Using the Extended CODE Orbit Model
First Experiences *

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Abstract

The Extended CODE Orbit Model, an empirical orbit model proposed by *Beutler et al.* [1994], was used for the first time in the actual parameter estimation procedures (using the Bernese GPS Software), to model the orbits of the GPS satellites at the CODE Analysis Center of the IGS. Apart from six Keplerian elements this orbit model consists of nine instead of the usual two parameters to take into account the deterministic part of the force field acting on the satellites.

In this article we focus on the optimum use of this Extended CODE Orbit Model for the CODE IGS activities. Of particular interest are the generation of *rapid orbits*, with only 12 hour delay after the last observation, and (IGS) orbit prediction.

Introduction

The Center for Orbit Determination in Europe (CODE), is one of at present seven Analysis Centers (AC's) of the International GPS Service for Geodynamics (IGS). CODE has been formed as a joint venture of the Astronomical Institute of the University of Bern (AIUB), the Swiss Federal Office of Topography (L+T), the German Institute for Applied Geodesy (IfAG), and the French National Geographical Institute (IGN). CODE is located at the AIUB in Bern.

Since the start of the IGS in June 21, 1992, CODE has produced ephemerides for all active GPS satellites and daily values for the earth rotation parameters. Starting January 2, 1994, all the individual AC orbit (and clock) solutions have been evaluated and combined into official IGS orbit/clock solutions by the Analysis Center Coordinator, [*Beutler et al.*, 1995;

* **reference:** *IGS 1996 Analysis Center Workshop*, edited by R.E. Neilan *et al.*, pp. 13--25, Central Bureau, JPL, Pasadena, Ca, March 19--21 1996.

Kouba, 1995]. The IGS combinations/evaluations, summarized in weekly IGS reports, clearly demonstrate the steady improvements in both, precision and reliability, for all AC's. The CODE orbit position RMS, compared to the combined IGS orbit, reached the 10 cm level by the end of 1994. By the end of 1995 the RMS had decreased to a level of 6 cm.

Thanks to this improvement of the orbit quality it has become clear that the classical orbit model, using eight parameters, is not accurate enough to guarantee an orbit quality below the 10 cm level. Different AC's solved this problem in different ways by either using deterministic or stochastic orbit models. At CODE the estimation of small velocity changes (pseudo-stochastic pulses) for all satellites at noon and midnight was implemented, starting June 4, 1995, to deal with the model deficiencies of the classical orbit model. However, by mid 1995 it also became clear that the Extended CODE Orbit Model as proposed by *Beutler et al.* [1994] and used in the IGS orbit comparisons for the long-arc analysis [*Beutler et al.*, 1995] should also be capable of producing orbits better than the 10 cm level RMS. Therefore, in early 1996, the model was finally fully implemented into the Bernese GPS Software Version 4.0 and first experiences were gathered.

We will first show some results of the initial tests performed to get a better understanding of the model. We will then discuss two interesting applications of the Extended CODE Orbit Model. Apart from using the new model for our normal processing method (overlapping 3-day arcs) we also apply the new model for the production of our rapid orbits (12 hour delay) and for orbit predictions.

The Extended CODE Orbit Model

In *Beutler et al.* [1994] and *Rothacher et al.* [1996] the new orbit model is discussed in detail, therefore here only the basic characteristics are summarized.

For the Extended CODE Orbit Model the acceleration $\vec{a}_{rpr}$ due to the deterministic part of the solar radiation pressure model is written as:

$$\vec{a}_{rpr} = \vec{a}_{ROCK} + \vec{a}_D + \vec{a}_Y + \vec{a}_X \tag{1}$$

where $\vec{a}_{ROCK}$ is the acceleration due to the Rock-model, and

$$\begin{aligned} \vec{a}_D &= [a_{D0} + a_{DC} \cdot \cos u + a_{DS} \cdot \sin u] \cdot \vec{e}_D = D(u) \cdot \vec{e}_D \\ \vec{a}_Y &= [a_{Y0} + a_{YC} \cdot \cos u + a_{YS} \cdot \sin u] \cdot \vec{e}_Y = Y(u) \cdot \vec{e}_Y \\ \vec{a}_X &= [a_{X0} + a_{XC} \cdot \cos u + a_{XS} \cdot \sin u] \cdot \vec{e}_X = X(u) \cdot \vec{e}_X \end{aligned} \tag{2}$$

where a_{D0}, a_{DC}, a_{DS}, a_{Y0}, a_{YC}, a_{YS}, a_{X0}, a_{XC}, and a_{XS} are the nine parameters of the

