mmVu™ Performance Analysis: mm-level Displacement Detection in Real-Time using GNSS

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Introduction:

To illustrate the capabilities of Gemini Navsoft Technologies' (GNT) mmVu™ Deformation Monitoring software for displacement detection, multiple simulations were conducted on GNT's testing facility.

The objective of this paper is to describe the repeated experiment with different GPS equipment and different version of the GNT's mmVu™ software with different processing settings. Tests were conducted on different days at different times yet under similar observation conditions. Slightly different GPS observation geometry was obtained at the time of each experiment.

The GNT's mmVu™ software consists of two independent filters running in parallel. The Time-Delayed Doppler (TDD) and Double-Differenced Carrier (DDC) observation are utilized in the filters.

The TDD filter is characterized as a band pass filter that can mitigate the error sources and noise of GPS observations having low- and high-frequency components in their error spectrum. Due to the nature of the TDD observations, sufficient time must be given to allow the filter to converge on the true position before being able to reliably track movements.

The DDC filter is a regularized low pass filter that factors the quality of DDC observations and a time constant in a smoothing process. A regularization process is implemented to make the DDC filter quickly extract displacement trends with mm level precision in less than a few hours.

The TDD Q value specifies the amount of uncertainty to add to the covariance matrix of the unknowns at each epoch of observations. The Q value should be based upon the anticipated rate of displacement of the monitored stations. Larger Q values allow the filter to respond more quickly to displacements, but results in greater uncertainty in the unknowns.

The TC value used with DDC solutions specifies the period of time over which DDC solutions should be used in calculating filtered DDC solutions. Large TC values result in higher precision but slower filter response time and vice versa.

The reason for the use of different filters is the redundancy in detection. Advantages and disadvantages of different filters are compared in Table 1.

Table 1: Advantages and disadvantages of the DDC and TDD filter.

Filter Type	Advantages	Disadvantages
DDC Filter	▪ High precision results ▪ Quick response to the changes in the observations ▪ Reduces high frequency receiver system noise ▪ Outperforms TDD filter under short-range baseline or typical environment	▪ Integer ambiguity resolution is required to guarantee high precision results ▪ Under challenging environment (e.g., obstructions, large height differences, or long-range baselines), solutions can be biased due to the residual effects of multipath, iononspheric and tropospheric delay, satellite orbit error etc.
TDD Filter	▪ High precision results ▪ Reduces low frequency errors in the observations. ▪ Reduces high frequency receiver system noise. ▪ No integer ambiguity resolution is required. ▪ Outperforms DDC filter under long-range baseline or challenging environment	▪ Delayed response to the changes in the observations ▪ Slow convergence time

Experiments:

The GNT testbed consists of two monuments. Base station antenna and monitored station are located on separate monuments (Figure 1). Monitored antenna is located on a translation stage with controlled movements.

Figure 1: Displacement Detection Simulation Environment.

The translation stage allows both horizontal (mostly east direction) and vertical movements of the monitored station antenna with sub-millimetre level precision. Translation stage linear positioners are shown on Figure 2. (see: http://www.newmarksystems.com/linear-positioners/nls4-series/)

Figure 2: GNT Translation Stage Linear Positioners.

Two NovAtel L1/L2 GPS receivers were used for the simulation tests. They were both collecting data at 5 second sampling rate. The data from both receivers were streamed in to a PC running mmVu™ deformation monitoring software using wireless data communication.

Three different tests were conducted to validate the deformation detection capacity:

1. **25 mm Vertical Displacement (Translation Stage August 29, 2012)**

The objective of this experiment is to test capabilities of multiple filters on with default settings: i.e., TDD Q values of 1.0 mm, 0.5 mm and 0.1 mm. DDC TC values of 0.2 hr, 1.0 hr, and 6.0 hr. The filter was initialized for almost two days prior to the introduction of the vertical displacement. 25 mm vertical displacement was introduced on August 31, 2012 at 12:55 UTC.

