Instantaneous Network RTK Positioning in Regions of Active Deformation

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BIOGRAPHY

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ABSTRACT

Geodetics, Inc. has developed and implemented a universal approach to wide-area network RTK that provides precise, instantaneous (Epoch-by-Epoch™) positioning from multiple base stations, with a latency of about 1 second with existing wireless services. This approach has been successfully demonstrated in several geographical locations experiencing active tectonic and volcanic deformation including southern California, Japan, New Zealand and Sicily, and land subsidence in Venice, Italy and Orange County, California.

In this paper, we address two issues involved in providing precise network RTK services in areas of active ground deformation. First, the RTK base network coordinates evolve with time. The Geodetics RTD server, which controls the base network and supplies network RTK base station data, monitors the network geometry on an Epoch-by-Epoch™ basis and monitors any changes in base station coordinates due to deformation or station degradation. One of the base stations is held fixed, with respect to which the coordinates of the remaining stations are estimated. The RTD server is being upgraded so that a model for the motion of the Master (and other stations) will be able to be specified by the network operator. The model contains site velocity, known offsets (due to coseismic deformation, for example), and seasonal effects. Not taking into account significant deformation of the base network will eventually degrade the quality and accuracy of RTK positions.

The second issue relates to network RTK clients, and the choice of datum with respect to which coordinates are specified. GPS orbits (broadcast and precise) are provided with respect to the International Terrestrial Reference Frame. ITRF coordinates of any site on Earth are changing significantly due to tectonic plate motions. However, in surveying practice, coordinates are referred to a static geodetic datum, and often to local datums. The outstanding question for wide-area network RTK is how to take advantage of the natural GPS reference frame provided by ITRF, and still provide support for traditional geodetic practices.

INTRODUCTION

Regional-scale precise continuous GPS (CGPS) networks are being deployed for two primary geodetic purposes: in the last 2-3 years for active (real-time to near-real-time) geodetic control and since the early 1990's for crustal deformation monitoring at tectonic plate boundaries. Only recently have these two functions begun to overlap, but slowly. For example, the U.S. Plate Boundary Observatory is in the process of deploying 850 new CGPS stations in the tectonically-active Western U.S. (including Alaska), and absorbing over 200 stations from existing networks in the region including AKDA (Alaska), BARD (northern California), BARGEN (Basin and Range), EBRY (East Basin and Range and Yellowstone), PANGA (Pacific Northwest), and SCIGN (southern California). The current PBO plan (http:// http//pbo.unavco.org/data/) is to download 15-second sampled data through commercial wireless providers on a daily basis, although there are also plans to collect data sampled 5 times per second (5 Hz) in a rotating buffer in these receivers, and to retrieve the high rate data after a large earthquake to support GPS seismology (*Nikolaidis et al*., 2002; *Larson et al*., 2004; *Bock et al*. 2004). Although there is a provision in the PBO plan to allow users with real time data needs to tap into the receiver's serial port and stream high rate data through user-provided communication channels, this is not currently considered a science priority by the EarthScope project (http://www.earthscope.org/). On the other hand, the SCIGN project (http://reason.scign.org) is in the process of upgrading its 250+ sites to real time (< 1 s latency) high rate (1 Hz – one sample per second) operations for the purpose of seismic early warning, damage mitigation, and to increase sensitivity to transient motions. Several southern California counties (Orange, Riverside, San Diego, Imperial), the U.S. National Geodetic Survey (though the California Spatial Reference Center), the Metropolitan Water District of Southern California, and NASA are supporting this effort to ensure that wide-area network RTK support for non-scientific positioning and navigation applications will also be routinely available. In Japan, one of the most damage-prone countries from seismic and volcanic events, the national GEONET project (http://www.gsi.go.jp/) has deployed 1200 CGPS stations and most of these have been converted recently to real time high-rate (1 Hz) operations, which are able to support real time data users. In New Zealand, another nation straddling an active tectonic plate boundary, the nation-wide GeoNet project (http://www.geonet.org.nz) established for geological hazards monitoring is evaluating wide-area network RTK support, together with Land Information New Zealand (http://www.linz.govt.nz).

