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Preliminary Results from Real-Time GPS Monitoring in the San Francisco Bay Area

John Langbein and Christian Guillemot
US Geological Survey, Menlo Park, CA

Primary contact: langbein@usgs.gov

BACKGROUND: A web-based monitoring system has been implemented to display displacement estimates in real-time for various combinations of USGS, Plate Boundary Observatory (PBO) and Bay Area Regional Deformation (BARD) network stations in the San Francisco Bay area. Tools and utilities developed in-house are used to analyze the quality of estimated positions and gain a better understanding of the challenges involved in integrating displacement data into earthquake early warning (EEW) algorithms.

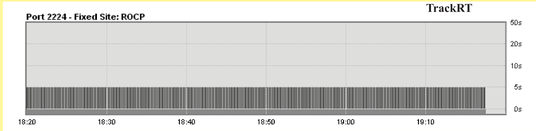
Comparisons of results obtained from a variety of software packages have led to a closer examination of the epoch-per-epoch delays with which those estimates are generated.

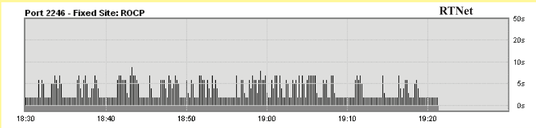
USGS at Menlo Park uses two different programs to process streamed, GPS data in real-time, RTNet and TrackRT. These two programs handle GPS data delays differently . RTNet defines a maximum waiting period (user selectable) beyond which the data for that epoch and station are skipped from the solution. Thus the latency in generating position estimates for each epoch varies with time and may be as low as 2 seconds, up to the specified waiting period, with occasional overshoots (bottom panel). For TrackRT the waiting period is constrained by the NTRIP client that captures the GPS data stream and forwards it to the software. TrackRT does not output the position estimates until the specified waiting period has elapsed. This approach means that the latencies are essentially constant (top panel).

Although a shorter waiting period tends to decrease the completeness of the streamed output by the software, the impact appears to be relatively minor.
For example, the shorter waiting period of 3 sec shown below for the same set of 9 stations resulted in 2 periods of 12-30+ seconds each during the previous hour when no differential solutions were output for the entire set. Note, however, that the graph does not show gaps shorter than 12 seconds (i.e. less than the bin size) which are more likely to occur.

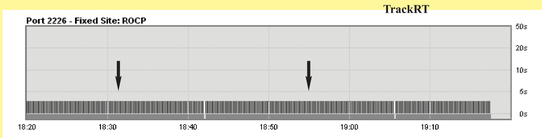
Observed maximum delays of position estimates per 12-second segment displayed for one hour - Number of sites in solution set: 9

Nominal waiting period of 5 seconds



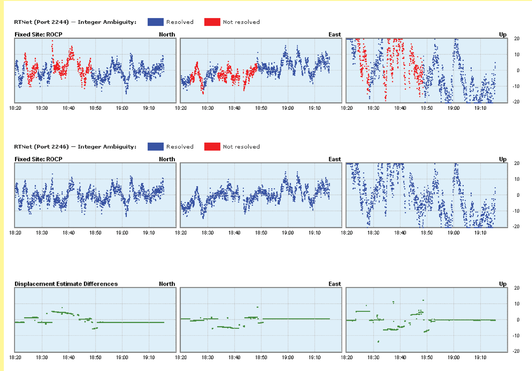


Nominal waiting period of 3 seconds



Differences in the position estimates for station TRCP using two different waiting periods for RTNet. Top is 3 seconds and middle is 5 seconds. For the shorter waiting period, RTNet is unable to resolve integer ambiguities for a significant portion of the hour which yields a slightly higher RMS (not shown). A similar observation can be made for TrackRT during the same hourly segment with a higher number of unfixed biases for the shorter waiting period. Overall the impact on the quality of the solutions is modest with position displacement estimates remaining within 5 to 10 mm of each other during those intervals when ambiguities are not resolved.

