Advances in RTK and Post Processed Monitoring with Single Frequency GPS

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Abstract. In many monitoring applications, such as tall buildings, bridges and volcanoes, GPS offers significant advantages over other measurement techniques. GPS allows a high rate of measurement and long distances between the control and monitoring points and does not require line of sight to the control points. The traditional dual-frequency GPS receivers used in surveying are high accuracy but also relatively high cost per monitored point and therefore often prohibitive for the deployment of a GPS monitoring network. Until recently, cost effective L1 sensors and software have not been able to provide the necessary level of accuracy and reliability. A new solution from Leica Geosystems provides real time and post processed RTK positioning with L1 only GPS receivers for monitoring applications. The solution is built on Leica's RTK positioning algorithms, which have proven world-class performance in the surveying industry. The positioning algorithm used in the Leica GX1230 RTK GPS receivers has been implemented in the GPS Spider reference station software and tuned for monitoring applications, giving GPS Spider the capability to compute real time ambiguity fixed solutions for single and dual frequency GPS in addition to its powerful site configuration and data management tools. A direct link has been made between GPS Spider and Leica GeoMoS, Leica's geodetic monitoring software, so that users can combine GPS with the sophisticated terrestrial measurement capabilities of Leica's robotic total stations and utilize GeoMoS's flexible messaging and data analysis capabilities. In addition the RINEX data logged by GPS Spider may be automatically post processed for users with the highest accuracy and reliability requirements. This paper presents results from the system, including using a new ambiguity resolution technique, called quasi-static initialisation, designed for single frequency monitoring. Results from L1 processing are compared to a dual frequency solution in terms of accuracy and reliability. Data was collected with a range of baseline lengths up to 20km in medium multipath environments, typical of many monitoring applications. The L1 system is shown to have remarkable accuracy and reliability, especially in terms of price versus performance.

Keywords. GPS, single frequency, monitoring

1 Introduction

GPS is a very interesting tool for monitoring because it has a number of distinct advantages over terrestrial positioning technologies. GPS is able to measure at high rates with low latency, operate in all weather conditions, has synchronized measurement, does not require line of site to ground marks/targets, can measure over long baselines, has low maintenance and a long service life and can provide timing for other sensors, such as accelerometers. These unique characteristics make GPS particularly interesting for monitoring large structures such as high-rise buildings and suspension bridges, but also for seismic and land slide applications (e.g. van Cranenbroeck and Troyer, 2004) and for the provision of control for other instruments, such as robotic total stations, in unstable areas.

The main disadvantage of GPS for monitoring is cost. Each point to be measured must have an antenna, a receiver, ground mark, power, communications and, possibly, protection against lightning and vandalism or theft. Hence, lower cost single frequency (L1 only) GPS receivers are attractive. Single frequency GPS receivers do not require as many tracking channels making them cheaper and more energy efficient and also do not require proprietary algorithms to extract high-quality measurements from the encrypted code on the L2 frequency. The disadvantage of single frequency receivers is that much less measurement data is available to help resolve the carrier phase ambiguities and to model the ionosphere. Also, many lower cost single frequency receivers have poor multipath mitigation capabilities and are more prone to having cycle slips than their higher cost dual frequency cousins due to the use of less stable oscillators. In monitoring applications, accuracy is of paramount importance, so only ambiguity-fixed positions are of interest. A highly reliable ambiguity resolution strategy is needed to prevent wrong fixes, which will be detected immediately by the monitoring system as an apparent movement.

In this paper a comparison is made between the performance of a single frequency and a dual frequency monitoring system in terms of accuracy and reliability. The processing kernel that has been developed for this testing is based on that used in Leica Geosystems' high-end GX1230 RTK GPS sensors and the LGO software. The kernel, which is integrated into the Leica GPS Spider reference station and GPS monitoring software, is able to process single and dual frequency data in real time and post processing. Two ambiguity resolution techniques are used for this testing: kinematic on-the-fly (OTF) and a new quasi-static (QS) approach. The OTF technique allows full dynamics of the rover antenna suitable for use in formula one racing. The quasi-static approach assumes lower dynamics such as would be experienced in most monitoring applications. An overview of the GPS Spider and related software and hardware is given. The test setup is described and empirical results are presented that show the comparative performance of single and dual frequency monitoring.

