Wireless Instantaneous Network RTK: Positioning and Navigation

Yehuda Bock, Paul de Jonge, David Honcik and Jeff Fayman, Geodetics, Inc., La Jolla, California

BIOGRAPHY

Dr. Yehuda Bock is President 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. Paul de Jonge received his Ph.D. in geodesy at the Delft University of Technology in the Netherlands, and held a postdoctoral researcher position at Scripps prior to joining Geodetics. He has been involved in GPS and other space geodetic techniques since 1987. Mr. David Honcik has 20 years experience in structured software design for applications including Windows programs, graphics, telecommunications, aerospace, flight simulation, and real-time embedded systems. Before joining Geodetics, Mr. Honcik consulted for a variety of companies including Microsoft and Qualcomm. Dr. Fayman holds a Ph.D. in Computer Science from the Technion, Israel Institute of Technology where he published over 20 papers in the academic literature in the fields of robotics, computer vision and computer graphics.

ABSTRACT

We describe a universal approach to network-based real time kinematic (RTK) positioning that provides precise, instantaneous (Epoch-by-Epoch™) positions from multiple base stations. We demonstrate this approach for the 10-station Orange County Real Time Network (OCRTN) in southern California, where distance to closest base station can range up to 35 km within the county. The flow of data is fully controlled by the Geodetics RTD (Real Time Dynamics) software. RTD also monitors the network's integrity and geometry Epoch-by-Epoch™ and allows the site coordinates to adjust to accommodate ground motion due to tectonic/seismic deformation and ground subsidence.

RTD establishes a server/client relationship with the Geodetics Smart Client, which resides on a Windows CE-based PDA. Unlike conventional network RTK, the positioning calculations are performed by the client and not in the receiver. Thus, it is a universal approach and compatible with any geodetic-quality GPS receiver. The client collects raw or RTCM data through a direct serial connection to the local receiver, and base station data from the server through TCP/IP. RTCM data from at least 3 (user-selectable) base stations can be acquired with current CDMA, GPRS or GSM wireless technologies at a receiver sampling rate of 1 Hz, and with a latency of 1 second. A streamlined data format can more than double the throughput.

At each observation epoch, the Smart Client performs an instantaneous rigorous network solution. Epoch-by-Epoch™ technology provides single-epoch initialization and re-initialization, compared to several seconds to several minutes for an ambiguity-fixed solution with conventional in-the-receiver RTK and other network-based solutions. We demonstrate that the precision (one-sigma) of a single-epoch position is less than 1 cm in the horizontal and 4-5 cm in the vertical. Precision and reliability can be improved by observing multiple epochs at a site, thereby averaging out multipath and related effects. We also demonstrate that the RTD/Smart Client combination is well suited to the navigation of dynamic platforms with respect to multiple base stations.

INTRODUCTION

Geodetics, Inc. has developed a new class of instantaneous, real-time precise GPS positioning and navigation algorithms, which we refer to as Epoch-by-Epoch™ [*de Jonge et al.,* 2000]. Compared to conventional RTK, integer-cycle phase ambiguities are independently estimated for each and every observation epoch. Therefore, complications due to cycle-slips, receiver loss of lock, power and communications outages, and constellation changes are minimized. There is no need for the initialization period (several seconds to several minutes) required by conventional RTK methods. More importantly there is no need for reinitialization immediately following loss-of-lock problems such as occurs when a mobile GPS receiver passes under a bridge or other obstruction.

Using robust quality control it is straightforward to detect and reject bad data points (outliers) due to, for example, severe multipath effects and poor satellite geometry. Typically outliers can range from 1-3 % of data collected. After outliers are excluded, site positions estimated from a set of multiple single-epoch solutions are usually more precise and reliable than conventional batch solutions. Our algorithms also allow for estimation of tropospheric refraction, and resolution of integer-cycle phase ambiguities over extended ranges (tens of kilometers) in the presence of typical ionospheric refraction [*Bock et al*., 2000]. Epoch-by-Epoch™ positioning provides a single-epoch accuracy of 5 mm in the horizontal and 10-20 mm in the vertical for local networks (less than 5 km), and 10 mm and 30-50 mm in the vertical for larger-scale networks. Furthermore, positioning is extremely efficient - a single epoch from a single baseline can be processed in several milliseconds on a typical CPU.

Figure 1. Orange County Real Time Network. SCIGN stations upgraded to real-time high-rate operations are denoted by blue diamonds and a 4-character site id.

In this paper we describe a new approach to network RTK that provides precise, instantaneous (Epoch-by-Epoch™) positions with respect to multiple base stations, with a latency of 1 second with existing wireless services. We demonstrate this capability using data from the 10-station Orange County Real Time Network (OCRTN) in southern California [*Andrew*, 2003] (Figure 1), operated by the County of Orange Public Facilities and Resources Division in partnership with Scripps Institution of Oceanography's California Spatial Reference Center (http://csrc.ucsd.edu) and the Southern California Integrated GPS Network (http://www.scign.org).