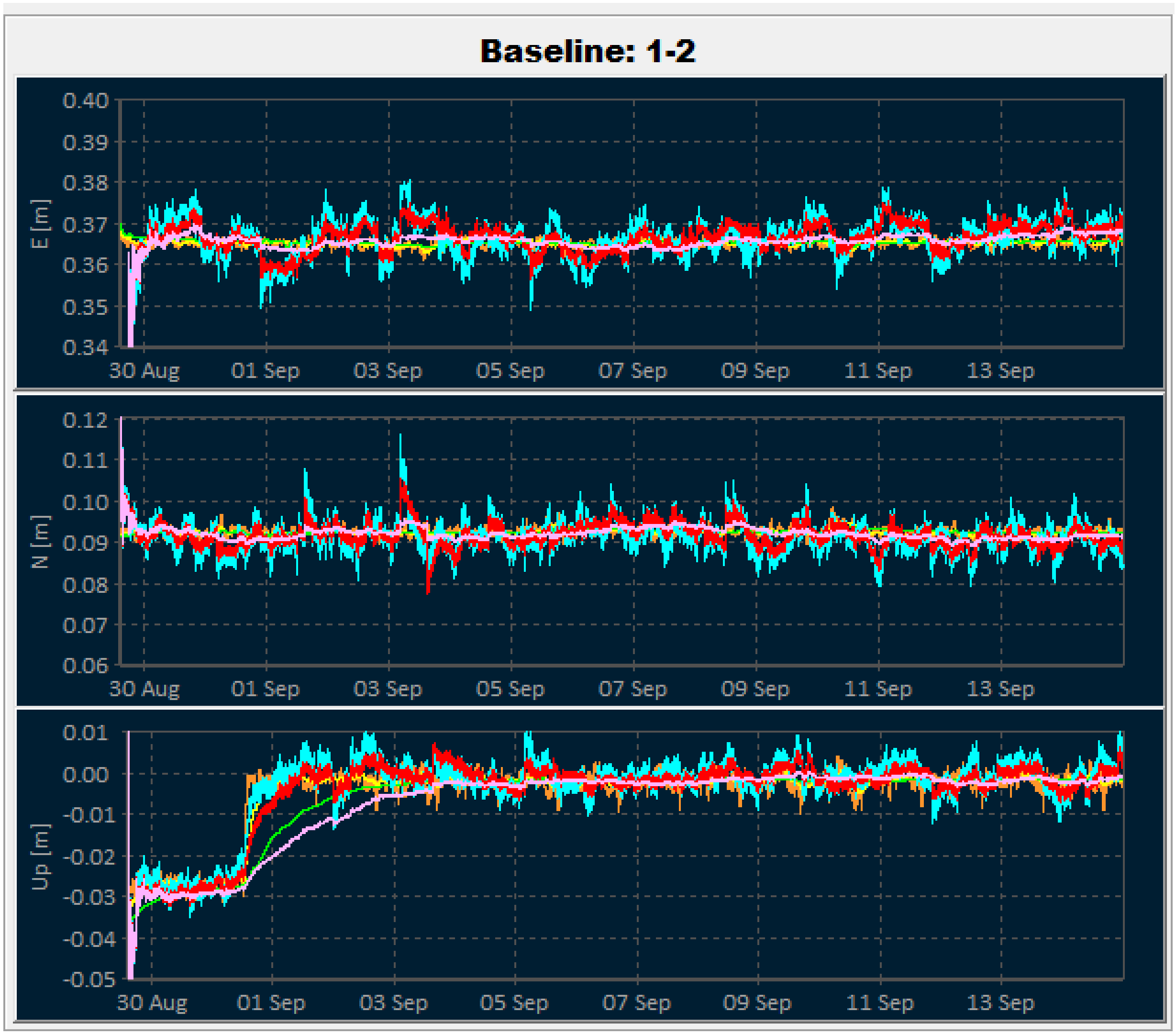

Figure 3: 25 mm displacement (bottom plot) in the up component detected by DDC filter with 0.2 hr TC value (orange), 1.0 hr TC value (yellow), 6.0 hr TC value (green) and TDD filter with 1.0 mm Q value (cyan), 0.5 mm (red), 0.1 mm (pink).

Figure 3 shows the 25 mm displacement in the up component detected by DDC filter and TDD filter. It can be seen from the plot that the detection time of the more responsive filters (DDC TC value of 0.2 hr and TDD Q value of 1 mm is in order of hours and in case of the less responsive filters (DDC TC value of 6 hr and TDD Q value of 0.1 mm) is in order of days (see Table 2 for more details).