Normalized Displacement Estimates and Differences - Plotting Interval is 2 seconds
Station TRCP

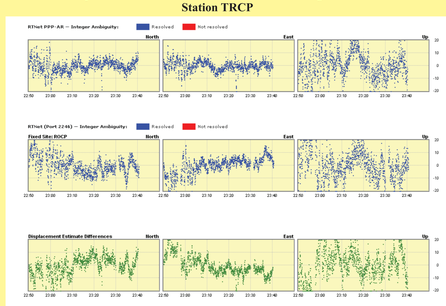


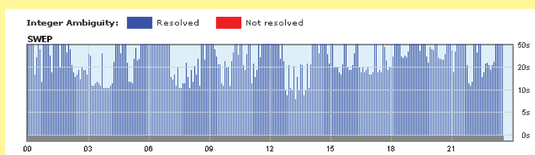
Our observations show that a transient outage greater than 10 to 15 seconds in the data stream from an individual station will typically result in a gap of in the positions stream that extends an additional 30 seconds or more beyond the end of the outage. Moreover, it often takes another 15 to 20 minutes for the estimates to stabilize enough to make them useful again for EEW applications. On the other hand, both RTNet and TrackRT recover almost instantly from transient data outages of 10 seconds or less. It is unclear at this point whether the command file configuration can be optimized to allow for a faster recovery following a longer outage.

Precise Point Positioning

RTNet has the capability to compute 1-sec position estimates in a precise positioning mode (PPP) with ambiguity resolution(AR) . Comparisons of time series of position estimates generated with PPP (and differential mode) are shown in the panels below for a one-hour window. Overall, PPP solutions compare advantageously to the differential solutions with most estimates staying within +/- 10 mm for the N-S and E-W components.

Normalized Displacement Estimates and Differences - Plotting Interval is 2 seconds
Station TRCP

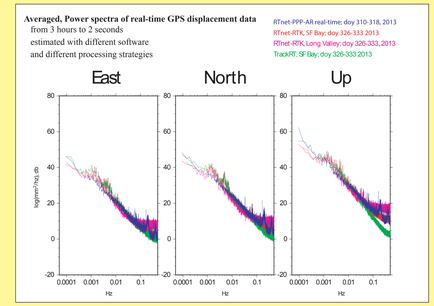




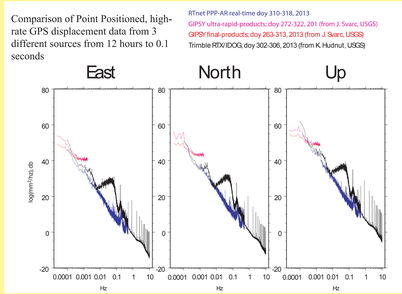
The current implementation oF PPP requires real-time information from an additional data stream consisting of satellite-clock corrections obtained from a remote server. Latencies associated with those corrections can be very large as shown in the above panel for a 24-hour window. Though the positions estimates are output every second by the software, these values are frequently behind current UTC time by 50 seconds or more.

Although we use commercial software and hardware, our use does not imply any endorsement of these products.

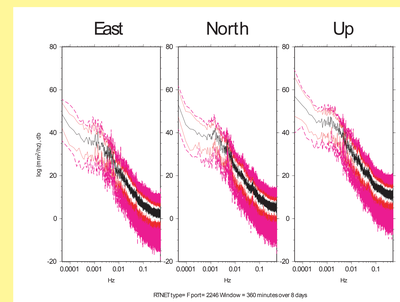
The precision of high-rate GPS can be quantified using power spectral techniques to measure the background noise, or drift inherent to these data.



PPP-AR has an apparent peak at 0.2 Hz (or 5 seconds), due to 5 second updates for satellite clocks.
Long Valley data have highest, high frequency noise, due to using lower resolution RTCM stream rather than BINEX.
TrackRT has lowest, high-frequency noise; the cause is unknown.