2 Advanced GPS Monitoring

2.1 Overview

The traditional approach to real time GPS monitoring is to deploy RTK enabled receivers to the field, which was sent corrections from a nearby reference station. This distributed processing approach has some distinct disadvantages:

- two communications lines are required per measured point (one to receive the corrections and one to transmit the resulting coordinates),
- only one baseline can be computed per point,
- single frequency RTK is not supported,
- post processing is not possible, and
- archiving of the raw data is not possible.

In the decentralized approach used by Leica GPS Spider, only a single communication channel is required to send the raw observations to the monitoring server. Multiple baselines may be computed for each point using different reference stations or processing parameters. Single frequency RTK is supported, as is post processing and archiving of both raw data and results. In the case of unreliable communications, it is also possible to log directly to the memory of the GPS and then download the data periodically for post processing, rather than relying on having a permanent open communications channel.

The Leica GPS Spider software is a dual-purpose software. It offers comprehensive GPS reference station capabilities for the configuration and control of GPS sensors, archiving of data and dissemination of correction data for single-base and network RTK positioning. Leica GPS Spider boasts a state of the art network processing kernel designed for the new Master-Auxiliary concept (Leica Geosystems, 2005). In addition to the reference station capabilities, GPS Spider has advanced baseline processing capabilities for monitoring applications. The marriage of reference station and GPS monitoring features produces a flexible and powerful application with sophisticated communications, processing, data management and security functionality. GPS Spider may be combined with the Leica GeoMoS geodetic monitoring software for integration with robotic total stations, inclination and other geotechnical sensors and to leverage its advanced limit checks, messaging and analysis features. The baseline processing in GPS Spider is divided into two parts: real time processing and post processing.

2.2 Real Time Monitoring With GPS Spider

The real time processing kernel is based on that used in the GX1230 RTK rover, but has been modified for monitoring applications. For example, because the dynamics are lower for monitoring applications than in surveying, it has been possible to add support for single frequency RTK. The Leica SmartCheck technology, which is an evolution of the repeated search process described by Euler and Ziegler (2000), is used to continuously re-verify the ambiguity fix to ensure the highest reliability. The improved kernel in GPS Spider is able to reliably compute RTK-fixed positions from both single and dual frequency data at up to 20Hz.

In version 2.0 of the software two ambiguity resolution techniques are available: Kinematic on-the-fly (also known as OTF or While Moving initialisation) and Initialisation on Known Marker (IOKM). The OTF ambiguity resolution allows for full receiver dynamics during the initialisation at the cost of reliability, especially for single frequency processing. The IOKM ambiguity resolution assumes strictly limited receiver dynamics (which is not practical for monitoring) but has much higher reliability. For this paper a third technique has been implemented, namely quasi-static initialization (QS). The QS technique is a combination of the previous two techniques – it allows for the antenna to be in motion during the initialisation but not to the same extent as OTF initialisation.

2.3 Post Processing

The post processing kernel used in GPS Spider is based on that used in LGO. Like with the real time processing, a repeated search process is used to ensure highly reliable ambiguity resolution. In addition, the initialisation on float marker technique described by Kotthoff *et al*. (2003) is used to further improve the long range performance. Post processing intervals of between 10 minutes and 24 hours are possible for single frequency data (1 minute to 24 hours for dual frequency).

2.4 Algorithm Validation Test Setup

In order to validate the QS technique and to quantify the performance of the single frequency baseline processing in GPS Spider, test data has been collected for a range of baselines from 30m to 20km (Table 1). Position results derived from five days of 1Hz data collected using the new Leica GMX902 dual frequency monitoring GPS receivers are presented in this paper. The GMX902 (Figure 1) is a lower cost yet high performance and robust (MIL-STD-810F, ISO9022, IP67) sensor designed specifically for monitoring applications. Each baseline was processed in real time using L1 only data and using L1/L2 data and with both OTF and QSI ambiguity resolution for a total of four real time solutions per baseline. Each baseline was also post processed using both L1 only data and using L1/L2 data with periods of 10 minutes, 30 minutes and 1 hour, giving a total of six solutions per baseline for the post processing.