Extended model, and

$\vec{e}_D$	is the unit vector sun-satellite,
$\vec{e}_Y$	is the unit vector along the spacecraft's solar-panel axis,
$\vec{e}_X$	$= \vec{e}_Y \times \vec{e}_D$,
u	is the argument of latitude

The Extended CODE Orbit Model clearly is a generalization of the standard orbit model which is, at this time, still used for the official CODE solutions.

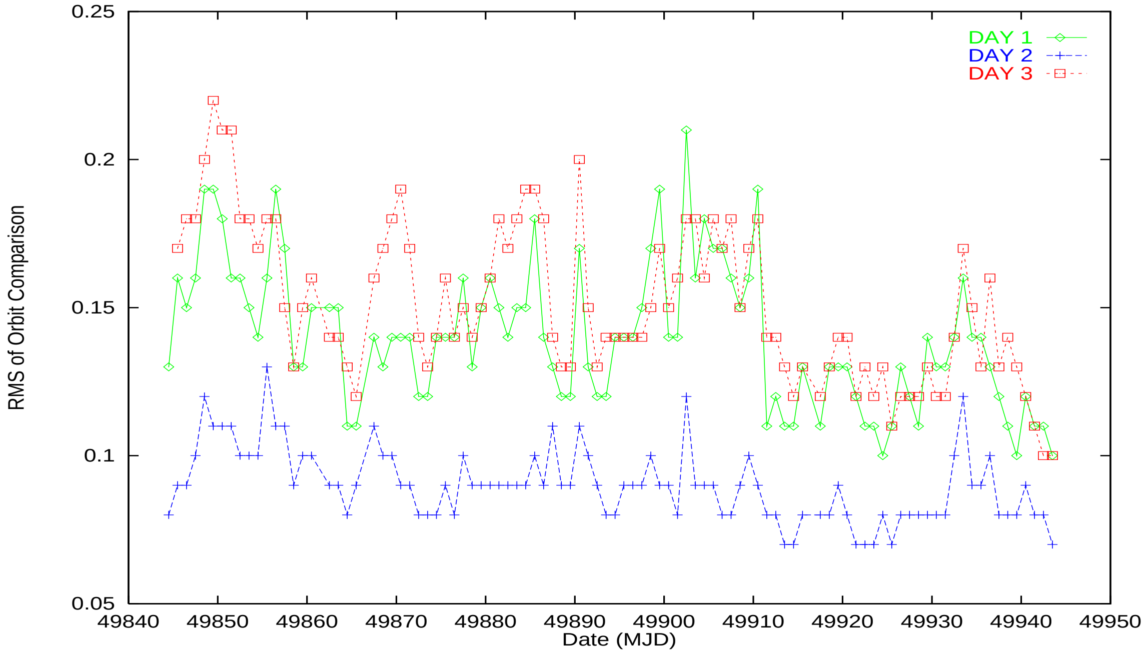
To gain experience with the model a test data set of 4 weeks was selected (GPS weeks 0836--0839). Several different 3-day solutions and a couple of 5-day solutions were performed. Furthermore, a test solution, based on the complete (15 parameter) model, was added to the variety of solutions in our reprocessing experiment of the 1995 IGS data.

