the satellite. Its Z-axis points in the direction to the center of mass of the Earth, and therefore along the satellite antennas. The X-axis is positive toward the half plane that contains the Sun and the Y-axis completes a right-handed system and points along one of the solar panel beams.

For high precision geodetic work it is advised to estimate scale term and a force in the Y-direction, the Y-bias, in addition to the ROCK model. The ROCK model therefore only serves as a-priori information. Both the scale term and the Y-bias are parameters which are supposed to vary slowly in time. Although the cause of the Y-bias is unknown its effect on the orbit is very significant. The claimed accuracy of the ROCK models is about 3%.

Taking the nominal value of $1 \cdot 10^{-7} m/s$ for the solar radiation pressure and the claimed accuracy of 3% of the T20 model the expected error is approximately $3 \cdot 10^{-9} m/s$. Furthermore the size of the Y-bias, which is not included in the ROCK models is about $1 \cdot 10^{-9} m/s$. The effect of both error sources is about 3 meters (RMS over 24-hours)!

Of course we have to keep in mind here that the ROCK models were developed for orbit estimation using pseudo-range data! With pseudo ranges the orbit estimates have an accuracy of about 1 meter. For this type of accuracy the ROCK model is adequate to serve as a-priori model provided the scale term and the Y-bias are estimated.

Clearly for IGS type of accuracies, e.g. centimeter type orbit accuracies, the ROCK-models are inadequate, even when the scale and Y-bias are estimated. This is also obvious from the additional orbit parameters which most of the IGS ACs are estimating, be it deterministic and/or stochastic parameters.

However, additional orbit parameters may weaken the GPS solutions significantly, especially the LOD estimates. Therefore it should be studied if an improved RPR-model can be found. Possibly it can be derived from the available IGS products and experiences. When developing a new RPR-model there are two questions which should be asked:

- How accurate/reliable can a new RPR-model be derived?
  - which parameters should be estimated/modeled
  - how accurate can these parameters be estimated
    - ... from real GPS data
    - ... from precise orbits
  - how accurate can we model these parameters (to what extend are the selected parameters correlated).
- What may be expected from a new (improved) RPR-model:

Improved (orbit) estimates. With a good RPR-model less orbit parameters will have to be estimated, or the estimated parameters may be (more) constrained, e.g. stochastic pulses. This may be especially useful for the rapid orbits.

More reliable orbit predictions. If less parameters are used for the orbit predictions they will become more reliable. This, however, depends on the type of parameters. Constant accelerations are much more “dangerous” than periodic (e.g. once per revolution) accelerations. Nevertheless good a-priori knowledge of the value of the RPR-parameters will help in identifying “bad” predictions.

Better orbit predictions? This will be difficult because, a better RPR-model will not directly lead to better predictions. For the predictions usually the precise orbits are used as pseudo observations. This means that the “observations” are 3-dimensional positions which are a very strong observation type; much stronger than the double differenced phase observations normally used. This implies that a relatively large number of parameters can be estimated without too much problem. However, if the RPR-model improves the rapid orbits then also the predictions will become better. The quality of the orbit predictions depends quite strongly on the quality of the rapid orbits.

Actually the ACs CODE and JPL have successfully developed new and improved RPR-models over the last years, [Bar-Sever 1997, Springer et al. 1997]. Table 4 list the results

RPR MODEL	FIT RMS (cm)	Prediction	
		Median (cm)	RMS (cm)
No Model	75	133	159
T20	76	134	161
T20 Scaled	72	119	151
JPL Scaled	10	45	58
CODE	6	17	31
“BEST”	5	17	22

Table 4. Orbit Fit (7-day) and Orbit Extrapolation (2-day) using different RPR-models. Only scale (or D_0) and Y-bias estimated.

of a test using the different available RPR-models. It shows the RMS of fit using seven days of precise orbits. The orbit resulting from the 7-day fit was extrapolated for 48-hours. The last 24-hours of this extrapolation were compared with the “true” orbit. The CODE IGS Final products (orbit and EOPs) were used. In all cases only the scale term (or a constant acceleration in the direction sun-satellite) and the Y-bias were estimated. Only for the solution labelled “BEST” more RPR-parameters (9) were estimated. This solution is given as reference to show the best obtainable predicted orbit for the selected test.

Table 4 shows that including the ROCK-model as a-priori RPR-model does hardly give any improvement, both in fit and in prediction. Although it was clear for a long time that the ROCK-models are not very accurate, this is a still surprise! Very clearly both the CODE and JPL RPR-models perform much better than the ROCK-model. The results also show that indeed it is very difficult to get better orbit predictions. However, the reduction of the number of parameters (from 9 to 2) without significant loss of accuracy should make the prediction more reliable. More important will be to study the effect on the orbit estimates. If the RPR-models help to improve the (rapid) orbit estimates then also the predictions will be improved.