Table 1. List of baselines processed

Num	Station1	Station2	Baseline Length
1	HEER	BRON	30m
2	HEER	KEW1	3.3km
3	HEER	RUTH	14km
4	HEER	FLDK	20km

Figure 1. The Leica GMX902 monitoring receiver

The antennas for the sites were placed in non-ideal locations with obstructions and high multipath environments to simulate the conditions of real monitoring sites. Figures 2 through 6 show sky plots of the MP1 code multipath residuals for each site generated using the Leica GNSS QC data analysis and quality control software. The elevation mask of 10 degrees is shown as a darker grey on the sky plots. The site HEER clearly has a multipath problem in the north-east quadrant and an obstruction above 10 degrees in the north-west quadrant. The site KEW1 has particularly high multipath and also an obstruction in the north-west quadrant. RUTH has a large obstruction to the west. BRON and FLDK also have some obstructions and overall a medium level of multipath.

Fig. 2 MP1 sky plot for site HEER

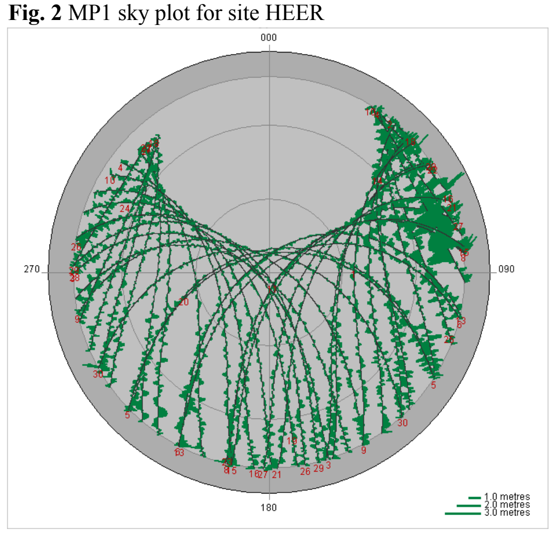


Fig. 3 MP1 sky plot for site BRON

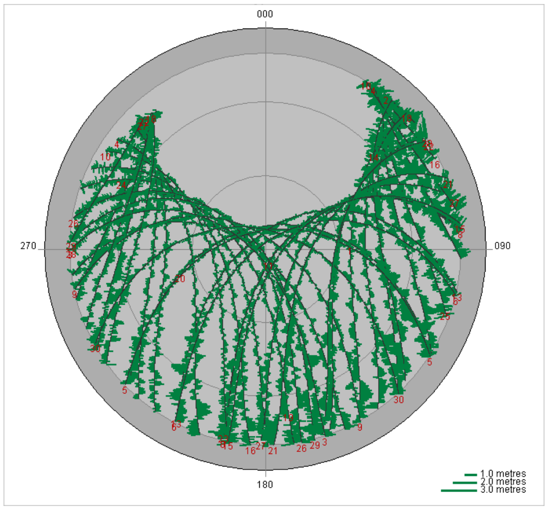


Fig. 4 MP1 sky plot for site FLDK

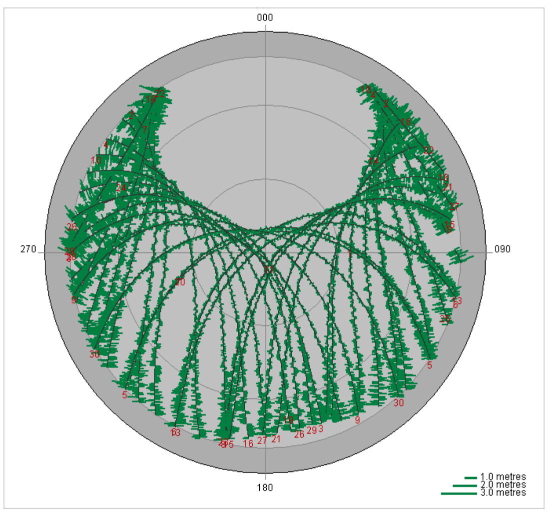


Fig. 5 MP1 sky plot for site KEW1

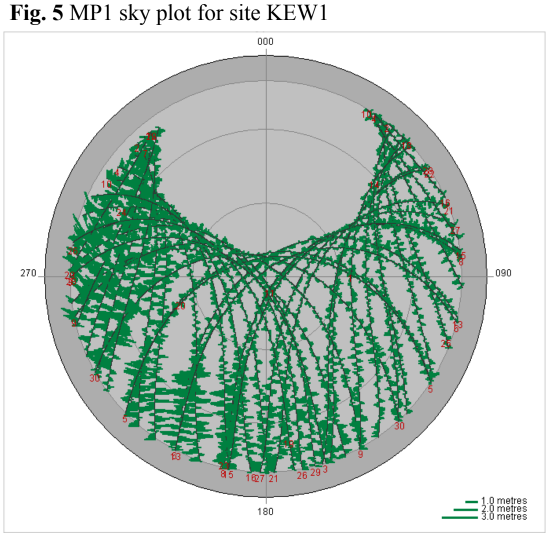
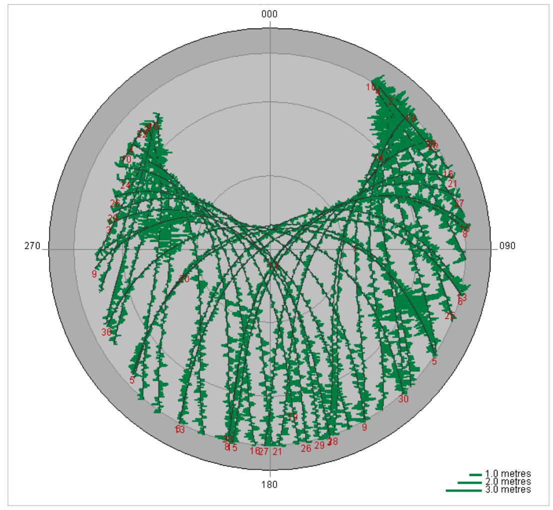


Fig. 6 MP1 sky plot for site RUTH



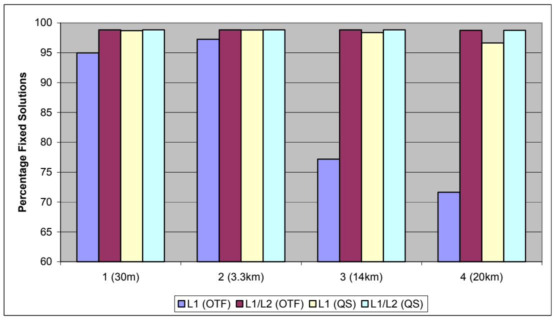
Note that in this paper the most basic positions calculated from the processing kernels are analyzed. In a real monitoring installation using the Leica GPS Spider and/or Leica GeoMoS software, it would be possible to smooth and/or average the results for higher precision and accuracy. In the case of post processing, longer intervals could be used to further improve the precision and accuracy.