2. 5 mm Horizontal Displacement (Translation Stage June 1, 2012)

The objective of this experiment is to test capabilities of multiple filters on with default settings: i.e., TDD Q values of 1.0 mm, 0.5 mm and 0.1 mm. DDC TC values of 0.2 hr, 1.0 hr, and 6.0 hr. and then to repeat the processing with the settings for this specific displacement. The filter was initialized for almost five days prior to the introduction of the vertical displacement. 5 mm horizontal displacement, mostly in the east direction, was introduced on June 6, 2012 at 12:03 UTC.

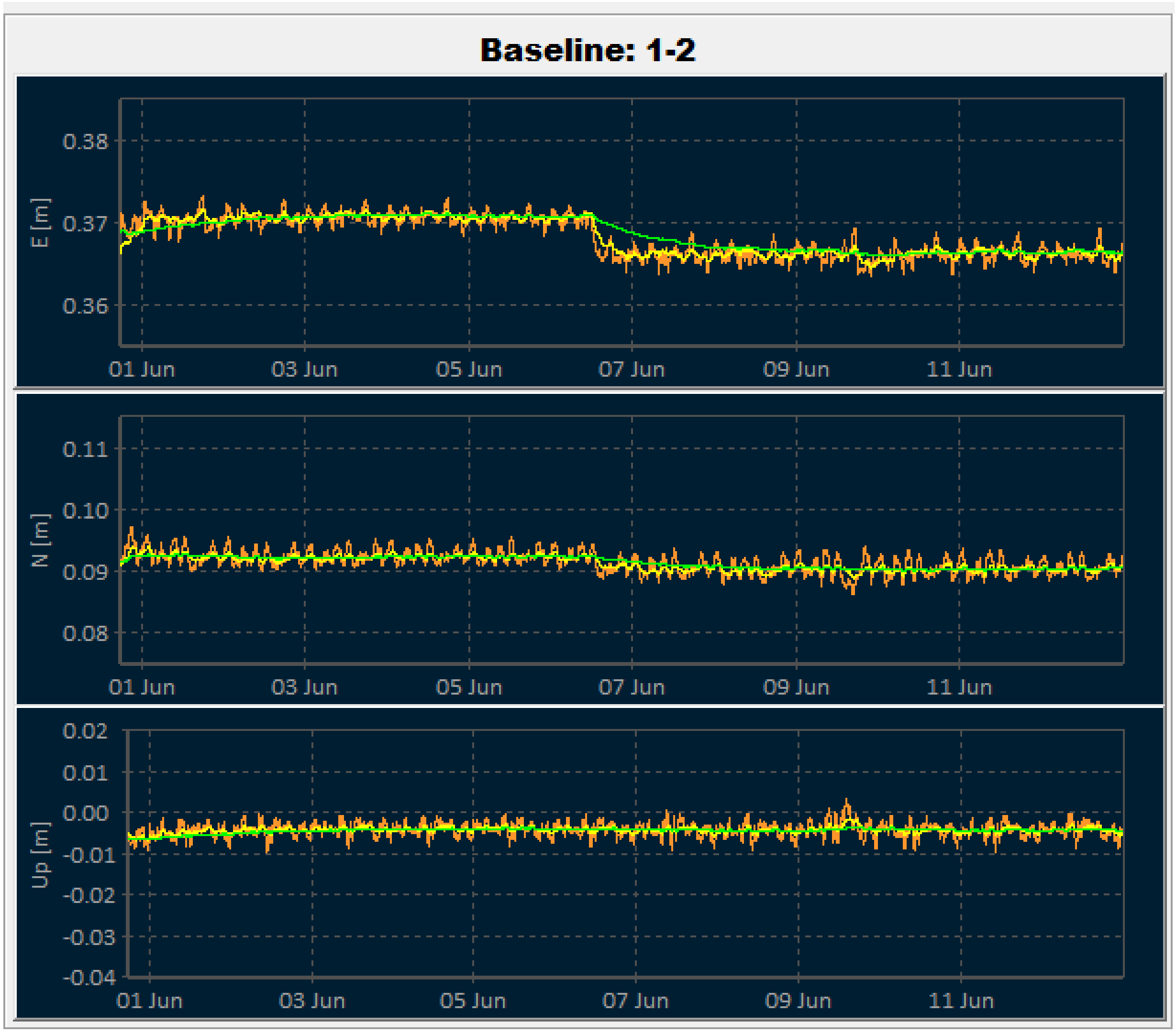

Figure 4: 5 mm displacement mostly in the east component (top plot) detected by DDC filter with 0.2 hr TC value (orange), 1.0 hr TC value (yellow), 6.0 hr TC value (green) and TDD filter with 1.0 mm Q value (cyan), 0.5 mm (red), 0.1 mm (pink).

Figure 4 shows the 5 mm displacement mostly in the east component detected by DDC filter. It can be seen from the plot that the detection time of the more responsive filters (DDC TC value of 0.2 hr and DDC value of 1 hour is in order of hours and in case of the less responsive filters (DDC TC value of 6 hr) is little over 1 day (see Table 3 for more details). The TDD filter Q values of 1.0 mm and 0.5 mm are not shown because they not have high-enough resolution to show the discontinuity. The TDD filter Q value of 0.1 mm shows the discontinuity, so this filter setting was used in the reprocessing of this experiment.

To test capabilities of multiple TDD filters, the following filter settings were used: TDD Q values of 1.0 mm, 0.1 mm and 0.01 mm. DDC TC values of 0 hr, 1.0 hr, and 3.0 hr.