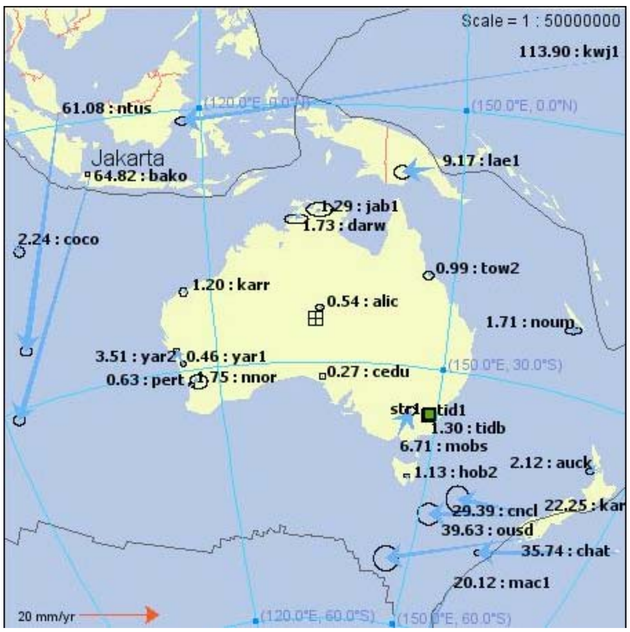

Figure 1a. ITRF2000 velocities of stations with respect to the Australian plate. The magnitude of the station velocities is given in mm/yr to the left of the four-character station code. Since the Australian continent is part of the rigid Australian plate, a reference frame for a wide-area network RTK system in Australia could be defined with expected relative station motions only at the mm/yr level. However, station velocities of stations in neighboring countries are in the range of 20-114 mm/yr, with respect to the Australian plate. Error ellipses are 95% confidence.

Providing geodetic control has always been a challenge in the presence of crustal deformation. The geophysicist is interested in quantifying and modeling deformation (changes in coordinates) from the global to the local scale, while the surveyor and national geodetic organizations are mostly interested in stationary station coordinates. For the surveyor, monitoring is local, for example dam and bridge deformation where the assumption is that stable reference stations are easily within reach of the targeted infrastructure. For the geophysicist, a stable reference frame is often on the scale of rigid tectonic plates. Even this is problematic for the North America plate, for example, which is affected by broad regions of global isostatic adjustment (post-glacial rebound).

Wide-area network RTK has been based on the assumption that the base stations are stationary, so that regional systematic errors such as satellite orbits, tropospheric refraction, and ionospheric refraction can be modeled and transmitted to users for efficient and precise longer range surveys than possible with traditional single-base RTK. This assumption is violated in areas of active deformation. For example, SCIGN's first real time high rate effort was in Orange County (*Andrew*, 2003). The county sits on a mostly non-deforming tectonic block on the Pacific plate side of the North America – Pacific plate boundary in southern California, and therefore the county's surveying office can maintain a "static" internally consistent horizontal datum. However, large areas of Orange County and neighboring LA County are subject to seasonal and secular groundwater-induced deformation (*Bawden et al*., 2000; *Watson et al*., 2002) that introduces systematic errors for network RTK users.

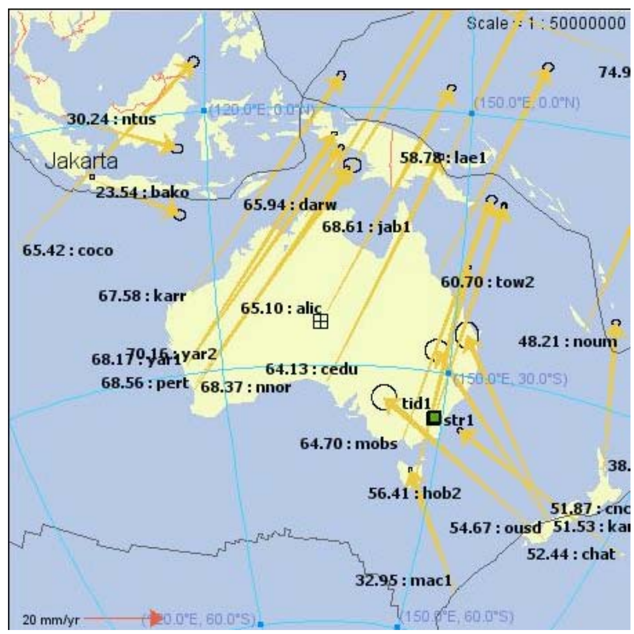

Figure 1b. Absolute station velocities with respect to ITRF2000. A reference frame for a wide-area network RTK system in Australia could still be defined with expected relative station motions at the mm/yr level, but the large absolute motions could be taken into account by assigning *a priori* station velocities to base stations. Neglecting the large absolute station velocities of order 55-70 mm/yr will result in a growing discrepancy with precise satellite orbits based on ITRF2000.