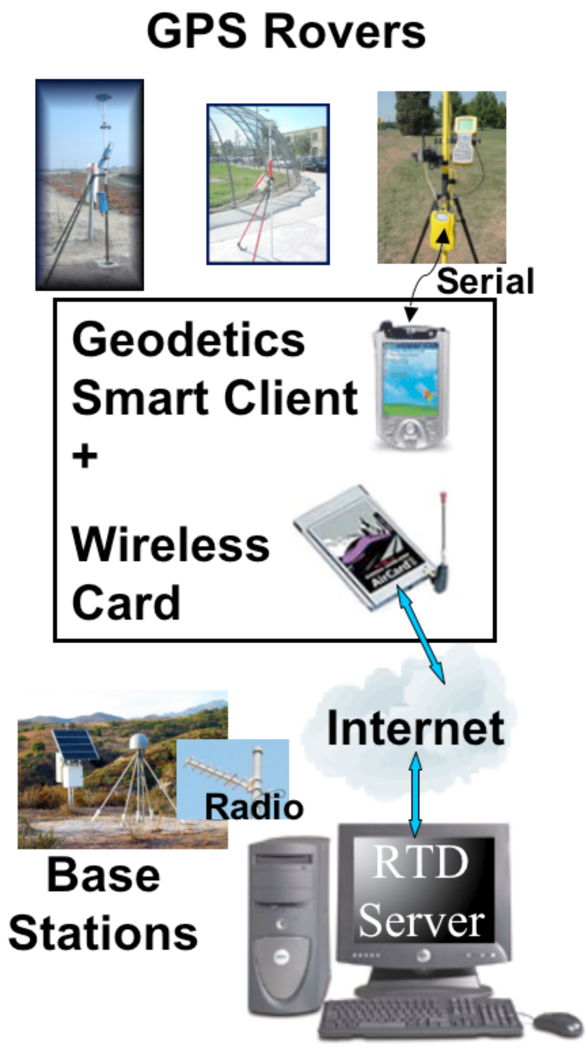

Figure 2. Schematic of the components required for wireless instantaneous network RTK using the Geodetics RTD Server and Smart Client software with wireless modem card.

RTD SERVER AND SMART CLIENT SYSTEM DESCRIPTION

The Geodetics RTD Server and Smart Client provide the necessary software for wireless instantaneous network positioning and navigation (Figure 2) in Orange County. The network is fully controlled by the Geodetics RTD software operating on a PC workstation. RTD handles data streaming, re-formatting, processing, archiving, and dissemination, and serves data though TCP/IP. The RTD server is unique in that it provides real-time data while monitoring the integrity and network geometry on an Epoch-by-Epoch™ basis, allowing site coordinates to vary with time.

RTD provides several TCP/IP-based client services (Figure 3) that relieve users of the time and cost of having to set up and maintain RTK base stations. The RTD server replaces the RTK base station and TCP/IP communications replace the limited-in-range, line-of-sight radio link between RTK base station and rover. OCRTN was designed to support existing RTK-enabled dual-frequency GPS receivers, within their current limitations as well as within the current limitations in the RTCM real-time data transmission formats. The main limitation is that current RTK receivers and real-time formats will only allow data from a single base station at a time. The system was also designed to minimize the start-up costs for a surveyor to use the system. The only extra costs incurred by a user are the purchase of a wireless modem and a subscription to a commercial cellular service.

RTD provides two types of servers to support conventional RTK positioning. The *Standard RTK Server* provides RTCM version 2.1 data messages (18, 19, 3 and 22) by assigning a unique port number to each site. Thus, the surveyor can choose any station in the network to serve as the base station. In this mode, the user can sequence between different sites to multiply-determine position, as a way of improving precision and reliability [*Andrew*, 2003]. Recognizing that the closest base station often provides the best solution, the *Enhanced RTK Server* provides RTCM data from the closest site in the network based on a NMEA position message sent by the field receiver to the server. In these two modes, the computations are performed in the field GPS receiver, using the embedded RTK algorithms, which vary from manufacturer to manufacturer, and between receiver models.

Ambiguity-fixed solutions require several seconds to several minutes in typical field operations using OCRTN, based on surveys conducted with several types of dual-frequency geodetic receivers with internal RTK capability [*Andrew*, 2003]. Distances from the closest base station can range up to 35 km in certain areas of Orange County (Figure 1), and there are periods of time when ambiguities cannot be resolved, with conventional RTK capabilities. Surveyors in Orange County avoid periods with less than 6-satellite visibility when using the standard RTD servers [*Andrew*, 2003].

RTD's *Smart RTCM Server* in combination with the Geodetics *Smart Client* overcomes the above stated limitations and provides instantaneous network RTK. In this mode, RTCM messages concatenated from a user-selectable number or list of base stations are provided through a single TCP/IP port. The messages use standard messages (18, 19, 3, and 22), as well as additional information in special RTCM message blocks. The Geodetics *Smart Client* software can decipher these messages and use Epoch-by-Epoch™ technology to determine the instantaneous position of the local receiver with respect to the chosen base stations. The *Smart Client* operates on any Windows CE platform, for example a PDA, equipped with a wireless modem card.

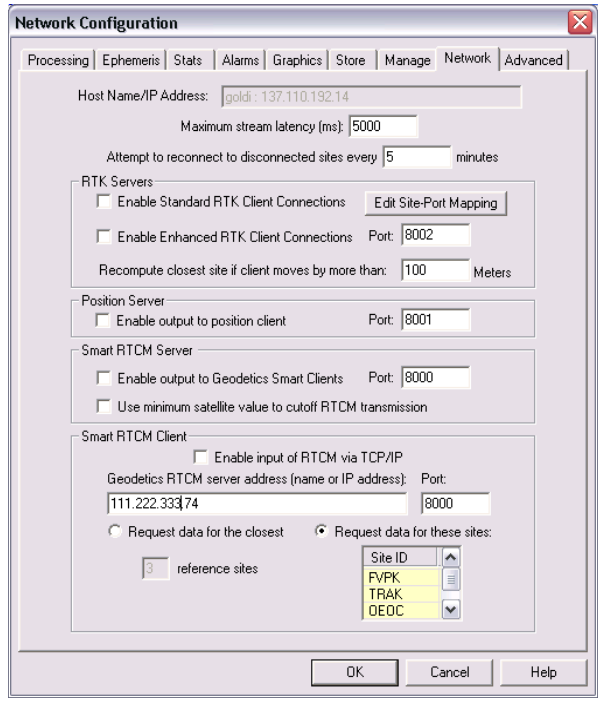

Figure 3. RTD server screen shot showing the various Server/Clients.

