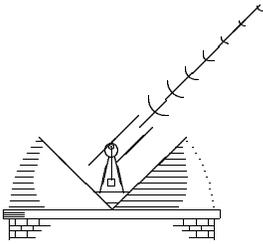


Improving Orbit Predictions

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Abstract *Accurate predictions of satellite orbits give ranging stations instant target acquisition, excellent tracking and the guarantee of narrow range gates. These in turn lead to better data distribution through the pass and less noise. It is suggested that the existing IRV system can be improved by moving to daily computation and distribution of IRVs to replace the present scheme of weekly/monthly/yearly IRVs supplemented by daily TBFs. Daily IRVs have, by definition, zero timebias and the need to form TBFs would vanish. There are also advantages to be gained from computing more IRVs per day, e.g. every 2 hours rather than every 24 hours. With the ease and low cost of almost instantaneous data transfer via the Internet it is further suggested that the shortcomings of the simple IRV force model can be overcome by supplying stations with fully modelled predictions for each pass. Such a radical step would require careful design, new standards, new responsibilities and adequate safeguards against network failures.*

Introduction

I want to make a fairly simple-minded review of the way in which orbit predictions are currently computed and distributed, and then enquire how the overall process can be improved. At the Shanghai workshop it became clear that several people were thinking along very similar lines about the desirability of standardising and coordinating the distribution of timebias functions. The *ad hoc* Timebias Function Working Group was formed and has been successful in implementing the scheme (Wood 1997) now in daily use. Talking to colleagues at this workshop I again detect a consensus for change, this time regarding orbit predictions.

My viewpoint is that of an operations manager at an observing station, not that of an orbit specialist! The aim of any proposed changes must be to improve both data quality and data quantity at *all* stations. It has to be recognised that individual stations differ hugely in the resources which they can devote to upgrading their operational software, even to the extent of automating regular data input via email or FTP. It seems to me, therefore, that any proposals for improvement should either involve no (or absolutely minimal) changes to existing software, or should recommend a significant upgrade giving immediate, substantial benefits, but designed in such a way that further changes are not required for a very long time. Clearly any scheme which is adopted must have automation in mind from the very beginning.

Questions

So in this talk I would like to address three questions:

- Why are good predictions important?
- What are the strengths and weaknesses of the present predictions system?
- How can we use the ever-growing power of the Internet to maximise the accuracy of predictions?

Importance of good predictions

To state the obvious: a good prediction is one which gives the most accurate description of a satellite's motion on the sky. *Perfect* predictions ensure:

- **instant acquisition**—no time is wasted in trying to locate the satellite in the field of view, either at the start of a pass or when resuming an interrupted pass;
- **excellent tracking**—the satellite image remains accurately centred for the whole duration of the pass; and
- **flat tracks in a narrow range gate**—there are no across-track or timebias errors in the predicted range.

In short, you get more data points and less noise.

It goes without saying, therefore, that it is in everybody's interest to provide observing stations with the best possible predictions.

Terminology: This paper uses the following terms:

A **PRECISE ORBIT** for a particular satellite is the fully modelled fit which an analysis or prediction centre produces from observations made by the whole network during a given time interval.

A **PREDICTION FILE** is produced at an observing station before each satellite pass and contains altitudes, azimuths, ranges and velocities at, say, one minute intervals, and is used to control the motion of the telescope and the gating of the detector.

Strengths and weaknesses of IRVs

Tuned Inter-Range Vectors (IRVs or TIVs according to taste) provide observing stations with the link between precise orbits and prediction files. Prediction centres compute precise orbits and then project them forward for a few days, a week, a month, a year depending on the stability of the orbit of a particular satellite. An IRV file is derived from the projected orbit and contains the positions and velocities of the satellite at 00:00 UT each day tuned so that a simple integrator, used in any 24 hour period, reconstructs a good approximation to the projected orbit.

Strengths: One of the attractions of this approach in the past was that it required only small data files to be sent—and it was also quite straightforward to provide all stations with the same simple orbit integrator to convert IRVs to prediction files. In practice it is well-known that any differences between the real and predicted orbits usually show up as an along-track error, or timebias. The trends in timebias as the IRV sets age can then be modelled and the resulting timebias functions (recalculated frequently as the network's normal point data become available) can be extrapolated to give up-to-date corrections to the prediction. This system, formalized over the last two years, is now in wide use throughout the network and works well.

Weaknesses: However, for low satellites (especially GFZ-1) there are problems with the fact that the integrator assumes only a simple force model and does not take account of atmospheric drag and solar radiation pressure. This has led to the development of an additional correction, the drag function, to try and describe these forces, and has been used with some success for both GFZ-1 and Zeia. As satellites subject to atmospheric drag sink in altitude the drag increases; and similarly the influence of solar radiation will play an increasing rôle as we approach the maximum of the solar cycle. Thus the shortcomings of IRVs plus corrections are likely to become more critical as we attempt more demanding observations in the years ahead.

A further weakness is that tuning IRVs over 24 hours is far from ideal. Andrew Sinclair (1994, 1996a) has described how tuning over 6 hour intervals can give better predictions for GPS satellites and this topic is discussed in more detail below.

Finally it is not usually possible to determine good timebias functions for high satellites (Etalon, GPS and Glonass) because of the relatively low density of observations. Stations only observe these satellites over a few (sometimes only one) short segments of the total orbit and this is often insufficient to provide either a good prediction or a meaningful timebias correction. This situation will not improve unless there is a substantial increase in the density of observations for these satellites, and this seems unlikely given present observing patterns.

