Kinematic Monitoring for Baselines Ranging from 3m to 30km

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1.0 INTRODUCTION

This report investigates the accuracy and reliability for the continuous trajectory determination of a moving object. Data in this report was originally treated as fully kinematic meaning that no dynamic constraints were employed. Also shown is a filtered trajectory, which would be suitable for capturing long-term measurements at the cm level. As accuracy degrades with baseline length, various lengths were investigated ranging from 3 meters to 30 kilometers.

For reasonable results to take place, the following standards should be met:

- Good GPS conditions
- Average 6+ satellites
- No signal blockage causing loss of lock
- Dual Frequency receivers

We gratefully acknowledge the Southern California Integrated GPS Network (SCIGN) and its sponsors, the W.M. Keck Foundation, NASA, NSF, USGS, SCEC, for providing data used in this analysis.

2.0 ANALYSIS OF SHORTER BASELINES

2.1 Test #1 - Baseline length of 3 meters

Two static GPS base stations were downloaded that have a baseline length of approximately 3 meters. The master station is CARH and remote station CARR are located in the Monterey county of California. The remote file was set to kinematic to simulate the effects of a moving object. Waypoint's Kinematic Ambiguity Resolution (KAR) algorithm was continuously invoked over a 24 hour period. The data was differentially processed using the following options:

- Both directions, Dual Frequency, Float Solution, KAR ON.
- 'Use L2 for Ionospheric Processing' must be disabled for short baselines (less than 10 km).
- 'Engage KAR continuously every 5-15 minutes.' This is important. For CARH to CARR, the engage time is every 5 minutes.
- C/A Code Standard Deviation = 3.00 meters.

After processing, the kinematic trajectory is also further filtered using a simple Kalman filter. It uses a simple velocity model and employs spectral densities equivalent to a low pass filter window of about 12 hours. Figure 1 and Figure 2 show the error of the raw (unfiltered) and filtered trajectories of the easting and northing directions respectively.

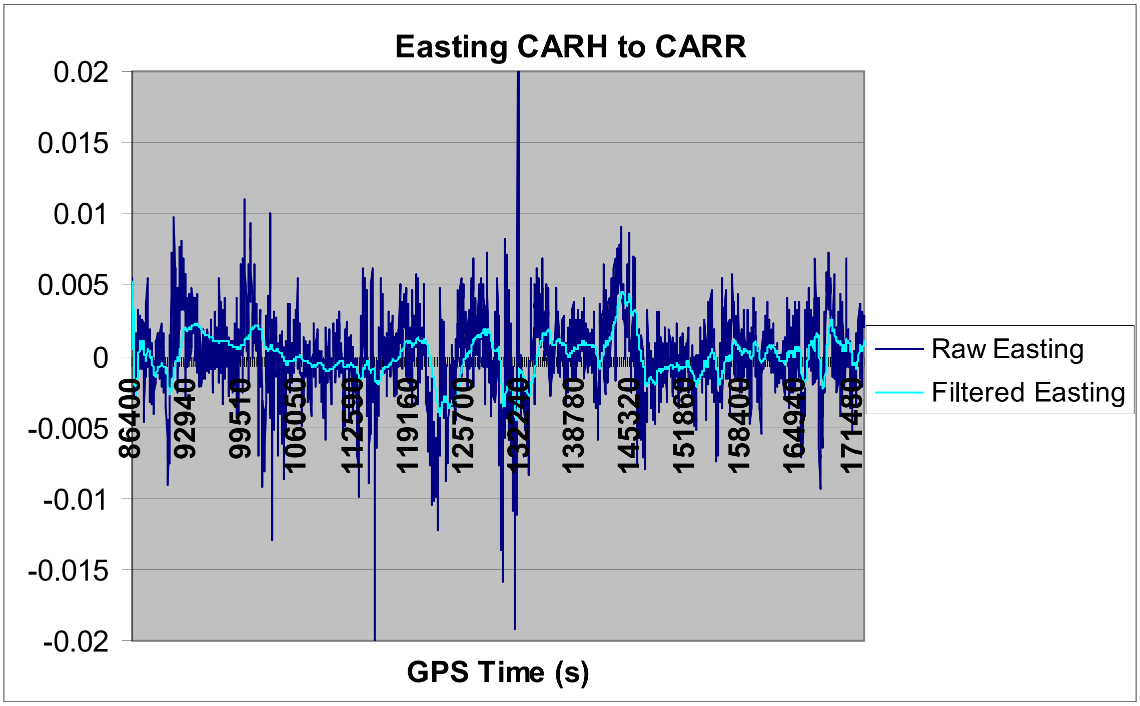

Figure 1 - Raw and Filtered Delta Easting – 3 meter baseline

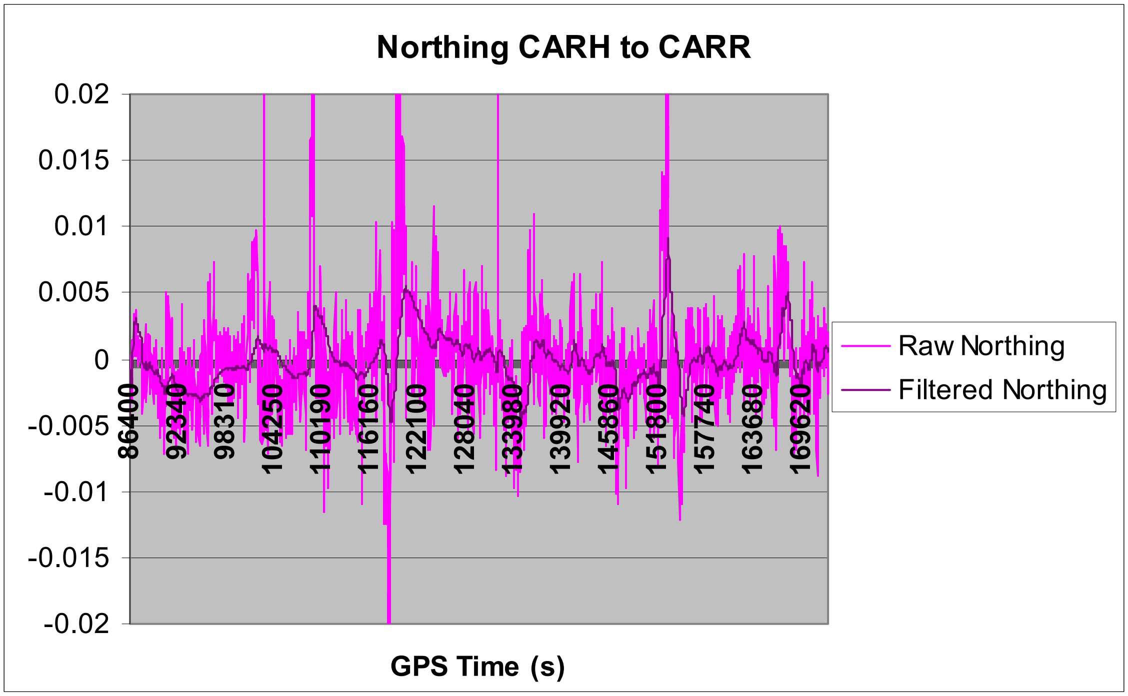

Figure 2 - Raw and Filtered Delta Northing – 3 meter baseline

We can observe the noise of the unfiltered data, plus the ‘line of best fit’ that is generated by the Kalman filter. It is seen in the eastings and northings that the station does not move. Large jumps or spikes during the unfiltered aspects can be attributed to a low number of satellites or a significant increase in the carrier phase RMS values. Figure 3 and Figure 4 show the number of satellites plot and L1 phase RMS plot respectively.