4. Quality assurance

The inter-comparison of rapid orbits provides for an accurate assessment of the quality of the IGS rapid orbits. That is not the case for predicted orbits, where the different ACs are using basically the same information to generate the predictions. There are ways to decide which satellites are less predictable, like checking the fit rms for the four days and considering whether they are in the eclipse season or a maneuver is going to be performed.

This is a very important matter because users of the predicted orbits should use them in combination with the accuracy exponents that define the prediction error in order to get the best estimate of their derived products.

Lets assume that we have a parameter that we want to estimate based on the values of other variables and the estimation error for the parameter linearly depends on the error or the values of the variables. The estimates of the variables have an accuracy estimate attached and also a true accuracy. The accuracy estimate is used to weight the variables (that are used as observations) in the estimation of the parameter. For simplicity lets assume that the all variables provide the same observability for the parameter, and lets suppose that this is unity. The least-squares error for the parameter will be:

$$\varepsilon_x = \frac{\sum_i \frac{\varepsilon_i}{\hat{\sigma}_i^2}}{\sum_i \frac{1}{\hat{\sigma}_i^2}} \qquad \text{(EQ 1)}$$

It can be observed that the error itself would be the same if all the accuracy estimates would be multiplied by a constant. That is not the case for the estimate of the accuracy of the parameter. Assuming that the values of the variables are not correlated:

$$\hat{\sigma}_x^2 = \frac{\sum_i \frac{\sigma_i^2}{\hat{\sigma}_i^4}}{\left(\sum_i \frac{1}{\hat{\sigma}_i^2}\right)^2} \qquad \text{(EQ 2)}$$

The optimal set of weights (accuracy estimates of the variables) will be the one that would minimize the accuracy estimate of the parameter. The values of the accuracy estimate that result are:

$$\hat{\sigma}_i = K \cdot \sigma_i \qquad \text{(EQ 3)}$$

In order to express how much a non-optimal selection of accuracy estimates affects the results of the user of the orbits we can construct the value:

$$L = \frac{\hat{\sigma}_x(\sigma_i, \sigma_i)}{\hat{\sigma}_x(\hat{\sigma}_i, \sigma_i)} = \sqrt{\frac{n \cdot \left(\sum_i \frac{1}{\hat{\sigma}_i^2}\right)^2}{\left(\sum_i \frac{1}{\sigma_i^2}\right)^2 \cdot \sum_i \frac{\sigma_i^2}{\hat{\sigma}_i^4}}} \qquad \text{(EQ 4)}$$

In practical terms the true accuracy is never known, but we could substitute with the comparison rms:

$$L = \sqrt{\frac{n \cdot \left(\sum_i \frac{1}{\hat{\sigma}_i^2}\right)^2}{\left(\sum_i \frac{1}{rms_i^2}\right)^2 \cdot \sum_i \frac{rms_i^2}{\hat{\sigma}_i^4}}} \qquad \text{(EQ 5)}$$

As an example the IGS predicted orbits for day 0942/0 produced the following values:

$$\begin{aligned} rms &= 137.8cm \\ wrms &= 49.0cm \\ L &= 0.403 \\ wrms_{optimal} &= 20.1cm \end{aligned} \qquad \text{(EQ 6)}$$

A more than twofold improvement in accuracy for the users of the orbits could have been achieved by setting the accuracy exponents to the (at the time of the combination unknown) optimal values!

It can be shown that the critical factor for the degradation of the accuracy is to set a low value for the accuracy exponent of a satellite that has not been predicted accurately. To mistakenly tag a good satellite as bad has a much smaller impact.

5. Recommendations

1. Ask the Operational Data Centers to give the highest priority to the delivery of data from stations that are not in Europe and North America. If there are lists of stations to be handled, these stations should be at the top of the list and they should be delivered to the global data centers as soon as they are processed, without waiting for other stations.

2. Investigate ways of reducing the data retrieval delays. The goal is to get the data available within 2 (3 at most) hours after 00:00 UTC.

3. Implement more frequent downloading of the data (six or twelve hour files) so some (for late stations) or additional (for fast stations) data is available for rapid orbits.

4. Generate a set of predicted Earth orientation parameters based on the rapid eops and on a prediction model that can be used to generate the predicted orbits.

5. Study and improve the way in which accuracy exponents are assigned for rapid and predicted orbits.

6. Use information from NANU to exclude from predicted orbits those satellites that are going to be maneuvered.

6. Bibliography

Bar-Sever, Yoaz E. (1997), New and Improved Solar Radiation Models for GPS Satellites Based on Flight Data, Final Report for the Air Force Materiel Command Space and Missile Systems Center/CZSF, April 12 1997.

