How Precise is OPUS?

Part 1: Experimental Results

NOAA's National Geodetic Survey (NGS) introduced its Online Positioning User Service (OPUS) in 2001 as a means to provide both easy and accurate access to the National Spatial Reference System (NSRS). Surveyors and others can submit dual frequency GPS data to the OPUS web page **www.geodesy.noaa.gov/OPUS** and receive an email containing positional coordinates, with pertinent error estimates, for the location where their data were collected, often within minutes. OPUS computes these coordinates by processing the user-submitted data with corresponding GPS data from the U.S. Continuously Operating Reference Station (CORS) network and/or the International GNSS Service (IGS) network. OPUS-computed coordinates are thus consistent with NGS-published coordinates for the stations contained in the combined CORS/IGS network, and consequently they are consistent with the NSRS. By incorporating OPUS-computed coordinates into their survey work, geospatial professionals and others can be highly confident that their work is consistent with other survey work that has been tied to the NSRS.

This article is the first of three that will explore with what precision OPUS can compute positional coordinates. In this article, precision is measured by processing GPS data from each of several CORS/IGS stations and comparing the OPUS-generated coordinates with corresponding NGS-published coordinates where the published coordinates have been independently determined from many days worth of GPS data. The second and third articles will appear in subsequent issues of this magazine.

A limiting condition of the original OPUS utility is that its users must submit at least two hours of dual frequency GPS carrier phase data to be reasonably confident that OPUS will correctly resolve the integer ambiguities associated with these data. When these ambiguities are correctly resolved, OPUS-computed coordinates will be precise to a few centimeters.

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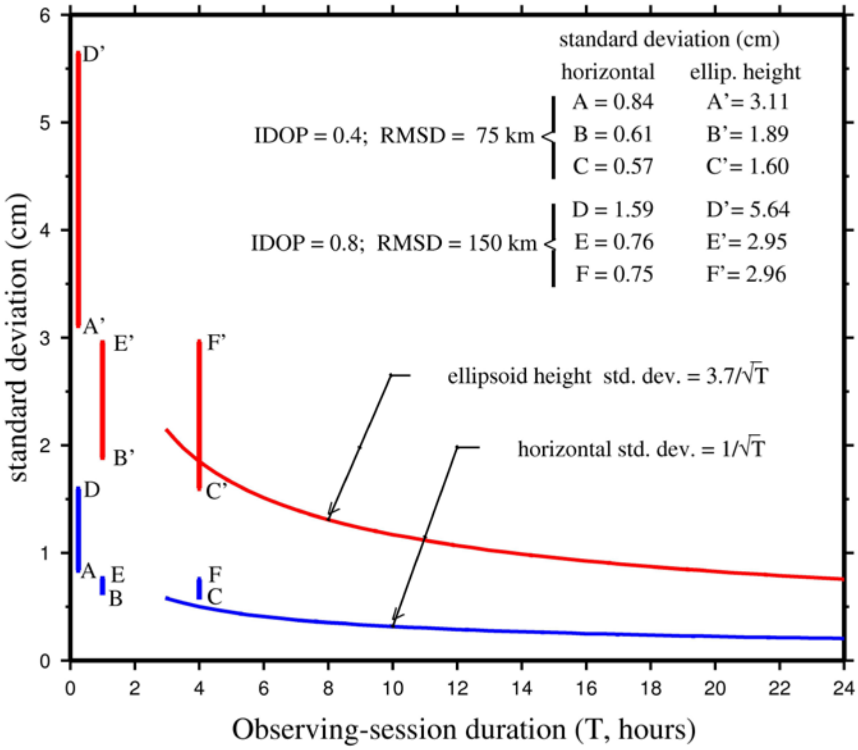

Figure 1. Curves show estimated standard deviations of coordinates computed with OPUS-S for observing sessions between 3 hours and 24 hours in duration. Vertical bars show estimated standard deviations of coordinates computed with OPUS-RS for observing sessions of 15 minutes, 1 hour, and 4 hours. The bottom of each vertical bar corresponds to the standard deviation for IDOP = 0.4 and RMSD = 75km. The top of each vertical bar corresponds to the standard deviation for IDOP = 0.8 and RMSD = 150km. The red curve and the red vertical bars represent standard deviations in ellipsoid height. The blue curve and the blue vertical bars represent standard deviations in each horizontal dimension (north-south or east-west). Note for illustrative purposes, this plot displays OPUS-RS standard deviations for 4-hour observing sessions; however, the operational version of OPUS-RS limits data submissions to a maximum duration of 2 hours.