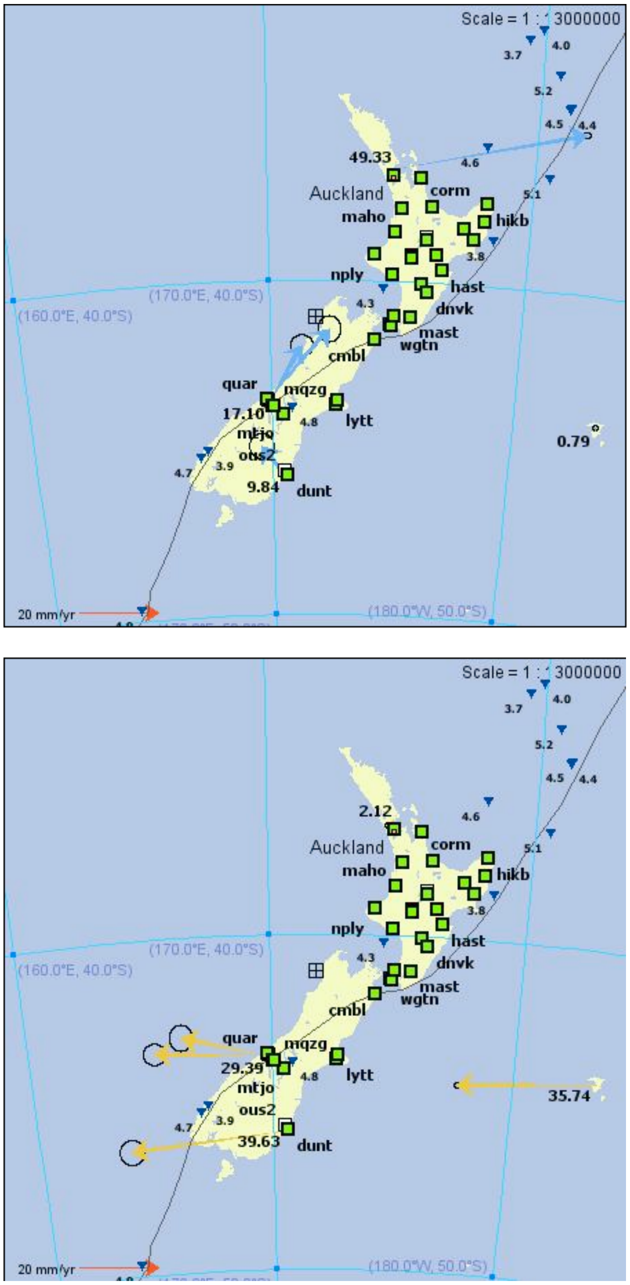

Figure 2. Upper Panel. ITRF2000 velocities of New Zealand GeoNet stations with respect to the Pacific plate. **Lower Panel.** ITRF2000 velocities of New Zealand GeoNet stations with respect to the Australian plate. The magnitude of the station velocities is given in mm/yr to the left of the four-character station code. Error ellipses are 95% confidence. A reference frame for a wide-area network RTK system for GeoNet would have to take into account up to 50 mm/yr relative site motions (see also Figure 7), as well as 50 mm/yr absolute motions with respect to ITRF2000 (see Figure 1b).

There is a subtler problem in defining a "fixed" reference frame for CGPS regional networks. GPS precise ephemerides (precise to ultra-rapid) provided by the International GPS Service (IGS) and its global analysis centers are tied to a GPS realization of ITRF2000 that adopts coordinates and velocities for about 100 global tracking stations, with respect to an arbitrarily chosen time epoch. The velocities are necessary to account for global plate tectonic motion. Thus, the GPS datum is a global one and is time variable, so that all CGPS base stations have changing coordinates with respect to the ITRF. The GPS broadcast ephemeris is tied to an older version of the International Terrestrial Reference Frame (ITRF96). On the other hand classical geodetic datums are static. For example, the current GPS datum in the U.S. is NAD83, defined by the origin, orientation, and size and shape of a reference ellipsoid (WGS84) that differs significantly from the ITRF in terms of origin and orientation. For surveying applications in countries lying on stable tectonic blocks (e.g., Australia), it is possible to maintain a classical geodetic datum and maintain internal consistency since the relative positions of stations remains constant. However, the deviation of static GPS coordinates from ITRF will quickly grow (e.g., in Australia at a rate of 60-70 mm/year) (Figure 1). Of course, further complications arise for regions straddling plate boundaries (e.g., California, Japan, and New Zealand) where the CGPS networks are also deforming internally at rates of 50 mm/year (Figure 2).

RTD MONITORING FUNCTIONS

The Geodetics RTD software suite has been designed to simultaneously monitor deformation (changes in the relative positions of the base stations) and serve data for Epoch-by-Epoch™ wide area network RTK. The reference frame of choice for RTD analysis is ITRF (*Altamimi et al.*, 2002) although conversion to geodetic datums is also supported. All internal calculations are performed with respect to an Earth-centered, Earth-fixed (ECEF) Cartesian system (X, Y, Z), preferably ITRF, to ensure consistency with the input GPS orbits (broadcast or precise), which are not adjustable parameters in RTD.