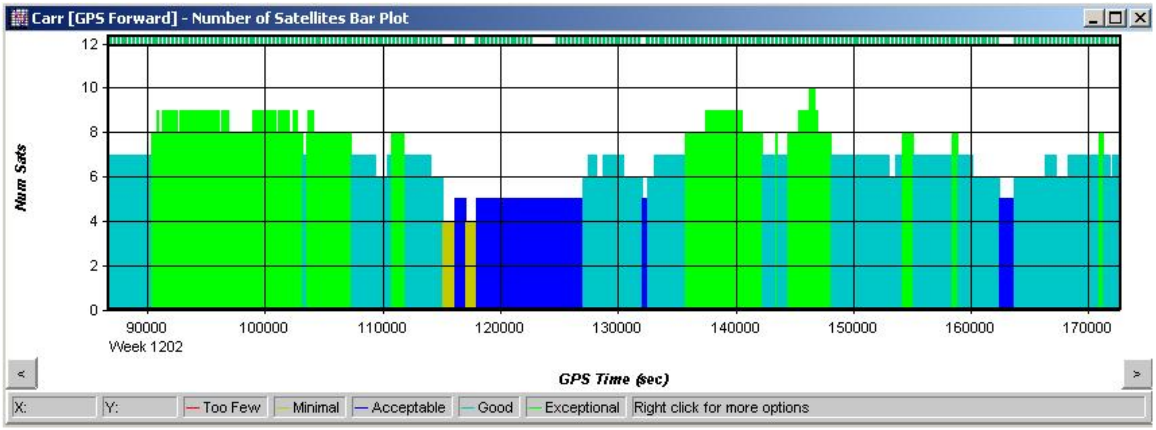

Figure 3 - Number of Satellites Plot – 3 meter baseline

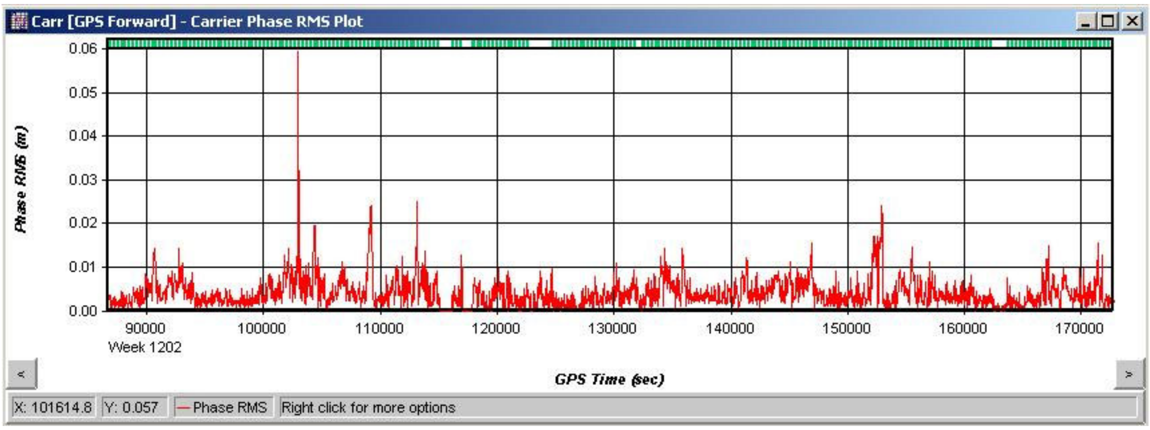

Figure 4 - L1 Phase RMS Plot – 3 meter baseline

There are separate events of significant increases of L1 phase RMS values as well as a low number of satellites. These can be associated correspondingly to the unfiltered aspects in Figure 1 and Figure 2.

Statistics of CARH to CARR (3 meters) (30 second data interval):

Number of raw Easting within **+/-** 5mm: **89.9%**
Number of raw Northing within **+/-** 5mm: **84.2%**
Number of raw Easting within **+/-** 10mm: **99.1%**
Number of raw Northing within **+/-** 10mm: **96.2%**

Average used KAR time (forward): **60 seconds / 2 epochs**
Percentage of no solution (forward): **6.25%**

Percent KAR Successes (forward): **100%**
Average used KAR time (reverse): **60 seconds / 2 epochs**
Percentage of no solution (reverse): **6.94%**
Percent KAR Successes (reverse): **99.65%**

2.2 Test #2 - Baseline length of 400 meters

Two more base stations were downloaded having a 400 meter separation between the master and remote. The master station is CTDM and the remote is FHFF, located in the Los Angeles region of California. KAR was set to engage every 10 minutes and using the same processing options and Kalman Filter Program, filtered results were obtained. Figure 5 and Figure 6 display the filtered graphs.

