EPOCH-BY-EPOCH™ POSITIONING APPLIED TO DAM DEFORMATION MONITORING AT DIAMOND VALLEY LAKE, SOUTHERN CALIFORNIA

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Abstract

We describe the application of Epoch-by-Epoch™ positioning to dam deformation monitoring at Metropolitan Water District's Diamond Valley Lake, the largest water reservoir in southern California. Epoch-by-Epoch™ positioning is a new methodology whereby precise GPS positions can be estimated instantaneously with only a single epoch of dual-frequency phase and code data collected by two or more receivers over distances of several tens of km. The key is to be able to correctly resolve integer-cycle phase ambiguities independently for each and every observation epoch, thereby avoiding the initialization and re-initialization periods associated with real-time kinematic (RTK) methods. Geodetics, Inc. and Leica Geosystems have jointly developed a Windows application program called CRNet (Continuous Reference Network) which incorporates Geodetics' Real-Time Network Analysis (RNA) module containing the Epoch-by-Epoch™ algorithms. The algorithms are specifically designed for high-precision real-time monitoring/alert of, for example, dams, bridges and volcanoes. The first installation of the software is at Diamond Valley Lake where it has been running for several months. Seven Leica CRS1000 receivers and AT303 antennas are deployed on three large earthen dams and at two reference sites located on stable rock close to the two larger dams about 8 km apart. Data are collected at a 2 s sampling interval, transmitted continuously to a central facility via radio modems and analyzed instantaneously with CRNet in network mode. The coordinates of 6 sites are freely estimated at each epoch relative to the assumed fixed coordinates of one of the reference sites. Horizontal coordinate precision (one-sigma) for a single-epoch position is about 10 mm and about 5 times worse in the vertical but the user can specify any observation interval over which the single-epoch solutions can be averaged using robust estimation techniques; at Diamond Valley Lake this interval is set to one minute. Alarms are issued if preset displacement thresholds are exceeded and transmitted electronically to designated operators. If each end of the reservoir is analyzed independently, thereby cutting station spacing to less than a kilometer, then single-epoch precision can be improved to about 4 mm horizontally and 10 mm vertically. Although not yet implemented, sidereal-day averaging can further improve single-epoch coordinate precision by about 50% in each component.

1. Introduction

Geodetics, Inc. has developed a new class of instantaneous, real-time GPS positioning algorithms, referred to as Epoch-by-Epoch™ positioning, which have unique advantages for real-time monitoring and alert applications. In partnership with Leica Geosystems, we have developed a 32-bit Windows application program called CRNet (Continuous Reference Network) which incorporates Geodetics' Real-Time Network Analysis (RNA) module and its embedded Epoch-by-Epoch™ algorithms. In this paper, we report on the first installation of CRNet to monitor dam deformation. The project is located at Metropolitan Water District's Diamond Valley Lake, the largest drinking water reservoir in southern California (Figures 1 and 2).

Data are collected at a 2 second sampling interval and are transmitted continuously to a central facility via dedicated radio modems and analyzed instantaneously. The coordinates of 6 sites are freely estimated at each epoch in network mode relative to the assumed fixed coordinates of one of the reference sites.

Figure 1. An aerial view from the west of Diamond Valley Lake in Riverside County. With a surface area of 4,500 acres and a storage capacity of 800,000 acre feet (260 billion gallons), the reservoir will provide six months of emergency supplies in the event of a major earthquake, provide additional water for drought protection and peak summer needs, and nearly double the region's surface water storage capacity (*Metropolitan Water District of Southern California*, http://www.mwd.dst.ca.us/). Shown is the northern end of the West Dam and the smaller Saddle Dam. The West Dam is monitored in real-time by two Leica CRS1000 receivers, the Saddle Dam by one receiver. Altogether seven Leica CRS1000 receivers and AT303 antennas are deployed on three large earthen dams and at two reference sites located on stable rock close to the two larger (West and East) dams. (See Figure 2 for a map view of the GPS network).

