Comparison of Real-Time Kinematic GNSS Positioning Techniques Using Moving and Stationary Antennas

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The use of high-rate and real-time GNSS measurements for hazards monitoring and scientific applications is still in its infancy and there is great potential for its integration with strain, gravity and seismic measurements. Many commercial vendors and public agencies now offer real-time positioning services that provide sub-decimeter accuracy, with some approaching the sub-centimeter level. As GNSS network operators begin transitioning into offering real-time products, they will need to consider a number of factors including but not limited to: cost, position accuracy, solution latency, network topology and bandwidth. Periodic evaluation of real-time positioning systems will need to be conducted in order to optimize their integration into hazard-monitoring and multi-disciplinary networks. Controlled outdoor kinematic and static experiments provide a useful method for evaluating real-time systems, helping to identify system limitations, and characterize performance and reliability. Preliminary findings from tests using a static antenna and a comparison of real-time kinematic positioning methods will be highlighted.

For the purpose of characterizing the performance of real-time kinematic software, UNAVCO has begun development of a low-cost portable kinematic antenna test system. Comparisons of real-time GNSS positioning algorithms can now be made at our facility and at remote locations. Coordinated multi-site simulation of antenna displacements over a regional sized network could provide a useful test for real-time GNSS earthquake source determination algorithms. Various GNSS site geometries could be investigated to determine adequate configurations for capturing the ground displacement information needed to resolve earthquake source models. Preliminary designs will be discussed.

Trimble's recently released real-time positioning service, RTX, promises ~4 cm accuracy with 95% confidence using a global Precise Point Positioning algorithm. RTX can be run on individual receivers that receive orbit and clock corrections via cellular network or satellite in the proprietary compressed format CMRx, or on a centralized server running network software that collects raw data streams. Many GNSS network operators are currently investigating its potential for hazard monitoring applications. In order to extract RTX positions from logged or streamed GNSS data modifications to UNAVCO's teqc software are in development and nearing public release.

Long-term static testing of Trimble's RTX service is ongoing at UNAVCO and will be used to characterize the stability of the position time-series produced by Trimble's real-time positioning service. Receiver-based RTX was enabled at the Plate Boundary Observatory site P041 in June, 2013, and time series results to date show standard deviations of 2.22, 2.75 and 8.40 cm for north, east and up components, respectively. Position analysis for this and other PBO stations using server-based will be presented for comparison. 1-d kinematic tests using moving antennas have been conducted at the UNAVCO facility and comparisons between server- and receiver-based RTX with real-time and post-processed kinematic algorithms including GIPSY, Track, and TrackRT will be shown.

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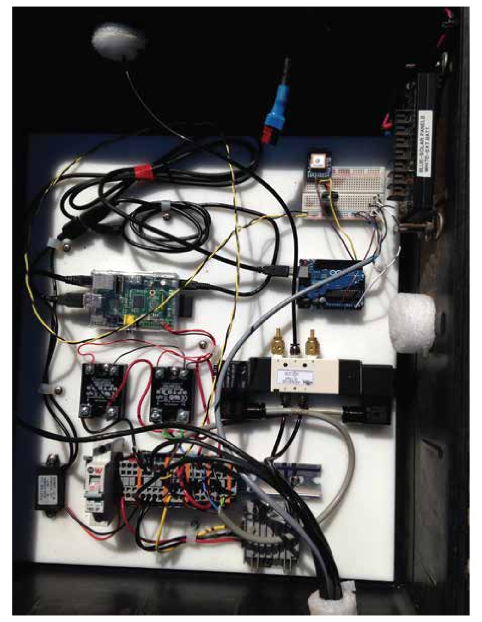
Goal: Develop a low-cost portable kinematic test system.

