Epoch-by-EpochÔ Positioning and Navigation

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BIOGRAPHY

Paul de Jonge received his Ph.D. in geodesy at the Delft University of Technology in the Netherlands, and he currently works for Geodetics. Dr. Yehuda Bock is the President and CEO of Geodetics. He is also a Research Geodesist and Senior Lecturer at the Scripps Institution of Oceanography where he directs the Scripps Orbit and Permanent Array Center (SOPAC) and the California Spatial Reference Center (CSRC). Dr. Michael Bevis is the Vice-President of Geodetics and a Professor of Geophysics and Geodesy at the University of Hawaii.

ABSTRACT

Geodetics, Inc. has developed a new class of instantaneous, real-time GPS positioning algorithms based on dual frequency phase and pseudorange data, which we call Epoch-by-Epoch™ positioning. The main advantage of this approach over traditional real-time methods is that integer-cycle phase ambiguities are independently estimated for each and every observation epoch, allowing precise positions (1-2 cm horizontal and 5-10 cm vertical) to be estimated given only a single epoch of data from two or more receivers, in either baseline or network mode. Our algorithms are extremely efficient – a single epoch on a single baseline can be processed in several milliseconds. There is no need for the initialization period associated with conventional RTK algorithms. More importantly there is no need for reinitialization immediately following loss-of-lock problems such as occur when a mobile GPS receiver passes under a bridge or other obstruction. Accordingly, our approach minimizes the amount of time a receiver spends in a non-productive prepositioning mode of operations. Epoch-by-Epoch™ positioning has other advantages, including a significantly extended range relative to conventional RTK, and a better framework for quality control. The Epoch-by-Epoch™ approach can also be applied to the autonomous real-time determination of precise attitude and heading (about 0.05 degrees) of a moving platform instrumented with 2-3 receivers and a rigid multiple-antenna structure. A combination of this autonomous navigational capability with precise instantaneous (relative) positioning is ideal for many applications such as automated airborne landing systems, harbor navigation, automated highways, machine control, and GPS/INS integration. Epoch-by-Epoch™ positioning also provides a useful architecture for static positioning, since relatively rare but highly discordant solutions (i.e. solution 'outliers' associated with extreme levels of measurement noise) can be recognized and excluded from any position averaging. When single epoch solutions are averaged by a median filter, the scatter of the averaged solutions is inversely proportional to the logarithm of averaging time.

INTRODUCTION

Geodetics, Inc. has developed an innovative suite of software modules that implement Epoch-by-Epoch™ analysis of dual-frequency phase and range data from two or more GPS receivers. The central feature of this approach is that a high accuracy geodetic solution, based on instantaneous integer-cycle ambiguity resolution, is achieved for each measurement epoch using only the observations collected at that epoch. Accordingly, each solution is independent of the solutions obtained for the previous and following epochs. Because Epoch-by-Epoch™ analysis routinely resolves the complete set of double difference ambiguity parameters for each epoch, the technique delivers horizontal accuracies comparable to those achieved in conventional kinematic and RTK processing. Our software can be used to process networks consisting of two or more GPS receivers, and allows nearest-neighbor station spacings several times wider than conventional RTK.

Epoch-by-Epoch™ data processing is achieved by a core library of geodetic routines called the Rapid Network Analysis (RNA) library. All of the application software developed by Geodetics to date, and several applications currently under development, are built around the proprietary RNA library. Our algorithms are extremely efficient and allow the simultaneous, real-time network positioning of at least 10 receivers sampling at a 1 Hz interval on a standard medium-scale PC workstation. A single epoch on a single baseline can be processed in only several milliseconds. Although Epoch-by-Epoch™

analysis is instantaneous, in the sense that it produces a solution for each epoch or instant, without direct or indirect reference to data collected at any other time, it provides a useful computational architecture for post-processing of multiple-epoch data batches as well as for real-time positioning. We illustrate some of these applications in the following sections.