At the network configuration stage, the user assigns *a priori* station coordinates for each station and inputs the metadata (e.g., antenna height/eccentricity, antenna type, antenna phase center model) that uniquely describes the geodetic reference point for each station. RTD users can import antenna model files using the standard adopted by the IGS and supported by the U.S. National Geodetic Survey (http://www.ngs.noaa.gov/ANTCAL/). The *a priori* coordinates of the stations are assigned two levels of constraints as described below. The user assigns one station as the "Master" with respect to which the coordinates of all the other stations are estimated. In non-dynamic applications (an RTD network can be fully in motion), the *a priori* coordinates of the Master station are either assigned to be fixed or tightly constrained to their *a priori* values.

RTD performs instantaneous (Epoch-by-Epoch™) network positioning in a two-stage estimation process, independently at each observation epoch. At the first stage ("float" solution), relative station positions, per-station zenith-delay troposphere parameters, and (double-difference) phase ambiguity parameters are estimated, and the phase ambiguities are resolved to their integer values. In the second stage ("fixed" solution), the station positions and per-station zenith delay parameters are estimated with the phase ambiguities fixed at their integer values. At the first stage, the user assigns station coordinate constraints (called "advanced" station constraints in RTD), to aid in ambiguity resolution. For networks with inter-station spacing of up to several 10's of kilometers station constraints can be assigned loosely (1 m or greater in each component – the default advanced constraints in RTD are 100 m in each coordinate), and therefore changes in network geometry due to deformation or station problems are easily detected. As inter-station spacing increases progressively tighter advanced station constraints can be applied. *A priori* constraints on the order of an LC (ionosphere-free) wavelength of 10 cm can be used to resolve phase ambiguities on an Epoch-by-Epoch ™ basis for station spacing of 100 to 200 km. Once phase ambiguities are resolved there is no longer a need (or benefit) to apply station constraints (beyond the 100 m default) in the second stage. *That is, the RTD server then provides an independent minimally constrained network adjustment at each observation epoch.* See Figures 3-5 for an example of a long-lived dam monitoring project in seismically active southern California (total plate motion across the 200 km wide Pacific-North America plate boundary in this area is about 50 mm/yr and magnitude 7 earthquakes can cause up to several meters of deformation).

Assigning *a priori* (preferably ITRF) station coordinates and accurate metadata is an important step for both monitoring and serving applications. For a new network configuration, the RTD user is recommended to:

(1) Collect (with RTD) at least 3 consecutive days of 24-hour RINEX files for all network stations, ensuring that accurate metadata have been assigned for each station.

(2) Submit RINEX files to an ITRF positioning service such as SOPAC's SCOUT utility (http://sopac.ucsd.edu/scout), JPL's Auto-GIPSY point positioning (http://gipsy.jpl.nasa.gov/orms/goa/), or NGS' OPUS (http://www.ngs.noaa.gov/OPUS/) utility. Compute mean coordinates for each station and assign the epoch date at the mid-day.

(3) If available, assign a velocity for each station. This is straightforward, for example, for CGPS stations that have a long history of operations. If not, one could use a plate motion model (if the station is on a rigid plate – see for example *Prawirodirdjo and Bock*, 2004), or a velocity model for stations at plate boundaries such as the NGS HTDP program for the U.S. (http://www.ngs.noaa.gov/TOOLS/Htdp/).

(4) Periodically, submit RINEX data from the Master station to an ITRF coordinates generator as a check. The relative motion of the other stations with respect to the Master station as described previously are monitored by the RTD server (but can also be checked periodically with an ITRF coordinates generator). As more data are collected it is possible to iteratively refine the motion model from the RTD solutions for all or a subset of the stations.