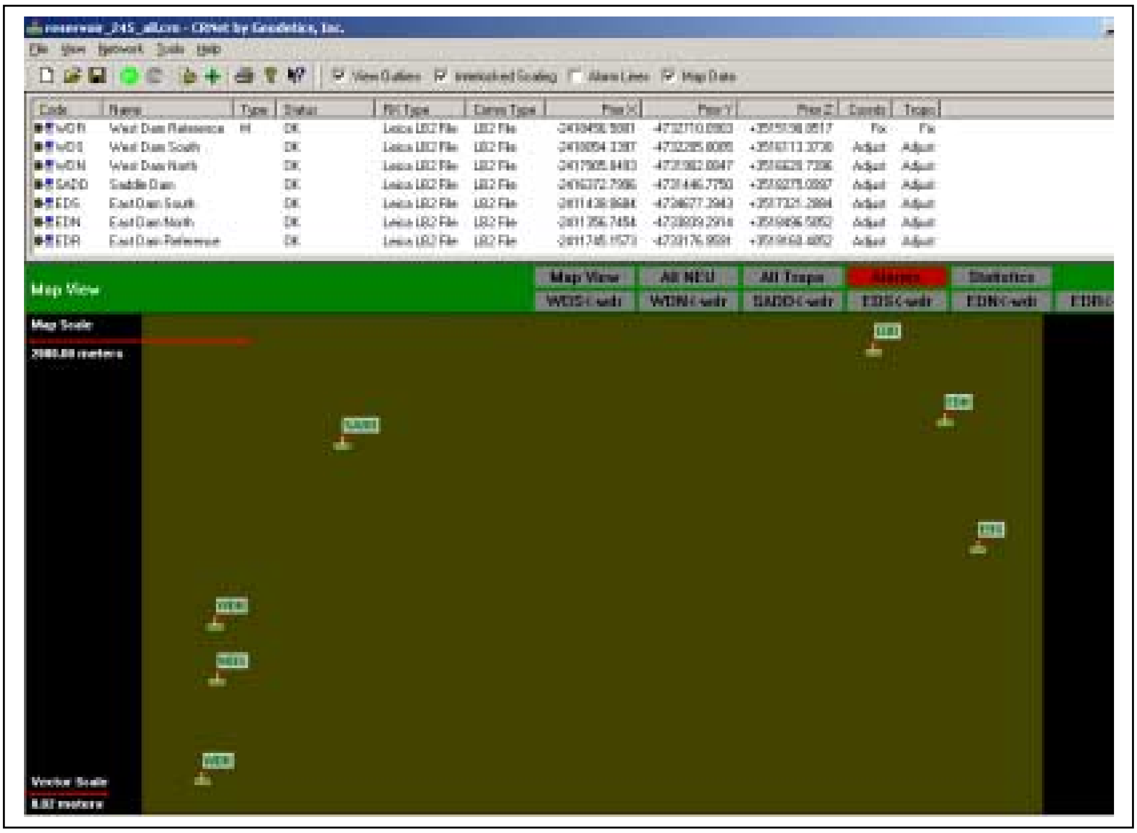

Figure 2. A map view of the continuous GPS network of 7 Leica CRS1000 receivers and AT303 antennas deployed at Diamond Valley Lake to monitor three earthen dams that enclose the reservoir. Sites WDN and WDS are located on the West Dam, SADD is on the Saddle Dam, and EDN and EDS are on the East Dam. Reference sites WDR and EDR are located on stable rock close to the West and East Dam sites, respectively, and are about 8 km apart. This figure is a screen shot of the CRNet Map View window.