KINEMATIC POSITIONING

Conventional RTK software partitions the integer ambiguity problem into an initialization stage that typically lasts 30-40 seconds. During this time phase ambiguities are assessed using multiple epochs of data, and when the integer ambiguities are finally resolved with sufficient confidence, initialization ends and actual positioning begins. Should a serious loss of satellite lock occur, as might happen when a mobile GPS receiver passes under a bridge, then once the hardware recovers and the GPS data stream begins anew, it is necessary for the software to reinitialize – that is, to return to the problem of resolving integer ambiguities as a preliminary to actual positioning. The total delay associated with loss of lock depends on the hardware as well as the software, since the receiver also has to reinitialize tracking after a loss of lock. The high performance, dual frequency GPS receivers available to civilians can recover from a very brief loss of lock in a second or two, but typically take 10-20 seconds to recover from a sustained loss of lock. This hardware down time is followed by additional down time associated with software initialization. Military dual frequency receivers, with direct access to the P code, can relock the satellites much more rapidly than non-classified receivers, with high performance military units ‘cold starting’ in less than one second.

Because Epoch-by-Epoch™ algorithms estimate the integer ambiguities instantaneously, they completely eliminate the software downtime associated with initialization and reinitialization. Accordingly Geodetics’ software cuts the total hardware plus software initialization/reinitialization time to something very close to the hardware initialization time. This leads to significantly improved performance in civilian applications, and dramatically improved performance with military hardware.

The second architectural advantage of Epoch-by-Epoch™ positioning is that a mobile receiver can be positioned against a network of reference stations, and not just a single base station. This makes it easier to implement wide-area RTK based on multiple reference stations. Using 3-5 reference stations will provide the infrastructure necessary to support RTK positioning throughout a major metropolitan region. Network-oriented geodetic analysis also assists in system integrity monitoring.

CASE STUDY 1: VEHICLE TRACKING

Figures 1 and 2 show position and velocity solutions obtained for a vehicle tracking test implemented by Applanix Corporation on March 3, 2000 in Ontario, Canada. The vehicle was a passenger van that traveled up to 6 km away from a GPS base station at speeds of up to 70 km/hour. The GPS sampling interval was one second. All results shown in these figures are raw single-epoch solutions. Figure 1 focuses on a subset of this test in which the vehicle made four circuits of the same C-shaped section of road. We color code each of the four circuits so as to provide relative timing information in plots featuring only spatial axes. This allows us to confirm that the two tracks apparent in the blow-up map (Fig. 1) correspond to the two sides of the road, with both sides being traversed in all four circuits. The 3-D plot shows the first three visits to one end of the track, and one can clearly resolve the manner in which the vehicle was turned around. Note that the vehicle arrives well-centered in the right lane, but leaves the turn less well centered in the adjacent lane (at least for the first 40 meters).

The velocity solutions (Fig. 2) were obtained by simple differencing of the position solutions, without any smoothing or editing. The velocity solutions are produced at a frequency of 1 Hz, but are offset by 0.5 seconds relative to the position time series. Because they are produced by differencing single-epoch positions, velocity time series are strongly sensitive to small errors in position. We can detect an artifact in the vertical velocity (Vu) time series about 115 seconds into the test.

After completing the four circuits around the C-shaped track, the vehicle stopped for 178 seconds. Both the velocity solutions and the positions during this period are shown in the lower half of Figure 2. Note that the up coordinate has an order of magnitude more scatter than does the north or east coordinate. In part this reflects the fact that we were estimating atmospheric parameters as part of each epoch analysis. A shorter static test took place at greater distance from the base station later in the test, and the horizontal scatter associated with these solutions is shown in the lower left section of Figure 1.

REAL-TIME ORIENTATION

When three antennas are fixed to a rigid structure with spacings of order 1-2 meters, it is possible to determine the orientation of the antenna array (i.e. its pitch, roll and heading angles) without reference to any external static base station. The solutions for the lengths of the inter-antenna vectors can be examined in real-time in order to monitor the integrity of the orientation determinations. Angular resolutions of about 0.05 degrees are achieved using Geodetics’ Vector software, which is based on RNA. Of course, when a static reference station is available, then it is also possible to solve for the position and velocity of the antenna array, thereby achieving a complete kinematic description of the system.