The Smart Client connects to the local receiver through a direct serial connection, and to the Smart RTCM Server through the wireless card. The receiver can be instructed to stream raw or RTCM data at a particular sampling rate (typically 1 Hz). The Smart RTCM Server can be instructed to stream data from the base stations closest to the rover, or from a specified set of stations. In either case, the user specifies a single IP and port number. The number of stations is limited only by the wireless bandwidth. From our experience in southern California, 1 Hz data from 3 base stations can be acquired with currently available CDMA-based wireless services. Recent tests in Japan indicate that at least twice as many base stations can be accessed using available GSM-based services. This additional bandwidth can be used to stream data at higher rates, which is advantageous for precise navigation of moving platforms.

Unlike conventional RTK, the positioning is performed by the Smart Client, not in the receiver, and is compatible with any geodetic-quality GPS receiver (RTK upgrade not required). At each observation epoch, the Smart Client calculates a precise position for the rover receiver based on a rigorous Epoch-by-Epoch™ network solution of the data from the base stations and rover station, hence *Instantaneous Network RTK*. This server/client relationship provides single-epoch initialization and re-initialization compared to several seconds to several minutes provided by conventional RTK algorithms.

While other network RTK solutions provide extended range compared to conventional RTK, they do not improve significantly the time to fix integer-cycle phase ambiguities. Compared to virtual network approaches, Smart Client uses unaltered RTCM data from real base stations, and (optionally) supplemented by network corrections transmitted in special RTCM message blocks. This avoids reference frame localization issues associated with virtual base stations. Network corrections are primarily intended to reduce ionospheric refraction effects that are the limiting factors for instantaneous ambiguity resolution at extended ranges [*Bock et al*., 2000]. Zenith delay parameters estimated as part of the Epoch-by-Epoch™ positioning algorithm reduce the effects of tropospheric refraction and improve vertical coordinate accuracy. The broadcast ephemeris is usually sufficient for most scenarios, but the Smart Client can also be programmed to retrieve precise real-time orbits through the wireless connection.

STATIC RESULTS WITH THE SMART CLIENT

We describe a three-day experiment during which a static receiver (SERV) in Costa Mesa (at the facility of Surveyor Service Company - SERVCO) was positioned once per second with the Smart Client, with respect to the three closest OCRTN base stations. Data communications were through a wireless link (Sierra Wireless AirCard 555, with CDMA 2000 technology and Verizon wireless service). The distances from the base stations were 4.6 km, 10.4 km, and 16.6 km, with the rover surrounded by base stations as shown in Figure 4.

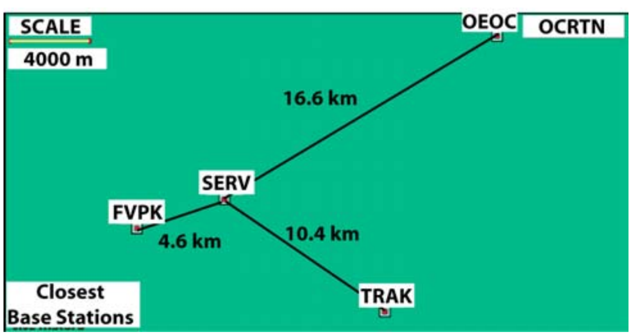

Figure 4. Geometry of Smart Client experiment where the RTD server chose the closest 3 base stations to station SERV.

RTD uses robust statistics (median and interquartile range – IQR, the range of the middle 50% of the data) to determine outliers. In this experiment the outlier criteria was 4 times the IQR (approximately 3σ if the single-epochs solutions were normally distributed). We chose the 5-satellite minimum for the number of simultaneously visible satellites required for a solution. Out of 86,400 possible epochs per day, there were less than 1% outliers on average and 1.6% outages (Table 1, Figures 5 and 6). The majority of the outliers, as expected, repeated from day to day (with a sidereal shift of 3 minutes, 56 seconds), and was primarily due to poor satellite geometry. The outages resulted from TCP/IP disconnects or dead wireless periods. Excluding the outliers, the standard deviation in the North, East and Up components of the field receiver coordinates was 7.0 mm, 5.5 mm, and 40.7 mm, respectively, for *one single-epoch solution*. Troposphere delay parameters were estimated every epoch at all 4 sites, which reduced the precision of the vertical component by at least a factor of two due to correlation between multipath, troposphere delay parameters, and the vertical coordinate, but should have improved its accuracy [*Bock et al*., 2000].

Table 1. Smart Client Demo: Closest Base Stations

Date	Sol-utions	Out-liers	Out-ages	σN (mm)	σE (mm)	σU (mm)
8/19	84341	948	2059	6.9	5.6	42.1
8/20	85145	836	1255	7.1	5.5	40.1
8/21	85607	636	793	6.9	5.3	40.0
Mean	85031 98.7%	807 1%	1369 1.6%	7.0	5.5	40.7

Further improvement in coordinate precision can be achieved by binning single-epoch solutions, i.e., collecting a longer interval of data on site. Improvements in precision for static platforms are degraded primarily by multipath whose main effects tend to average out after about 15 minutes of observation [*Bock et al*., 2000]. The standard deviations for a variety of site occupations ranging from 1 sec to 1 hr are shown in Table 2 below. In Figures 7 and 8, we display the solutions for 30-second and 1-hour survey intervals.