3 Results

3.1 Real Time Processing

The first value that is analyzed is the availability of ambiguity-fixed positions. Ambiguity-fixed positions provide the highest accuracy possible with GPS and so are preferred for monitoring applications. Ambiguity resolution is more difficult when processing single frequency data because of the reduced redundancy and limited information on atmospheric error that is available from the system. Figure 7 shows the percentage of fixed solutions for each baseline, each frequency and each ambiguity resolution technique over the five data period. The 1Hz data spanning five days gives a total number of 432,000 possible fixes. As might be expected, the dual frequency processing gives very high availability of ambiguity-fixed positions (approximately 99%) for all baselines, even using OTF initialisation. Single frequency processing using OTF initialisation clearly has more difficulty fixing for the longer baselines. The QS initialisation gives consistently high results for both single and dual frequency data and all baseline lengths.

Fig. 7 Availability of Ambiguity Fixed Positions (Real Time Processing)



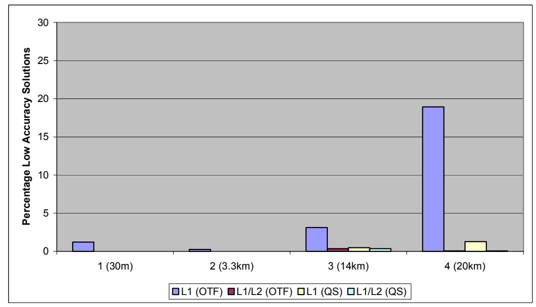
The availability of an ambiguity fix is related to the reliability of the ambiguity fix. A high availability of fixed positions should not be at the cost of having more incorrectly fixed ambiguities, since wrong ambiguity fixes will result in low accuracy position solutions.