First Results

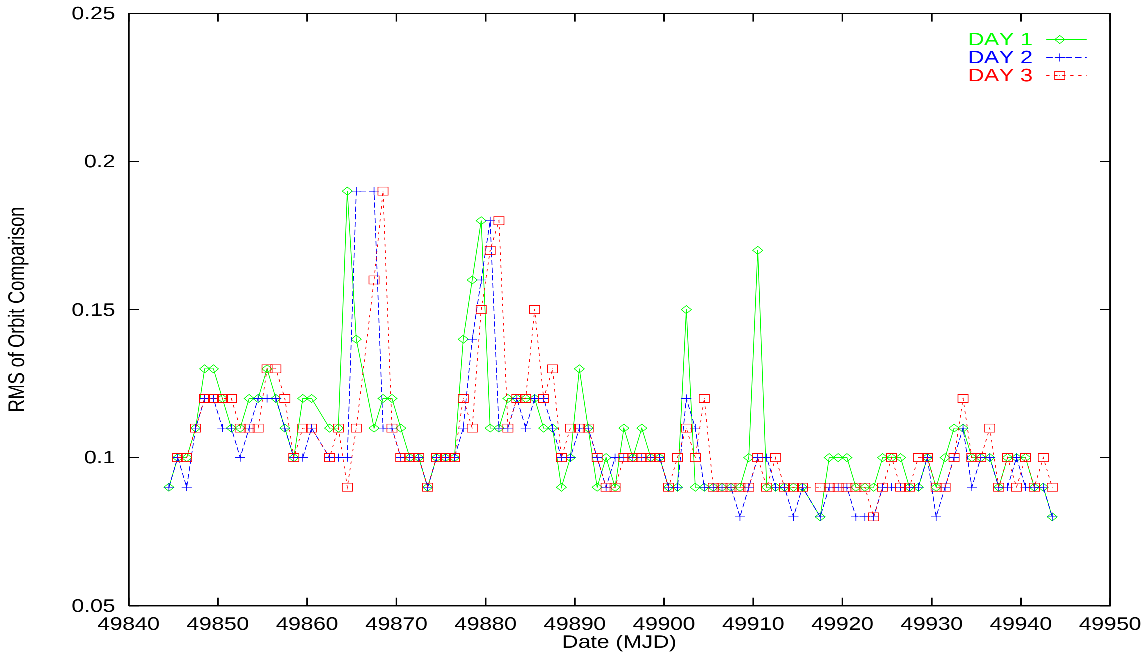
The most striking result stems from our 1995 reprocessing experiment where we created two different types of solutions. One was based on our current IGS routine strategy estimating the conventional (8 parameter) orbit model and 2 pseudo-stochastic pulses per day for all satellites in the along-track and radial directions. This means that for each satellite five of these pulses are estimated over a 3-day arc, all in all ten additional parameters per satellite. So, for each satellite 18 parameters are estimated: 6 Keplerian elements, 2 radiation pressure coefficients and 10 velocity changes. The second type of solutions used the Extended CODE Orbit Model where pseudo-stochastic pulses were estimated only for the eclipsing satellites and satellite PRN23, which has a solar panel defect. This means that 25 parameters were estimated for the eclipsing satellites and satellite PRN23, but only 15 parameters for all other satellites.

For both types of 3-day solutions individual precise orbit files were created for each day of the 3-day arcs. These (daily) precise files were then compared to the IGS final orbits. The RMS errors of the comparisons, using 7 parameter Helmert transformations (w.r.t. the IGS final orbits), are shown in Figure 1 for the 1995 reprocessing. Clearly the first and third day show a significant decrease of precision when using the conventional orbit model whereas with the Extended CODE Orbit Model all days are of the same high quality.

That the middle day of the conventional orbit model shows a smaller RMS than the middle day of the Extended model is most likely explained by the fact that this solution is very similar to the CODE solution which was taking part in generating the IGS final orbit. However, a detailed analysis using fully independent Satellite Laser Ranging (SLR) data, seems to indicate that using the complete model for the 3-day solutions actually leads to a slightly less accurate orbit solution for the middle day. Different tests using the 4-week data set indicated that for 3-day arcs the Extended model provides too many degrees of freedom. Not all nine parameters should be estimated using an arc length of ‘‘only’’ three days.



(a) Conventional Orbit Model



(b) Extended CODE Orbit Model

Figure 1. Unweighted RMS values of the orbit comparisons of the 3 individual days of a 3-day arc with the final IGS orbits.