Table 2. Statistics for a variety of survey intervals

Interval	σN (mm)	σE (mm)	σU (mm)
1 sec	7.1	5.5	40.1
30 sec	6.4	4.8	35.8
1 min	6.1	4.6	34.8
2 min	5.7	4.2	33.1
5 min	4.8	3.8	27.2
10 min	4.5	3.6	22.4
15 min	4.1	3.1	23.0
30 min	3.0	3.2	21.1
1 hr	3.1	2.5	18.5

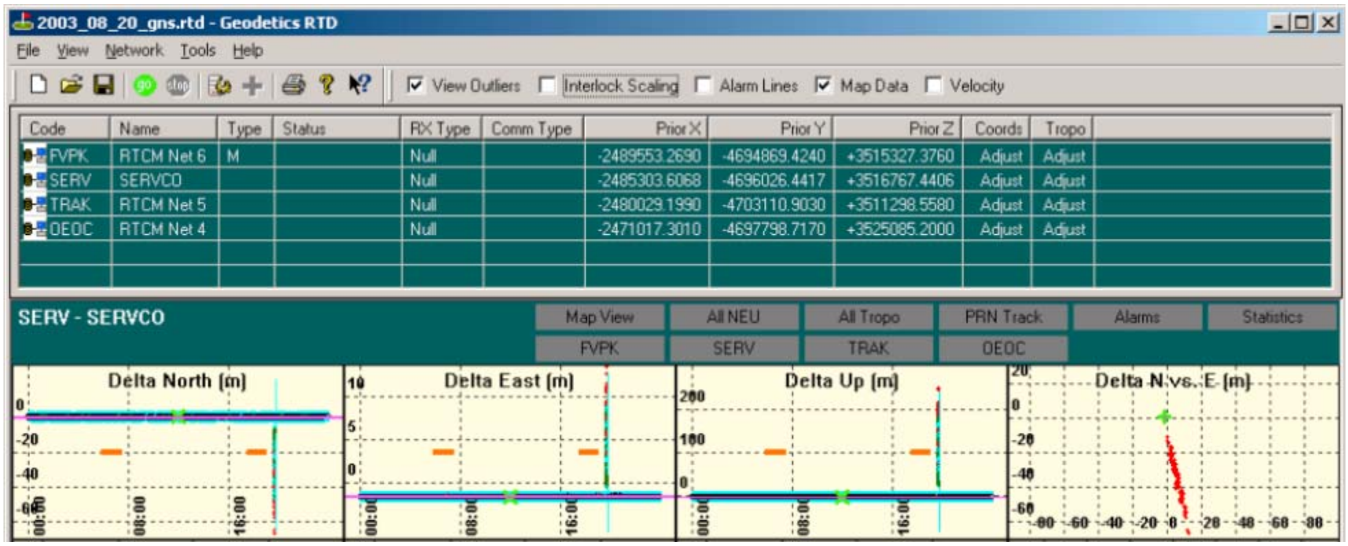

Figure 5. RTD screen shot showing all single-epoch solutions for rover SERV on August 20, 2003 with respect to OCRTN base stations FVPK, TRAK and OEOC (see Figure 4). The four plots (from left to right) show the Delta North, Delta East, Delta Up, and Delta North vs. East solutions (in units of meters), including two intervals of data outages due to communication problems (denoted by orange horizontal bars), and an interval of outliers (denoted by red points) due to poor satellite geometry. For the first three plots, the horizontal axis is in hours (0-24 hours GMT) and the vertical axis is in meters. For the fourth plot, both axes are in meters. Outliers are defined here as exceeding 4 times the interquartile range (IQR).