2. Description of Software

The primary application of CRNet is to collect data from a local or regional (e.g., metropolitan or statewide) reference GPS network and compute the numerical history of each site's spatial coordinates largely for the purposes of monitoring the integrity of the system. Any sustained and significant apparent motion of one (or more) of the continuous GPS sites manifests either a real displacement of the site or problems with the quality of the data being collected at that site, either of which could cause serious problems in an active geodetic reference system. In this class of application, CRNet is being used to collect reference data and to monitor its integrity.

In some applications the network is intended specifically to monitor in real time the stability of a natural or man-made structure such as a volcano, an earthen dam (the subject of this paper – see Figures 1 and 2), or a bridge and to issue alerts if significant movements of the structure are detected. That is, the central purpose of the network is deformation monitoring. A deformation network is composed of two sub-networks: a stable reference network typically composed of two or three sites located outside a zone of potential deformation, plus the monitoring sites which are located inside the zone of potential deformation. Typically the motions of the monitoring sites are considered relative to one or more of the reference sites.

Although CRNet is intended to control a continuous GPS network to monitor deformation, it can also serve and process survey data for non-continuous (temporary) field sites with respect to the network. Furthermore, CRNet can also be used to post-process data that it did not collect or that it collected much earlier.

CRNet gathers data from a group of *dual-frequency* GPS receivers or data (RINEX) files to calculate raw single-epoch position solutions. Data downloading is accomplished either in streaming mode (as in the example of radio modems streaming data to a central location presented in this paper) or in batch mode where CRNet gathers data according to a fixed download schedule. Depending on the application, the user can specify a range of download intervals from once every 5 minutes to once every 24 hours.

Epoch-by-Epoch™ positions produced by CRNet (Figure 3) are instantaneous positions that are fully independent at each epoch of observation. Furthermore, the software provides rigorous instantaneous network adjustments independently for each epoch of observations. That is, it provides a precise instantaneous snapshot of the network geometry at each epoch of observation. The single-epoch positions are further processed using robust estimation over a user-specified interval from 30 seconds to many days to monitor changes of the network over time.

Figure 3. A screen shot of CRNet's "All NEU" window for Diamond Valley Lake. Shown is the North, East and Up single-epoch solutions for four of the sites relative to the West Dam reference site (WDR). The North and East solutions are presented in map view. The Up solutions are presented as a horizontal histogram. All units are in meters. Note that at this early stage of the network implementation, the two West Dam antennas were located on eccentric geodetic pillars for multipath and motion testing (see Figure 4).

3. Advantages of Epoch-by-Epoch™ Positioning for Deformation Monitoring

Epoch-by-Epoch™ positioning has distinct advantages for real-time deformation monitoring and alert applications. The central feature of this technology is that a high accuracy positioning solution, based on instantaneous integer 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. Successful resolution of integer-cycle phase ambiguities is a prerequisite for achieving the most precise position estimates with GPS by transforming precise but ambiguous phase measurements into precise unambiguous range measurements. However, in our approach there is no need for an initialization period associated with conventional RTK and static algorithms since the resolution of ambiguities is instantaneous. Moreover, there is no need for reinitialization since receiver losses of lock and cycle slips are irrelevant at the single-epoch level. Therefore, there is no need for traditional and time-consuming GPS data editing. This allows for a very efficient processing algorithm that is especially designed for real-time applications. CRNet can process a single observation epoch for a pair of stations in several milliseconds on a standard PC workstation.

Another important advantage of Epoch-by-Epoch™ positioning is that no prior assumptions are required regarding the location or movement of the monitored stations because each observation epoch is independent. So there is no need for Kalman filters or other Bayesian estimation methods that do require some prior knowledge of the positions of the monitored sites or more importantly their expected motions. Thus, in our approach there is no need to distinguish among different types of motion whether secular, periodic, instantaneous, or erratic. This provides an unbiased estimate of changes in site position at each observation epoch[1].