Fliegel, H. F., and T. E. Gallini (1989), Radiation Pressure Models for Block II GPS Satellites, in Proceedings of the Fifth International Symposium on Precise Positioning with the Global Positioning System, pp. 789--798, National Geodetic Survey, NOAA, Rockville, Md., April 1989.

Fliegel, H. F., W. A. Feess, W. C. Layton, and N. W. Rhodus (1985), The GPS Radiation Force Model, in Proceedings of the First International Symposium on Precise Positioning with the Global Positioning System, edited by Clyde Goad, pp. 113--119, National Geodetic Survey, NOAA, Rockville, Md., March 1985.

Fliegel, H. F., T. E. Gallini, and E. R. Swift (1992), Global Positioning System Radiation Force Model for Geodetic Applications, Geophysical Research Letters, 97(B1), 559--568.

Springer, T.A., G. Beutler, and M. Rothacher (1997), Improving the GPS Orbit Model, presented at the 1997 AGU Fall Meeting, EOS Transactions, 00(00), 00--00, December 9 1997.

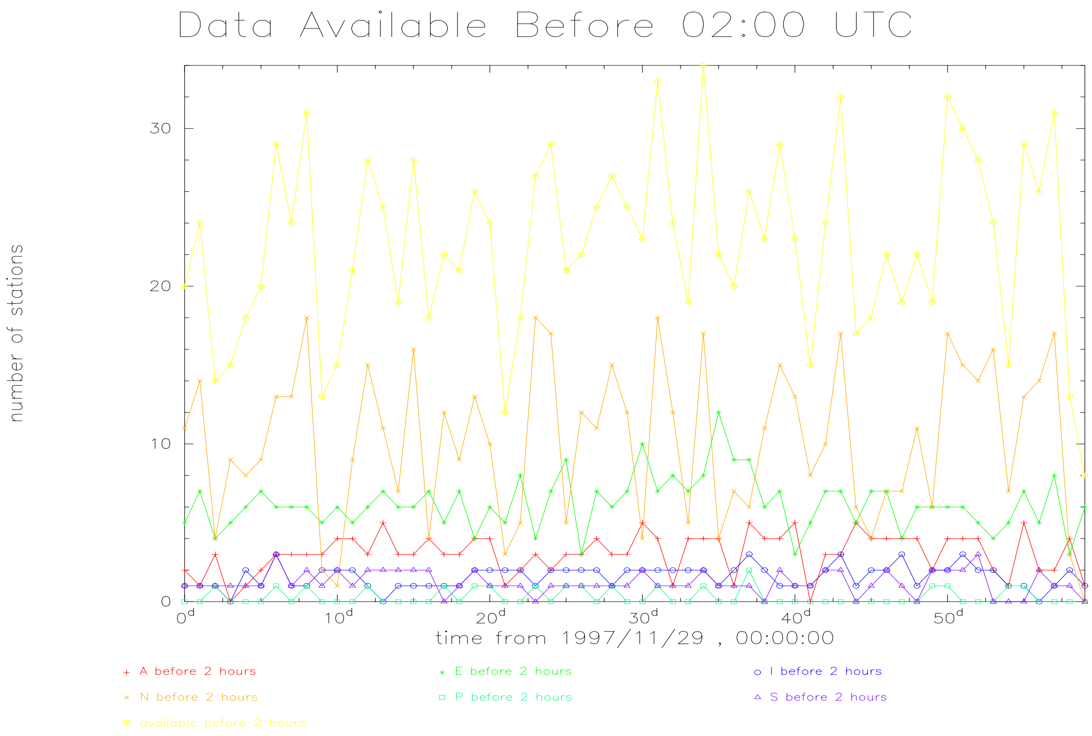

Fig. 2 Data available at CDDIS before 02:00 UTC

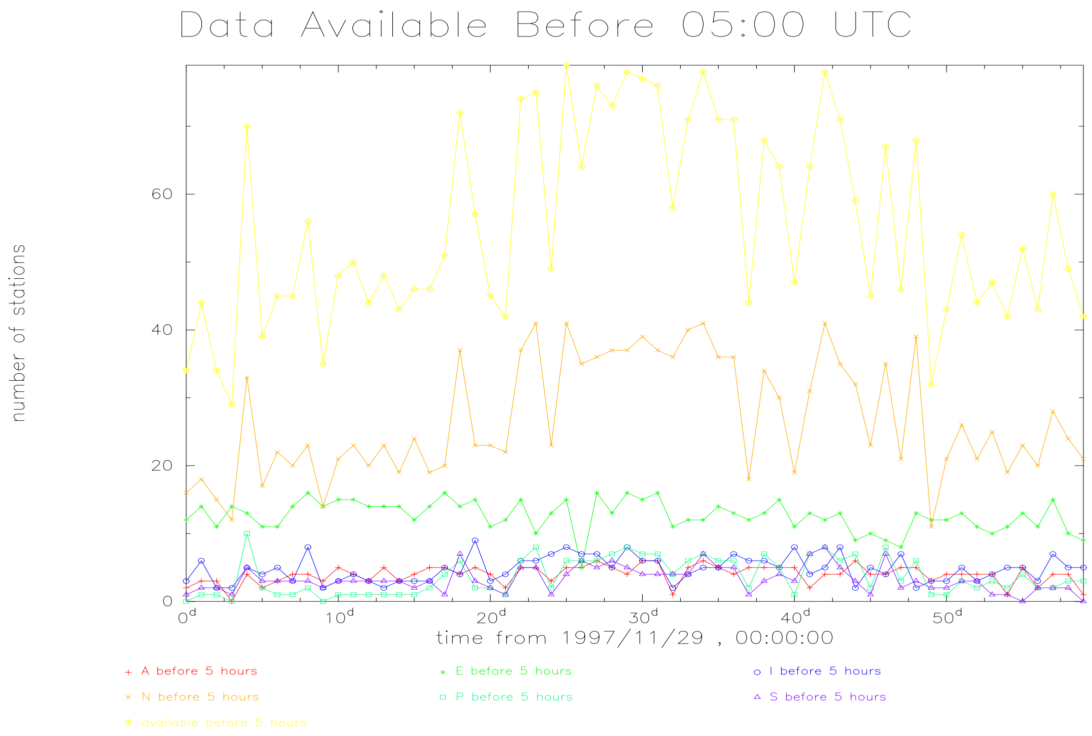

Fig. 3 Data available at CDDIS before 05:00 UTC