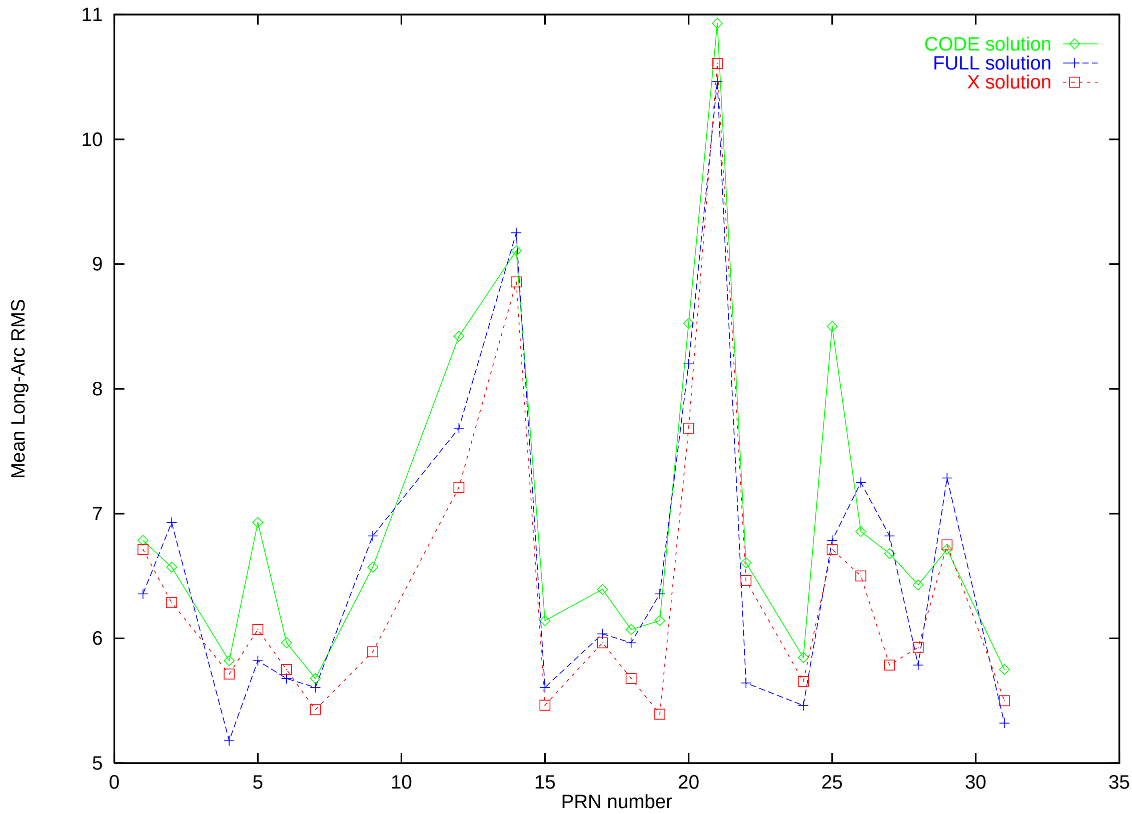


Figure 2. Mean long-arc RMS values over the 4-week test period.

Correlations between the orbit parameters but also with other parameters, like UT1-UTC, are significant. With 5-day arcs the correlations seem to decrease to an acceptable level. We should note that no tests were performed using a priori constraints on the orbit parameters. If a certain orbit parameter was set up it was estimated without any constraints.

One of the aims of the tests with the 4-week data set was to determine how to make optimum use of the Extended Model for 3-day arcs which we are using for our official IGS contributions since 1992. The best strategy we have found so far is to not estimate any ''X'' terms (a_{X0}, a_{XC}, a_{XS} in (2)) of the Extended model and still use five pseudo-stochastic pulses over three days for each satellite. Figure 2 shows the quality, per satellite, of the official CODE solution, a solution using the full Extended model (labelled ''FULL'') and a solution using the Extended model without estimating any X-terms (labeled ''X''). The RMS is the mean of all the long-arc (7-day) orbit checks performed for the 4-week test data set. Clearly the X-solutions perform better than both other solutions for most satellites. Only for a few satellites the ''FULL'' solution performs better than the ''X'' solution.