Single epochs solutions are, of course, still susceptible to the various error sources that are common to all GPS processing methods. Multipath and other site-specific errors (e.g., signal diffraction, signal attenuation, antenna phase center variations) dominate on short baselines while tropospheric errors are more dominant on longer baselines. However, it is far easier to detect and eliminate outliers in independent single-epoch solutions than in batch- or filter-based processing methods. CRNet statistics are based on two robust estimators, the median and the interquartile range (IQR), which are less sensitive to data outliers than the traditional mean and standard deviation.[2] Outliers are defined by default in CRNet as points that exceed three times the IQR of a coordinate time series (the user has the option to specify a different multiple of the IQR). Since outliers are easier to detect and eliminate in single-epoch solutions, the precision obtained with Epoch-by-Epoch™ positioning in conjunction with robust outlier detection can actually be enhanced (all else being equal) compared to traditional RTK or batch GPS processing.

[1] Thus, Epoch-by-Epoch™ positioning is also well suited for tracking dynamic platforms (http://www.geodetics.com/).

[2] The median is used to characterize the central or characteristic value, and the IQR is used to characterize the dispersion of the data about their central value. The IQR is defined as the range of the middle 50% of the data (the difference between the 75th and 25th percentiles). When a data sample is drawn from a normal distribution, its mean very nearly equals its median and its standard deviation equals about three quarters of the IQR.

4. Motion Detection and Alert Generation Test

The primary purpose of the Diamond Valley Lake monitoring system is to detect deformation of the three earthen dams that may lead to structural instability and possible catastrophic failure and to automatically alert operators in the event that motions exceed a user specified distance tolerance in any of three orthogonal components (North, East, and Up). These motions may range from nearly-instantaneous displacements that may accompany a large seismic event, for example, to long-term secular trends such as creep. Furthermore, the GPS sites provides a continuous reference grid for an automatic (but not continuous) monitoring of many other points on the dam surfaces using an electromagnetic distance measurement system [*Whitaker et al.*, this volume].

In order to test the detection and alert capabilities of CRNet a test was run at the reservoir. The antenna was removed manually from the West Dam North pillar and moved on foot to a nearby pillar about 20 m to the North. As shown in Figure 4, an alarm was automatically generated and displayed on CRNet's graphical interface. In Figure 5, we display the instantaneous Epoch-by-Epoch™ positions that track the motion of the antenna as it is was being moved from pillar to pillar.