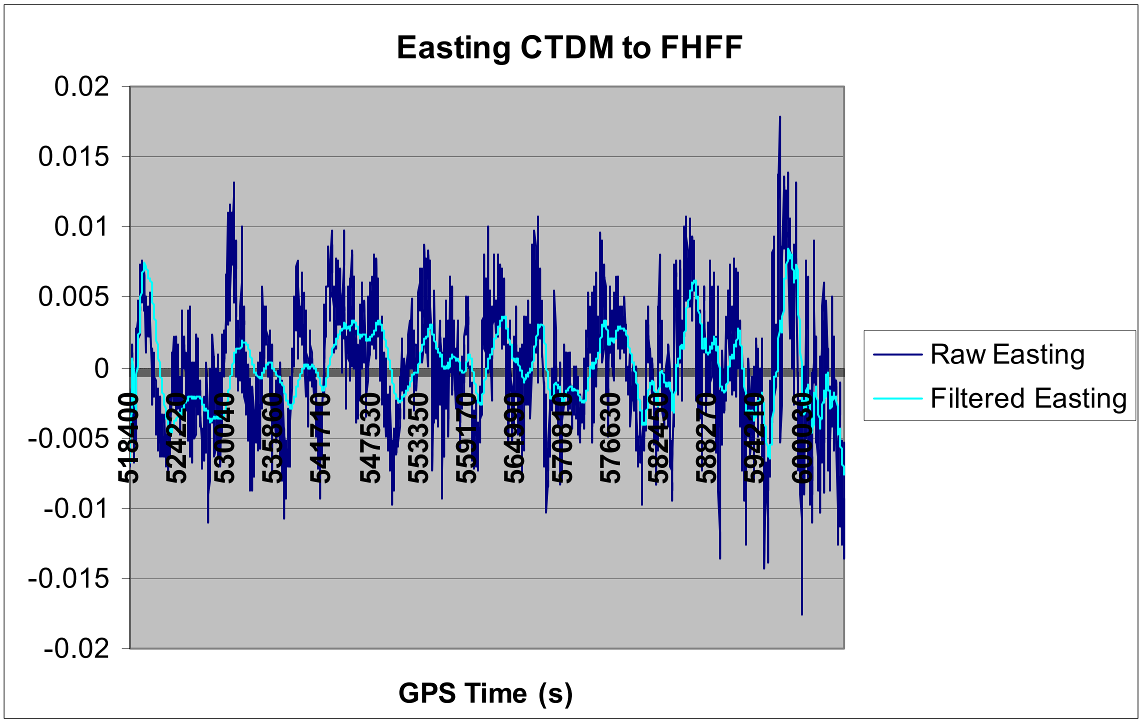

Figure 5 - Raw and filtered Delta Easting – 400 meter baseline

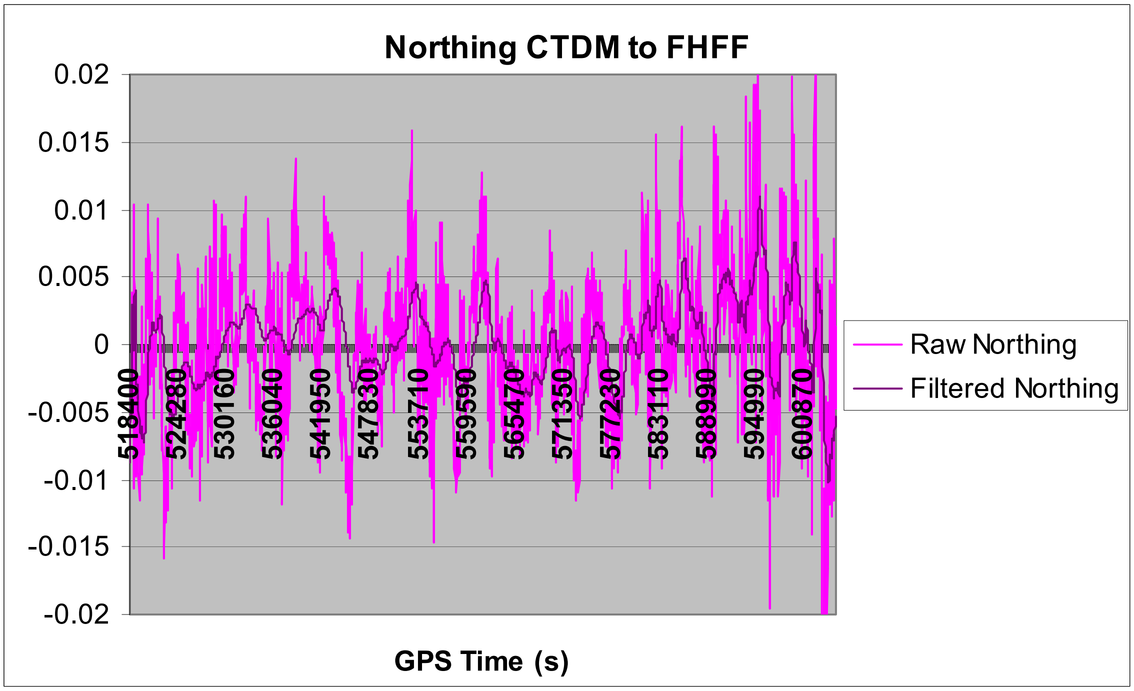

Figure 6 - Raw and Filtered Delta Northing – 400 meter baseline

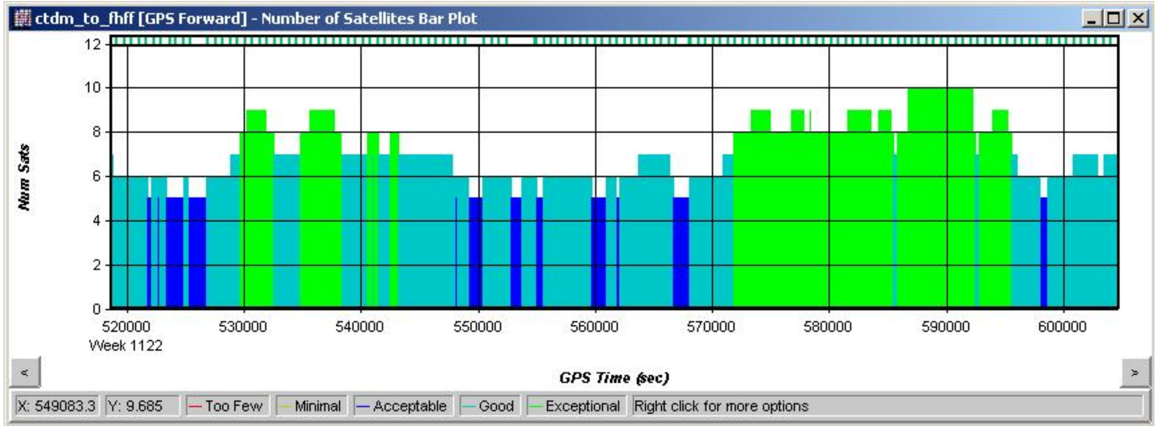

Figure 7 - Number of Satellites Plot – 400 meter baseline

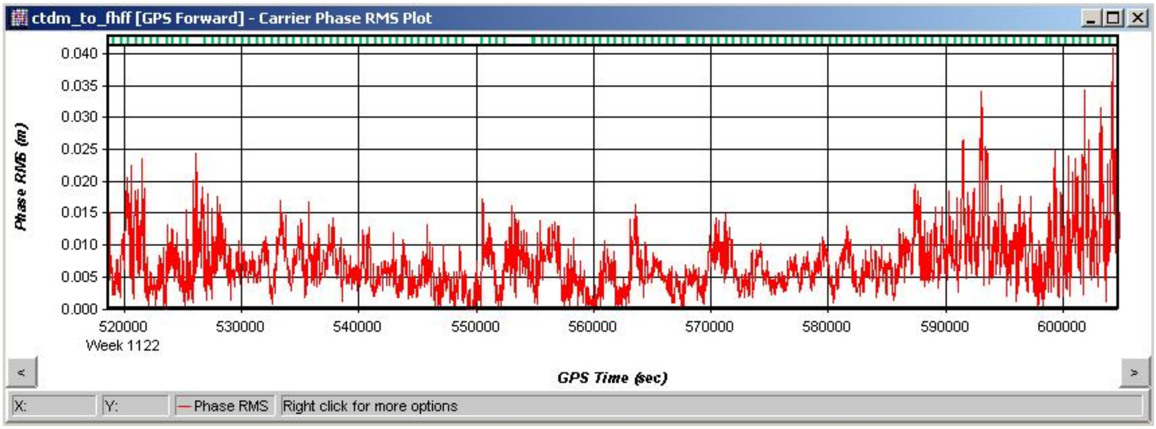

Figure 8 - L1 Phase RMS Plot – 400 meter baseline

There is an increase of phase noise near the end of Figure 8 that corresponds to an increase in noise of the unfiltered data in Figure 5 and Figure 6.

Statistics of CTDM to FHFF (400 meters) (30 second data interval):

Number of raw Easting within +/- 5mm: **74.7%**
Number of raw Northing within +/- 5mm: **65.1%**
Number of raw Easting within +/- 10mm: **97.8%**
Number of raw Northing within +/- 10mm: **93.0%**

Average used KAR time (forward): **90 seconds / 3 epochs**
Percentage of no solution (forward): **6.25%**
Percent KAR Successes (forward): **98.61%**
Average used KAR time (reverse): **90 seconds / 3 epochs**
Percentage of no solution (reverse): **5.56%**
Percent KAR Successes (reverse): **97.91%**

2.3 Test #3 – Baseline length of 1.8 kilometers

The next two base stations downloaded are located in the Monterey county of California. The base station is POMM and the remote is MIDA, with a separation of about 1.8km. KAR was engaged for every 10 minutes.