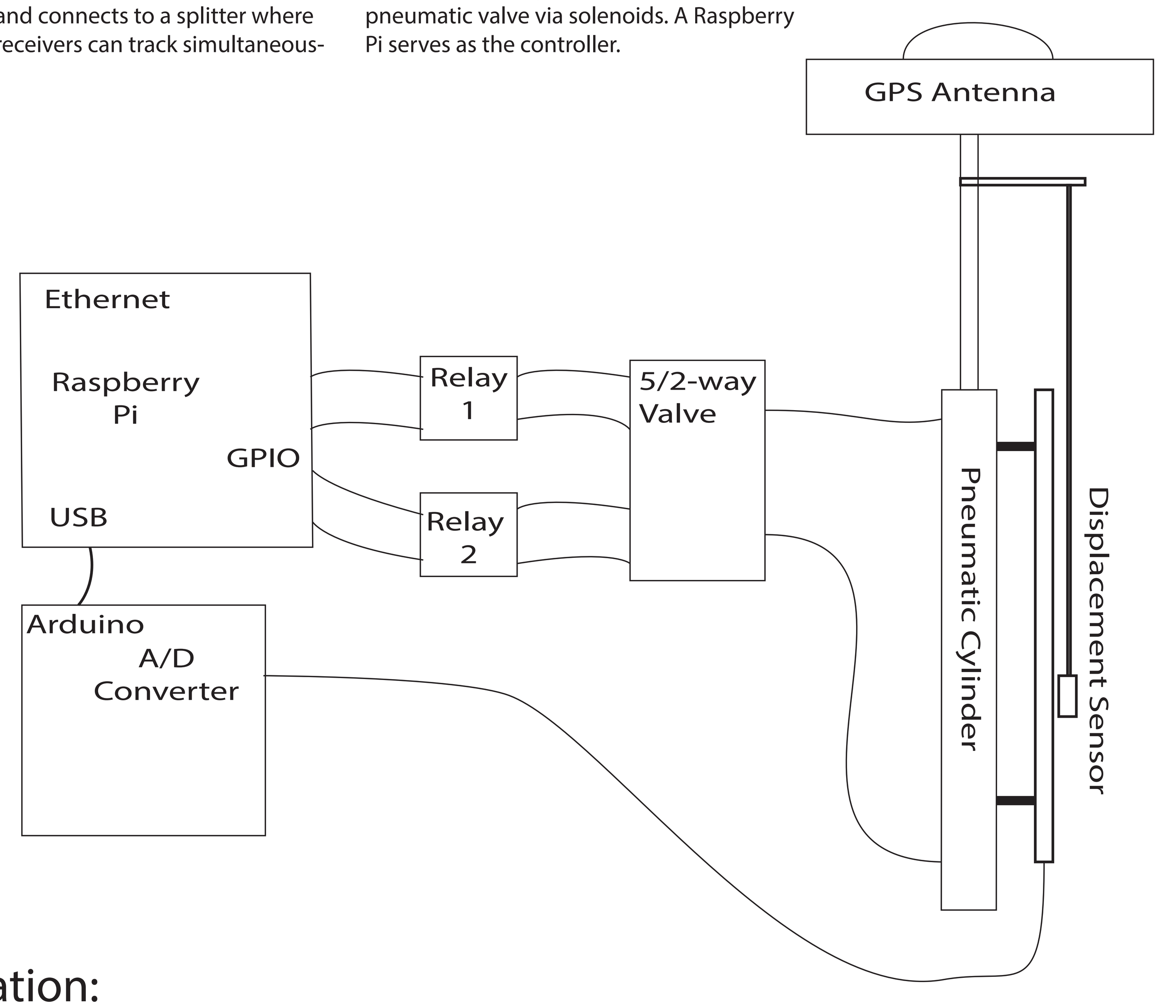
System Design:

Pneumatic cylinder with 300 mm maximum displacement showing Trimble Zephyr antenna and linear position sensor attached. The antenna cable lead into the building and connects to a splitter where multiple receivers can track simultaneously.



Equipment box containing the various electronics for controlling and measuring the kinematic motion of the pneumatic cylinder. Two relays control a 5/2-way pneumatic valve via solenoids. A Raspberry Pi serves as the controller.

A close up of the pneumatic cylinder, linear position sensor and Trimble Zephyr antenna.