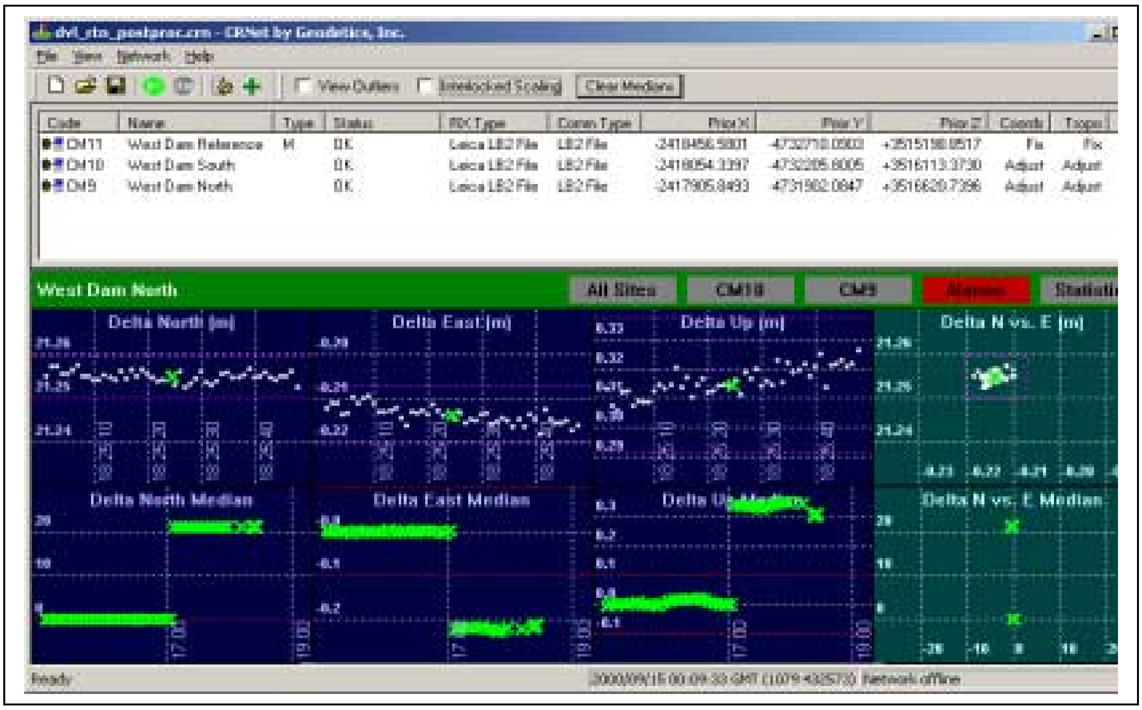

Figure 4. CRNet screen shot of the motion detection and alert generation test on Diamond Valley Lake's West Dam. The three sites involved in the test are shown in the upper panel along with their prior coordinates in ITRF97 (units of meters). The plots show the site positions for site West Dam North relative to its nominal a priori coordinates (prior to moving the antenna), in terms of local North, East, Up, and North vs. East components. The upper plots show the once every 2 seconds single-epoch solutions for the last minute of data. Note that the horizontal scatter is a few mm and the vertical scatter is about 10 mm. The blue rectangle on the upper right plot indicates the 3 times interquartile range (IQR) for the North and East components. Any single-epoch value that falls outside of this rectangle is flagged as an outlier and excluded from the 1-minute median computation (no outliers in this example). The lower plots show the time series of 1-minute median values for the hour before and after the antenna was moved. The Alarms box was triggered (colored red) when the first 1-minute median value, recorded after the antenna was moved, was greater than the detection threshold of 10 cm (in all of the three components).