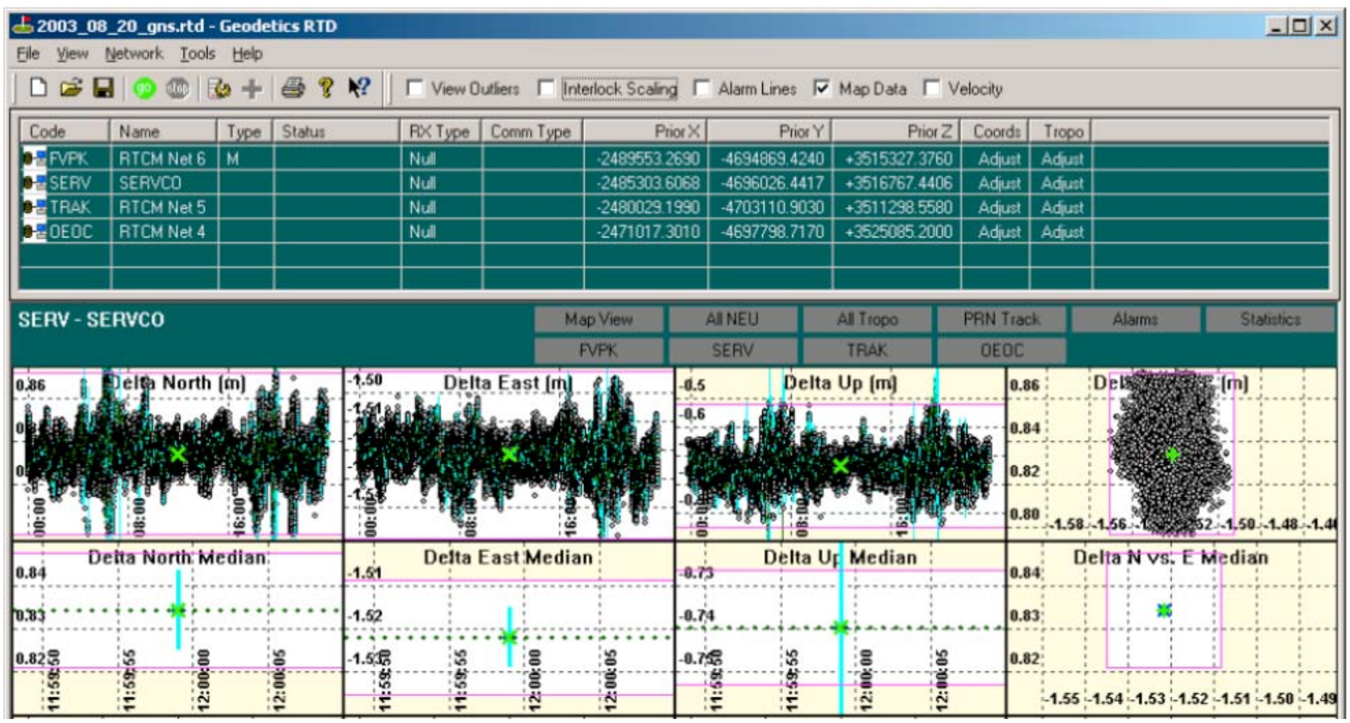

Figure 6. Same as Figure 5 but with outliers removed.

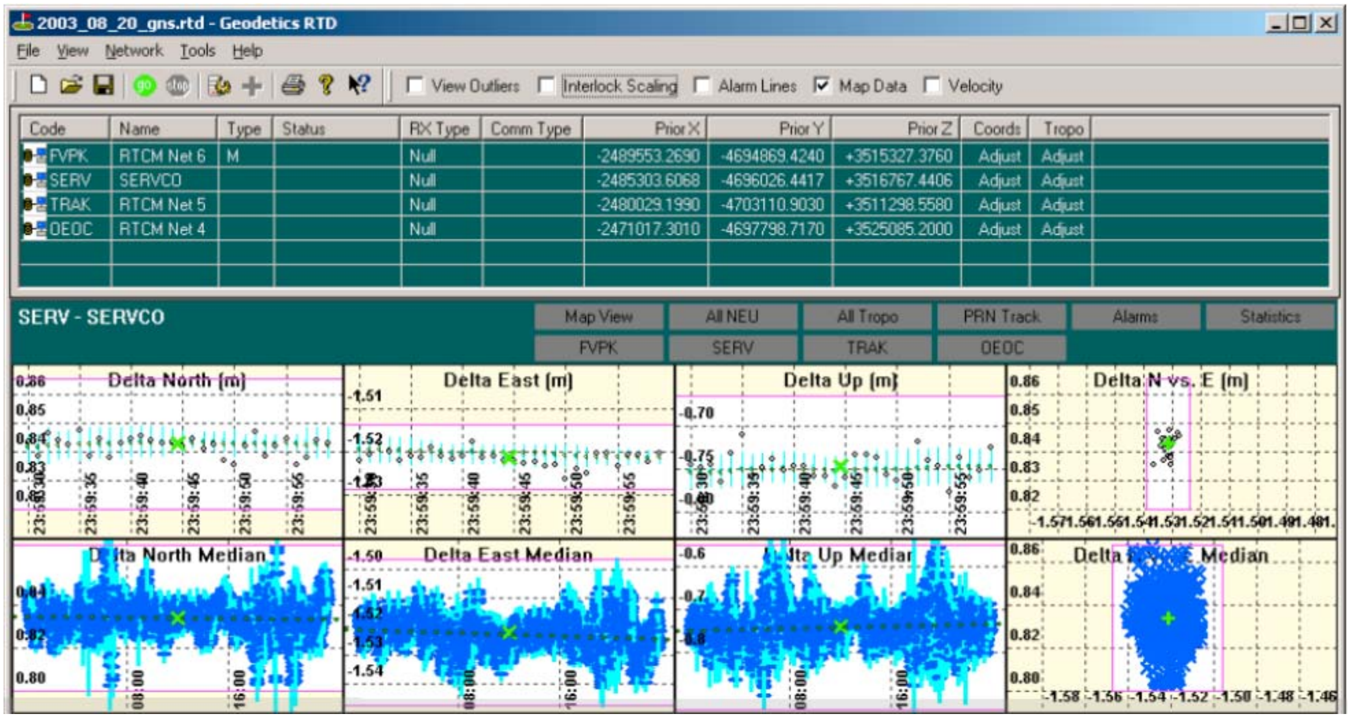

Figure 7. RTD screen shot showing 30-second median values for rover SERV on August 20, 2003 with respect to OCRTN base stations FVPK, TRAK and OEOC (see Figure 4). The first row of plots shows the Delta North, Delta East, Delta Up, and Delta North vs. East solutions (in units of meters) for the last 30 single-epochs solutions on that day. For the first three plots, the horizontal axis is in hours (0-24 hours GMT) and the vertical axis is in meters. For the fourth plot, both axes are in meters. The second row of plots shows the 30-second median values for the entire day. Medians are denoted by dark blue points, while the IQR's of the corresponding 30 single-epoch solution are denoted by light blue vertical bars.