STATIC POSITIONING

For static positioning applications, such as surveying or deformation monitoring, it is advantageous to collect and analyze multiple epochs of data, in order to mitigate positioning errors deriving from measurement noise. Even in a multiple epoch framework, Epoch-by-Epoch™ positioning provides some significant advantages. The dominant source of error affecting dual frequency measurements is multipath noise. The level of multipath noise rises and falls with passing time, but is always present to some degree. The best means of suppressing multipath noise is to average the position solutions obtained over many epochs. The other class of measurement error are high amplitude 'glitches' or outliers associated with grossly problematical measurements, as might occur, for example, when a receiver is subject to a burst of very high amplitude radio frequency interference. While relatively rare in most settings, measurements outliers can disrupt even position solutions obtained by averaging over multiple epochs. However, when solutions are obtained on an instantaneous basis, it is relatively simple to recognize badly discordant solutions, and simply reject these solution outliers, and prevent them from affecting the averaged position. Perhaps the simplest way of averaging position coordinates over multiple epochs of data is by use of the median rather than the mean, as described by Bock et al. (2000). When the influence of outliers is eliminated by robust averaging of the single epoch solutions, the accuracy of the averaged solution tends to improve in proportion to the logarithm of total averaging time (Bock et al., 2000). Outliers can be identified and counted, and can be used as a means of monitoring the quality of the data being collected by a CGPS network.

CASE STUDY 2 : DEFORMATION MONITORING

The Metropolitan Water District of Southern California has constructed a continuous GPS network at Diamond Valley Lake reservoir to monitor the stability of its earthen dams. This network collects GPS observations with a sampling interval of 30 seconds. Figure 3 shows results we have obtained using Epoch-by-Epoch™ analysis for day 194 of this year (2000). These results were obtained by solving for the geometry of the entire network, fixing just one station (the reference station WDR) to its prior coordinates. We show the raw single-epoch results, and in several plots we superimpose lower frequency solutions obtained by robust averaging in successive (abutting but non-overlapping) time windows. The averaging is performed by computing the median of the north, east and up coordinates in each time window. Because these windows do not overlap, each of the averaged solutions is independent of its neighbors in the same time series.

A pair of semilog graphs show the relationship between the scatter of the single epoch and multi-epoch solutions (obtained by averaging N single epoch solutions at intervals of (N-1)/2 minutes) and averaging time. Note that coordinate scatter varies in inverse proportion to the logarithm of averaging time, as noted previously by Bock et al. (2000). By averaging static solutions over longer periods of time, the precision of the resulting solution is improved but, since these solutions occur less frequently, this improvement comes at the cost of poorer temporal resolution. Of course it is possible to set up an alarm system with a higher alarm threshold when little or no averaging is taking place, and simultaneously consider one or more averaged time series associated with more sensitive alarm levels. In this way one can "both have one's cake and eat it too", and avoid the difficult choice between detecting smaller levels of deformation and detecting larger motions more quickly. The lowest frame in Figure 2 shows that monitoring a time series produced by finding the median position of each station every hour, should allow an alarm system to detect any horizontal displacement greater than about 15 mm (about 3σ), without setting off significant numbers of false alarms.

Note that the ratio of vertical to horizontal scatter in the single epoch solutions is much lower in this case study than that seen in the vehicle tracking study. In large part this is because atmospheric parameters were not estimated in this static analysis, though the low multipath environment at the dam, and the use of choke ring antennas, may also have helped.

ACKNOWLEDGMENTS

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REFERENCE

Bock, Y., R. Nikolaidis, P. J. de Jonge, and M. Bevis, 2000, Instantaneous geodetic positioning at medium distances with the Global Positioning System, *Journal of Geophysical Research*, in press.