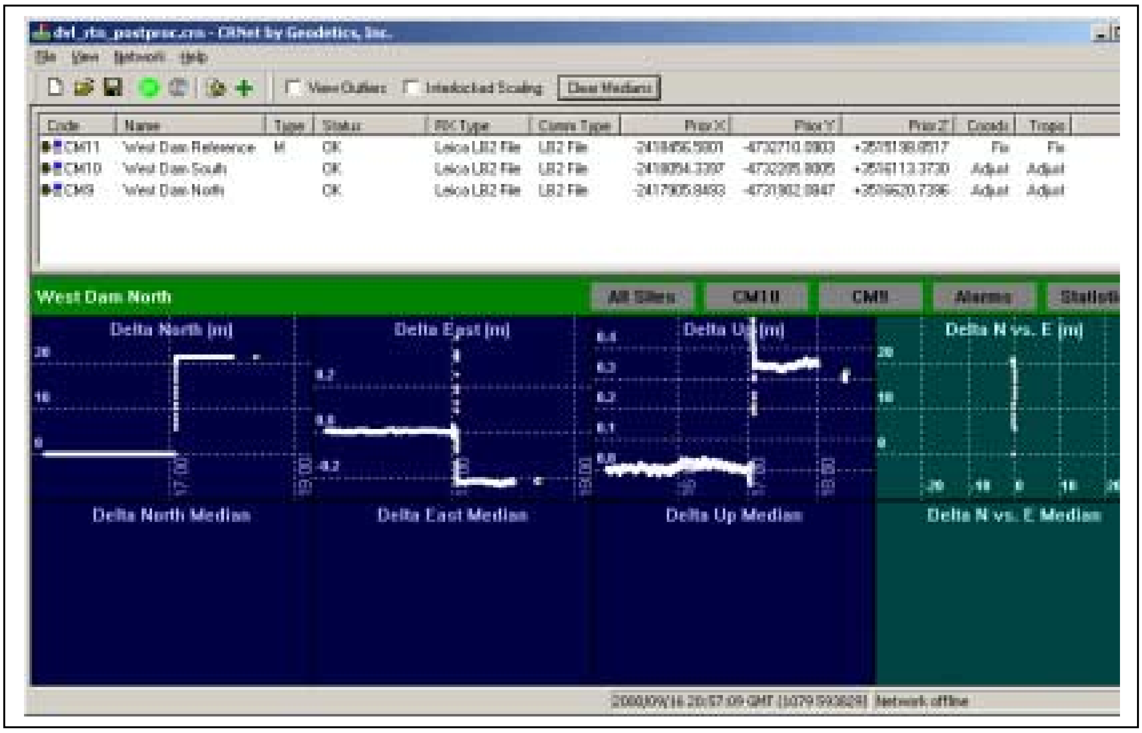

Figure 5. CRNet screen shot of the single-epoch solutions for the motion test at Diamond Valley Lake. The plots show the site positions for site West Dam North relative to its nominal a priori coordinates (prior to moving the antenna), in terms of local North, East, Up, and North vs. East components. The motion of the antenna between the two pillars covered about 20 meters and occurred in a primarily Northerly direction as seen in the left- and right-most panels. The motion in the Up component is quite instructive and illustrates the power of the technique. Here is the sequence of events. The surveyor approached the geodetic pillar (West Dam North) and disconnected the antenna cable as indicated by the small increase in scatter in the Up component and the subsequent data gap. The surveyor then raised the antenna off the pillar and an assistant reconnected the antenna cable. The surveyor then raised the antenna over his head and moved it about 20 meters to the North. The antenna was then lowered and placed atop the second geodetic pillar but not tightened down onto its base. About 20 minutes later the antenna cable was again removed (see second data gap) and the antenna was rotated onto its base until secured (see the slight decrease in Up component after the second data gap).

5. Assesement of Longer-Term Precision

Under normal tracking conditions, using the GPS broadcast ephemeris, and using the ionosphere-free linear combination of L1 and L2 phase ("LC" or "L3"), the coordinate precision (one-sigma) obtained routinely at Diamond Valley Lake is illustrated in Figure 6. For the intervals longer than a single epoch, the position coordinates are determined as the median value of all single-epoch positions within the interval excluding position coordinate outliers. Outliers are defined as 3 times the IQR. CRNet also computes a median value for each 24-hour period and calculates a trend through the 24-hour medians. In Figure 7 we show the median values over a 5-week period for one of the sites.