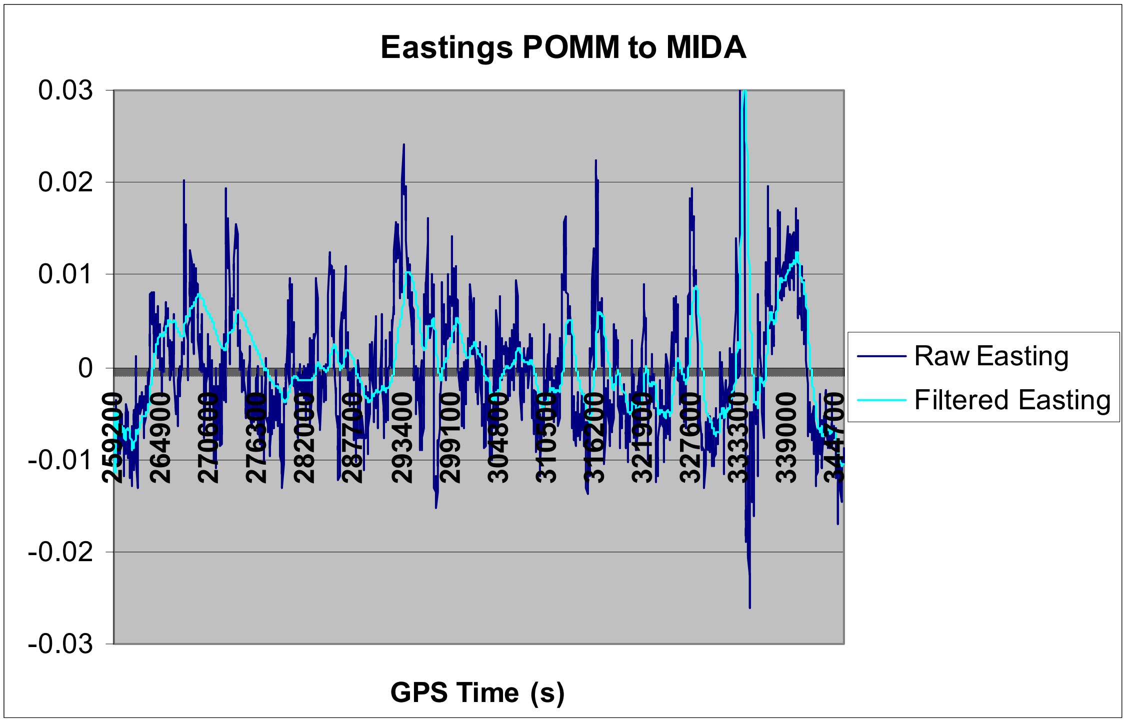

Figure 9 - Raw and Filtered Delta Easting – 1.8 km baseline

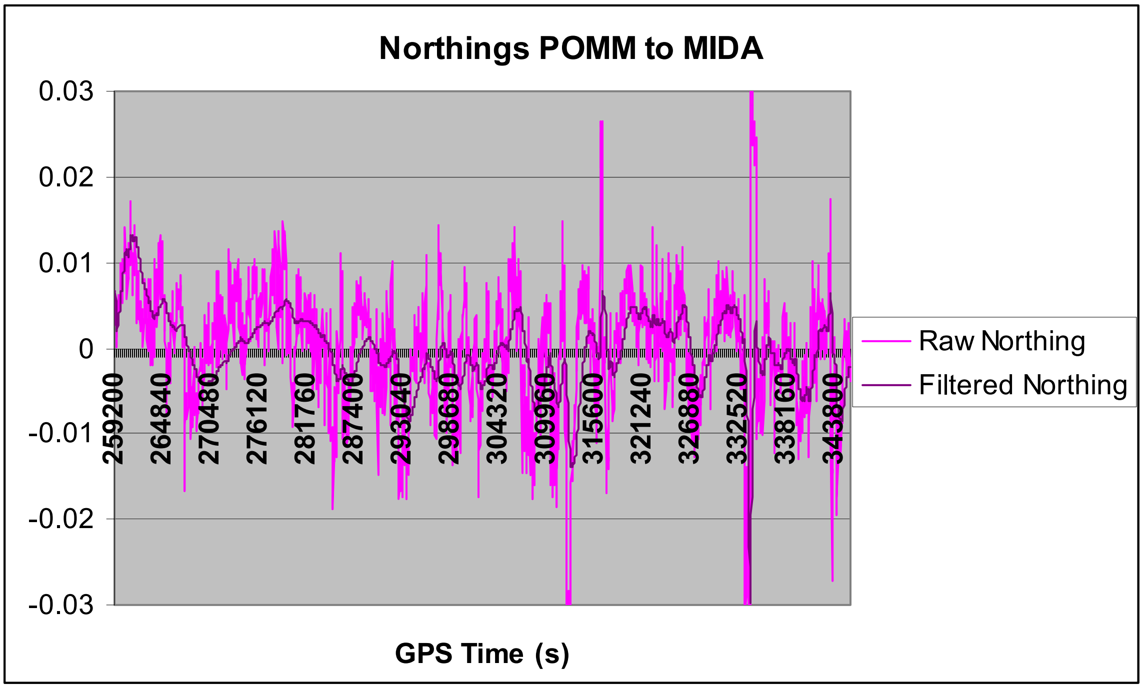

Figure 10 - Raw and Filtered Delta Northing – 1.8 km baseline

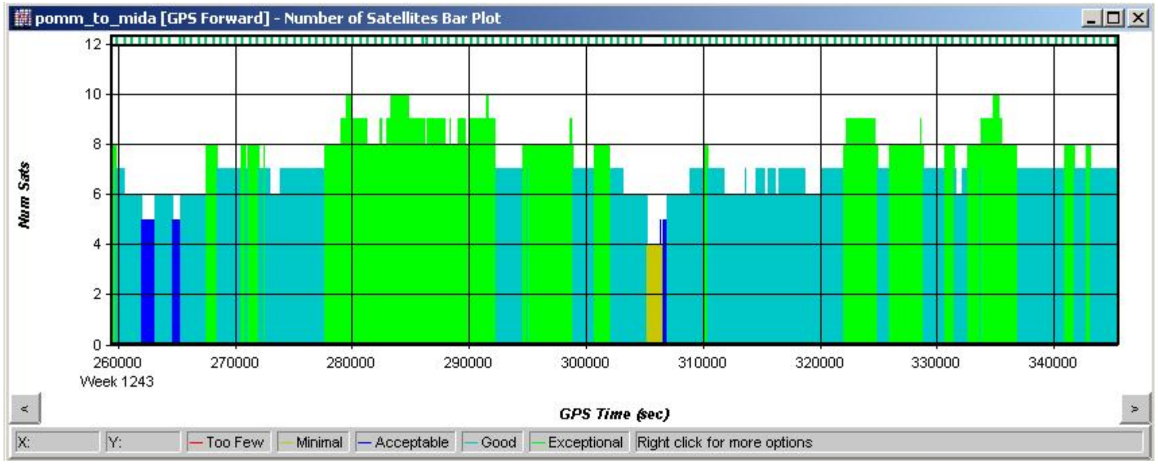

Figure 11 - Number of Satellites Plot – 1.8 km baseline

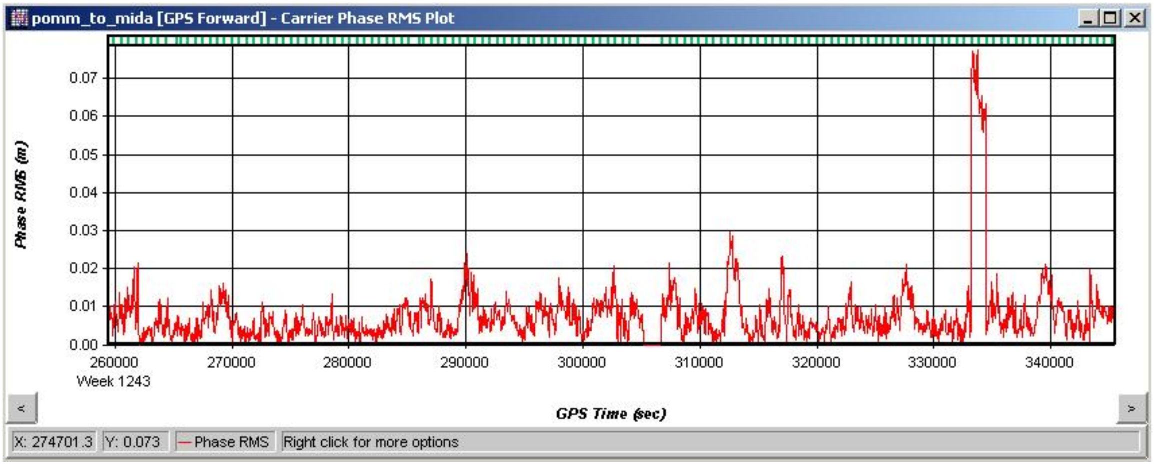

Figure 12 - L1 Phase RMS Plot – 1.8 km baseline

Statistics of POMM to MIDA (1.8 km) (30 second data interval):

Number of raw Easting within **+/-** 5mm: **50.5%**
Number of raw Northing within **+/-** 5mm: **55.7%**
Number of raw Easting within **+/-** 10mm: **86.0%**
Number of raw Northing within **+/-** 10mm: **86.4%**

Average used KAR time (forward): **90 seconds / 3 epochs**
Percentage of no solution (forward): **5.56%**
Percent KAR Successes (forward): **97.22%**
Average used KAR time (reverse): **90 seconds / 3 epochs**
Percentage of no solution (reverse): **6.25%**
Percent KAR Successes (reverse): **96.53%**

3.0 ANALYSIS OF LONGER BASELINES

3.1 Test #4 – Baseline length of 10 kilometers

This next portion of the report will deal with longer baselines and their overall effects. The base station CVHS and remote station VYAS contains 24 hours of data and has a separation of 10 km, located in Los Angeles. The longer baseline will introduce more significant effects from the ionosphere so it is important that corrections are imposed during processing. Under the Dual Frequency tab, enable the option 'Use L2 for Ionospheric Processing' and select the iono-free model. Figure 13 and Figure 14 show the graphs of the 10 km baseline, with KAR being engaged every 10 minutes.