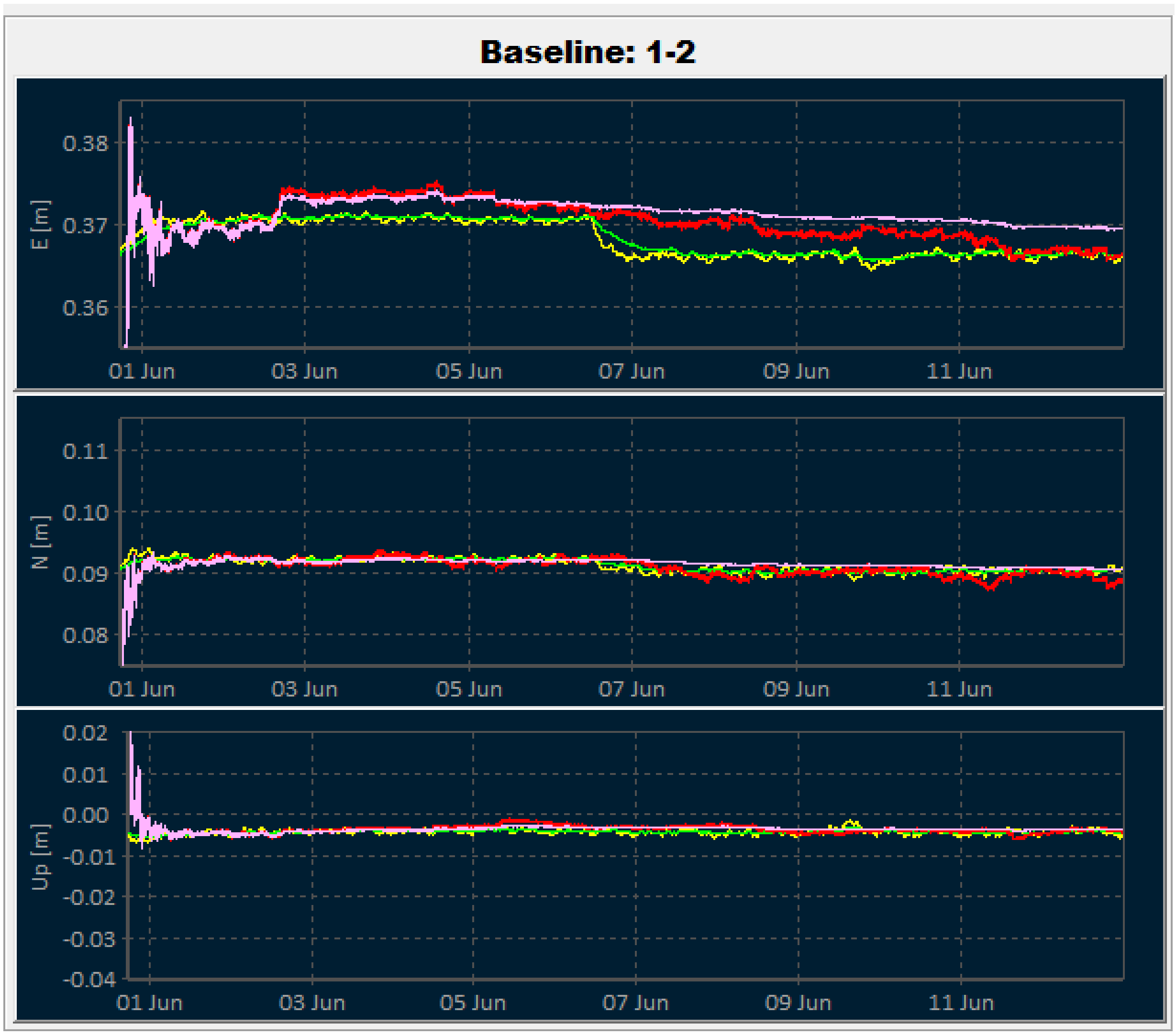

Figure 5: 5 mm displacement mostly in the east component (top plot) detected by DDC filter with 1.0 hr TC value (yellow), 3.0 hr TC value (green) and TDD filter with 0.1 mm (red), 0.01 mm (pink).

Figure 5 shows the 5 mm displacement mostly in the east component detected by DDC filter and TDD filter. It can be seen from the plot that the detection time of the more responsive filters (DDC TC value of 1 hr and DDC TC value of 3 hours) is in order of hours and in case of the less responsive filters (TDD Q value of 0.1 mm and TDD Q value of 0.01 mm) is in order of days (see Table 4 for more details). The DDC filter with TC value of 0 hr (RTK solution) and TDD filter with Q value of 1 mm are not shown on the plot because one (DDC filter with 0 hr TC value) is not part of the standard solution and the other (TDD filter with Q value of 1 mm) does not have high-enough resolution to show the discontinuity. The discrepancy between the TDD solutions and the DDC solutions in the east direction from June 3 to 6 of 2012 is currently under investigation.

3. 5 mm Horizontal and Subsequent 5 mm Vertical Displacement (Translation Stage May 22, 2012)

To test the capabilities of the filter with multiple discontinuities the standard filter setting were used: i.e., DDC filter with 0.2 hr TC value, 1.0 hr TC value, and 6.0 hr TC value and TDD filter with 1 mm Q value, 0.5 mm Q value, and 0.1 mm Q value. The filter was initialized for two days prior to the introduction of the horizontal displacement. 5 mm horizontal displacement, mostly in the east direction, was introduced on May 24, 2012 at 19:13 UTC and 5 mm vertical displacement was introduced on May 25, 2012 at 11:53 UTC. There is an unintentional data gap for about 6 hours on May 24, 2012, a couple hours before the introduction of the horizontal displacement.