In order to quantify the likelihood of the system to produce invalid or low accuracy positions, the difference between each calculated position and the known coordinates of the site have been compared. All positions that deviated by more than 5cm in horizontal or 10cm in vertical from the true coordinate were flagged as low accuracy position fixes. A position outside this tolerance could be caused by an invalid ambiguity fix or by higher than normal ionospheric activity.

Figure 8 shows the percentage of solutions that exceed these tolerances. Dual frequency processing is clearly highly reliable, even with OTF initialisation. Single frequency processing with OTF initialisation has some reliability issues, but with QS initialisation is comparable to dual frequency, up to about 10 or 15km. For the 20km baseline the single frequency solution with QS initialisation is also showing signs of having reliability issues due to its limited ability to model atmospheric errors. The conclusion that can be drawn from Figures 7 and 8 is that in terms of ambiguity resolution, real time single frequency monitoring with baselines of up to about 10km is viable using the quasi-static initialisation. What remains then is to test the accuracy of the solution.

Since it is well known that GPS is more precise that it is accurate, a measure of accuracy rather than precision has been used for this analysis. The accuracy is calculated as the standard deviation of the calculated positions about the known coordinates. For this calculation only the coordinates that were within the previously mentioned tolerances were used to isolate the accuracy of the position solution from the reliability of the ambiguity fix.

Fig. 8 Percentage of Solutions with Low Accuracy Position



Two components, northing and height, are shown respectively in Figures 9 and 10. Northing was used for the horizontal component because it is typically less accurate than easting because of the satellite geometry. For the shorter baselines (30m and 3.3km) both single frequency and dual frequency solutions are accurate to about 4mm or better in northing. Interestingly for the 14km baseline single frequency actually gives slightly higher accuracy, though both are in the order of 1cm for the northing component. For the 20km baseline, the dual frequency solution is clearly more accurate in northing. For the height both solutions have a similar pattern. The main influence on the height accuracy is the troposphere, which was not modelled in either the dual or single frequency solutions. Thus for baselines in the order of 10km, dual frequency does not provide a significant advantage in terms of accuracy, if the ambiguities have been correctly fixed.

Fig. 9 Accuracy of Northing Component in Real Time (1 Sigma)

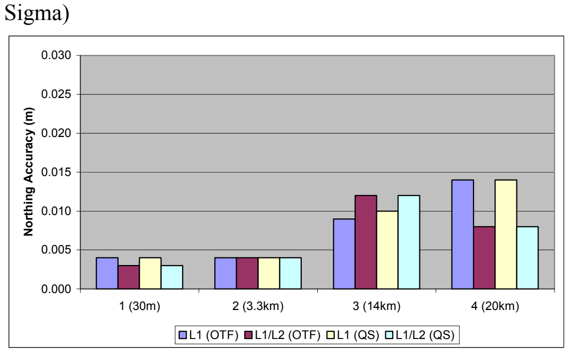
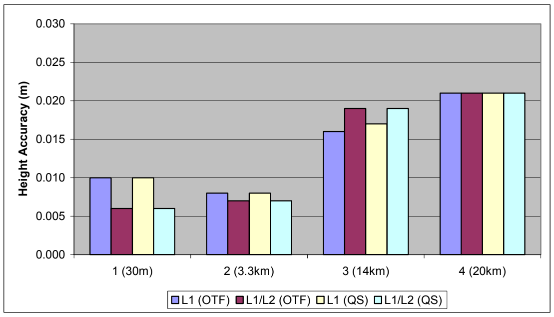


Fig. 10 Accuracy of Height Component in Real Time (1 Sigma)



The results presented so far are have been based on static data in order to show the accuracy and reliability of the system. In order to demonstrate the advantage of the quasi-static approach in a dynamic environment, a further test was conducted in which one antenna was moved. Five minutes of static data was collected prior to the enforced movement. The antenna was moved manually in an easterly direction at one-minute intervals by approximately 1cm for 25 minutes after which an exponential movement was made simulating a landslide. Figure 11 shows the movement in easting, northing and height calculated using a very short (30m) baseline with dual frequency data. The reference value for the movement is the known initial starting position of the site. This data set is used as the reference for comparison against the results from a 14km baseline. The same movements determined with the 14km baseline using dual frequency OTF, single frequency OTF and single frequency QS processing are shown in Figures 12, 13 and 14 respectively. Note that only ambiguity-fixed positions are shown in the graphs.