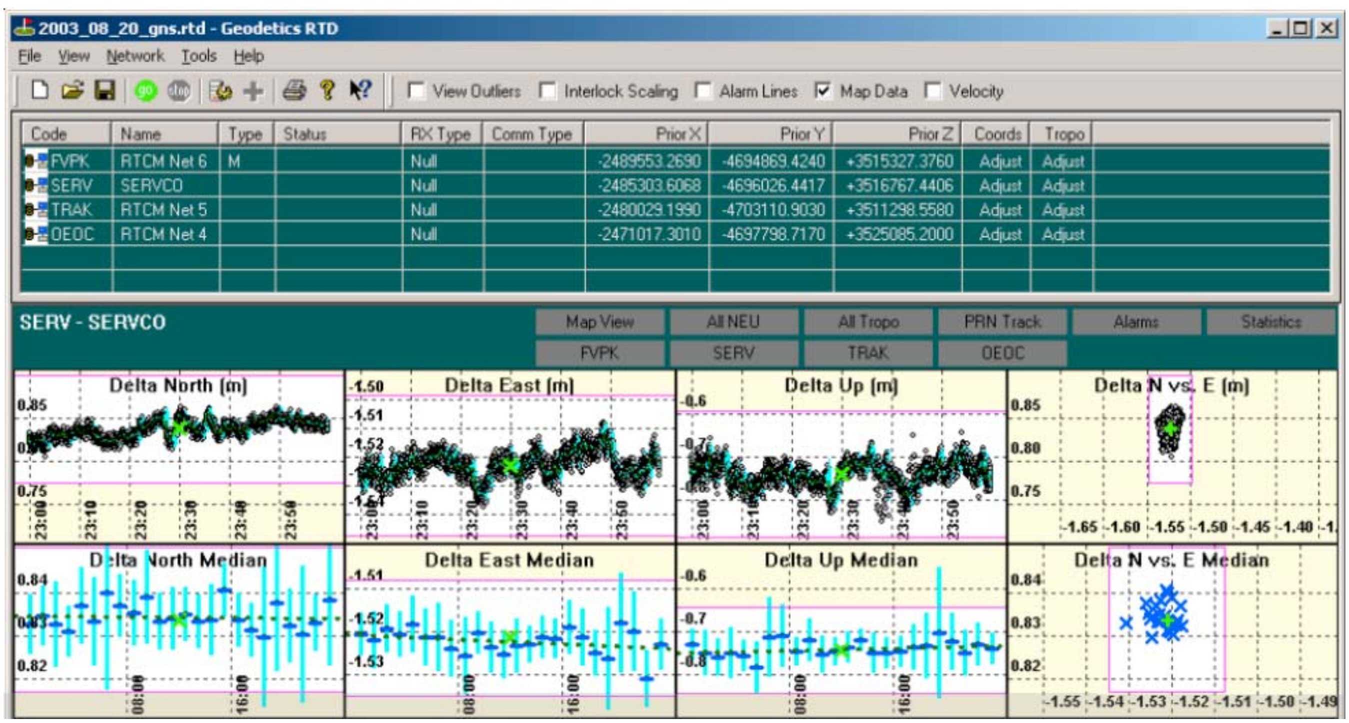

Figure 8. Same as Figure 7 but for 1-hour medians.

We tested the Smart Client at longer distances and less favorable geometry (Figure 9) by choosing three base stations in the network to the east of the field receiver, at distances of 16.6, 20.7, and 31.7 km, and collecting 2 days of data separated by 1 week.

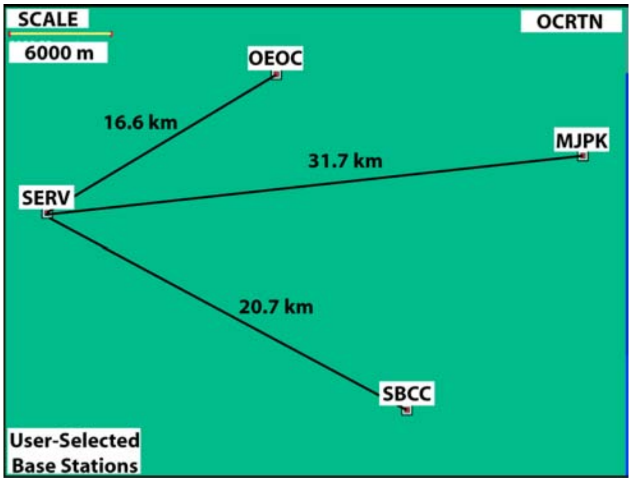

Figure 9. Geometry of Smart Client experiment, where the base stations were chosen to demonstrate a less favorable geometry.

The results of this experiment are summarized in Table 3. Although the number of outliers has increased by a factor of 3, to 3.4%, the number of outages remains the same (as expected) and the standard deviations of the position components have increased by only 10-20%.

Table 3. Smart Client Demo: User-Selected Base Stations

Date	Sol-utions	Out-liers	Out-ages	σN (mm)	σE (mm)	σU (mm)
8/23	85755	3249	645	8.6	6.9	58.1
9/1	85541	2573	859	7.5	8.4	48.8
Mean	85031 99.1%	2911 3.4%	752 0.9%	8.1	7.7	53.4

NAVIGATION WITH THE SMART CLIENT

Single-epoch initialization and re-initialization makes the RTD/Smart Client combination convenient for real-time positioning of moving platforms with respect to multiple base stations. In Figures 10 and 11, we show the trajectory of a vehicle equipped with a Trimble 5700 GPS receiver (code TRIM) and a Zephyr antenna mounted on the roof. The vehicle's position was computed in real-time with respect to two OCRTN base stations, SCMS and SBCC.

The detection of outliers is more difficult on a moving platform, but is enhanced by having access to multiple base stations. In Figure 11 one can clearly distinguish outliers in the Up velocity component, which correlate well with outliers also detected at one of the base stations whose position has been well determined. Thus, the ability to perform instantaneous *network* RTK enhances the reliability of vehicle navigation.

ADDITIONAL FEATURES OF THE RTD SERVER

The RTD server provides real-time data while monitoring the integrity and network geometry on an Epoch-by-Epoch™ basis, allowing site coordinates to adjust for tectonic/seismic deformation and ground subsidence that occur in Orange County [*Bawden et al*., 2001, *Watson et al*., 2001]. Figure 12 shows the time series of daily vertical positions for station SACY located in the zone of subsidence. The RTD server also detected surface waves of amplitudes up to 30 mm and duration of 700 seconds from the Mw 7.9 November 3, 2002 Denali Fault earthquake in Alaska, more than 3500 km away [*Bock et al*., 2003].