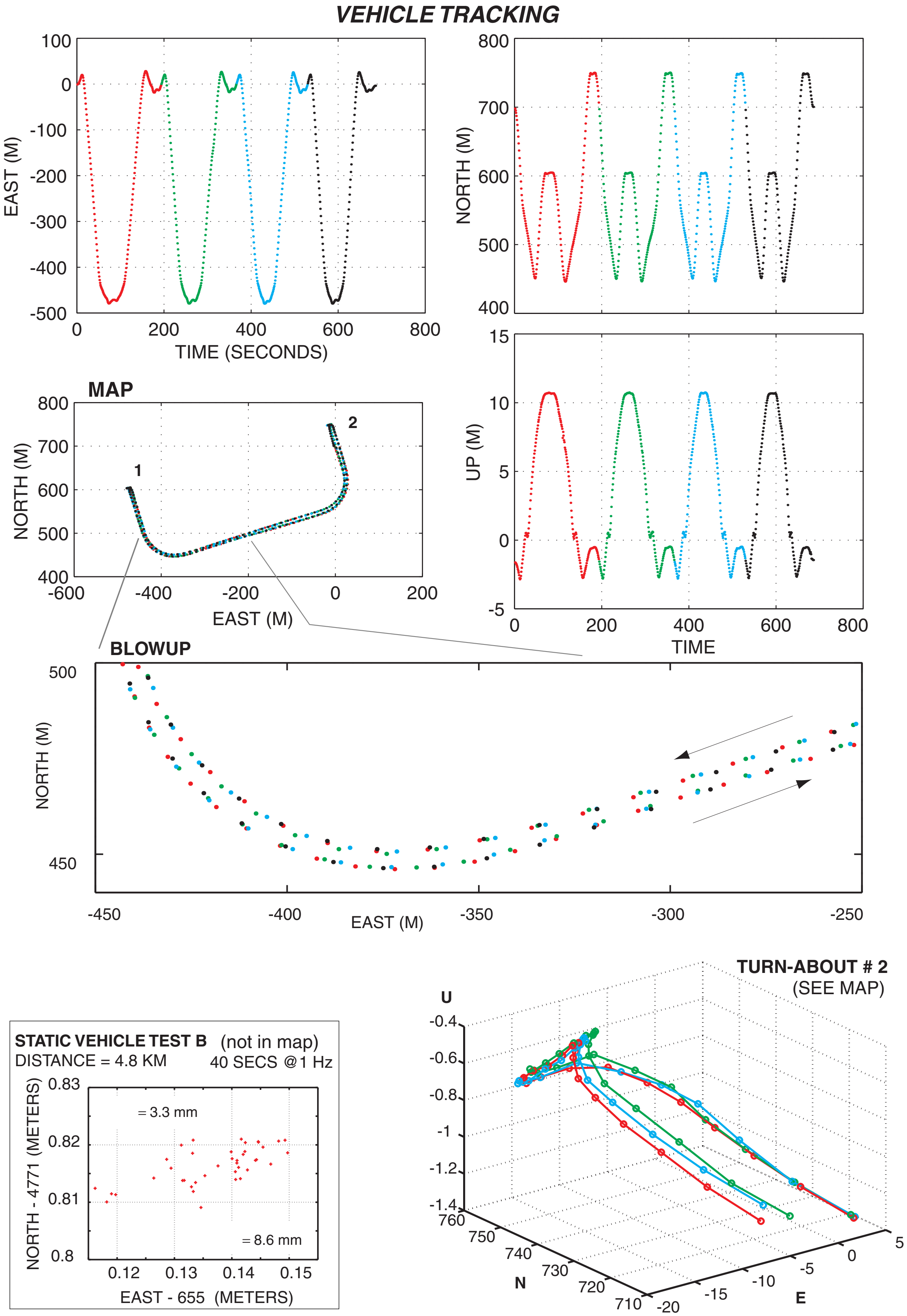
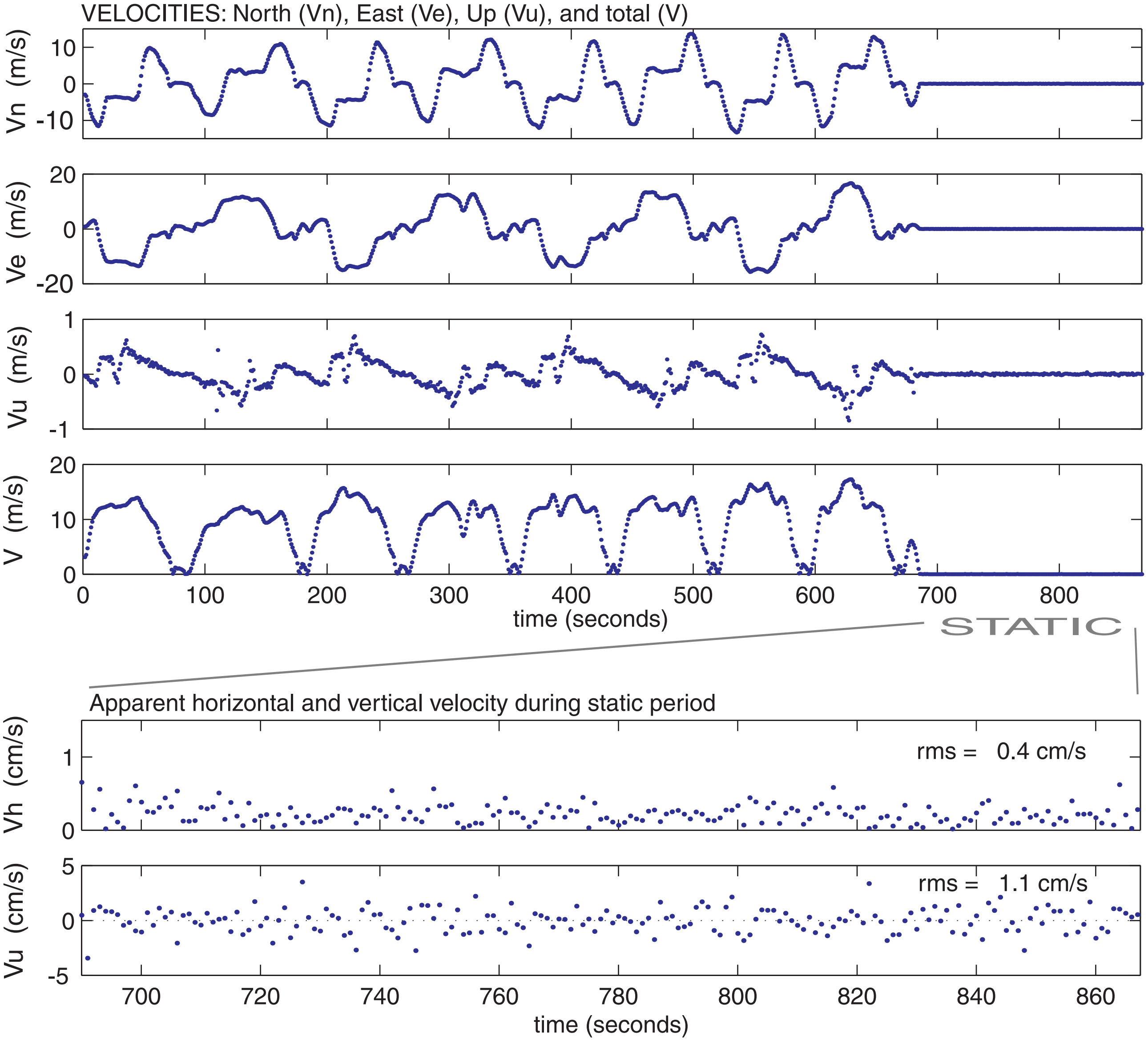
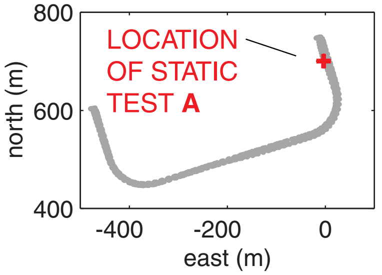


