GNSS Solutions:

Satellite Almanac Life Expectancy

"GNSS Solutions" is a regular column featuring questions and answers about technical aspects of GNSS. Readers are invited to send their questions to the columnist, **Dr. Mark Petovello**, Department of Geomatics Engineering, University of Calgary, who will find experts to answer them. His e-mail address can be found with his biography below.

Mark Petovello is an Assistant Professor in the Department of Geomatics Engineering at the University of Calgary. He has been actively involved in many aspects of positioning and navigation since 1997 including GNSS algorithm development, inertial navigation, sensor integration, and software development.

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For how long can an almanac be used?

The designers of the Global Positioning System, in figuring out how they could help GPS receivers determine their position more quickly, designed the almanac in order to identify GPS satellites' orbital positions or *ephemerides* (singular: *ephemeris*). They knew that each GPS satellite would have to broadcast its own precise, meter-level ephemeris to the receiver, but because they were constrained by the navigation message data size, each satellite could not deliver the precise ephemerides for all other satellites.

The almanac was developed as a coarse equivalent to the precise ephemeris, reducing the number of bits required to transmit the necessary data at the cost of reduced accuracy of orbital propagation. The propagated orbits are, however, still accurate enough for the intended purpose of determining which satellites are above the horizon and computing a rough estimate of its Doppler shift (for a given receiver position).

When downloaded by the receiver, the almanac data is stored in no particular format, although the 2nd Space Operations Squadron makes the almanacs available via their web site in the SEM and YUMA formats. The almanac file format descriptions as well as the almanacs themselves can be downloaded from the GPS section of the Celestrak website: <http://celestrak.com/GPS>.

Because almanacs provide a reduced accuracy ephemeris and are used in the receiver for operations as well as in many planning tools for analysis, a look at how long these almanacs can be used is warranted. The GPS Control Segment generates a new almanac every day and sends it to each satellite with the next scheduled navigation data upload.

Just because a new almanac is available, does that always mean it must be downloaded and used? For continuously operating receivers, there is little additional cost to extracting and using the latest almanac data. However, for power-limited receivers, downloading an almanac may take more time and power than is deemed acceptable.

Furthermore, for mission analysts, retrieving a new almanac every day may require additional tasks that may not be logistically easy or worthwhile. We'll look at these two areas and determine how long an almanac can be used for predicting PDOP and Doppler shift.

Mission Planning

Almanacs are used in mission planning to predict dilution of precision (DOP) — a key component in navigation accuracy. DOP is not the only element of navigation accuracy; the other is the measurement accuracy, but DOP is a key indicator of mission success.

Because DOP is a geometrical effect, predicting it requires knowing the geometry of the GPS constellation relative to an approximate user position at some point in time. This is accomplished by propagating the orbits of the GPS satellites using some type of propagator.

The official propagator for GPS elements sets is defined in the IS-GPS-200D interface specification document — and is the one used in virtually all GPS receivers. This propagator can use either almanac element set — the coarse positioning information sent down by all satellites for the entire constellation or the more precise ephemeris information set sent down by each individual satellite.

The almanac data are routinely posted on the Internet and can be used to predict DOP and, thus, also for mission planning. To understand how long a given almanac can be used for mission analysis, we need to look at the accuracy of predicted DOP values over time.

To illustrate how well DOPs can be predicted with an almanac, we will predict the position DOP (PDOP) at a single location at 15-minute intervals for several weeks using the same almanac from the start of the prediction period. Although small differences will arise for different user positions, these are not large and the results included can therefore be considered as indicative of global trends. Then, we will compare the predicted PDOP values with those values calculated using the truth ephemeris valid for that day.

For this purpose, truth ephemerides are created by the National Geospatial-Intelligence Agency (NGA) roughly three days after the fact for all GPS satellites and are available via their web site: <http://earth-info.nga.mil/GandG/sathtml/ephemeris.html>.

Analyzing almanac DOP predictions using this technique will give us a picture of how well DOP predictions stand up over time and allow us to determine whether to use almanacs of a certain age for mission planning.