Operation:

GPIO pins on the Raspberry Pi control two DC relays, regulating air into a pneumatic cylinder, and displace the antenna vertically. A Turck linear position sensor outputs an analog voltage that is linearly proportional to the antennas displacement. Analog voltage measurements (10-bit) are recorded at up to 10 Hz using the built -in analog-to-digital converter on the Arduino (arduino.cc). An accurate time stamp for each measurement is provided by a low-power MTK3339 GPS module. The rate of the antenna's displacement can be crudely controlled by restricting the air exiting the pneumatic valve. Alternatively, the relays controlling the pneumatic valves can be driven using Pulse Width Modulation (PWM) allowing for more accurate control of antenna displacement and displacement rates.

Limitations:

While this system provides accurate independent measurement of displacement, the current configuration of the system is limited in both speed and acceleration. Increasing the pressure and/or size of the pneumatic system can increase the maximum antenna speed and acceleration. Position repeatability will be limited by friction and the compressibility of air in pneumatic systems. If highly repeatable displacements are desired then a more costly non-pneumatic system will be required.

Goal: Evaluate CenterPoint RTX Static and Kinematic Performance

Trimble RTX

In 2012 Trimble introduced the CenterPoint RTX real-time positioning service, providing centimeter accurate positions without direct use of reference stations. The RTX service can run on compatible receivers (Trimble NetR9) that receive orbit and clock corrections via cellular or satellite in the proprietary CMRx format, or on a centralized server running Trimble's PIVOT software. Trimble generates their own corrections using a proprietary global network.

UNAVCO has begun testing both the receiver based and server based RTX services in order to characterize their performance for applications in hazard monitoring and geological sciences. We have conducted preliminary experiments at two localities. Short-term (24hr) kinematic testing was conducted on the roof of the UNAVCO facility. Long-term stationary tests are ongoing at the Plate Boundary Observatory (PBO) site P041. For all results shown in this poster only GPS satellites were tracked.

In addition to the real-time processing conducted at PBO site P041, UNAVCO is currently using Trimble's PIVOT software to process ~350 PBO stations in real-time. Please see poster G53B-0929 entitled *The UNAVCO Real-time GPS Data Processing System and Community Reference Data Sets* for more information regarding UNAVCO's real-time products.

Server Client

Advantages:
- Pricing structure is advantageous for managing large networks.
- Can accept multiple streaming formats (tested BINEX).
- Is not dependent on receiver hardware.
- Tolerates 1-2 min correction outage before re-initializing.
- PPP solution is independent from other stations.

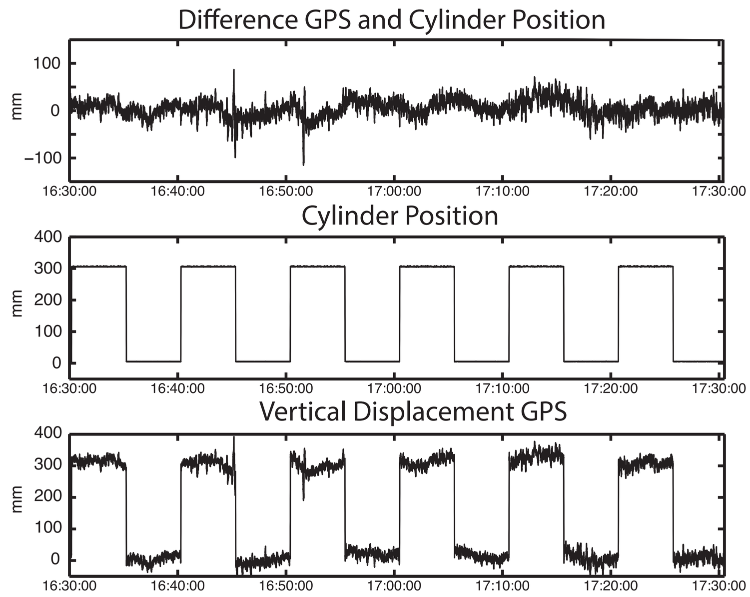
Disadvantages:
- Position estimates and the covariance matrix data are difficult to utilize in outside applications.
- Requires PIVOT license for each receiver and RTX module.
- Positions are not saved in the receivers memory.
- Position solution is limited to ≥1Hz
- Ambiguity resolution does not output the # of fixed biases.