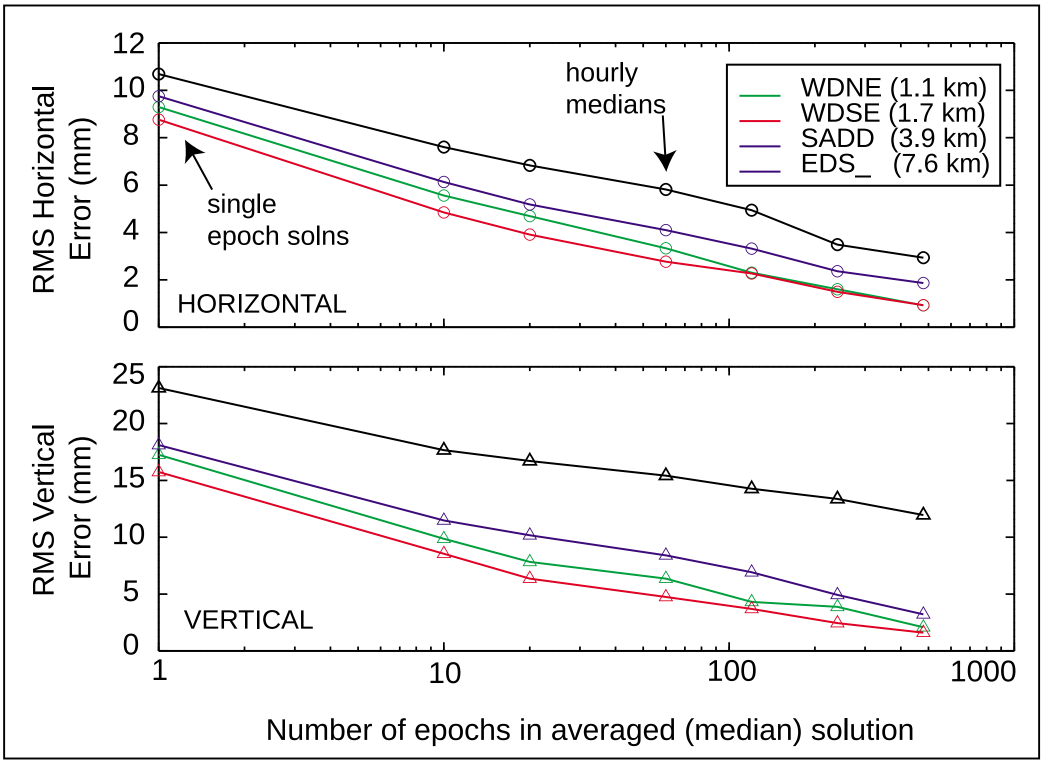

Figure 6. Typical precision versus temporal resolution (averaging time) based on analysis of data of day 194, 2000 at Diamond Valley Lake. Coordinates of four sites were obtained by solving for the geometry of the entire network, fixing just one station (the reference station WDR) to its prior coordinates. The semi-log graphs show the relationship between the scatter of the single-epoch and multi-epoch solutions and averaging time. For the intervals longer than a single epoch, the position coordinates are determined as the median value of all single-epoch positions within the interval excluding position coordinate outliers. Outliers are defined as 3 times the IQR. Note that coordinate scatter varies approximately in inverse proportion to the logarithm of averaging time. Also note the dependence of precision on baseline length. By averaging static solutions over longer periods of time, the precision of the resulting solution is improved but at the cost of poorer temporal resolution. (Adapted from Figure 3 of de Jonge et al., 2000).

6. Discussion

The results presented in the pervious section are based on a full, single-epoch, simultaneous network analysis of all 7 Diamond Valley Lake sites, with one or two reference stations (West Dam Reference and East Dam Reference) fixed to their a priori coordinates. Currently, the network is analyzed with West Dam Reference fixed and East Dam Reference very tightly constrained (effectively fixed). Note that it is not necessary to apply tight constraints to East Dam Reference. It is sufficient only to fix West Dam Reference and let all other sites adjust freely (actually with very loose constraints).

Another approach would reduce the positional precision given above by a factor of about three in the horizontal and by a greater factor in the vertical, compared to the precisions presented in section 5. In this approach, the network is split into two sub-networks with short inter-station spacing (see Figure 2):

(1) West Dam Reference, West Dam North, West Dam South, Saddle Dam
(2) East Dam Reference, East Dam North, East Dam South

Then, each network is analyzed with two separate CRNet processes using the L1 and L2 phase measurements as independent observations. The differential tropospheric effects on these sub-networks would be negligible so it would not be necessary to estimate tropospheric delay parameters. This would further increase the precision of the vertical coordinates. In this approach, a third CRNet process could monitor the 8-km baseline between West Dam Reference and East Dam Reference for stability. This third process could be run simultaneously or less frequently. Although not yet implemented, sidereal-day averaging to reduce multipath and other site-specific errors can further improve single-epoch coordinate precision by about 50% in each component.