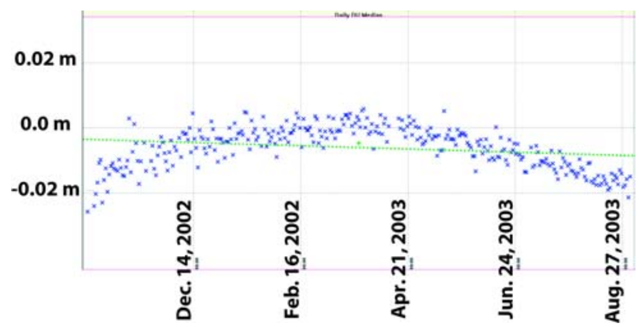

Figure 12. Time series of daily positions for site SACY computed by the RTD server for the last 10 months, indicates seasonal subsidence with amplitude of about 30 mm.

Furthermore, RTD can also monitor (relative) tropospheric zenith delays at each site, which can be converted to precipitable water over the region spanned by the network, an important parameter in short-term weather forecasting [*Bevis et al*., 1992; *Fang et al*., 2002].

CONCLUSIONS

We have demonstrated with several examples (two static and one dynamic) that Geodetics server/client software with Epoch by Epoch™ technology provides today the tools for wireless instantaneous network RTK for positioning and navigation. These capabilities will only be enhanced with GPS modernization, new GNSS satellite constellations, improvements in wireless technology and coverage, and increased personal computational power.

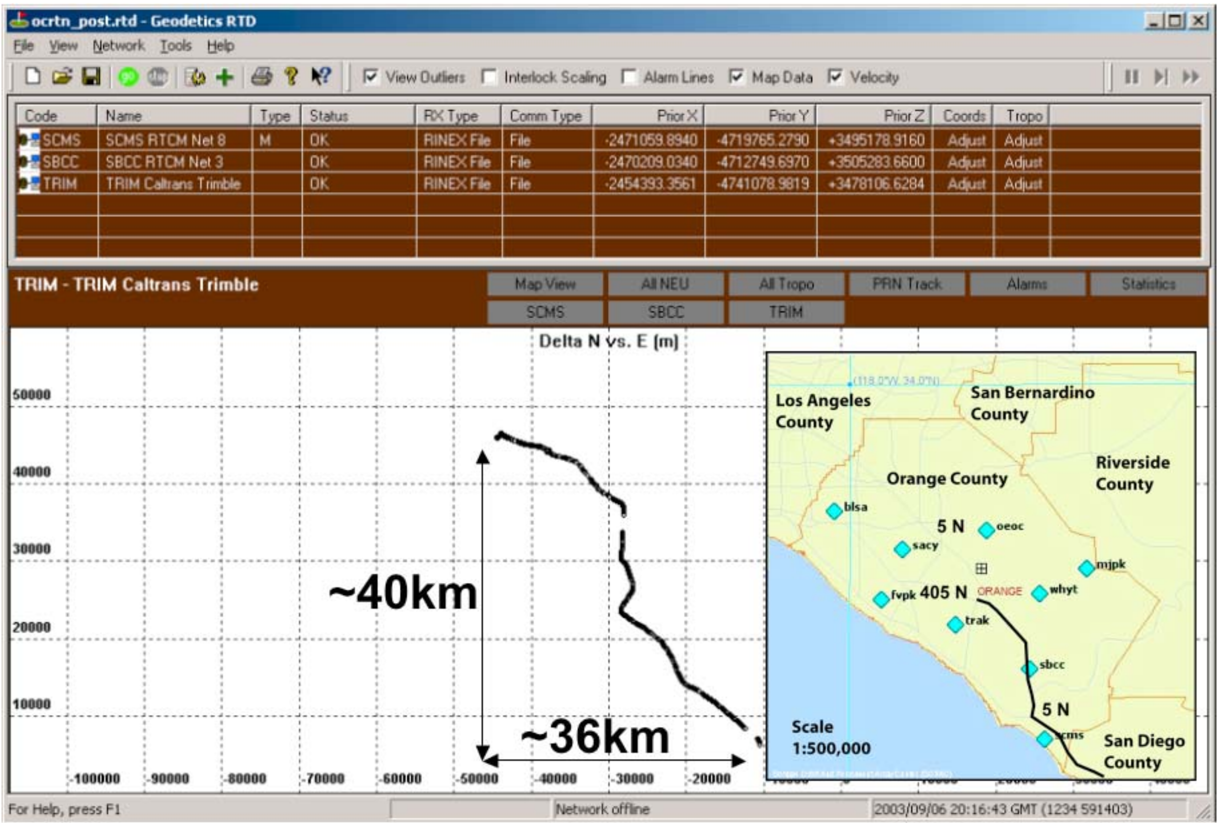

Figure 10. RTD screen shot showing the (North vs East) trajectory (in meters) of a vehicle equipped with a Trimble 5700 GPS receiver (code TRIM) with Zephyr antenna, with respect to two OCRTN base stations, SCMS and SBCC. The dark line on the map inset on the right shows the route taken by the vehicle along Interstate 5 North from the NW corner of San Diego County to the 405 N freeway near Irvine in Orange County, a distance of about 60 km over a time interval of nearly one hour on September 6, 2003.