Figure 1. Raw epoch-by-epoch solutions obtained using Geodetics RNA software from 1 Hertz dual-frequency GPS data collected during a vehicle tracking test. Data courtesy of Applanix Corporation.

VEHICLE TRACKING CONT'D





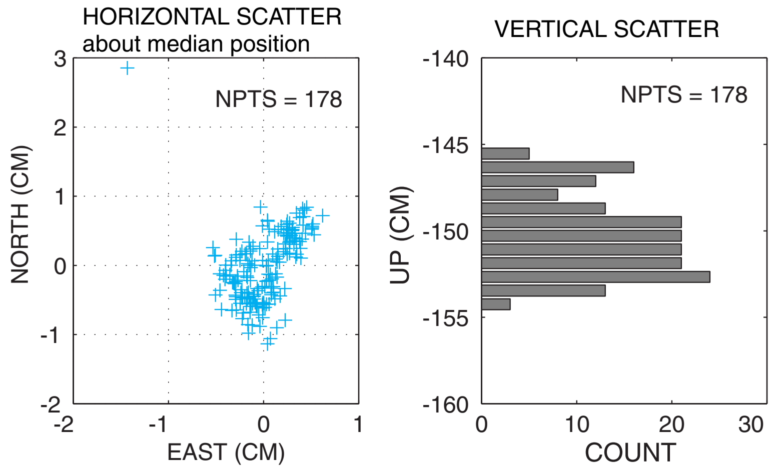


Figure 2. Upper six frames show velocities, estimated by differencing the 1 Hertz position estimates, during kinematic and static portions of the experiment. The two plots, right, show position repeatability when the vehicle was stopped.