Using an analysis period of Jan 1, 2008, through Jun 3, 2008, we designate January 1 as the 0 day prediction, January 2, the 1 day prediction, and so on. **Figure 1** shows PDOP for

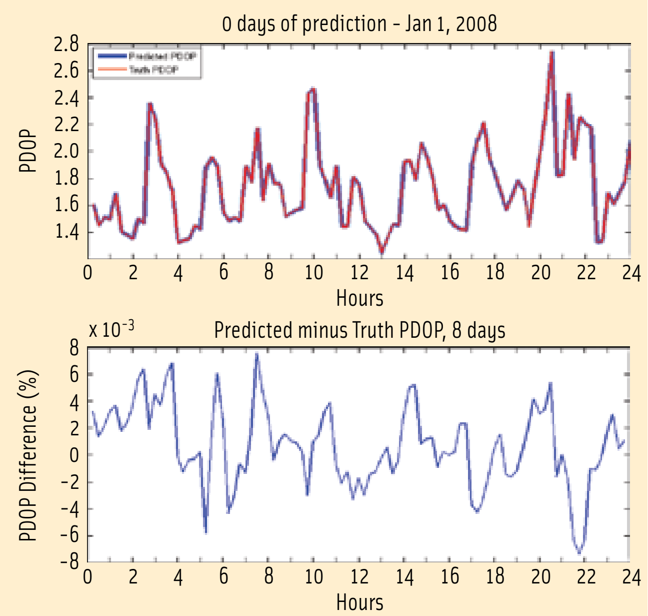

FIGURE 1 **Day 0 Prediction of PDOP – January 1, 2008**

the site on day 0, calculated using both the almanac and the truth ephemeris. The predicted PDOP agrees quite well with the truth PDOP, validating the almanacs' use as an ephemeris source for mission analysis.

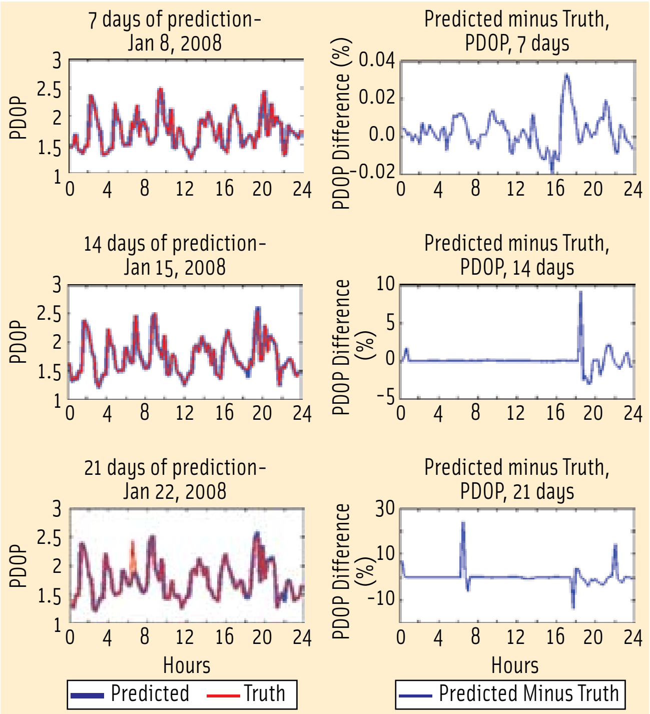

FIGURE 2 Several weeks of DOP prediction

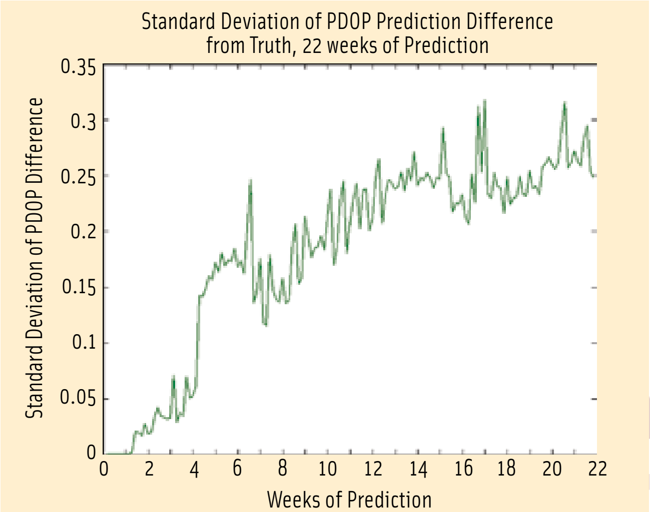

FIGURE 3 Standard deviation of PDOP difference from truth

Figure 2 shows how well PDOP can be predicted several weeks into the future. The predicted PDOP values at 14 and 21 days begin to show some significant deviations, but only at certain times. The predictions are still rather good this far out. Nevertheless, the severity of these errors — and therefore their usability for a particular mission — will ultimately be dictated by the application under consideration.