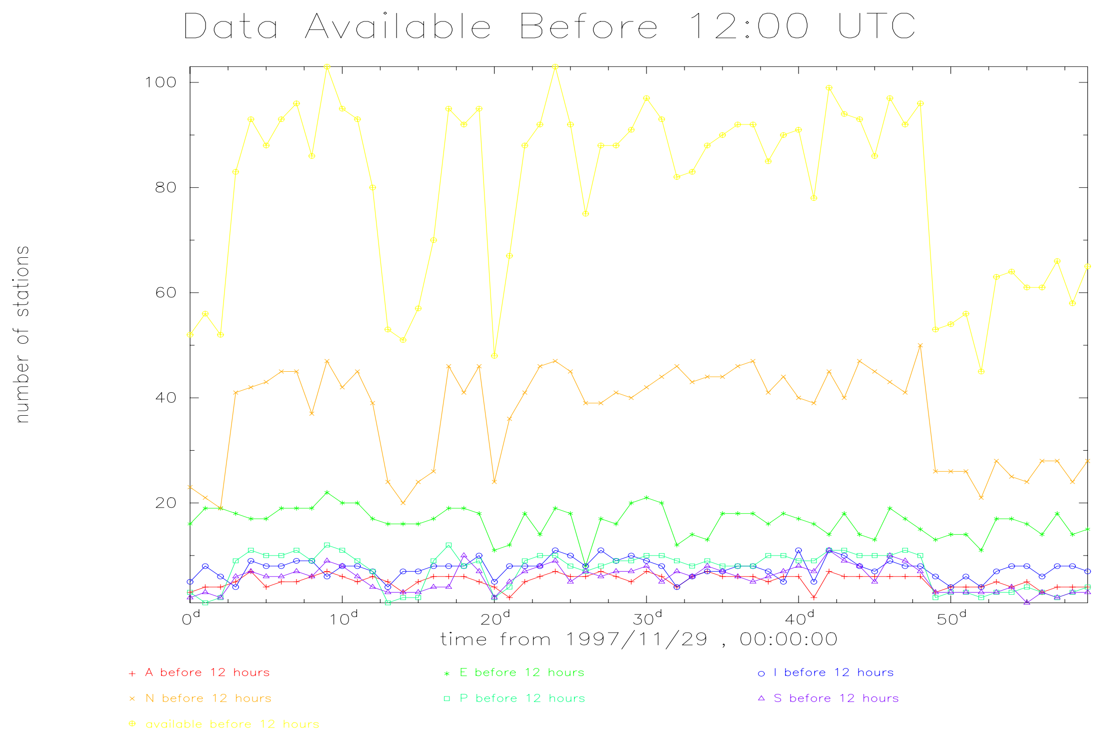

Fig. 4 Data available at CDDIS before 12:00 UTC

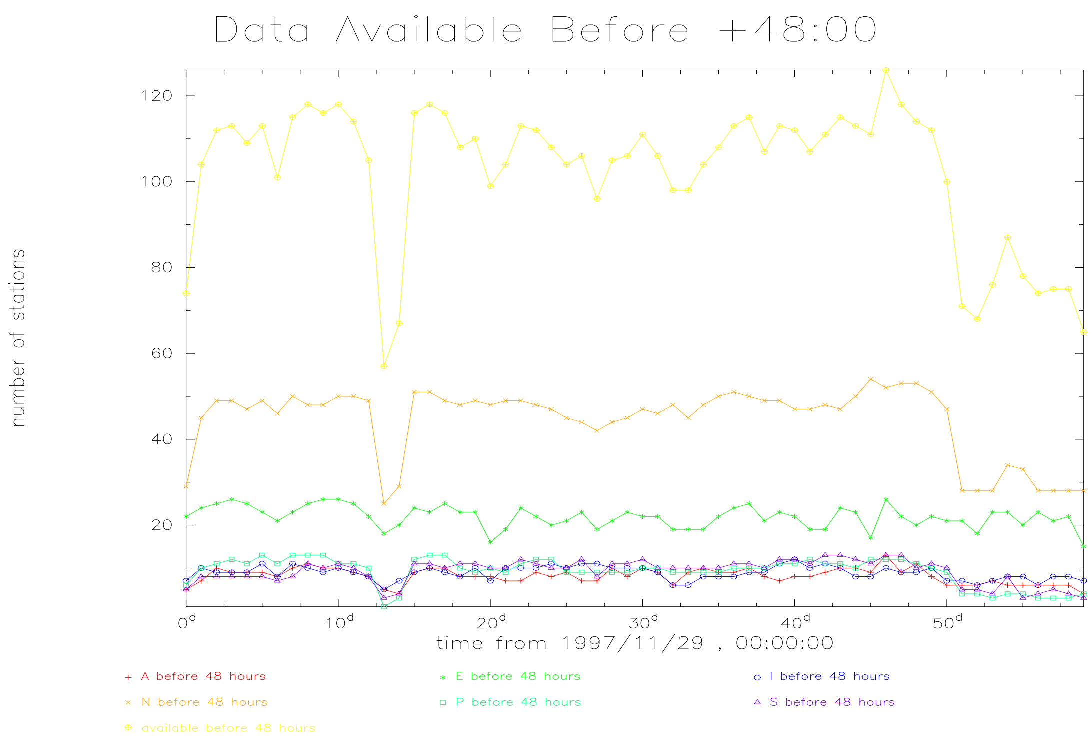

Fig. 5 Data available at CDDIS before 48 hours after collection

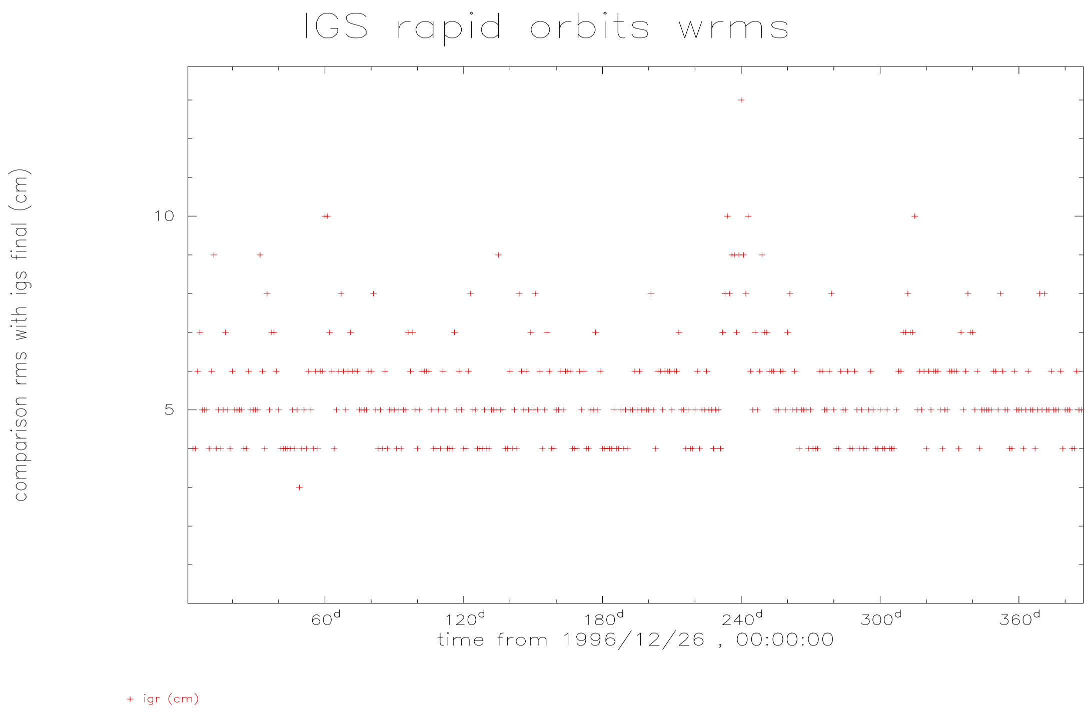

Fig. 6 Comparison weighted rms of rapid orbits with respect to final orbits

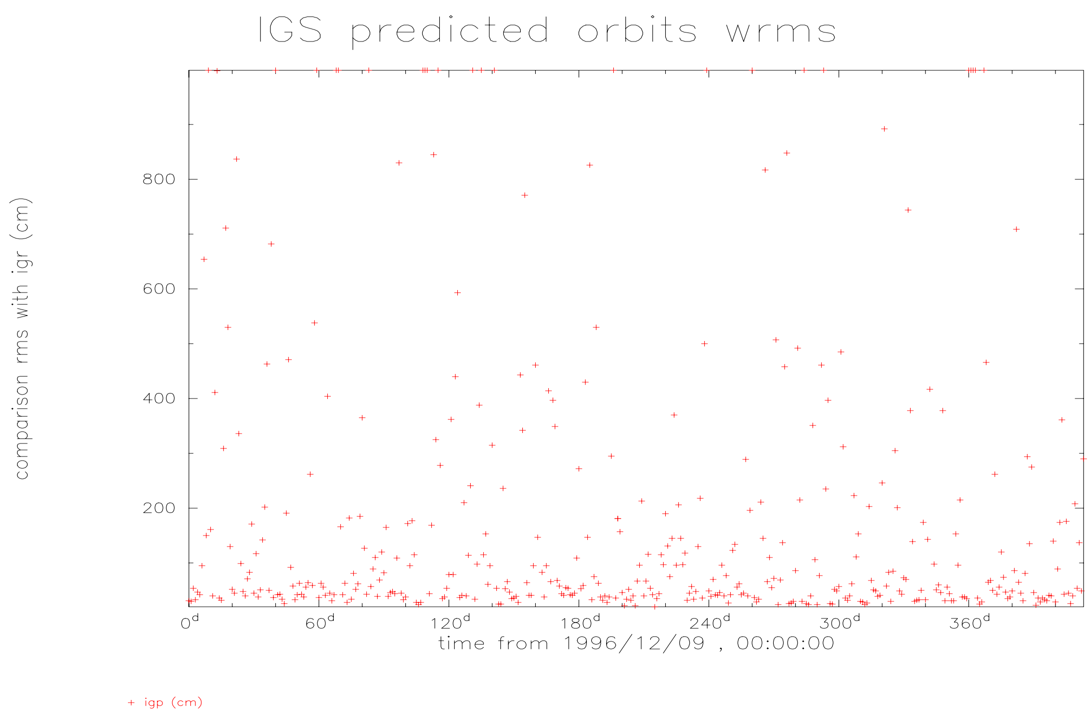