Fig. 11 Reference Values for the Antenna Movements Calculated Using a Very Short Baseline

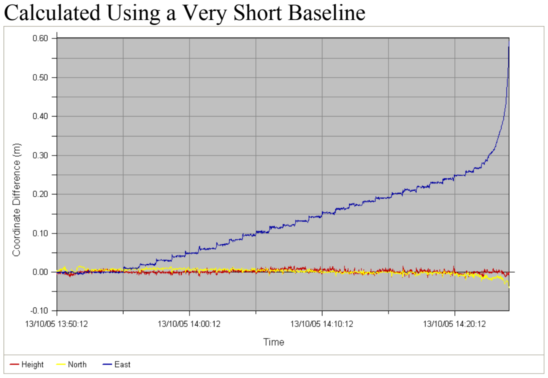


Fig. 12 Antenna Movements Calculated Using a 14km Baseline with Dual Frequency Data and OTF Ambiguity Resolution

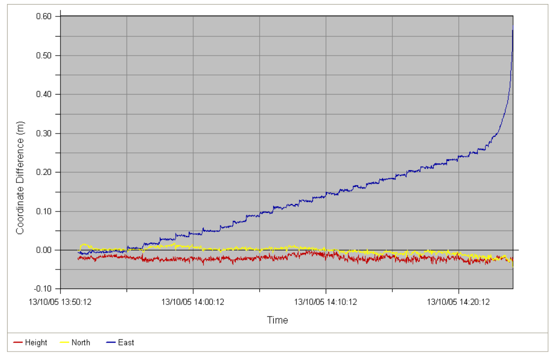


Fig. 13 Antenna Movements Calculated Using a 14km Baseline with Single Frequency Data and OTF Ambiguity Resolution

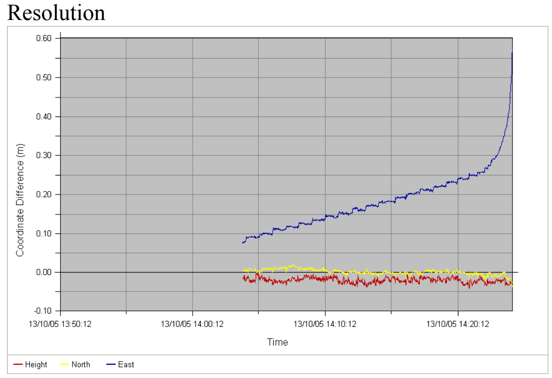
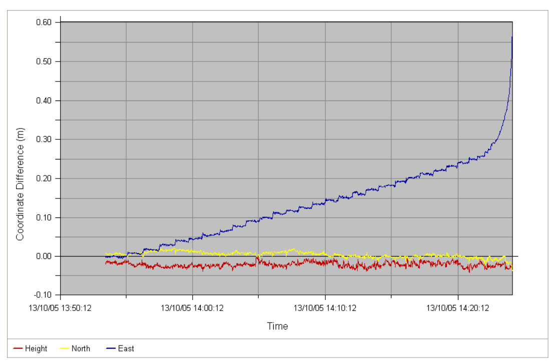


Fig. 14 Antenna Movements Calculated Using a 14km Baseline with Single Frequency Data and QS Ambiguity Resolution



Clearly the same movement is seen in all baselines. However, the 14km baseline processing single frequency data with OTF ambiguity resolution clearly took much longer to fix. With the quasi-static initialisation the single frequency data was able to fix much faster, though still noticeably slower than with dual frequency OTF processing.

Importantly, the quasi-static approach, like the OTF approach, was able to maintain its ambiguity fix throughout the very rapid movement at the end of the period, even with SmartCheck re-verifying the ambiguity fix every ten seconds. Thus the increased availability and reliability ambiguity fixes using the quasi-static approach is not at the cost of a practical limitation in the receiver dynamics for monitoring applications.

3.2 Post Processing

For the post processing similar tests may be performed. Since longer observation periods are used, it can be expected that the accuracy will be higher in post processing than in real time. For the 10 minute post processing a total of 720 positions were calculated per baseline over the five days of data. A total of 240 position solutions were calculated for the 30 minute post processing and 120 for the 1 hour post processing. Figure 15 shows the availability of fixed positions for the different baselines and solutions. With 10 minutes of data, the availability of ambiguity fixed positions is greater than 80% for single frequency data. Using 30 minutes or more of data, single frequency has an availability of fixed positions at over 95%. For dual frequency data the availability is 100%.