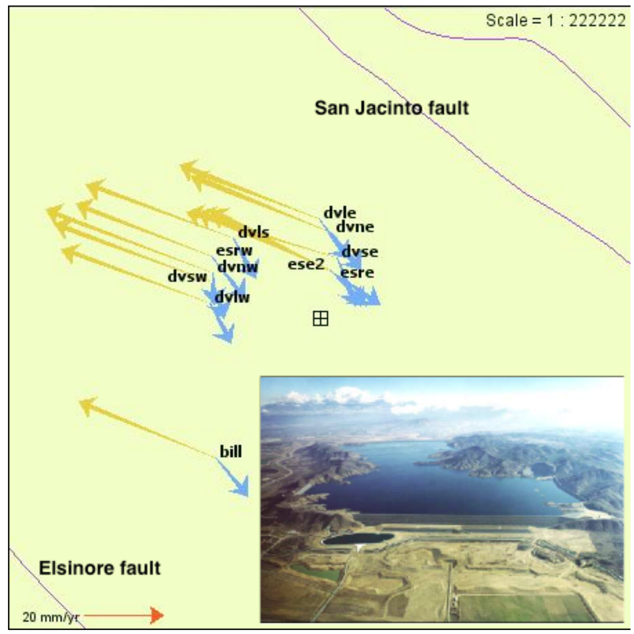

Figure 3. Dam monitoring network at Metropolitan Water District's Diamond Valley Lake (*Duffy et al*., 2001). Building three earthen dams created the lake: the West Dam (see stations DVNW and DVSW), East Dam (stations DVNE and DVSE), and Saddle Dam station DVLS). SCIGN stations DVLW, ESRW, DVLE, and ESE2 are on stable locations. The longest distance is 7.9 km. The dam is situated between the Elsinore and San Jacinto faults, so that seismic risk is a major concern. Site velocities and magnitudes are shown with respect to ITRF2000 (yellow vectors) and the Pacific plate (blue vectors), based on a SOPAC analysis. Site BILL is a nearby SCIGN station. These stations will also used for network RTK positioning by MWD survey crews. Picture inset (view of West Dam and Diamond Valley Lake).

Geodetics is upgrading RTD to allow for input of an *a priori* model of station motion, including station velocity, annual and semi-annual motions, coseismic (and other) offsets, and postseismic deformation as outlined by *Nikolaidis* (2002) and implemented in SOPAC's SECTOR utility (http://sopac.ucsd.edu/sector).