Fig. 7 Comparison weighted rms of predicted orbits with respect to rapid orbits

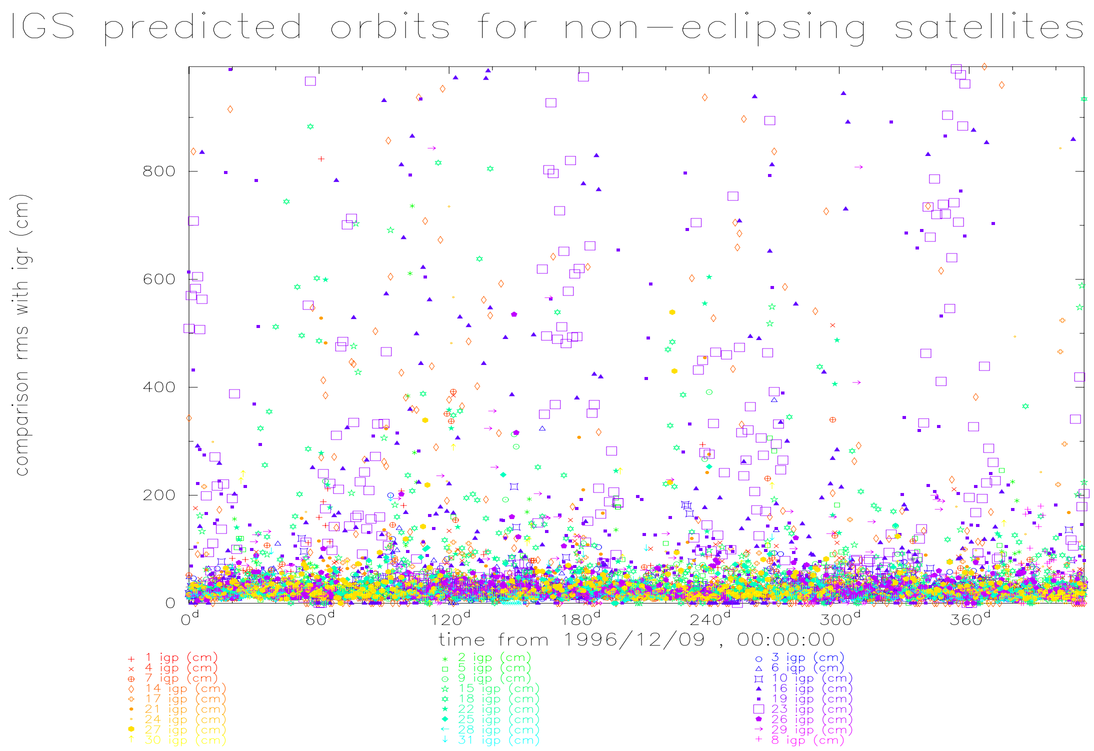

Fig. 8 Comparison rms of predicted orbits with respect to rapid orbits for non-eclipsing satellites

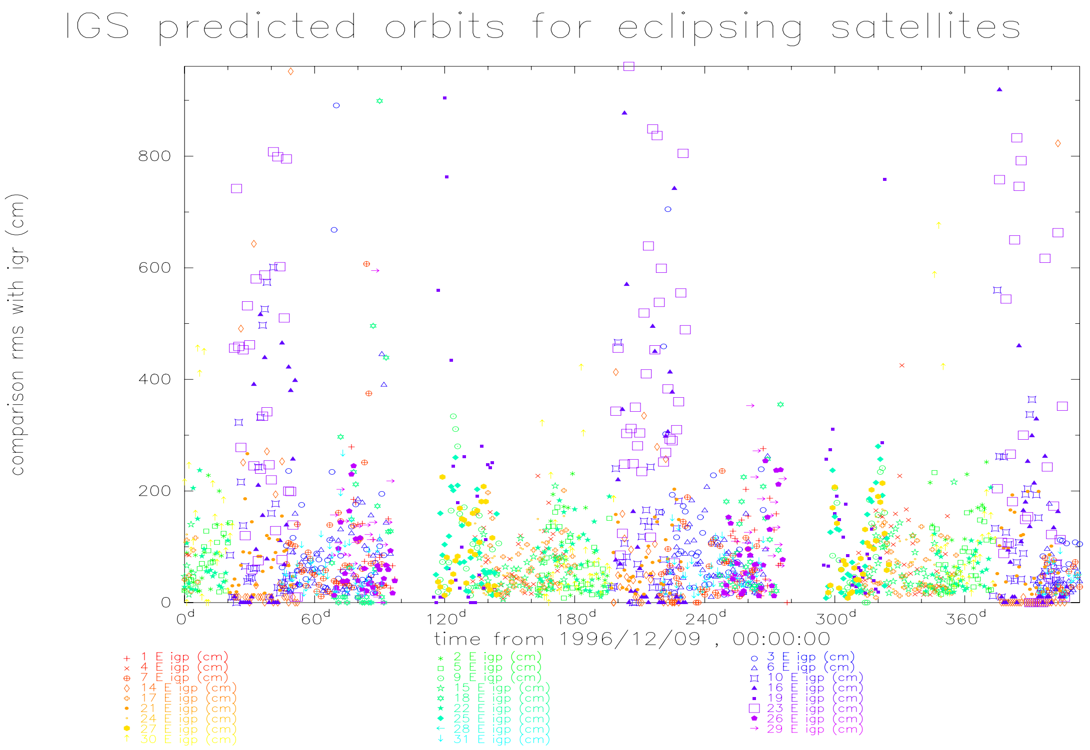

Fig. 9 Comparison rms of predicted orbits with respect to rapid orbits for eclipsing satellites