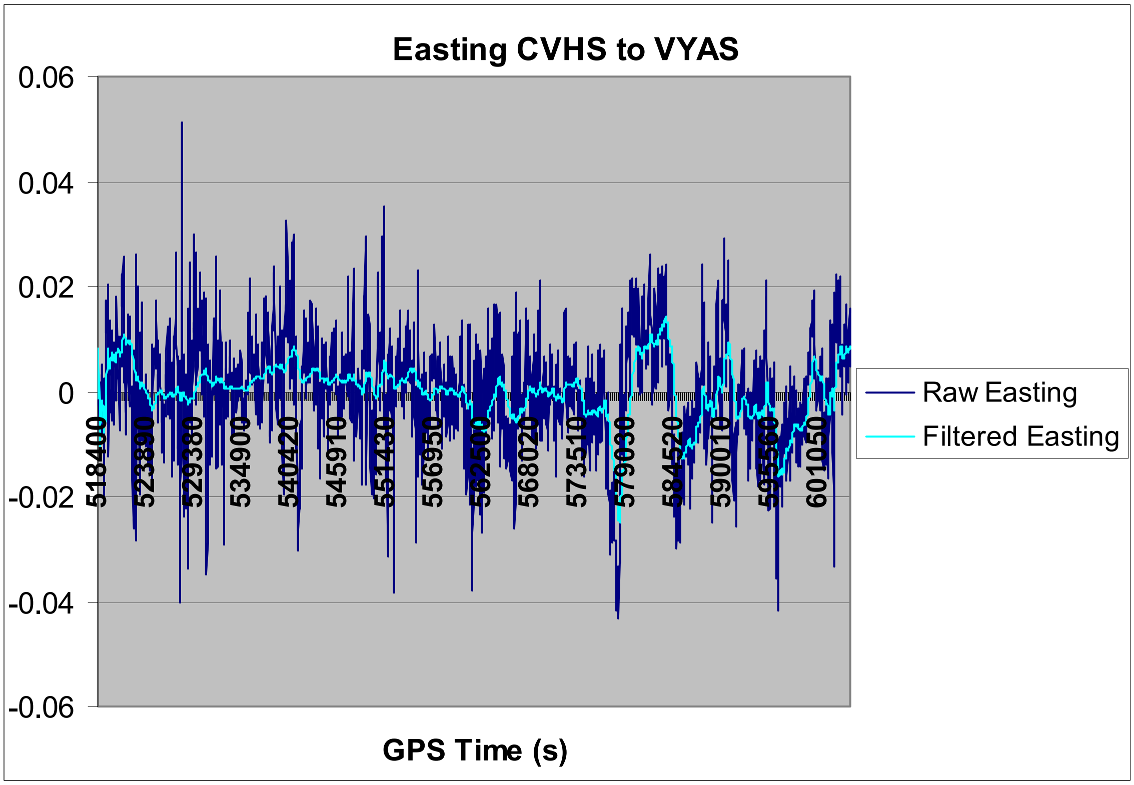

Figure 13 - Raw and filtered Delta Easting – 10 km baseline

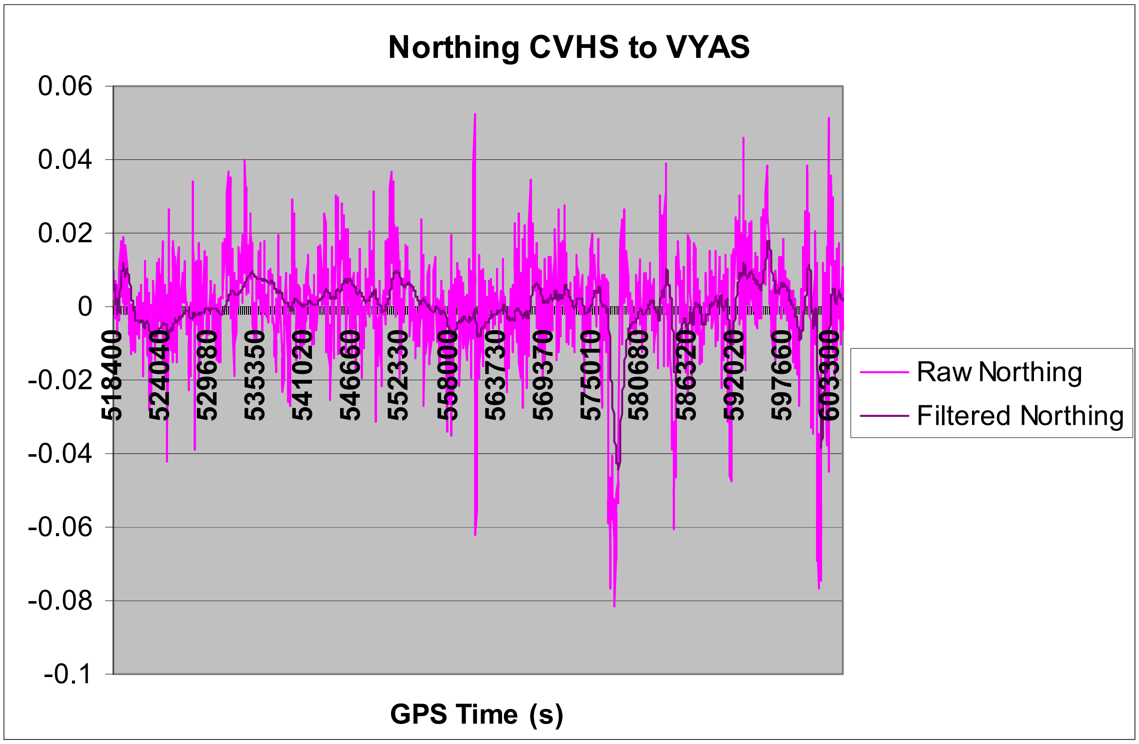

Figure 14 - Raw and Filtered Delta Northing – 10 km baseline

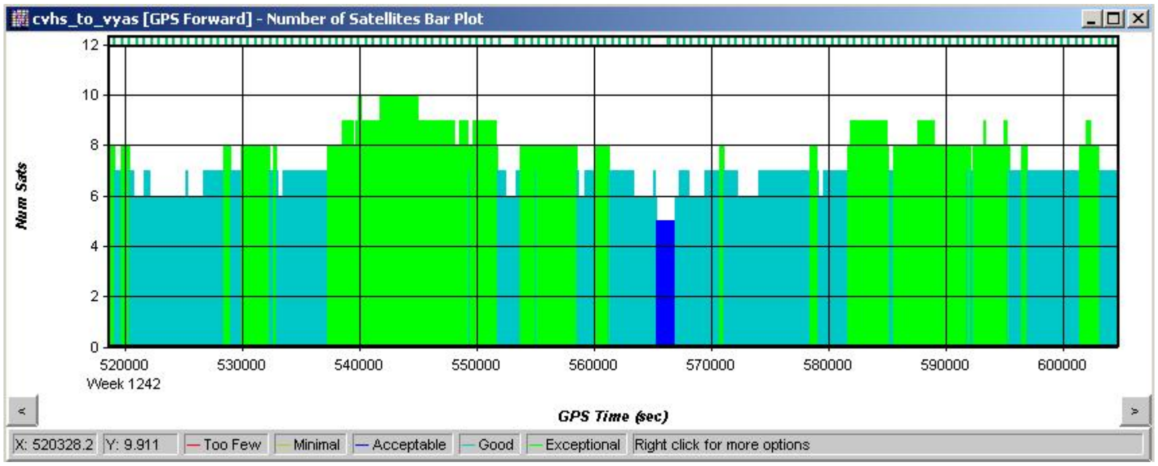

Figure 15 - Number of Satellites Plot – 10 km baseline

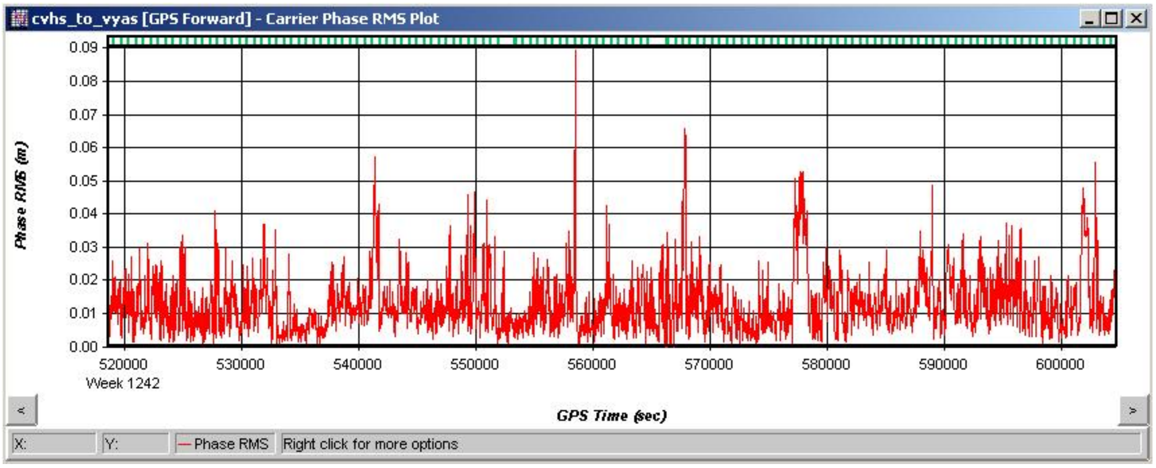

Figure 16 - L1 Phase RMS Plot – 10 km baseline

More noise is evident as the spikes reach +/- 4cm in Figure 13 and Figure 14. They seem to correspond to intense variations in L1 RMS phase values.