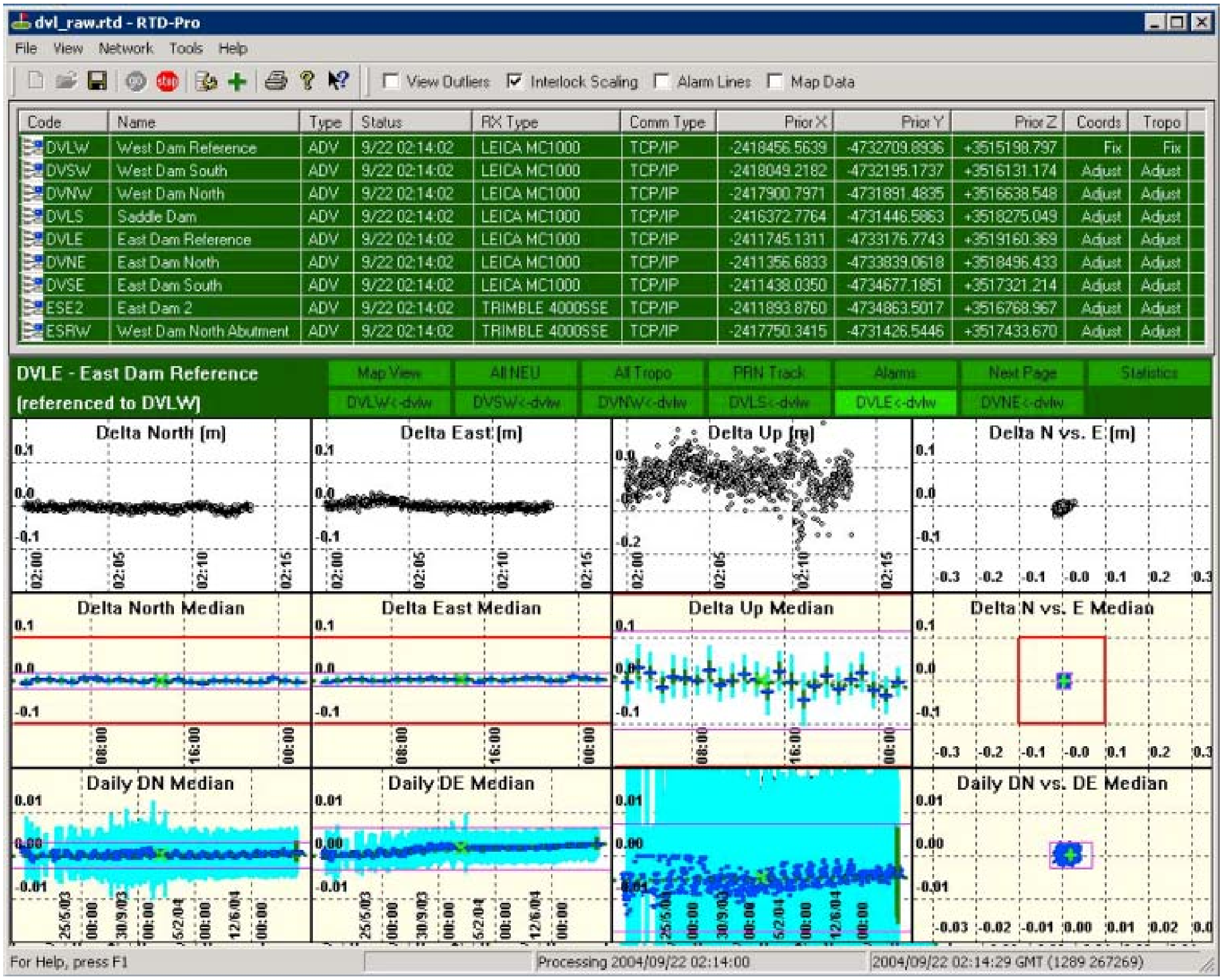

Figure 4. RTD screen shot for Diamond Valley Lake monitoring from March 2003 to September 2004. The Master Station DVLW has its *a priori* station coordinates and troposphere delays fixed. The other stations (the stable reference stations and the dam stations) are free to adjust with advanced constraints of 100 m in each coordinate at the “float” stage, and constraints of 100 m at the “fixed” stage. The upper plots are the most recent instantaneous positions for reference station DVLE, each one independently estimated. The middle plots are the most recent hourly medians. The lower plots are the daily medians. The vertical scales are in meters. Although the station is not expected to move, it is left free to adjust in order to provide a check on the stability of the reference stations and the quality of their data.

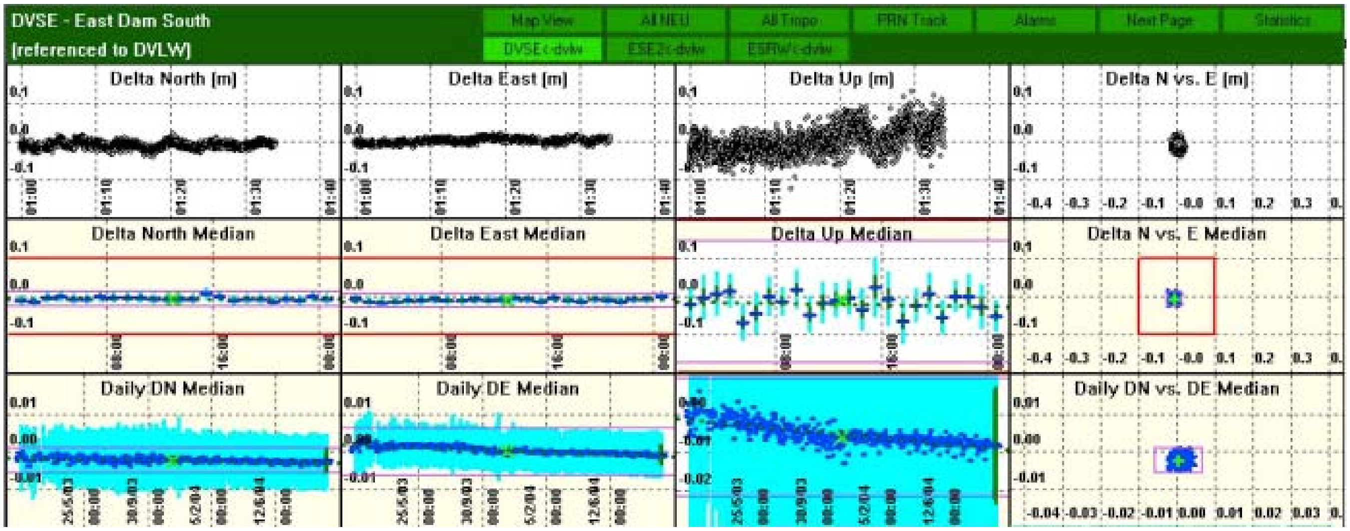

Figure 5a. Same as Figure 4a but the three series of plots are for station DVSE on the southern end of the East Dam. Note that the horizontal components are stable, but the vertical component shows a clear settling of the dam in the vertical by about 10 mm over the first 7 months followed by a 7-month stable period. See blowup below.