Receiver Client

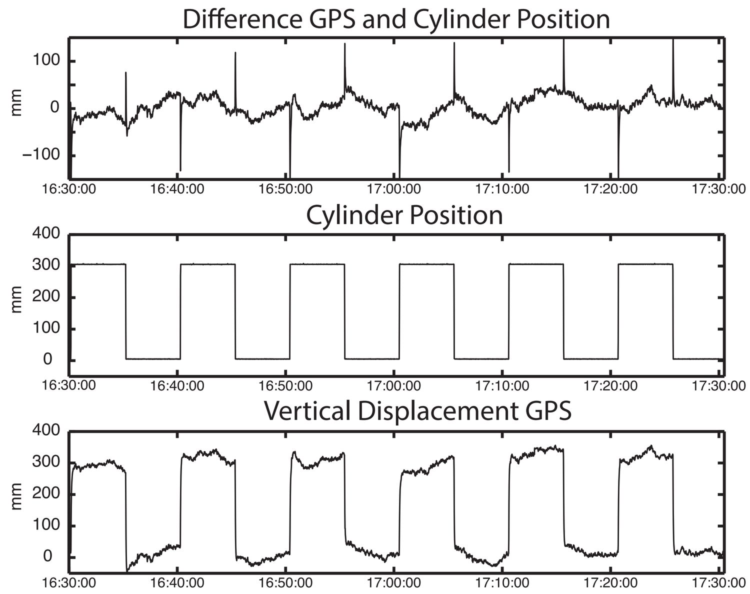
Advantages:
- Corrections received via L-band reduce bandwidth requirements for telemetered sites.
- Receiver can receive corrections even if telemetry fails.
- Does not require additional hardware or software.
- PPP solution is independent from other stations.
- Tolerates 1-2 min correction outage before re-initializing.
- Up to 50 sps

Disadvantages:
- Prohibitively expensive per-receiver license discourages use in networks.
- Full covariance matrix is not available in the RT27/T02 format.
- Requires compatible receiver hardware (NETR9)
- Ambiguity resolution does not output the # of fixed biases.

Preliminary Kinematic Test Results



Observed 10 sps kinematic RTX results from a repeated 300mm step test. The antenna was displaced 300mm vertically every 300 seconds. The receiver was set to track GPS-only. The Difference between RTX and cylinder position show no signs of an overshoot from a frequency dependent response.



Observed 1 sps kinematic TRACKRT results from the same repeated 300mm step test. The difference between the computed GPS displacement and cylinder position show an overshoot that is most likely related to TRACKRT's process noise parameters. For this experiment we used the default process noise values. There is a known trade off between ambiguity resolution and allowing more process noise.

Long-term Stationary Antenna Real-Time PPP Test Results

RTX was first enabled on the NetR9 receiver located at the Plate Boundary Observatory (PBO) site P041 in Boulder, CO in June of 2013. In July of 2013 UNAVCO began processing P041's BINEX stream using Trimble's PIVOT software on a centralized server. Time series statistics from P041 are shown in Table 1. In addition to P041, UNAVCO has been processing ~350 stations in the PBO real-time network since July of 2013. Averaged position estimate statistics for the entire PBO real-time network are shown in Table 2.