The stochastic pulses seem to absorb certain (orbit) model deficiencies more efficiently than the parameters of the Extended model, in particular for eclipsing satellites. The directions of the stochastic pulses are based on an orbit specific coordinate system (along-track, radial and out of plane components), whereas the components of the Extended model are defined as described in (2). Furthermore these pulses are estimated every 12 hours which makes them almost exactly ‘‘once per revolution’’ terms. They should therefore have a similar effect as the perturbation model proposed by *Colombo* [1989] which is well suited to absorb (gravity related) periodic unmodeled forces. In 1994 it was clearly shown [*Beutler et al.*, 1994] that the Extended model performs much better than the Colombo model. However, at that time the orbit accuracy, based on a 7-day arc fit, was of the order of 15 cm whereas today we are reaching the 5 cm level. With these orbit accuracies it is possible that the errors in the earth gravity field model (GEM-T3 model truncated to degree and order eight) are becoming significant.

It is clear that the modeling of the orbits of eclipsing satellites should be further improved. Implementing the ‘‘attitude’’ model [*Bar-Sever*, 1995] would improve the model for the eclipsing satellites, but other methods might be useful, too. An alternative method, to solve the modeling problems of the eclipsing satellites, might be a kind of ‘‘kinematic’’ solution for the motion of the satellite antenna phase center during the eclipse phase and for a time period of 30 minutes afterwards.

Applications of the Extended CODE Orbit Model

Rapid Orbits

Since January 1, 1996, the IGS is making available rapid combined orbits with a 36 hour delay. CODE participates in this new IGS activity with orbits which are available within 12 hours. The limiting factor for the accuracy of the rapid orbits is the availability of station data with a good geographical distribution. Especially with our 8 hours deadline, and the bad internet performance between Europe and America during office hours, the available data tend to have a bad geographical distribution. A good way to solve this problem is to use longer arcs. We have to keep in mind however, that we will have to use the last day of an n-day arc as rapid orbit product. With the conventional model the last day would be significantly less accurate than the middle day of the same arc, see Figure 1 The fact that with the Extended model all days of an n-day arc (n=1,2..5) are of the same quality makes it possible to use longer arcs for the rapid orbit computations thereby making the rapid orbit product much less sensitive to the geometry of the available data.

Figure 3 shows the quality of our rapid orbits since January 1, 1996. Around MJD 50130 (February 17) we started to use the Extended Orbit Model to produce 5-day arcs, the last day of this 5-day arc being our official IGS rapid orbit contribution. One clearly sees that, after some initial problems, the 5-day solution (the last day of a 5-day arc) is performing much better than the 1-day solution. In reality the performance is even better because here the unweighted RMS is given which is dominated by satellites with modeling problems,