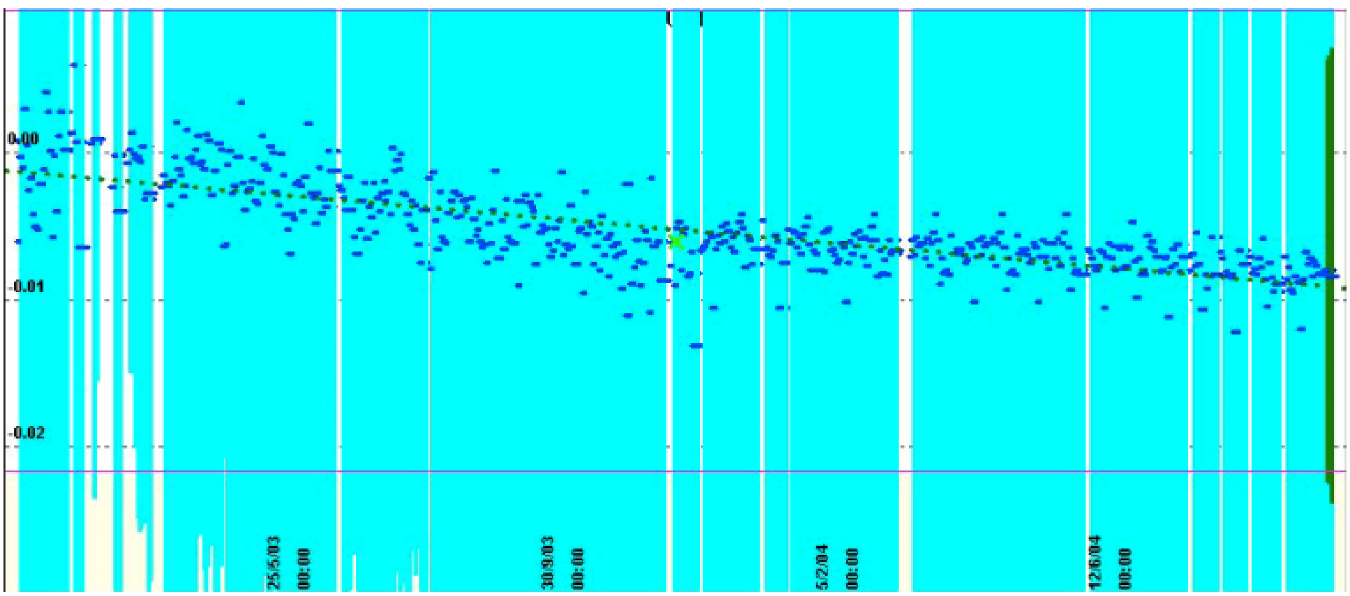

Figure 5b. Blowup of the vertical coordinate changes as seen in the daily medians for station DVSE. Vertical scale is in meters.

RTD SERVER FUNCTIONS

The RTD server can provide base station data to support wide-area network RTK, while monitoring changes in base station positions (i.e. deformation). RTD is programmed to transmit the *a priori* base station coordinates, so as to maintain a consistent reference frame for the RTK user. In this sense, deformation monitoring and network RTK service are kept distinct. The RTD server also supports the "RTD Rover" a client PDA application that can be used to position instantaneously a roving (static or dynamic) GPS unit with respect to multiple base stations (*Bock et al*., 2003). The RTD Rover controls the local receiver, captures its raw GPS data, and performs a network RTK solution independently for each observation epoch at the receivers' sampling rate (Figure 6). The RTD server can also be instructed to transmit the instantaneous positions of the base stations through a single IP connection. Finally, the RTD server supports "RTD Guests." In this instantaneous reverse RTK mode the local receiver's raw data are transmitted to the RTD server, its coordinates are computed at the server with respect to multiple base stations and then transmitted back to the user.

In support of RTD Rover, the base stations' raw data, the *a priori* coordinates, and optionally the precise ephemeris are transmitted through a single IP port to the PDA application. The RTD Rover assigns very tight constraints to the transmitted base station coordinates for both the "float" and "fixed" solutions. *That is, the RTD Rover provides an independent overly constrained network adjustment at each observation epoch.* By transmitting *a priori* absolute ITRF positions and velocities for the base stations at the server end and requesting IGS-supplied precise ephemeris to be sent to RTD Rover clients, Epoch-by-Epoch™ coordinates are consistently estimated with respect to ITRF. These are "true" instantaneous coordinates in the sense that they refer to the actual time epoch of the observations.

The user can then convert the ITRF station coordinates to another datum (e.g., NAD83) through standard transformation tools supplied with PDA software, for example, RTD Rover algorithms have recently been integrated with Carlson SurvCE (surveying application) software. A velocity model for the region spanned by the base station network can also be generated through interpolation (e.g., least squares collocation) and/or in combination with crustal motion models (e.g., the NGS HTDP program, New Zealand velocity model – Figure 7) so that the true coordinates can be converted to earlier epoch dates. For example the CSRC and NGS have specified an epoch coordinate date of 2004.0 for all CGPS stations in California (http://csrc.ucsd.edu/cdp/), at which ITRF2000 station coordinates and velocities are given for each station. Once at the earlier epoch date, coordinates can then be transformed to another datum through the appropriate transformation parameters.