Table 1. RTX statistics for P041

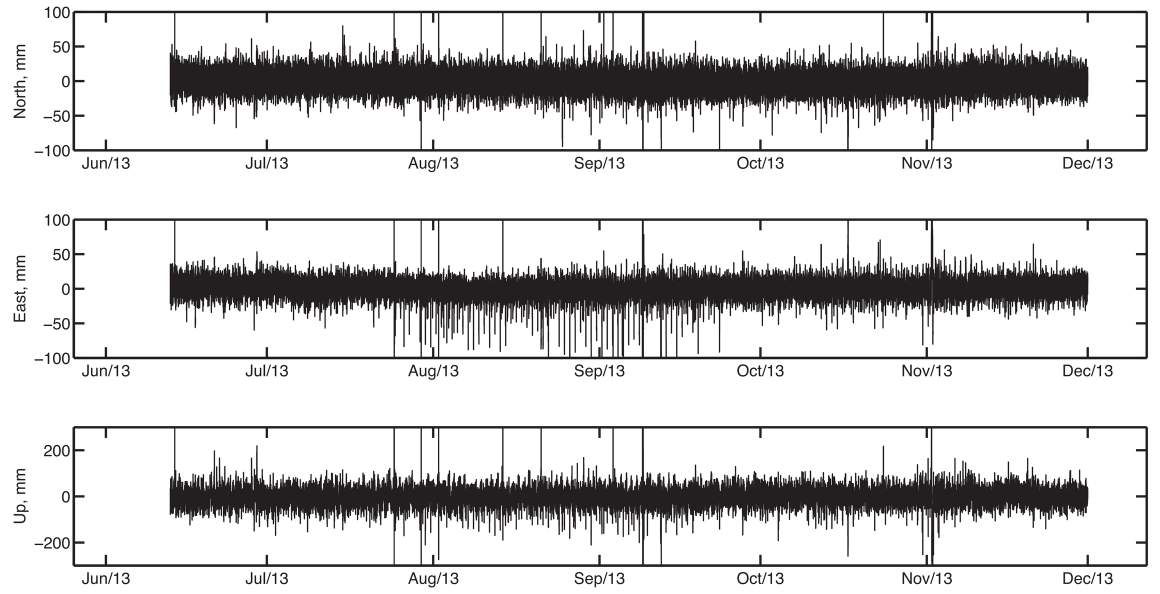
	Receiver Based RTX	Server Based RTX
North		
min (mm)	-473.9	-1572.7
max (mm)	1865.5	1839.0
std (mm)	23.3	28.1
outliers > 100 mm	396.0	398.0
kurtosis	1677.0	1151.0
skewness	30.9	-20.9
East		
min (mm)	-1077.9	-967.2
max (mm)	5858.3	953.9
std (mm)	22.5	22.6
outliers > 100mm	453.0	499.0
kurtosis	24494.0	154.0
skewness	94.3	1.5
Up		
min (mm)	-2002.7	-34688.4
max (mm)	5779.5	3364.6
std (mm)	64.4	89.7
outliers > 100mm	1384.0	918.0
kurtosis	4158.0	52749.0
skewness	52.4	-167.5

RTX position estimate statistics for long-term stationary test site P041. Receiver based RTX was enabled at P041 in June of 2013. Orbit and clock corrections were received via L-band satellite. Processing a BINEX stream with server-based RTX commenced in July of 2013.

Table 2. RTX statistics for PBO Real-time Network

	Server Based RTX
North	
min (mm)	-7334.4
max (mm)	6209.0
std (mm)	112.8
# epochs / (outliers > 100mm)	50.5
kurtosis	1877.8
skewness	-4.9
East	
min (mm)	-5759.3
max (mm)	7380.1
std (mm)	108.5
# epochs / (outliers > 100mm)	40.2
kurtosis	1959.2
skewness	6.2
Up	
min (mm)	-14843.7
max (mm)	8537.4
std (mm)	254.8
# epochs / (outliers > 100mm)	20.7
kurtosis	977.9
skewness	-10.0

RTX position estimate statistics for ~350 PBO stations in the real-time network. Values are averaged from the position estimate results of all sites in the PBO real-time network.



Left - Receiver RTX position estimates from P041. RTX was enabled at P041 in mid-June of 2013. Note that the scale is larger for the vertical component. Outliers greater than the axis limits were excluded for clarity. The positions shown were logged at 1min intervals. There is a period from the end of July to the middle of September that shows more frequent outliers in the east component. The cause is unknown.

Can outliers be distinguished from true motion?

Proper identification and removal of outliers in real-time position estimates will be required for integration in hazard-monitoring applications. Re-initialization of the RTX PPP solution causes large outliers in position. Re-initialization can occur during network outages, RF interference or any instance causing the receiver to lose lock or reboot. We have observed that the position uncertainties output by RTX tend to converge more rapidly after re-initialization than the position solution does. That could make it difficult to use the uncertainties in real-time to distinguish outliers from true motion. An alternative approach could use the number of fixed biases to weight the position estimates. However, RTX does not currently output this information.

The installation of accelerometers at real-time GNSS sites could be used to enhance real-time positioning for applications in hazard monitoring and geophysical sciences. Providing an independent measurement of a sites motion could allow for easy real-time identification of position estimate outliers.