Looking at the relative DOP difference graphs may not always give a good picture of how well DOP is predicted as a function of time. The standard deviation of the DOP differences may give us a better picture of how the DOP predictions vary over time. **Figure 3** shows the standard deviation of the PDOP differences — a single standard deviation value for a day, plotted over several weeks.

Now we can see that for over a week virtually no difference appears between the PDOP values calculated with an almanac and truth. The results are still very good up to a month — but after that, the standard deviation of the difference starts to rise sharply. **Figure 4** shows the PDOP values and their percent differences from truth for four, six, and eight weeks of prediction.

Based on these results, for mission planning purposes, an almanac can be used confidently for more than a week. Once an almanac becomes more than two weeks old, some caution is warranted, because occasions may occur when almanac PDOP spikes don't align with actual spikes, and vice versa. After four weeks, users should get a new almanac if possible, because the predictive quality at that age is no longer ideal.

Receiver Operations

A critical receiver operation is signal acquisition, where the receiver scans both frequency and code phase to lock onto a GPS signal. When scanning the frequency, the amount to scan is determined by the predicted Doppler shift of the desired signal.

For most applications (i.e., receiver velocities less than 100 km/h), the dominant Doppler shift is determined by calculating the velocity of the satellite and finding the velocity component along the line of sight to the receiver, scaled appropriately. Specifically, Doppler shift is computed as:

$$\Delta f_i = -\frac{f_T}{c}(\dot{\bar{R}}_{Satellite_i} - \dot{\bar{R}}_{Receiver}) \cdot \frac{\bar{R}_{Receiver} - \bar{R}_{Satellite_i}}{\left\| \bar{R}_{Receiver} - \bar{R}_{Satellite_i} \right\|}$$

where $\bar{R}_{Receiver}$ is the receiver position vector and $\bar{R}_{Satellite_i}$ is the *i*th satellite's position vector and Δf_1 is the change in the transmitted frequency from the *i*th satellite.

IS-GPS-200D does not specify the calculation of the velocity for the GPS satellites, but a common velocity calculation is used for this analysis. The velocity calculation determines the angular momentum of the satellite and then determines the Earth-centered, Earth-fixed velocity by means of Earth-centered inertial transformations. This formulation is accurate to 0.2 to 0.3 dm/s on average compared to NGA truth data.

Now we want to know how long an almanac can be used to predict the Doppler shift of a GPS signal. Ideally, we want to keep the receiver from opening its frequency search window, because that adds more calculations, thus requiring greater power consumption. This is particularly important for high-sensitivity receivers, which are particularly sensitive to frequency errors.

Knowing how long an almanac can be used to predict the Doppler shift will help optimize receiver operations by determining how often a new almanac should be downloaded, which, as mentioned earlier, may not be desirable for power-sensitive receivers/applications.

Because the mission analysis PDOP results showed good predictive behavior for several weeks, we will start the current analysis by looking at the standard deviation of the Doppler shift difference for three satellites, PRNs 13, 22, and 24. **Figure 5** shows the standard deviation for 22 weeks of prediction.

The standard deviations of the Doppler shift values are much less noisy than the PDOP prediction deviations. These results are also much better behaved, in that the standard deviations are smoothly varying functions of time. The actual Doppler shift values for these three PRNs and their absolute differences are plotted for several weeks of prediction in **Figure 6**.

A small difference in Doppler shift values appears between the almanac predicted Doppler shift and the truth value. This is good news for receiver operations — when defining the grid to sample over for signal lock, the chance of not finding a signal in the correct frequency bin due to an old almanac is small.

In particular, for "standard sensitivity" receivers the typical GPS frequency search bin size is roughly 667 Hertz — well above the Doppler shift prediction errors seen here.