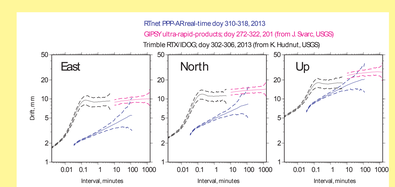
GIPSY results are for analyzing data, sampled every 5 minutes, and having about 1-hour latency. Results averaged over 8 sites spanning 50 days
Trimble RTX are PPP solutions performed on the receiver in real-time with satellite clock corrections provided by Trimble. Sampling interval is 20 sps. Latency is unknown at this time. Solution is from one site spanning a 5 day interval. Hump in spectrum between 0.01 and 0.1 Hz is from ~1-minute updates to the satellite clock corrections.
RTnet PPP-AR results are from 1 sps data from 8 sites spanning 8-days. Satellite clock corrections are provided at 5 second intervals computed by GPS-Solutions from a PBO network in Central Oregon. Latencies are 10 to 50 seconds.

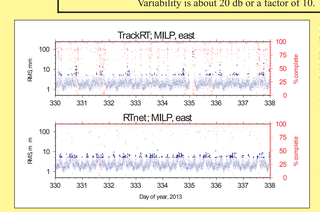


Variability in PSD:
Periodograms over a 6 hours to 2 second interval from displacement estimates using RTnet (RTK mode) from 8 sites spanning 8 days.
Plot shows the median periodogram (black), and the 75% and 95% intervals of the sorted, periodograms.
Variability is about 20 db or a factor of 10.

To first order, background noise is independent of processing software and strategy
Long-period noise is colored, represented by power law proportional to $1/f^{f1}$ where n~1.2 to 1.3.
PSDs have significant temporal variability.

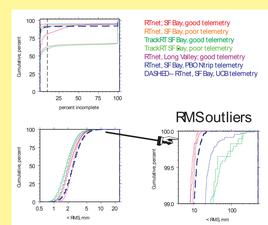
DRIFT: Although PSDs are useful, a more physical understanding of the implications of temporal correlated data can be assessed by computing the 'wander' (Agnew, 1992) or drift as a function of observation interval. For short intervals (seconds), the repeatability is about 2 mm, but increases to 10 mm for longer intervals (hours).





Data Quality and EEW: For GPS to be used in EEW, data quality must be assessed in real-time so that bad data do not contribute to the estimated parameters of a model of the evolving earthquake. One quick and dirty method is to simply evaluate the RMS variations and their completeness of the position estimates prior to the time of the earthquake. When either the RMS exceeds a specified threshold or there are significant gaps, then the EEW algorithm could reject those position estimates.

An example of a time-series of RMS and data completeness as a function of time for one site (MILP) computed for 1 minute windows for position estimates using RTnet (in its RTK-mode) and TrackRT. For this 8 day interval, RMS for RTnet varies between 0.7 and 5 mm. For TrackRT, most of the RMS also falls between 0.7 and 5 mm, but there are a number of outliers. Likewise, most 1-minute intervals are nearly 100% complete. RMS was only computed for intervals where both the completeness exceeds 90% and the software indicated that most of the integer ambiguities are resolved. As expected, the temporal variations show daily periodicity from the sidereal repeat of the satellite constellation which could be removed by both common-mode and sidereal filtering.



The cumulative histograms of both the RMS and the incompleteness of the position estimates emphasize the observations from the RMS time series but allow for comparisons between other sources of data.

CONCLUSIONS: For GPS to contribute to earthquake early warning, the data from each site must be received at the central office with minimal latency, the data assimilated and processed with minimal delay, and the position estimates must be precise. Realistic assessment of our results suggests that total delays or latencies are typically less than 5 seconds for position estimates computed in differential mode, and over short time-intervals relevant to EEW, precision is better than 2 mm. However, data outages as short as 15 seconds have a significant impact on the quality of the solutions that may extend for 15 minutes or longer after the data streaming has resumed. Also, the large latencies currently observed with precise point positioning currently preclude their use for EEW applications.