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Permanent Link to Dynamic Duo: Combined GPS/GLONASS Receivers in Urban Environments

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By Cillian O'Driscoll, Gérard Lachapelle, and Mohamed Tamazin, University of Calgary The impact of adding GLONASS to HS-GPS is assessed using a software receiver operating in an actual urban canyon environment. Results are compared with standard and high sensitivity GNSS receivers and show a significant improvement in the availability of position solutions when GLONASS is added. An assisted high sensitivity receiver architecture is introduced which enables high fidelity signal measurements even in degraded environments. High-sensitivity (HS) GNSS receivers have flourished in the last decade. A variety of advances in signal-processing techniques and technologies have led to a thousandfold decrease in the minimum useable signal power, permitting use of GNSS, in particular GPS, in many environments where it was previously impossible. Despite these recent advances, the issue of availability remains: in many scenarios there are simply too few satellites in view with detectable signals and a good geometry to compute a position solution. Of course, one way to improve this situation is to increase the number of satellites in view. GLONASS has been undergoing an accelerated revitalization program of late, such that there are currently more than 20 active GLONASS satellites on orbit. The combined use of GPS and GLONASS in a high-sensitivity receiver is a logical one, providing a near two-thirds increase in the number of satellites available for use. The urban canyon environment is one in which the issue of signal availability is particularly important. The presence of large buildings leads to frequent shadowing of signals, which can only be overcome by increasing the number of satellites in the sky. Even if sufficient satellites are visible, the geometric dilution of precision can often be large, leading to large errors in position. This work focuses on the advantages of using a combined GPS/GLONASS receiver in comparison to a GPS-only receiver in urban canyons. The target application is location-based services, so only single frequency (L1) operation is considered. We collected and assessed vehicular kinematic data in a typical North American urban canyon, using a commercially available high-sensitivity GPS-only receiver, a commercial survey-grade GPS/GLONASS receiver, and a state-of-the-art software receiver capable of

processing both GPS and GLONASS in standard or high-sensitivity modes. Processing Strategies The standard (scalar-tracking) GNSS receiver architecture is shown in Figure 1. In the context of this article, the key characteristic of a standard receiver is that the signals from the different satellites are each tracked in parallel and independent tracking channels, and usually only three correlators are used. The information from the channels is only combined in the navigation filter to estimate position, velocity, and time. In this way, there is no sharing of information between channels in order to attempt to improve tracking performance. Figure 1. Standard receiver architecture (courtesy Petovello et al). Within each channel, the down-converted and filtered samples from the front end (not shown in Figure 1) are then passed to a signal-processing function where Doppler-removal (baseband mixing) and correlation (de-spreading) is performed. The correlator outputs are then passed to an error-determination function consisting of discriminators (typically one for code, frequency, and phase) and loop filters. The loop filters aim to remove noise from the discriminator outputs without affecting the desired signal. Finally, the local signal generators — whose output is used during Doppler removal and correlation — are updated using the loop-filter output. Assisted HS GNSS Receiver. The assisted HS GNSS receiver architecture used in this work is shown in Figure 2. Notable differences to the standard receiver architecture are highlighted in red. Figure 2. Assisted high-sensitivity receiver architecture. Assistance information is provided in the form of broadcast ephemerides, raw data bits, and a nominal trajectory (position and velocity) that would normally be generated by the receiver. At each measurement epoch, the receiver uses the nominal position and velocity in conjunction with the ephemerides to compute the nominal pseudorange and pseudorange rate for each satellite in view. These parameters are passed to the signal-processing channels. Each channel evaluates a grid of correlators around the nominal pseudorange (code) and pseudorange rate (Doppler) values. The data bits are wiped off using the assistance information to permit long coherent integration times. For each signal tracked, the correlator grid is used to estimate code and Doppler offsets relative to the nominal values. These estimates are then used to generate accurate pseudorange and Doppler estimates. The number of correlators used and the spacing of these correlators in the code and frequency domains are completely configurable. A sample correlation grid computed during live data processing is illustrated in Figure 3. Measurements are generated by choosing the three correlators nearest the peak in the search space and using a quadratic fit to determine a better estimate of the peak location. In this work, a total of 55 correlators per channel were used. Figure 3. Sample grid of correlator points computed for GPS PRN 04. The assisted HS receiver is initialized in static mode in an open-sky setting during which reliable clock bias and drift estimates are derived. A high-quality oven-controlled crystal oscillator was used during this initial test to ensure that the clock drift did not change significantly over the period of the test (approximately 20 minutes). The clock bias during the test is updated using the clock drift estimate. Note that this architecture is a generalization of the vector-based architecture, where the navigation solution used to aid the signal processing can be provided by an external reference. Navigation Solution Processing. All navigation solution results presented here are obtained in single-point mode using an epoch-by-epoch least-squares solution with the PLAN Group C3NavG2 software, which uses both code and Doppler measurements. This

processing strategy enables a fair comparison amongst the different signal processing strategies, as the smoothing effect of specific navigation filters is eliminated by this approach. More realistic accuracy estimates of the measured pseudoranges can be obtained. It is understood that in an operational environment, a well-tuned filter will obtain significantly better navigation performance than the epoch-by-epoch solutions presented here. The measurements are weighted using a standard-elevation-dependent scheme. Thus there is no attempt to tune the weighting scheme for each receiver.