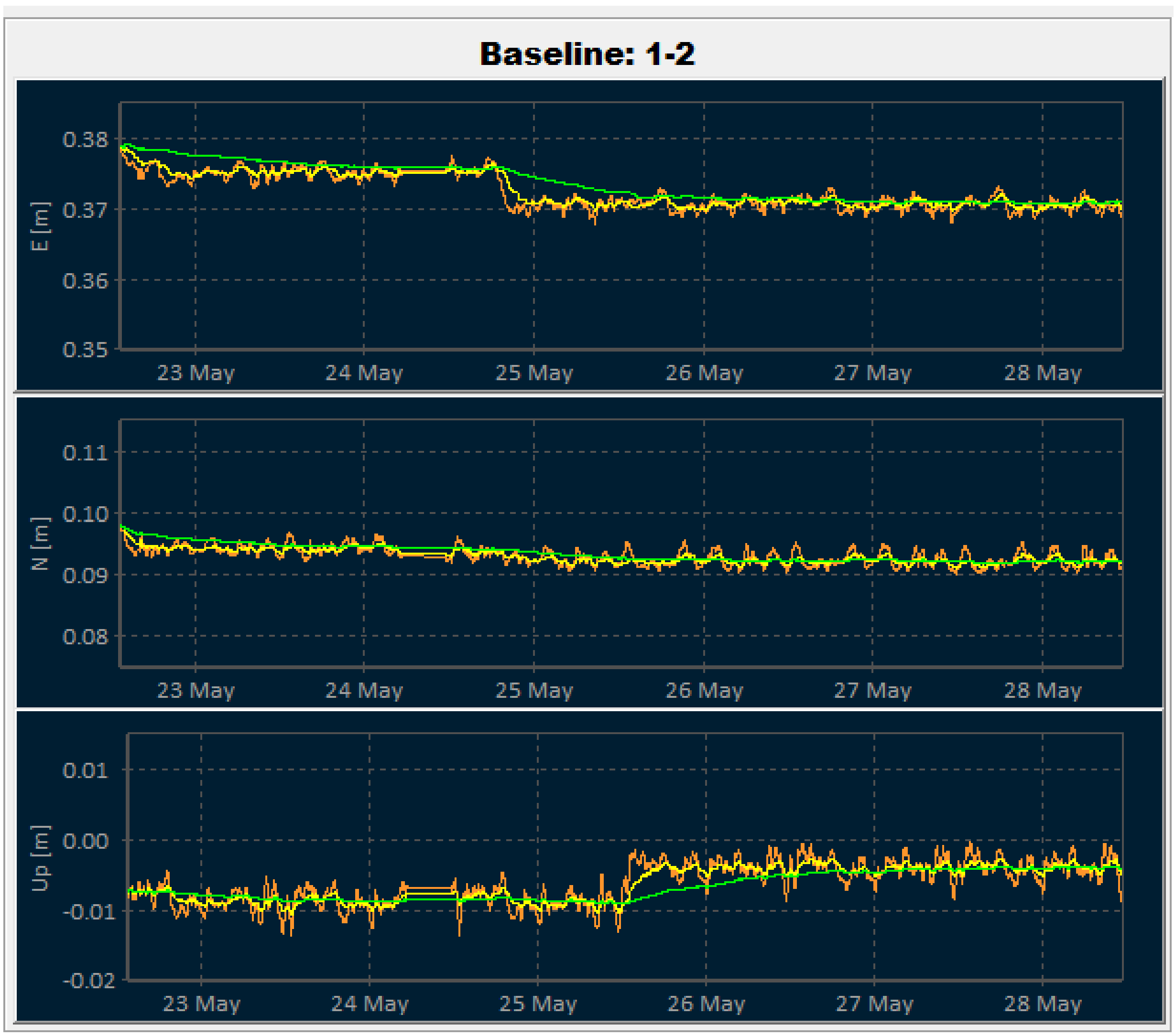

Figure 6: 5 mm displacement in the east component (top plot) detected by DDC filter with 0.2 hr TC value (orange), 1.0 hr TC value (yellow), 6.0 hr TC value (green) and subsequent 5 mm displacement in the up component (bottom plot) detected by the DDC filter with the same settings.

Figure 6 shows the 5 mm displacement in the east component and subsequent 5 mm displacement in the up component detected by DDC filter. It can be seen from the plot that the detection time of the more responsive filters (DDC TC value of 0.2 hr and DDC TC value of 1 hours) is in order of hours and in case of the less responsive filter (DDC TC value of 6 hours) is in order of days (see Table 5 and Table 6 for more details). The results of the TDD filter are not shown because the TTD filter Q values of 1 mm and 0.5 mm do not have the resolution to show the displacement and the TDD filter with 0.1 mm Q value takes a couple of days to detect the discontinuity.

Results:

The following tables show full displacement detection time from different filters from different experiments.

1. 25 mm Vertical Displacement (Translation Stage August 29, 2012)

Table 2: 25 mm vertical displacement detection time with standard filter settings.