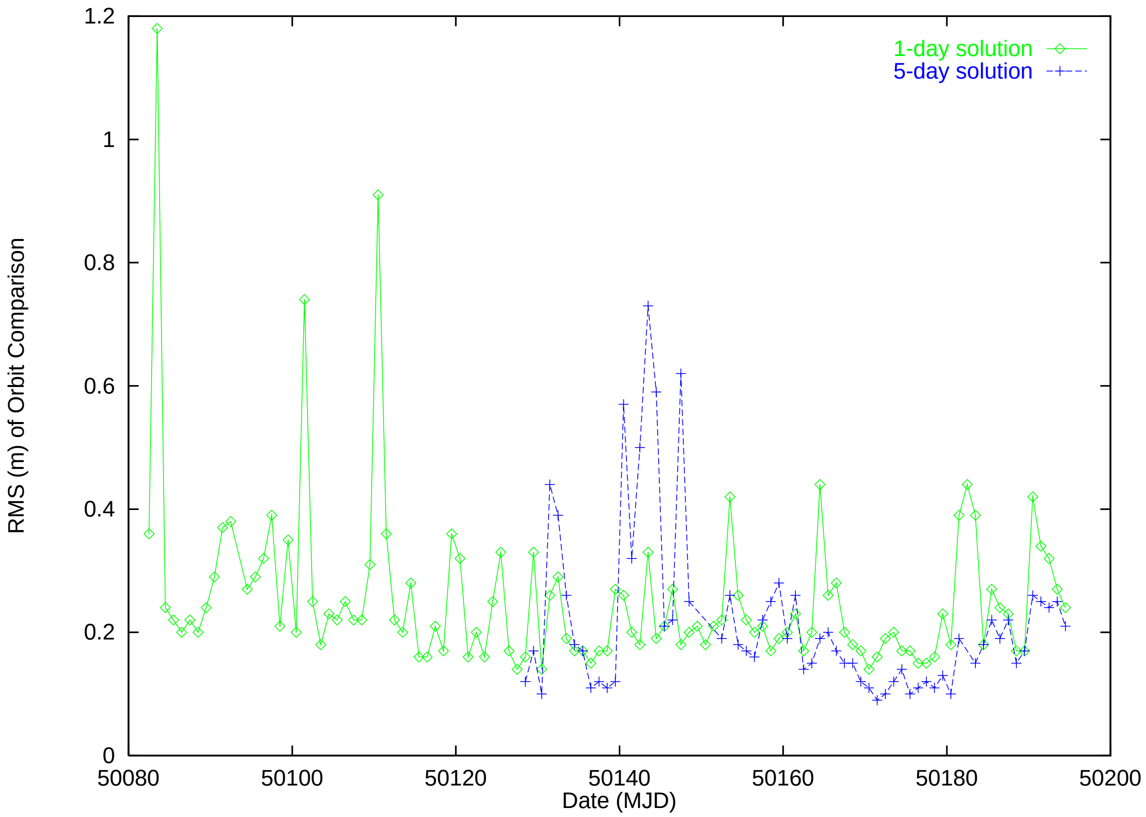


Figure 3. Unweighted RMS values of orbit comparisons showing the quality of the 1-day and 5-day rapid orbits. CODE orbits were used as reference.

which are of course more pronounced in the 5-day arcs than in the 1-day arcs. The peaks, which show up in the 1-day solutions due to a bad station geometry, are hardly visible in the 5-day solution, although the 5-day arcs are based on exactly the same observations (apart from using more days, of course).

Orbit Predictions

Everyone familiar with the weekly summaries of the IGS orbit combination is aware of the fact that the Extended CODE Orbit Model (used for the long-arc analysis of the IGS orbit combination) is capable of modeling the orbits of the GPS satellites over seven days at the few centimeter level. This indicates that the model should also be well suited to generate accurate orbit predictions.

At CODE we create 24- and 48-hour predictions based on our 1-day routine solutions for internal use. The 24-hour predictions are used as a priori orbits in the IGS routine processing rather than the broadcast ephemerides since the predictions have a better