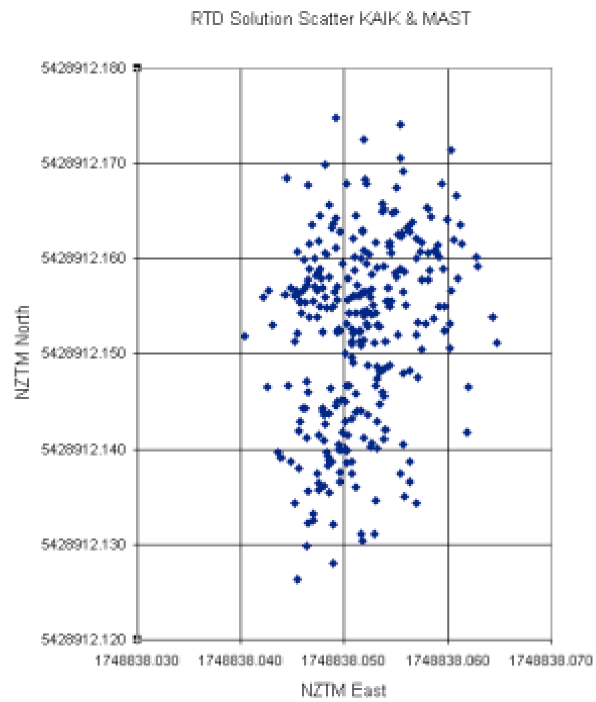

Figure 6. Result of an RTD Rover test in New Zealand. The RTD server was set to transmit ITRF2000 true coordinates for the GeoNet stations (see Figure 2). The RTD Rover collected 1-second data from two base stations, Masterton at a distance of 70 km, and Kaikaroa at a distance of 150 km. The Epoch-by-Epoch™ rover positions over this 5-minute period have a (min-max) spread of 5 cm in the north component and 2.5 cm in the east component, with an rms of 0.5 cm and 1.1 cm, respectively. (Courtesy of Graeme Blick, Land Information New Zealand).

CONCLUDING REMARKS

The Geodetics RTD software suite provides instantaneous wide-area network RTK functionality while simultaneously monitoring base network deformation, from high-frequency station changes due to, for example, seismic events to longer-period plate boundary motion and seasonal subsidence effects. It is recommended that Epoch-by-Epoch™ positioning be performed with respect to true ITRF coordinates, and as a final step (at both the server and client ends) to transform to epoch date coordinates, and then to a geodetic or local datum.

RTD also has the option to retrieve in real time ultra rapid precise satellite ephemerides (48-hours orbits published every six hours, with a lag of about 4 hours) from the IGS Central Bureau (http://igscb.jpl.nasa.gov/) or more rapid orbits from individual IGS analysis centers. RTD also has the capability to accept real time troposphere-delay models and/or ionosphere delay models, although these are not yet readily available. Real time troposphere zenith-delay models are useful to improve instantaneous vertical coordinate precision, by reducing the well-known correlations among vertical coordinates, multipath, and zenith-delay parameters (e.g., *Bock et al*., 2000). Real time ionosphere models should allow instantaneous ambiguity resolution over longer distances and the relaxing of advanced station constraints during the ambiguity resolution process.

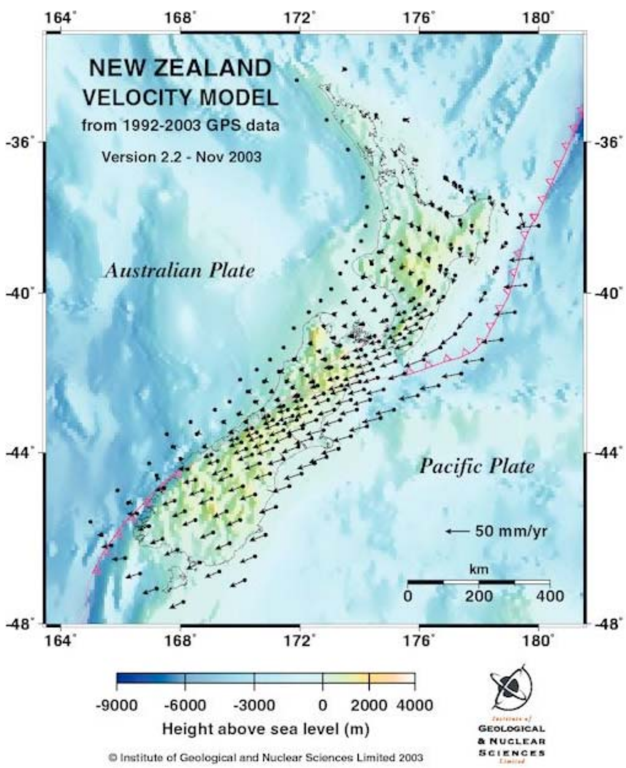

Figure 7. New Zealand station velocity model Version 2.2 based on GPS data collected from 1992-2003. This type of model can be used to convert true coordinates estimated with respect to the GeoNet base stations (see Figure 2) by instantaneous network RTK positioning to a well-defined earlier (or later) epoch date. (Courtesy of John Beavan, Institute of Geological and Nuclear Sciences, New Zealand).

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