<u>Statistics of CVHS to VYAS (10 km) (30 second data interval):</u>

Number of raw Easting within **+/-** 10mm: **69.7%**
Number of raw Northing within **+/-** 10mm: **64.3%**
Number of raw Easting within **+/-** 20mm: **93.6%**
Number of raw Northing within **+/-** 20mm: **89.2%**

Average used KAR time (forward): **210 seconds / 7 epochs**
Percentage of no solution (forward): **5.56%**
Percent KAR Successes (forward): **95.83%**
Average used KAR time (reverse): **240 seconds / 8 epochs**
Percentage of no solution (reverse): **5.56%**
Percent KAR Successes (reverse): **91.67%**

3.2 Test #5 – Baseline length of 20 kilometers

A 20 km baseline with base station CGDM and remote JPLM located in Los Angeles is shown Figure 17 and Figure 18. More noise is present in those graphs. KAR was engaged every 10 minutes, and L2 was used for ionospheric processing.

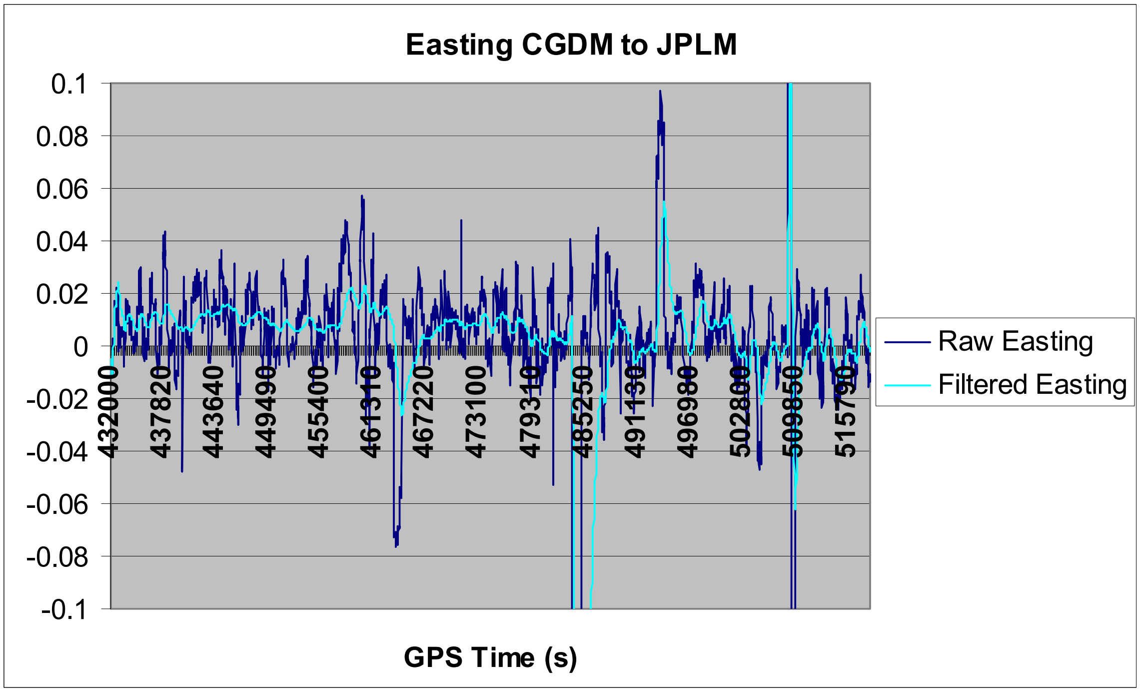

Figure 17 - Raw and Filtered Delta Easting – 20 km baseline

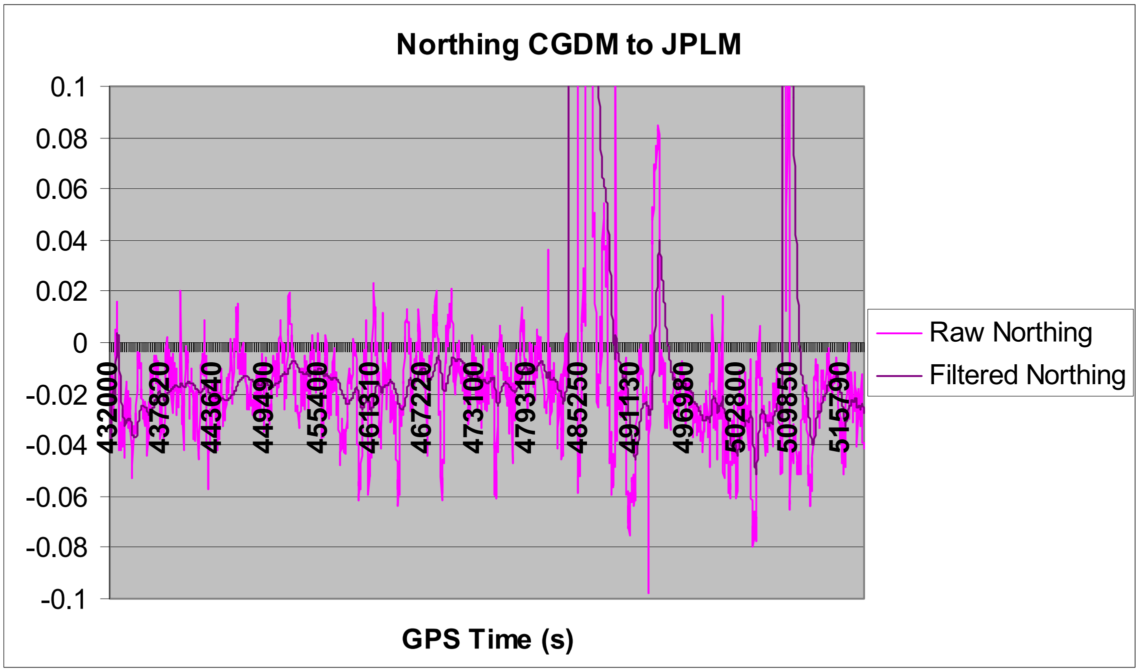

Figure 18 - Raw and Filtered Delta Northing – 20 km baseline

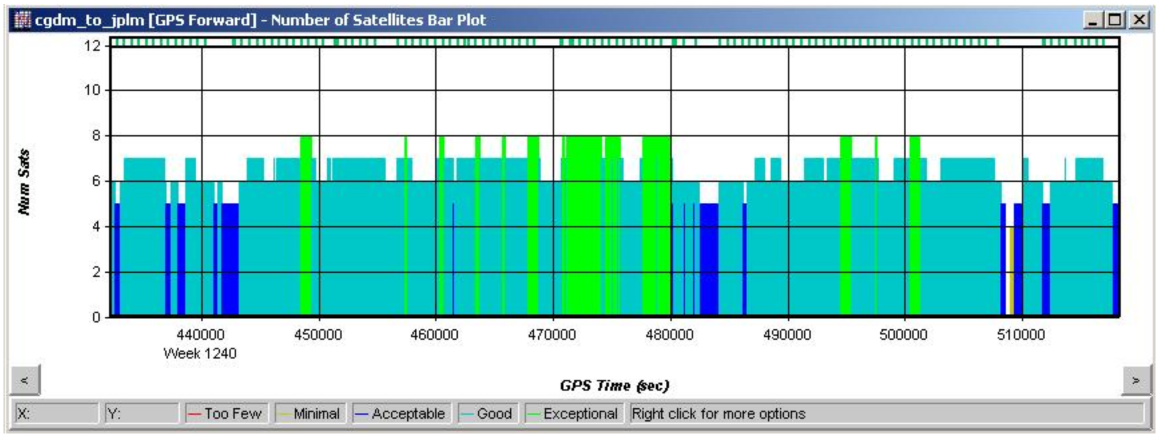

Figure 19 - Number of Satellites Plot – 20 km baseline

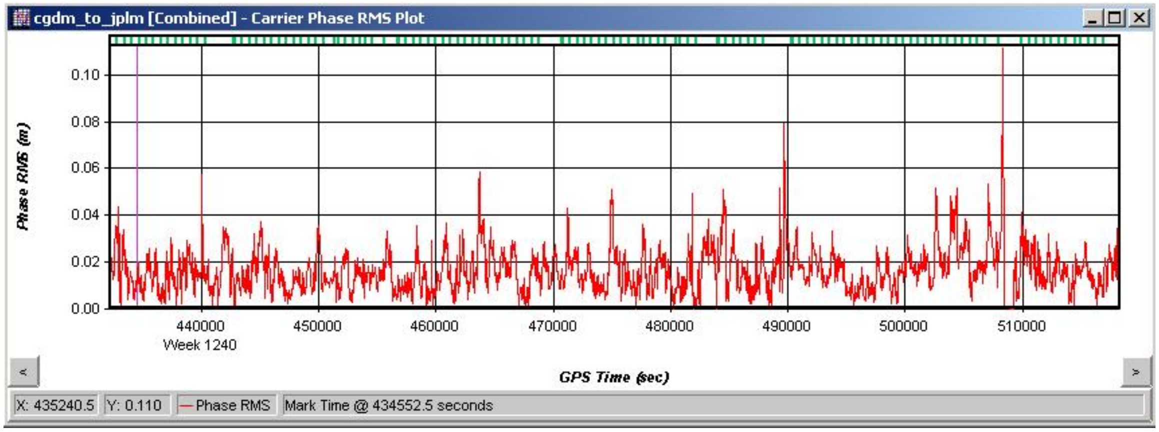

Figure 20 - L1 Phase RMS Plot – 20 km baseline

<u>Statistics of CGDM to JPLM (20 km) (30 second data interval):</u>

Number of raw Easting within **+/-** 10mm: **49.7%**
Number of raw Northing within **+/-** 10mm: **20.9%**
Number of raw Easting within **+/-** 20mm: **77.5%**
Number of raw Northing within **+/-** 20mm: **46.7%**

Average used KAR time (forward): **390 seconds / 13 epochs**
Percentage of no solution (forward): **13.19%**
Percent KAR Successes (forward): **92.36%**
Average used KAR time (reverse): **390 seconds / 13 epochs**
Percentage of no solution (reverse): **10.42%**
Percent KAR Successes (reverse): **91.67%**

3.3 Test #6 – Baseline length of 30 kilometers

A 30 km baseline with base station BSRY and remote WOMT located in San Bernardinois shown Figure 21 and Figure 22. Fairly good GPS conditions are evident in the first two-thirds of the day. KAR was engaged every 10 minutes and L2 for ionospheric processing was enabled.