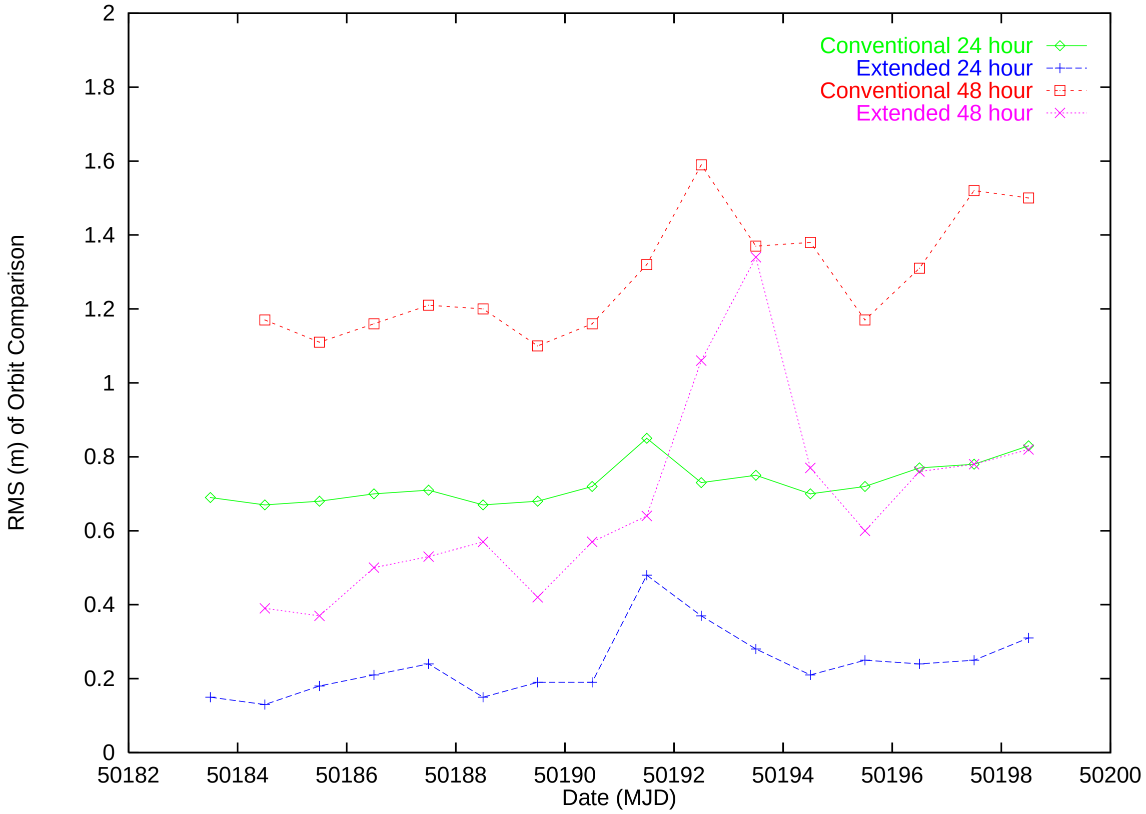


Figure 4. Unweighted RMS values of orbit comparisons showing the quality of 24- and 48-hour orbit predictions using the conventional and Extended orbit model. CODE orbits were used as reference.

accuracy. After the implementation of the Extended model into our software we noticed a significant improvement of our predictions. Figure 4 shows the quality difference of the orbit predictions using the conventional and the Extended model. With the conventional (8 parameter) orbit model our 24-hour predictions had a quality around the 75 cm level and the 48-hour predictions around the 130 cm level. With the Extended (15 parameter) model the quality of the predicted orbits is now around the 25 and 60 cm level for the 24- and 48-hour predictions respectively. As expected the Extended model is better suited for predictions than the conventional model. The 48-hour predictions of the Extended model are even better, in most cases, than the 24-hour predictions of the conventional model!

At these accuracy levels, and for real-time purposes, the extrapolation of the Earth Orientation parameters starts to play an important role. For predictions to be used in real-time data analysis, based e.g. on the IGS 36-hour orbits, it will be mandatory to predict the Earth Orientation parameters with an accuracy of about 1 milli arc second.

Summary and Outlook

Our first tests revealed that the Extended CODE Orbit Model is very well suited the CODE IGS activities but also for long-arc analyses (arcs longer than 3 days). Furthermore, we have shown that the model gives an important contribution to the generation of high precision rapid orbits and orbit predictions. Our rapid orbits, based on the Extended model, have an accuracy of approximately 10 cm. Prediction quality is at the 25 and 60 cm level for 24- and 48-hour orbit extrapolations, respectively.

For short arcs, 1- to 3-days, one has to be aware of correlations between some of the parameters of the Extended model. It may not be necessary, and possibly even harmful, to solve for all nine parameters of the Extended model. The best 3-day arc solutions were obtained by not estimating any ‘‘X’’ terms of the Extended model but still estimating five pseudo-stochastic pulses for each satellite in the along-track and radial directions. These pseudo-stochastic pulses, as implemented for the CODE IGS orbit products since June 4, 1995, seem to be capable of absorbing certain (orbit) model deficiencies more efficiently than the parameters of the Extended model. This aspect will be studied in more detail in the near future.

Long arcs are interesting from a scientific point of view but they are *not* practical for the routine IGS analysis as preformed at CODE. Currently we are therefore focusing on how to best implement the Extended model for 3-day arcs as we are using them in our IGS analysis. However, in the more distant future we might consider generating weekly 7-day arcs as our official IGS products.

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