Filter Type	**Full Displacement Detection Time**
DDC 01: TC value 0.2 hours	about 1 hour
DDC 02: TC value 1.0 hours	about 12 hours
DDC 03: TC value 6.0 hours	about 60 hours (2.5 days)
TDD 01: Q value 1.0 mm	about 4 hours
TDD 02: Q value 0.5 mm	about 24 hours (1 day)
TDD 03: Q value 0.1 mm	about 60 hours (2.5 days)

2. 5 mm Horizontal Displacement (Translation Stage June 1, 2012)

Table 3: 5 mm horizontal displacement detection time with standard filter settings.

Filter Type	**Full Displacement Detection Time**
DDC 01: TC value 0.2 hours	about 3 hours
DDC 02: TC value 1.0 hours	about 12 hours
DDC 03: TC value 6.0 hours	about 60 hours (2.5 days)
TDD 01: Q value 1.0 mm	N/A
TDD 02: Q value 0.5 mm	N/A
TDD 03: Q value 0.1 mm	about 120 hours (5 days)

Table 4: 5 mm horizontal displacement detection time with non-standard filter settings.

Filter Type	**Full Displacement Detection Time**
DDC 02: TC value 1.0 hours	about 10 hours
DDC 03: TC value 3.0 hours	about 36 hours (1.5 days)
TDD 02: Q value 0.1 mm	about 120 hours (5 days)
TDD 03: Q value 0.01 mm	over 144 hours (over 6 days)

3. 5 mm Horizontal and Subsequent 5 mm Vertical Displacement (Translation Stage May 22, 2012)

Table 5: 5 mm horizontal displacement detection time with standard filter settings.

Filter Type	**Full Horizontal Displacement Detection Time**
DDC 01: TC value 0.2 hours	about 2 hours
DDC 02: TC value 1.0 hours	about 6 hours
DDC 03: TC value 6.0 hours	about 24 hours (1.0 days)

Table 6: 5 mm vertical displacement detection time with standard filter settings.

Filter Type	**Full Vertical Displacement Detection Time**
DDC 01: TC value 0.2 hours	about 2 hours
DDC 02: TC value 1.0 hours	about 7 hours
DDC 03: TC value 6.0 hours	about 24 hours (1.0 days)

Summary:

From Table 2, Table 3, Table 4, Table 5 and Table 6 it can be seen that:

1. the DDC filter with TC value of 0.2 hr detects the displacement in 1 hours in case of 25 mm displacement and 2 or 3 hours in cases of 5 mm displacements.
2. the DDC filter with TC value of 1.0 hr detects the displacement in about 10 hours regardless of the size of the displacement.
3. the DDC filter with TC value of 6.0 hr detects the displacement in about 24 hours regardless of the size of the displacement.

The TDD filter settings had to be customized for to detect 5 mm displacement. For this size of displacement there does not seem to be a TDD filter with a specific Q value which would detect the displacement in the order of hours with high enough resolution.

Conclusions:

In the experiments described above all horizontal and vertical displacements were detected. It can be seen that larger TC values provide higher precision solutions but increase the time required for displacement detection.

The tables (Table 2, Table 3, Table 4, Table 5 and Table 6) show that the detection time of the more responsive filter (DDC TC value of 0.2 hr) is in order of from hours for both displacements and in case of the less responsive filters (DDC TC value of 1 hr and DDC TC value of 6 hour) is in order of days to detect the full displacement.

Vertical displacements of 25 mm and 5 mm were detected in the tests. Horizontal displacements of 5 mm were detected as well. It can be concluded that the direction of the displacement does not have an impact on the filter's ability to detect the displacement.

Recommendations:

The first recommendation is to repeat the experiment with different types of GPS receivers.

The second recommendation is to use the knowledge of the potential size of the displacement of a specific structure in the filter tuning process as there is no universal TDD filter Q value which would detect all displacements.

For further characterization of the TDD filter Q value, it is also recommended to change the TDD filter initialization time from days to weeks. This is mainly due to the slow convergence nature of the TDD filter.

It can be seen from the experiments that both TDD and DDC filters with default settings i.e. TDD Q values of 1.0 mm, 0.5 mm and 0.1 mm. DDC TC values of 0.2 hr, 1.0 hr, 6.0 hr can detect 25 mm displacement. 1 mm sudden displacement will be most likely very hard to detect. The third recommendation is to repeat the experiments for a variety a displacements from 25 mm down to 1mm.