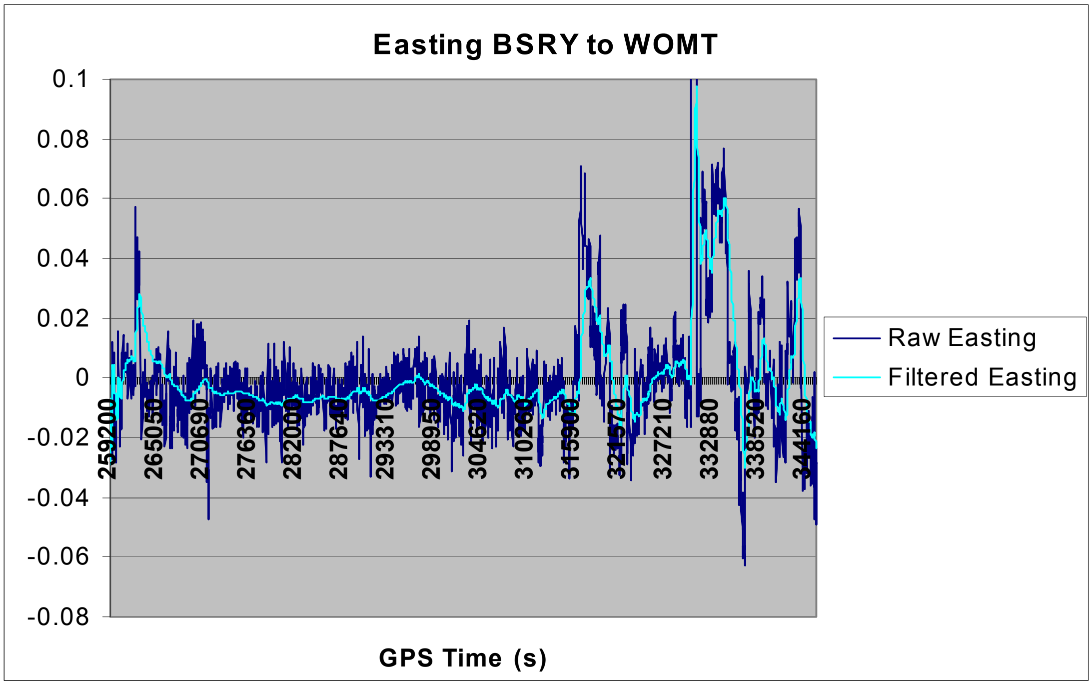

Figure 21 - Raw and Filtered Delta Easting – 30 km baseline

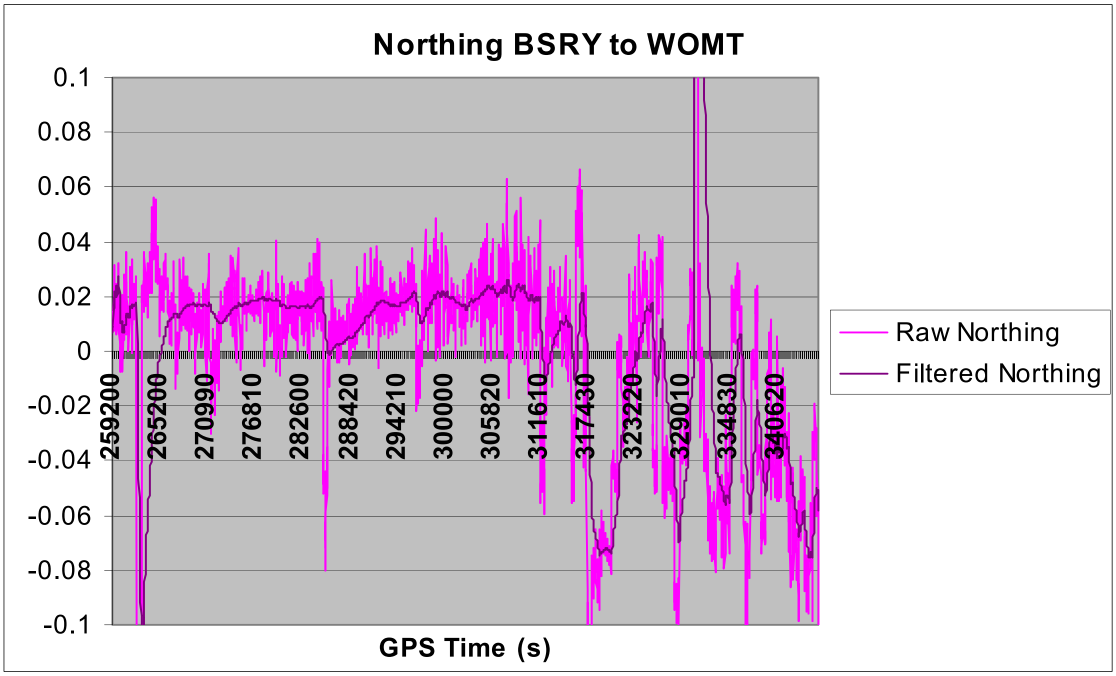

Figure 22 - Raw and Filtered Delta Northing – 30 km baseline

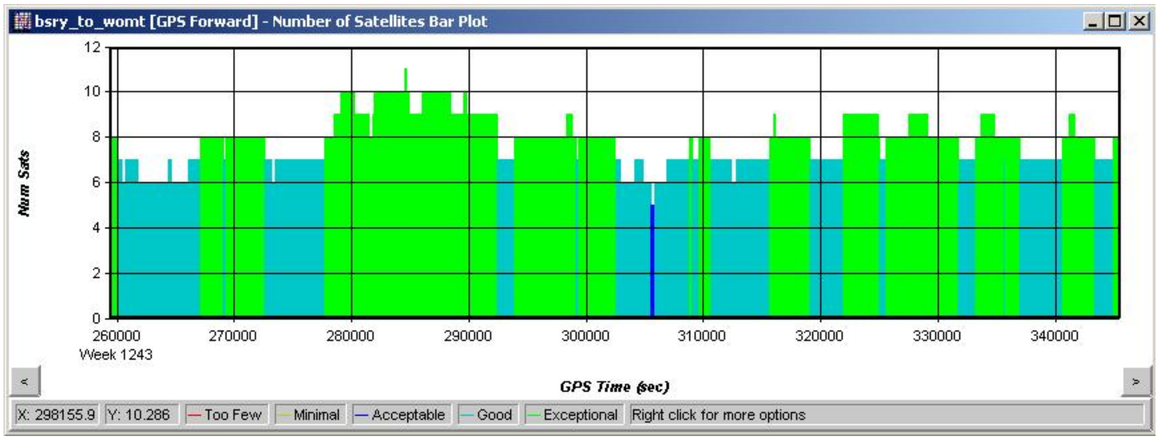

Figure 23 - Number of Satellites Plot – 30 km baseline

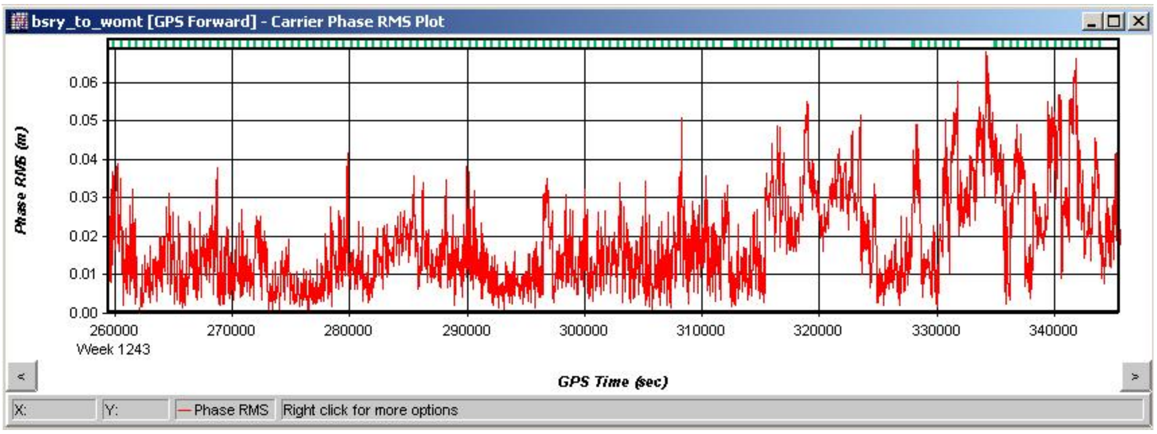

Figure 24 - L1 Phase RMS Plot – 30 km baseline

<u>Statistics of BSRY to WOMT (30 km) (30 second data interval):</u>

Number of raw Easting within **+/-** 10mm: **58.8%**
Number of raw Northing within **+/-** 10mm: **19.0%**
Number of raw Easting within **+/-** 20mm: **84.1%**
Number of raw Northing within **+/-** 20mm: **47.3%**

Average used KAR time (forward): **450 seconds / 15 epochs**
Percentage of no solution (forward): **11.11%**
Percent KAR Successes (forward): **84.72%**
Average used KAR time (reverse): **450 seconds / 15 epochs**
Percentage of no solution (reverse): **11.11%**
Percent KAR Successes (reverse): **85.42%**

4.0 SUMMARY

The data in Table 1 below contains a summary of the raw data aspects of each test:

Baseline Length	% Raw East +/- 5 mm	% Raw North +/- 5 mm	% Raw East +/- 10 mm	% Raw North +/- 10 mm	% Raw East +/- 20 mm	% Raw North +/- 20 mm
3 m	89.9	84.2	99.1	96.2	-	-
400 m	74.7	65.1	97.8	93.0	-	-
1.8 km	50.5	55.7	86.0	86.4	-	-
10 km	-	-	69.7	64.3	93.6	89.2
20 km	-	-	49.7	20.9	77.5	46.7
30 km	-	-	58.8	19.0	84.1	47.3

Table 1 – Raw Data Statistical Summary

These values are mutually independent. Multiply the eastings and northings together to obtain a 2-dimensional statistical vector. Table 2 below shows the KAR statistical summary for each test:

Baseline Length	Avg. Fwd. KAR Time (s) / # epochs	Avg. Rev. KAR Time (s) / # epochs	% No Fwd KAR Sol'n	% No Rev KAR Sol'n	% Fwd. KAR Success	% Rev. KAR Success
3 m	60 / 2	60 / 2	6.25	6.94	100	99.65
400 m	90 / 3	90 / 3	6.25	5.56	98.61	97.91
1.8 km	90 / 3	90 / 3	5.56	6.25	97.22	96.53
10 km	210 / 7	240 / 8	5.56	5.56	95.83	91.67
20 km	390 / 13	390 / 13	13.19	10.42	92.36	91.67
30 km	450 / 15	450 / 15	11.11	11.11	84.72	85.42

Table 2 - KAR Statistics Summary

The percentage of no forward and reverse KAR solutions indicate how often KAR does not engage. There are many factors that can cause KAR not to engage at all. A minimum of 5 satellites is required and 6 or more satellites are recommended. Satellite geometry is also another factor that decides whether KAR will turn on. Poor geometry resulting in high DOP's will prevent KAR from engaging. Other aspects such as bad GPS measurements or very long baseline length inhibit KAR from performing a search.