Otherwise, the coordinates might be precise to a few decimeters. To overcome the need for two hours of data, NGS developed the OPUS-RS utility, where "RS" stands for *rapid static.* Consequently, the original OPUS utility was renamed OPUS-S where "S" stands for *static.* OPUS-RS was designed so that users may submit as little as 15 minutes of dual frequency GPS data. OPUS-RS uses a data processing engine that differs significantly from that utilized in OPUS-S. The OPUS-RS processing engine was designed by researchers at the Ohio State University with support from NGS. NGS then refined the original design and developed appropriate software for a production environment. OPUS-RS was released for public use in 2007.

The primary difference between the OPUS-RS processing engine and the OPUS-S processing engine relates to how they respectively handle the travel-time delays caused by atmospheric refraction and experienced by a GPS signal during its journey from a satellite to the user's receiver, hereafter called the *rover.* In the case of OPUS-RS, the processing engine uses at least one hour of GPS data, overlapping in time with the user's observing session, from at least three and as many as nine CORS/IGS stations, each located within 250 km of the rover, to determine the atmospheric delays experienced at these CORS/IGS stations during the user's observing session. That is, OPUS-RS will use an hour's worth of CORS/IGS data even if the user's observing session is only 15 minutes long. (For longer observing sessions, OPUS-RS will always use at least as long a time span of data from the CORS/IGS stations.) The atmospheric delays include those caused by free electrons residing in the upper atmosphere as well as the delays caused by the distribution of molecules residing in the neutral atmosphere. The delays experienced at the CORS/IGS stations can be determined rather precisely because the computational process constrains the coordinates of these stations to values that have been previously determined from rigorous analysis involving many days, if not years, of data. Then OPUS-RS interpolates (or extrapolates) the computed atmospheric delays at the selected CORS/IGS stations to estimate corresponding delays at the rover. Finally, OPUS-RS constrains the atmospheric delays at the rover to their interpolated/extrapolated values when it computes the rover's coordinates. These constraints are weighted in inverse proportion to their estimated variance.

In the case of OPUS-S, the processing engine computes all atmospheric delays (for the rover as well as the selected CORS/IGS stations) simultaneously while it is computing the rover's coordinates. OPUS-S does not use any GPS data from the CORS/IGS network other than that collected during the user's observing session. Nor does OPUS-S assume that the delays, experienced at the rover, may be approximated by interpolating (or extrapolating) corresponding delays at nearby CORS/IGS sites. As described below, the use of interpolation/extrapolation not only affects how little data the user can submit, it also affects how precise the resulting coordinates will be.

Over the last decade, NGS researchers empirically determined that the standard deviations of coordinates computed with OPUS-S depends primarily on the duration of the user's observing session. In particular, for observing sessions spanning at least three hours, the standard deviation σ_h in each horizontal dimension (north-south or east-west) is well approximated by the equation

$$\sigma_h(cm) = \frac{1}{\sqrt{T}}$$

where T denotes the duration of the observing session in hours. Correspondingly, the standard deviation σ_v in the vertical dimension (ellipsoid height) is well approximated by the equation

$$\sigma_v(cm) = \frac{3.7}{\sqrt{T}}$$

Thus for $T = 4$ hours, $\sigma_h = 0.5$ cm and $\sigma_v = 1.85$ cm. **Figure 1** illustrates these relationships along with standard deviations that are obtainable with OPUS-RS as discussed later in this article.

NGS's studies showed that the precision of coordinates computed by OPUS-S do not depend significantly on the geometry of the CORS/IGS stations, nor on the distances from the rover to the various CORS/IGS stations (until distances exceed 1,000 km). OPUS-RS precision, however, does depend significantly on these two factors because OPUS-RS relies on interpolating/extrapolating atmospheric delays from the CORS/IGS stations to the rover. To measure this dependence, NGS personnel considered two quantities: (1) the *interpolative dilution of precision* (IDOP) for characterizing the geometry of CORS/IGS stations used in the OPUS-RS solution and (2) the *root mean square distance* (RMSD) for characterizing the collection of distances between the rover and the CORS/IGS stations used in the OPUS-RS solution.

As may be expected, OPUS-RS can better estimate atmospheric delays from the CORS/IGS stations to the rover through interpolation when the nearby CORS/IGS stations surround the rover on all sides, rather than through extrapolation if the nearby CORS/IGS stations are all located within a narrow wedge formed by two lines emanating outward from the rover, for example, when all of the nearby CORS/IGS sites are located both south and east of the rover. In particular, OPUS-RS results in coastal areas often suffer in precision due to the poor station geometry realized when the nearby CORS/IGS stations are all located landward of the rover. IDOP is a unitless quantity that provides a rigorous numerical measure for this concept. **Figure 2** demonstrates how IDOP varies as a function of the rover's location for the specific case when there are only four CORS/IGS stations located within 250 km of the rover and these four stations form the corners of a square. IDOP should not be confused with the well-known, unitless quantity called the *geometric dilution of precision* (GDOP); nor should IDOP be confused with measures related to GDOP such as PDOP, HDOP, VDOP, TDOP, etc. GDOP and its related measures quantify the geometry of the collection of GPS satellites visible from the rover, whereas IDOP quantifies the geometry of the CORS/IGS stations (being used by OPUS-RS) relative to the rover.