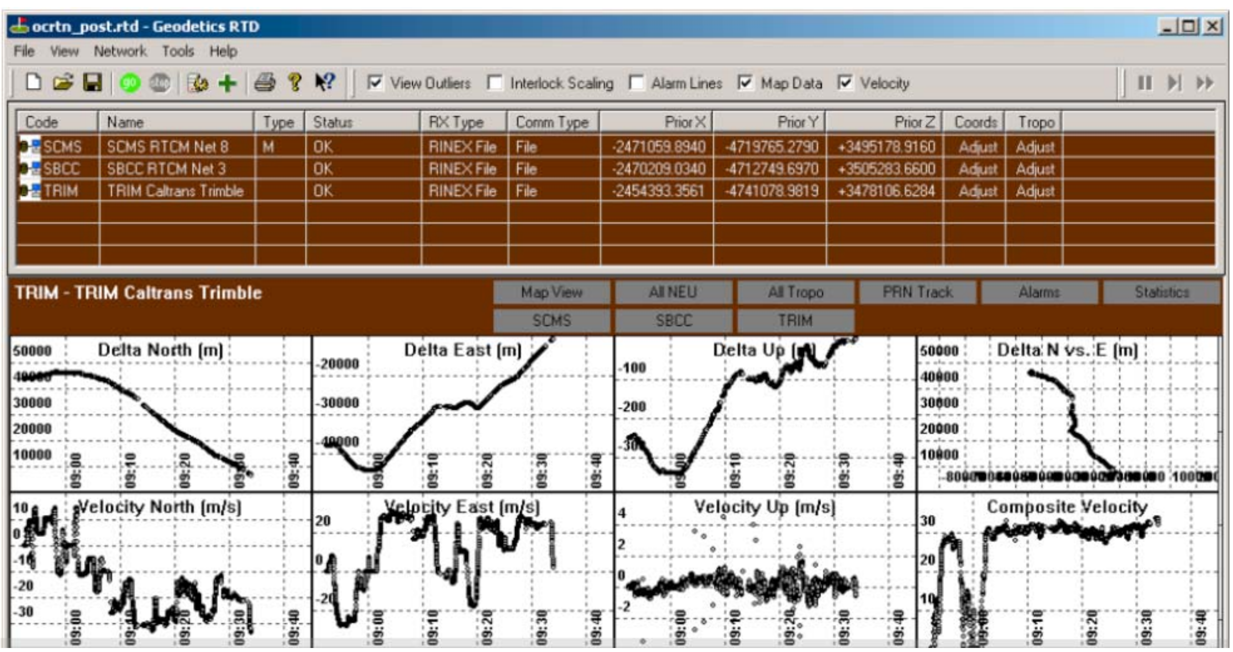

Figure 11. Smart Client Navigation. Same description as Figure 10**.** The first row of four plots shows the Delta North, Delta East, Delta Up, and Delta North vs. East solutions (in units of meters) for the vehicle's trajectory. For the first three plots, the horizontal axis is in hours and the vertical axis is in meters. For the fourth plot, both axes are in meters. The second row of plots shows vehicle velocities for the three components and the composite velocity.

ACKNOWLEDGMENTS

The Orange County Real Time Network is a collaboration of the California Spatial Reference Center, the Southern California Integrated GPS Network and Orange County's Public Facilities and Resources Division (PFRD). We thank Art Andrew, John Canas, and Yolanda Radig (all from County of Orange PFRD), Bill Haaf (Caltrans District 12), Mike Strom and James Yacino (Surveyor Service Company), and George Gribbins (Geodetics) for their support of the field experiments described in this paper. We acknowledge the Southern California Integrated GPS Network and its sponsors, the W.M. Keck Foundation, NASA, NSF, USGS, SCEC, for providing data used in this study, and the California Spatial Reference Center and its sponsors, NOAA's National Geodetic Survey, Caltrans, and County of Orange for providing data used in this study.

REFERENCES

Andrew, A. R. III, Real-Time Reality, *POB*, *28* (11), pp. 20-23, 2003.

Bawden, G. W., W. Thatcher, R. S. Stein, C. Wicks, K. Hudnut and G. Peltzer, Tectonic contraction across Los Angeles after removal of groundwater pumping effects, *Nature*, *412*, pp. 812-815, 2001.

Bevis, M., S. Businger, T. Herring, C. Rocken, R. Anthes, and R. Ware, GPS meteorology, Remote sensing of atmospheric water vapor using the Global Positioning System, *Journal of Geophysical Research*, *97*, pp. 15,787-15, 801, 1992.

Bock, Y., R. Nikolaidis, P. J. de Jonge, and M. Bevis, Instantaneous geodetic positioning at medium distances with the Global Positioning System. *Journal of Geophysical Research*, 105, pp. 28,223-28,254, 2000.

Bock, Y., P. J. de Jonge, D. Honcik, M. Bevis, L. Bock, and S. Wilson, Epoch-by-Epoch™ Positioning Applied to Dam Deformation at Diamond Valley Lake, Southern California, Proc. 10th International Symposium on Deformation Measurements, pp. 78-87, International Federation of Surveyors (FIG), Orange, California, 19-22 March, 2001.

Bock, Y., L. Prawirodirdjo, T. I. Melbourne, Detection of Arbitrarily Large Dynamic Ground Motions with a Dense High-Rate GPS Network, Geophysical Research Letters, 2003.

De Jonge, P. J., Y. Bock, and M. Bevis, Epoch-by-Epoch Positioning and Navigation. Proc. ION GPS -2000, The Institute of Navigation, Alexandria, VA, pp. 337-342, 2000.

Fang, P., Y. Bock, and S. Gutman, Evaluation of real-time ground-based GPS meteorology, EGS-AGU-EUG Joint Assembly, Nice, 2003.

Watson, K. M., Y. Bock, and D. T. Sandwell, Satellite interferometric observations of displacements associated with seasonal ground water in the Los Angeles basin, *Journal of Geophysical Research*, 107 (B4), 10.1029/2001JB000470, 2001.