The percentage of KAR successes means how well KAR chooses the forward and reverse solution at the engage time. This is best examined at the combined separation plot. Figure 25 illustrates an example of a bad KAR fix in the forward/reverse separation. It is well classified because it is box shaped between the forward and reverse KAR engage times. The KAR engage times (forward and reverse) are shown by the green and blue ticks at the top of the plot respectively. There are other incidents of spikes in the separation, but they are caused by bad GPS measurements and confirmed in the message log. These do not count as a bad KAR fix.

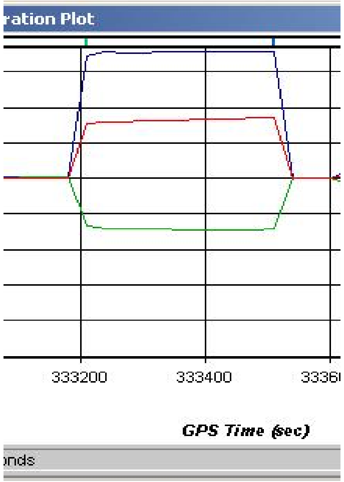

Figure 25 - Bad KAR Fix

5.0 CONCLUSION

The tables in the Summary show how accurate the data can be as a function of baseline length, as well as statistical quality on Waypoint's Kinematic Ambiguity Resolution algorithm for each baseline. It was expected that accuracy would degrade as the baseline increased in length. Generally the rule of thumb in terms of accuracy for kinematic short baseline processing is 2cm + 1PPM while maintaining a lock in GPS signals. We can observe that this is preserved quite well. For those applications that require stable and accurate monitoring of a moving object will require a short baseline, dual frequency data, and good GPS conditions.

The length of each epoch in these datasets is 30 seconds, which explains the high amount of KAR time used to resolve ambiguities. In addition, the software uses 60 s + 90 s/10km as a minimum for purposes of reliability. This also increases the time required for longer baselines. The percentage of KAR successes appears to be a function of the baseline length. KAR was designed to resolve ambiguities on shorter baselines, so it is recognized that KAR will perform better fixes when the base station and the remote are not too far apart (i.e. having common satellites is important). The percentage of no KAR solution is based on the quality of the GPS data and appears to be of consistent value for the shorter baselines. This may be because the data is located in southern California, which results in satellite coverage oscillating from 5-9 satellites during the 24 hour period. Instances of high DOP's at a particular time will prevent KAR from engaging.