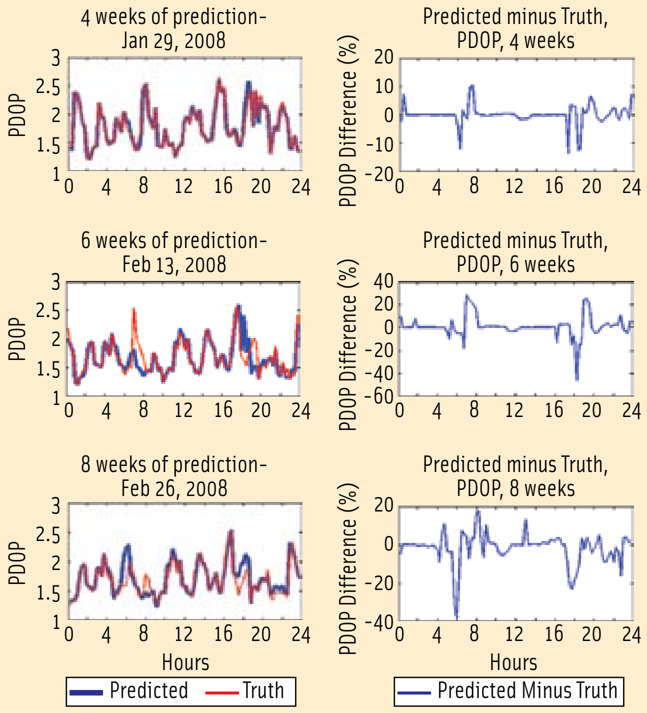

FIGURE 4 4, 6 and 8 Weeks of PDOP prediction

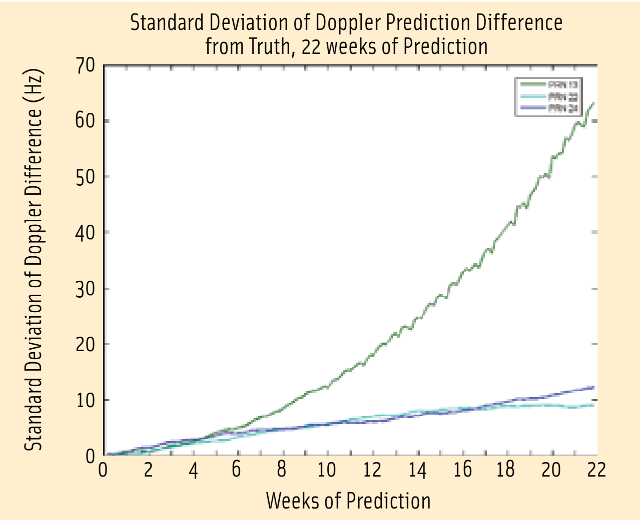

FIGURE 5 **Standard deviation of Doppler shift prediction**

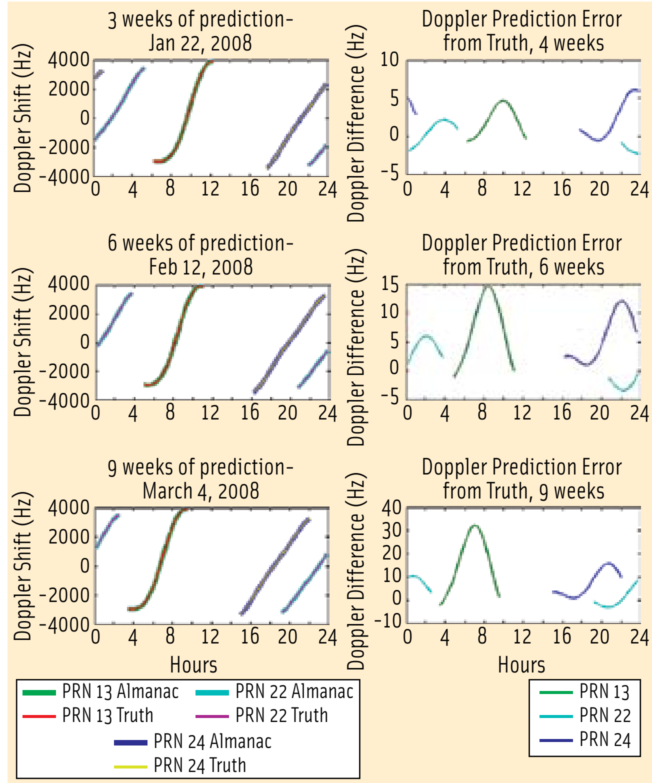

FIGURE 6 **Doppler Shift predictions for several weeks**

However, high sensitivity receivers can be sensitive to errors of 50 Hertz or less.

Satellite Maintenance

From the foregoing discussion, one may be tempted to use the almanac for long periods of time based on these results. However, with reference to Figures 5 and 6, the three PRNs that we examined did not undergo any maintenance during the 22-week period shown.

In contrast, Figure 7 shows the standard deviations of the Doppler differences for all satellites for the same period. Two satellites in particular stand out in this graph — PRNs 6 and 29. Both of these had a station-keeping maneuver performed early in the year. This made the predictions for their positions and velocities quite different from truth — and thus the Doppler shift predictions are noticeably wrong.