Also as may be expected, the closer the CORS/IGS stations are to the rover, the better OPUS-RS can interpolate/extrapolate atmospheric delays from the CORS/IGS stations to the rover. If n denotes the number of CORS/IGS stations involved in an OPUS-RS solution and d_i denotes the distance from the

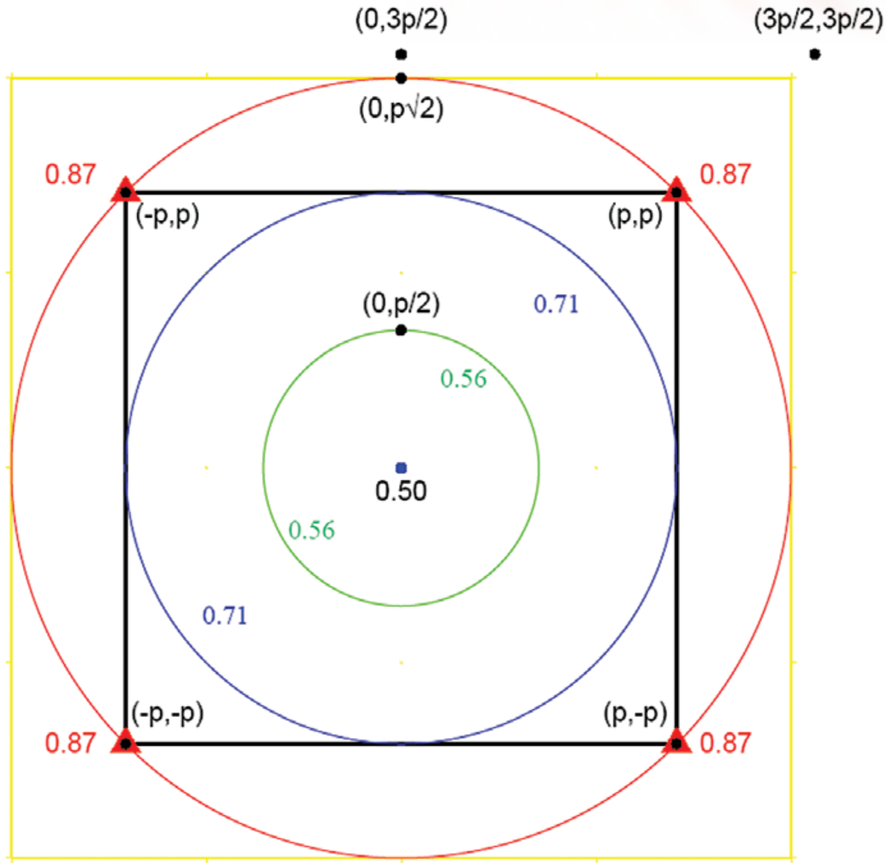

Figure 2. This figure displays how IDOP varies as a function of the rover's location for the specific case of four CORS/IGS stations (red triangles) that form the corners of a square whose sides are $2p$ in length. Actually, the value of p is arbitrary; it may be 1 km, 100 km, or any other distance. IDOP is a unitless quantity that measures how well refraction values, determined at the CORS/IGS stations, can be interpolated (or extrapolated) to estimate the corresponding value at the rover. In particular, if the refraction value at each CORS/IGS station is known with a standard deviation of $\sigma_{CORS/IGS}$, then the interpolated/extrapolated refraction value at the rover (assuming that refraction is a linear function of latitude and longitude for a given ellipsoid height) will be determined with a standard deviation of σ_{rover} = (IDOP) • $\sigma_{CORS/IGS}$. Thus, the smaller the value of IDOP, the better the refraction at the rover can be estimated. For this case, IDOP = $\sqrt{(r/p)^2+1}/2$ where r represents the distance from the rover to the square's centroid. The lowest IDOP value is 0.50, and it occurs when the rover is located at the square's centroid ($r = 0$). IDOP equals 0.56 when r equals $p/2$, it equals 0.71 when r equals p, and so forth. It can be shown that for a set of n CORS/IGS stations, the lowest IDOP value is $1.0/\sqrt{n}$ and this value occurs when the rover is located at the centroid of the n sites. Also, IDOP will generally increase in value as the distance between the rover's location and the centroid increases, but this increase will not necessarily be radially symmetric as it is in the case of four CORS/IGS stations located at the corners of a square.