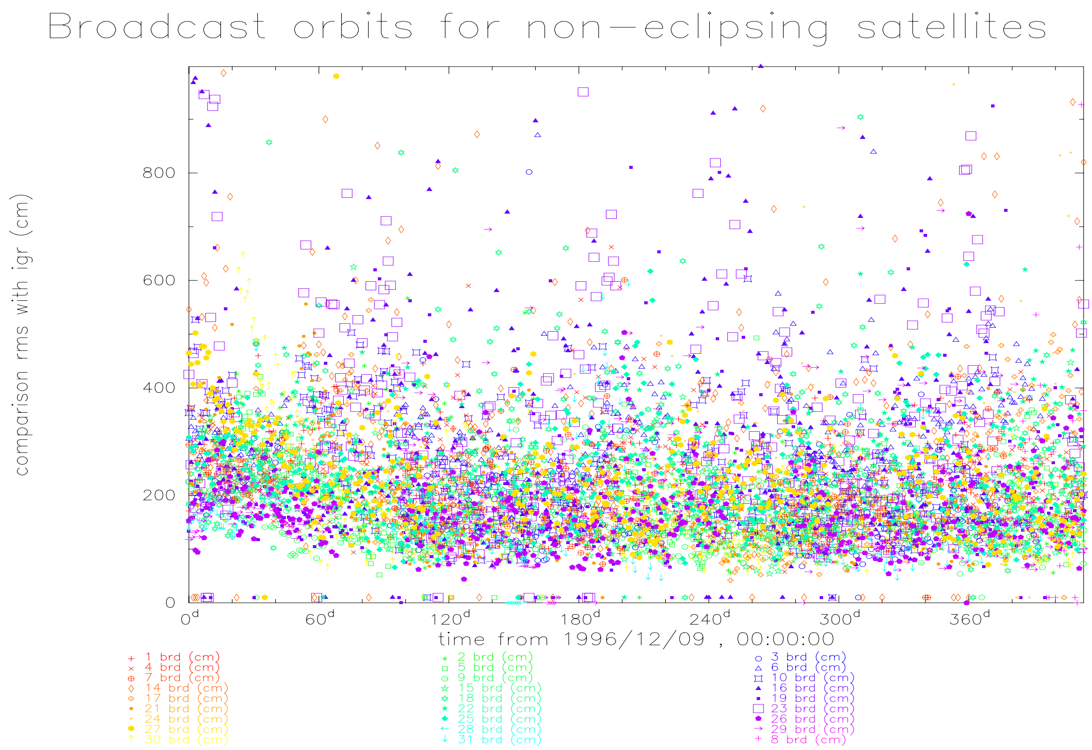

Fig. 10 Comparison rms of broadcast orbits with respect to rapid orbits for non-eclipsing satellites

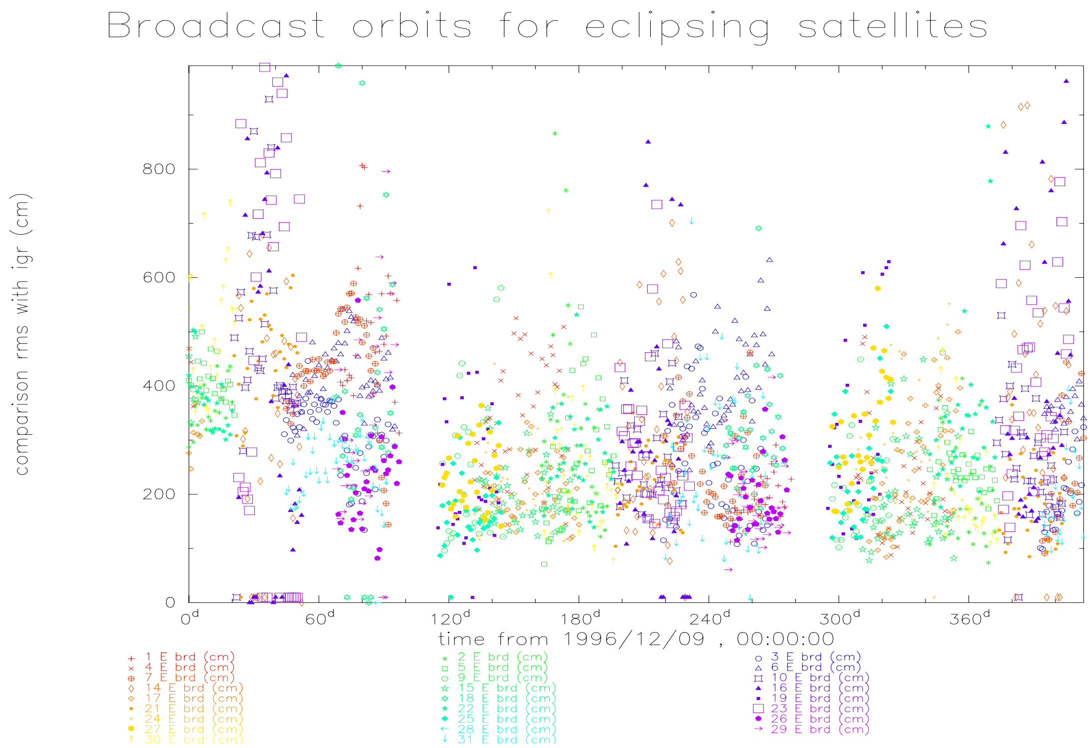

Fig. 11 Comparison rms of broadcast orbits with respect to rapid orbits for eclipsing satellites