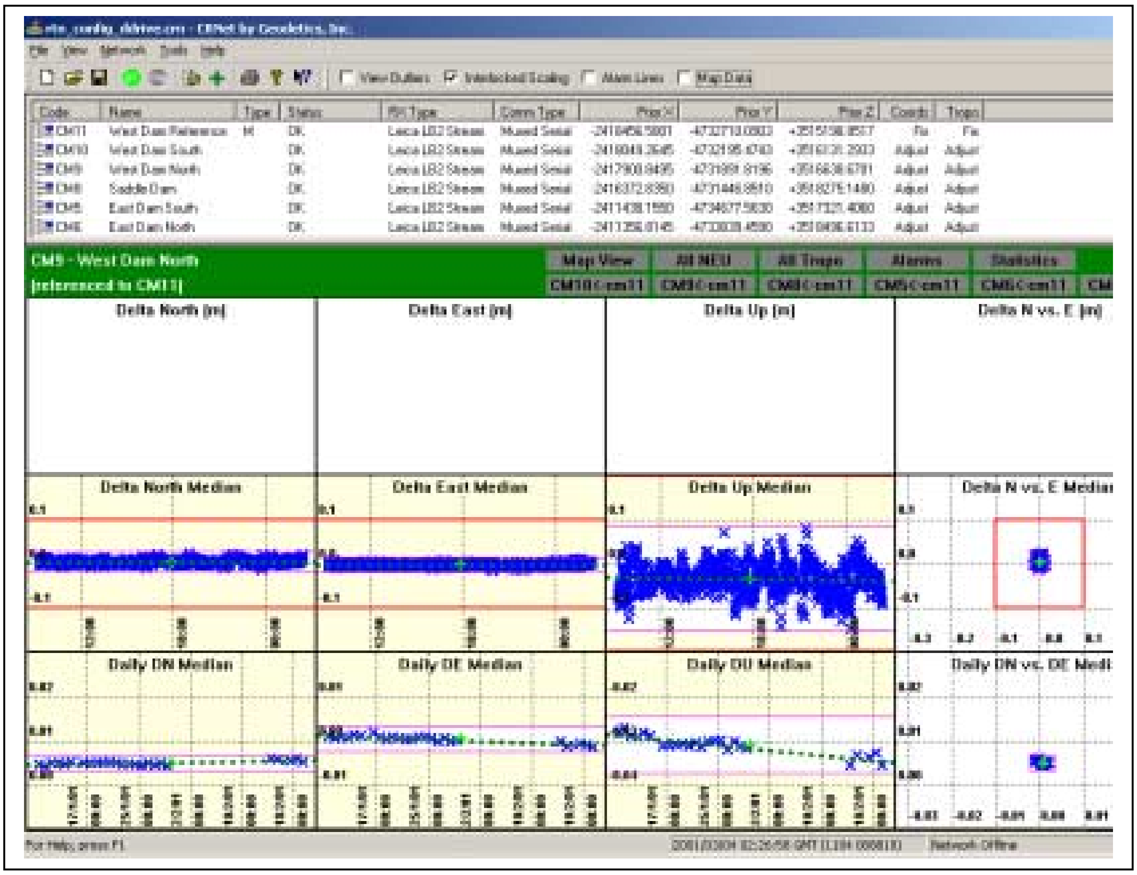

Figure 7. Time series of median values for the position of West Dam North. The middle plot frames shows the (1440) 1-minute medians for the last day in the series. Each 1-minute median is based on 30 single-epoch solutions with outliers excluded. The red bands denote the alarm threshold (10 cm in the horizontal components and 15 cm in the Up component). The lower plot frames show the time series of 24-hour medians over a five-week period (with a two week gap). Each 24-hour median is computed based on the 1440 daily medians. The pink bands indicate the outlier detection region (3 times the IQR). Note that the site has subsided by a total of about 20 mm and there is about a 0.2 mm/week drift in the East component over this period. Also, there is a constant bias of 5 mm in the North component relative to its original position when the site was first installed.

Acknowledgments

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