rover to the i^{th} CORS/IGS station (for $i = 1,2,\ldots,n$), then

$$RMSD = \sqrt{\frac{\Sigma d_i^2}{n}}$$

To determine how the precision of OPUS-RS depends on IDOP and RMSD, NGS performed thousands of OPUS-RS solutions for 15-minute observing sessions. For a particular solution, the experiment used data from a selected CORS/IGS station as the rover's data. The difference between the coordinates computed with OPUS-RS and the corresponding coordinates previously published by NGS (and based on many days of GPS data) supplied a measure of the solution's precision. However, any errors in the previously published coordinates themselves also would have contributed to the overall disagreement, so such differences will become smaller when more accurate CORS/IGS coordinates become available in the future. This process was repeated several times so as to use all CORS located in the contiguous United States as the rover and use numerous data sets collectively spanning the period from July 2007 to April 2008. The experiment was also repeated for observing sessions of one-hour duration and again for observing sessions of four-hour duration.

Figure 3 illustrates some of the results for the specific case when IDOP = 0.45. As revealed by this figure, coordinates computed with OPUS-RS using one hour of rover data are significantly more precise than those computed using 15 minutes of rover data, while those computed using four hours of rover data are only marginally more precise than those computed using one hour of rover data. Also, the experiments indicate that–for any given values for the three variables: IDOP, RMSD, and the duration of the observing session–the standard deviation of OPUS-RS in the vertical dimension (ellipsoid height) is between 2.8 and 4.0 times larger than the corresponding standard deviation in each horizontal dimension (north-south or east-west). This result agrees well with results (published in 2001) using OPUS-S where vertical standard deviations are approximately 3.7 times larger than corresponding horizontal standard deviations as revealed by the two equations given earlier in this article which involve these standard deviations.

The second and third articles will further discuss the precision of coordinates computed with OPUS-S or OPUS-RS. Also, more detailed information about OPUS and its precision may be found in OPUS-related articles available on the Web at **www.geodesy.noaa.gov/CORS/Articles/** and in a collection of scientific papers written by several authors and published by the American Society of Civil Engineers under the title, *CORS and OPUS for Engineers: Tools for Surveying and Mapping Applications.*

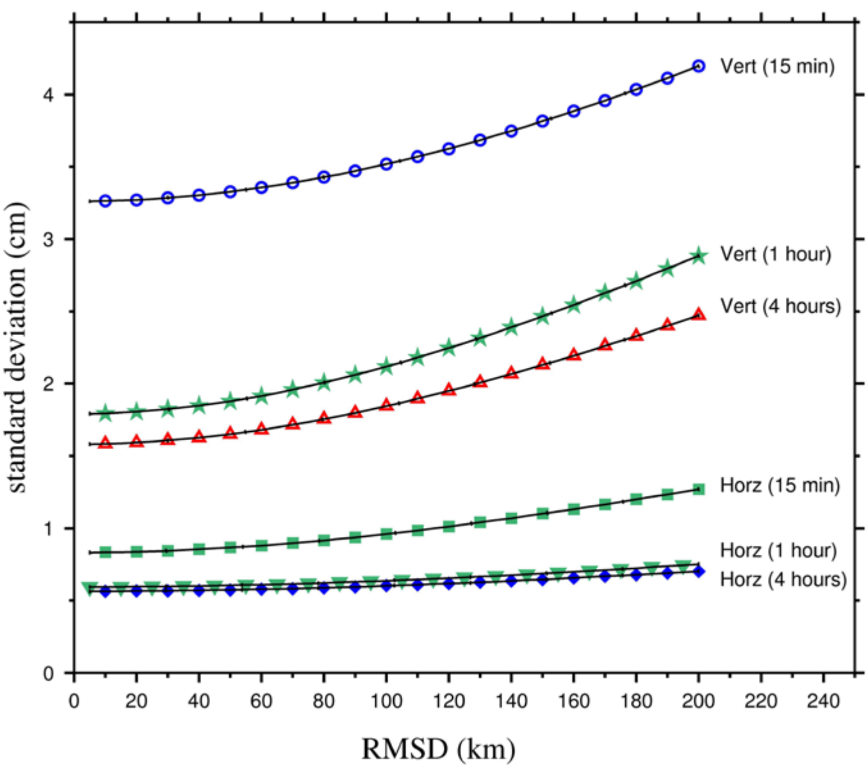

Figure 3. Predicted standard deviations in the vertical (ellipsoid height) and in each horizontal dimension (north-south or east-west), achievable with OPUS-RS, as a function of RMSD for data spans of 15 minutes, 1 hour and 4 hours and an IDOP value of 0.45.

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