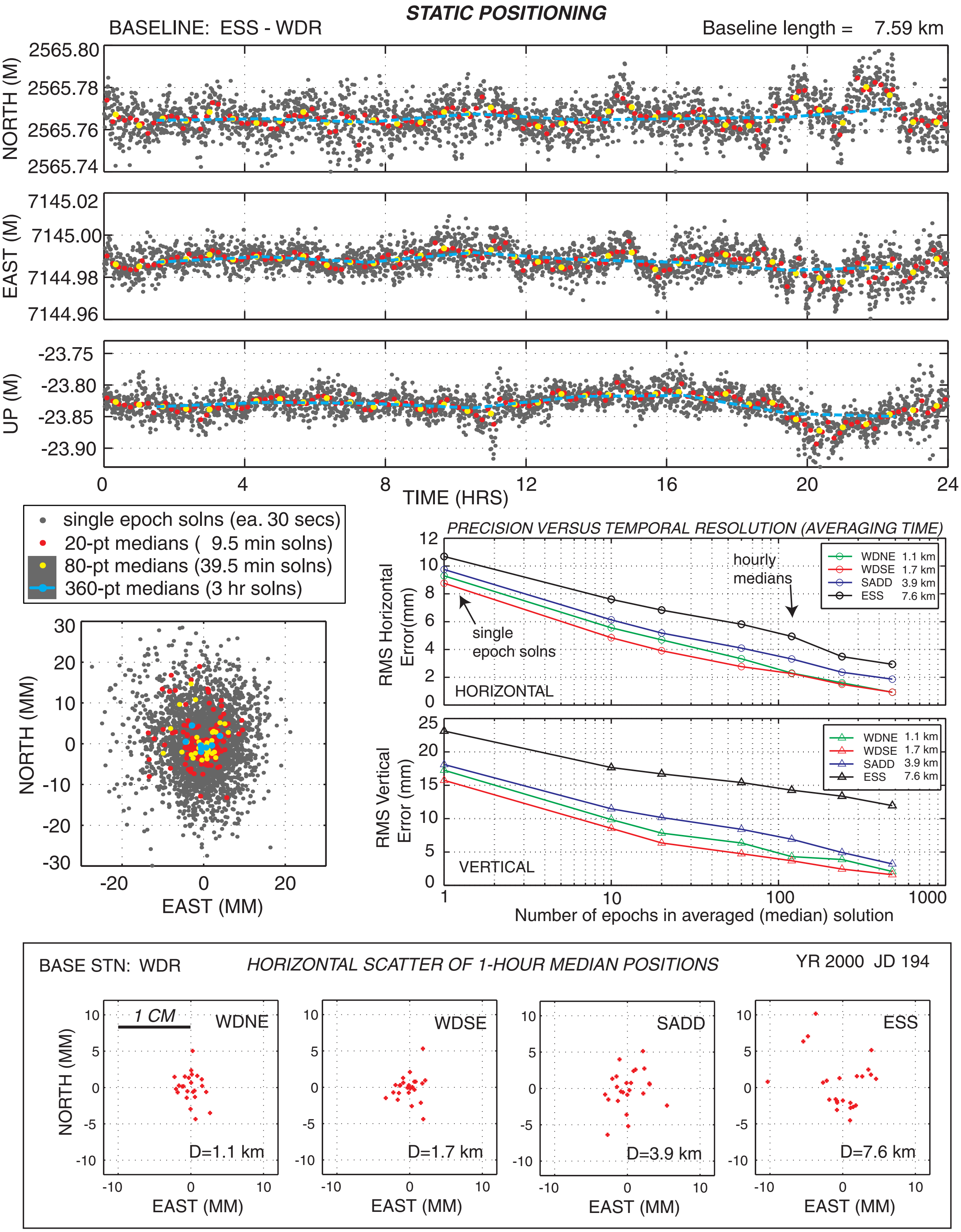


Figure 3. Single-epoch and time-averaged positioning of the GPS deformation network at Diamond Valley Lake reservoir. This monitoring network incorporates Leica CRS-1000 GPS receivers with IGS-style choke rings. Atmospheric delays were not estimated in this analysis. Data courtesy of Metropolitan Water District of Southern California.