As with the real time data, the quality of the fixing was tested by checking the calculated positions against a tolerance of 5cm in horizontal and 10cm in vertical. The higher reliability of post processing is clearly supported by the fact that almost no positions solutions were outside this tolerance. The single frequency processing of the 14km and 20km baselines had a very small number of poor accuracy solutions (0.42% and 0.83% respectively) when processing with 10 minutes of data. Figures 16 and 17 show the accuracy in northing and height respectively for post processing. As expected, post processing has a higher accuracy than real time processing. For the shorter baselines using more data for the post processing did not give significant improvements. With longer baselines, processing one or more hours of data gives the best results as this allows sufficient time for estimation of the tropospheric delay. The best would be if 24 hours of data were used, however this is only practical if very slow movements are expected (for example in dam monitoring).

It should be noted that the quality of the position results is directly related to the quality of the raw observations and that not all single frequency receivers will produce such reliable and accurate results. A single frequency receiver like the Leica GX1210 is recommended for applications requiring high reliability and accuracy. Also, in environments that are unsuited to GPS (e.g. with large obstructions and high multipath), or over longer baselines, dual frequency processing still has a clear advantage over single frequency.

Fig. 15 Availability of Ambiguity Fixed Positions (Post Processing)

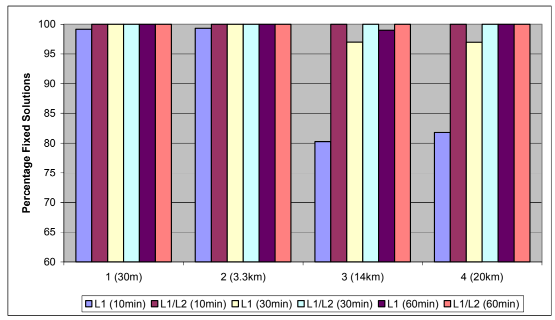


Fig. 16 Accuracy of Northing Component in Post Processing (1 Sigma)

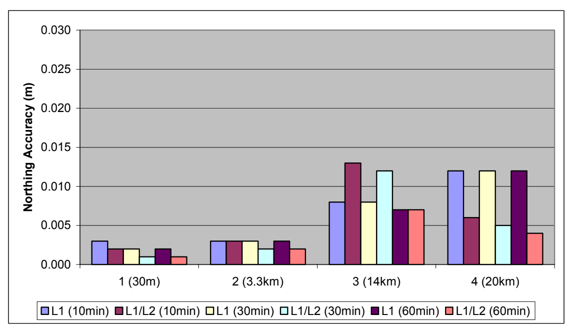
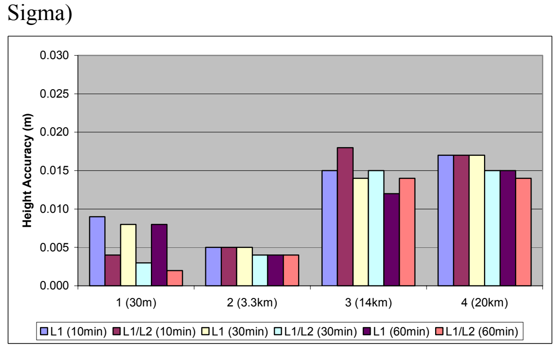


Fig. 17 Accuracy of Height Component in Post Processing (1 Sigma)



4 Conclusions

This paper has compared the single and dual frequency GPS monitoring solutions available in the Leica GPS Spider software. A new quasi-static ambiguity resolution technique was shown to enable high availability and reliability single frequency RTK in real time. In fact, for baselines up to approximately 10 kilometers the single frequency results using the quasi-static approach were shown to be at a similar level of reliability and accuracy as dual frequency. However, for high dynamic situations, the use of dual frequency receivers is essential due to the poor performance of OTF ambiguity resolution with single frequency data. In terms of accuracy, single frequency also gives comparable results to dual frequency for baselines up to 10 km or so. Post processing of the data was shown to give even higher levels of reliability and accuracy. Thus lower cost single frequency receivers offer very good balance between price and performance when used with appropriate processing software. Use of high quality receivers and antennas and careful site selection are still prerequisites for high accuracy GPS monitoring.

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