Satellite maintenance also affects PDOP predictions. Taking a look at Figure 2 again, we can see that in the 14-day prediction the PDOP prediction errors occur for roughly an hour in the beginning of the day and then from about 18 hours until the end of the day.

These PDOP errors correspond to a change in satellite positioning between the prediction and truth — specifically, with PRN 6. This satellite is visible and used in solutions for this site for the first 45 minutes of January 15, and from 18:30 until the end of the day — correlating well with the PDOP prediction errors.

Changes in DOP predictions resulting from maneuvers are the largest source of error when using older almanacs as an ephemeris source. The older the almanac, the more likely that a satellite has been added, removed, or undergone a maneuver resulting in predictions that will have errors.

An analysis of the most recent U.S. Air Force satellite outage file (2008_303_031939_v01.sof) — available on celestrak.com and the Analytical Graphics website — shows, on average, a satellite outage every 12.1 days beginning from January

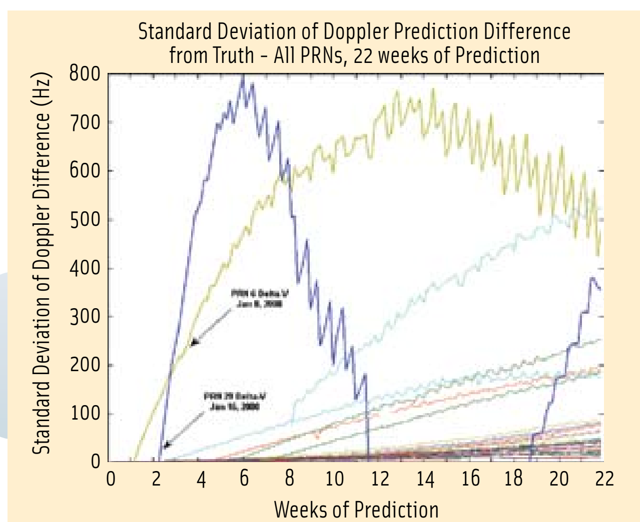

FIGURE 7 **Standard deviation of Doppler shift prediction differences – all satellites**

2006. Because of these outages, the predictive ability of the almanac will start to degrade on average after this amount of time.

To avoid these bad prediction situations, one could keep track of the satellite outages and update the almanac only when any satellite has undergone some maintenance. One way to do this might be to update the receiver's stored almanac only when a health change is detected for any satellite in the navigation data. Downloading an almanac at this frequency would keep the almanac age at or under 12 days on average, keeping the standard deviation of the Doppler Shift prediction under three Hertz, as determined from Figure 5.

Summary

Almanacs provide a good ephemeris for mission planning and receiver operations with the computed orbits providing a good basis for predictions well over two weeks into the future. For mission planning and PDOP prediction, an almanac of up to four weeks old would still work well. For Doppler shift prediction, the almanac could be used for an even longer period of time.

Both types of predictions will suffer, however, when satellite additions, removals, or maneuvers take place, drastically reducing the predictive ability of an almanac. One recommendation for optimizing the almanac download is to retrieve a new almanac only when the health indicator of any satellite changes.

Through the predictive analysis of PDOP and Doppler, we can conclude that even though almanacs are uploaded to GPS satellites each day, GPS receivers do not necessarily need to download and use it at this frequency. Given the error analysis described in this article, one can now determine the best schedule for downloading and using an almanac to suit a particular application.

TED DRIVER

Ted Driver is the senior navigation engineer at Analytical Graphics Inc. (AGI). He has worked on AGI's Navigation Tool Kit, having previously been the technical lead for the Navigation Tool Kit at Overlook Systems Technologies. Driver led the engineering team in developing the navigation algorithms and data stream definitions and is currently working on statistical prediction models for GPS accuracy. He was previously the senior GPS Operations Center analyst within the 2nd Space Operations Squadron at Schriever Air Force Base, Colorado. Driver has worked in the GPS field for 9 years, previously designing the environment and navigation models for the GPS High Fidelity Simulator currently in use at Schriever AFB. Driver received his bachelor's degree in physics from the University of California at San Diego and a master's degree in physics from the University of Colorado. He is a former president of the Rocky Mountain Section of the Institute of Navigation, and has recently helped the 2nd Space Operations Squadron re-establish the GPS Performance Analysis Working Group; a forum where Air Force personnel and GPS professionals discuss GPS performance status and issues. IG