Future trends

So what can be done to overcome or eliminate these problems? For the immediate future it is certainly worthwhile to consider what can be done to improve the existing IRV system and to investigate algorithms for real-time corrections to telescope tracking. But the main goal for the long-term must be to use the speed and efficiency of modern data transfer technology (now available to all) to utilise the full accuracy of the best orbit models at the telescope.

Improving the IRV system: One fairly obvious improvement would be to adopt a force model more elaborate than the very simple one now in use. Prediction centres would have to agree on the form of the new model and then create and tune IRVs accordingly. It would also be necessary to develop a new integrator for observing stations and distribute it for use by the whole network. One penalty might be an increase in the computing time required to prepare for observing.

Another approach would be to produce IRVs at less than 24 hour intervals, the current standard, and gain the advantage of tuning them over smaller time spans. Andrew Sinclair

has shown that this makes good sense for the GPS satellites and has utilised the daily CODE orbital data produced in Bern to form IRVs at 6 hourly intervals (Sinclair 1996b). They are deposited at EDC and our own website and may be used with existing software. Our experience is that range residuals from these IRVs are about one third of those from the once per day equivalents, *i.e.* almost always within ± 100 ns. Similarly derived IRVs for Glonass satellites are available for the IGEX-98 campaign, due to begin soon.

Perhaps the most promising improvements have been obtained as a by-product of the daily quality checks that Graham Appleby makes on the Eurolas Lageos passes (Appleby 1996, Hausleitner *et al.*, 1998). In an extension of this process to almost all the satellites currently being tracked, normal point data from the whole network are gathered each day and used routinely to recompute fresh orbits and thus new IRVs. Because they are based on such recent data there is no need for timebias, UT1–UTC or polar motion correction. For Lageos we find range residuals typically within ± 10 ns. We also find good improvements for Starlette and Ajisai, some improvement for Topex and GFO-1, but little or none for Stella. Additional experiments are underway to see how to get the best results from these IRVs for all satellites.

The computation of daily IRVs is now completely automated and designed so that it is easy to extend the system to new satellites. We retrieve all stations' normal points from EDC and CDDIS via FTP as soon as they are available and place the IRVs on our website for general use. The GPS and Glonass daily predictions are sent to EDC. I believe that, despite the larger IRV files and the need to handle additional Internet traffic to get them, most stations will find the effort well worthwhile. Again careful attention to formatting and filenaming should mean that stations can automate many of these procedures.

Real-time correction: Many stations already use measured range residuals to make corrections to the predictions during observing. In its simplest form this consists of assuming that all the error is along-track and solving for and applying a suitable timebias correction to bring the range residual close to zero, a technique often referred to as *track flattening*. For perhaps the majority of passes this is perfectly adequate. However, it should be possible to do much better than this for cases where there are also across-track and radial errors in the predictions, by using the range residuals to recompute the full orbit in real-time.

Full accuracy predictions: As I have already mentioned, the IRV system was specifically developed to minimise and simplify the data flows between prediction centres and observing stations in days when every byte had to be justified. Today we can contemplate much larger data transfers without too many anxieties about volume or cost, and indeed, as time goes by, volumes will continue to go up as times and costs continue to come down. With this in mind my suggestion is that prediction centres should use the full power of the very best available models and provide observing stations with a prediction file for each pass of each satellite. The format of the data in these new style prediction files, the precision of the quantities given, the time steps between tabulations *etc.* would be specified in a new standard. Two possibilities for the nature of the data in such files are geocentric XYZ coordinates and velocities (essentially what stations currently get from the IRV integrator) or full topocentric data, each at suitable time intervals. The first would still require stations

to prepare prediction files but would by-pass the IRV process altogether. The second would provide the prediction file directly without further processing.

The huge advantage is that prediction centres can then develop sophisticated models for each satellite (update techniques, adopt new gravity fields, refine atmospheric drag calculations and so on) and reflect these improvements directly in the files that they pass to observing stations, without the stations themselves having to make any changes in order to benefit from them. Although this scheme would give prediction centres a larger workload (and taking this on would have to be a matter for discussion) I see it as implementing a highly desirable division of expertise: prediction centres having full control over the form and complexity of modelling orbits; observing stations having confidence that they always have access to the best predictions, without them being degraded via IRVs and timebias functions. In addition the interface between the two (the new style prediction file and the interpolation software) can, with careful design, remain unchanged for many years. Thus, after one major upgrade, stations could enjoy a period of stability. Recognising that some stations will not be able to adapt as quickly as others, it would be sensible to run the new system in parallel with the IRV system for some time.

Network failures: Any scheme which places increasing reliance on the frequent delivery of data via the Internet must make proper provision for the times when the network is down. A simple solution would be to continue to supply IRVs and TBFs much as at present, in parallel with daily files, so that stations could fall back on old methods while they were out of contact. It is very rare for network outages to last for very long (and if they do all other data inputs also dry up) and so another safeguard is to produce IRVs each day for the next few days ahead, say 5. These will still be at least as good as the traditional IRVs, even at the end of 5 days. The penalty for this insurance is that IRV files are then five times larger than is needed for the day in question. However, even treating all current satellites in this way, would only involve data volumes which are relatively modest by today's standards and should not prove prohibitive in practice.

Recommendations

Full precision predictions are perfectly possible now, but there are practical and diplomatic problems to be overcome before they can become part of everyday life throughout the network. My hope is that the ILRS Data Formats and Procedures Working Group can set itself the goal of introducing such a scheme on a reasonable timescale. I would recommend that, before the next workshop, there should be: overall discussion of the functional requirements; agreement on standards for file contents and formats; and production or commissioning of the requisite processing software for observing stations.

Until then it is still possible to make very worthwhile improvements to the existing IRV scheme, and these should continue to be fully exploited.

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