Data Collection To test the relative performance of the various processing strategies, we conducted a test in downtown Calgary. Data was collected using a commercial HS GPS receiver, a commercial survey grade GPS/GLONASS receiver, and an RF downconverter and digitizer. The digitized data was post-processed in two modes (standard and assisted HS GNSS) using the PLAN group software receiver GSNRx. Raw measurements were logged from each of the commercial receivers at a 1-second interval. The parameters used in GSNRx are given in Table 1. The trajectory followed is shown in Figure 4. The majority of the route was travelled in an East-West direction, with significant signal masking to the North and South. The Opening Photo shows an aerial view of downtown Calgary where the test took place. Masking angles exceeded 75 degrees along the vehicle trajectory. Figure 4. Test Trajectory where the route is approximately 4 km with a 10 minute travel time. A sky plot of the satellites visible above a 5-degree elevation mask at the test location is shown in Figure 5. A total of 11 GPS and seven GLONASS satellites were present. Figure 5. Skyplot of GPS and GLONASS satellites over Calgary at the start of the test. A static period of approximately three minutes duration was used to initialize the assisted HS GNSS processing. During this period, the vehicle had a largely clear view of the sky. Nevertheless, three satellites were blocked from view during this period, namely GPS SVs 13 and 3, and GLONASS SV 22. As a result, these SVs were not available for processing in the assisted HS GNSS mode. The two commercial receivers were already up and running prior to the initialization period and so were able to process these three low-elevation satellites when they came into view during the test. See PHOTO on next page for a typical scene during the downtown test.

Analysis To study the impact of adding GLONASS, the analysis focuses on solution availability, the number of satellites used in each solution, the DOP associated with each solution, and the statistics of the least-squares solution residuals. In the absence of a reference solution, the statistics of the residuals nevertheless give a reasonable indication of the quality of the measurements used, provided sufficient measurements are available to ensure redundancy in the solution. Nevertheless, some pseudorange errors will be absorbed by the navigation solution, hence the statistics of the residuals can be viewed as only a good estimate of the quality of the measurements themselves.

Solution Availability. As previously discussed, the navigation processing strategy adopted is the same for all receivers used in the test. A single-point epoch-by-epoch least-squares solution is computed at a 1 Hz rate. If there are insufficient satellites in view at a given epoch, or the solution fails to converge in 10 iterations, no solution is computed. In this section, the analysis focuses on the percentage of epochs during the downtown portion of the test for which a solution was computed. Figure 6 shows the percentage of solutions computed for each receiver processing strategy as a function of HDOP and VDOP thresholds, respectively. Thus, for example, the assisted HS GPS-

GLONASS processing strategy yielded navigation solutions with a HDOP less than 6 between 80 percent and 85 percent of the time. For larger DOP thresholds, it is clear that there is little difference between GPS-only processing and GPS+GLONASS processing. The biggest differences are caused by the processing strategies employed. The advantages of HS processing are clear, at least in terms of solution availability. For this test and the particular geometry of the satellites in view during the test, GPS+GLONASS processing does yield a noticeable improvement in the VDOP, particularly at lower thresholds. Figure 6A. Percentage solution availability versus HDOP threshold. Figure 6B. Percentage solution availability versus VDOP threshold. Note that the standalone HS GPS receiver exhibits greater solution availability than the assisted software HS GPS-GLONASS receiver at higher DOP thresholds. This is most likely due to the low-elevation satellites that were excluded from the assisted HS processing due to their being masked during the initialization period as discussed earlier. Overall, however, there is little difference between GPS-only processing and GPS-GLONASS processing in terms of solution availability. This fact, of course, does not yield any information on the quality of the solutions obtained, which is discussed later. To gain further insight into the impact of GLONASS, Figure 7 shows the percentage of solutions computed that exhibit redundancy. Thus, of all solutions computed during the downtown portion of the test, Figure 7 illustrates the percentage of those solutions that have redundant measurements. For GPS-only processing, this implies that five or more measurements were used in computing the position, while for GPS-GLONASS processing a minimum of six measurements were required. In this case, the advantage of using GLONASS becomes more apparent. For all processing strategies the addition of GLONASS yields an increase of 5 to 10 percent in the number of solutions with redundancy. Although not studied herein, this would have a positive impact on fault detection.

Residuals Analysis To investigate the quality of the measurements generated by each processing strategy, the residuals from the least-squares solutions are studied. Only those epochs for which redundant solutions are computed are considered here, since non-redundant solutions lead to residuals with values of zero. As discussed above, the analysis of these residuals gives an estimate of the quality of the measurements generated. Figure 8 shows the histograms of the residuals from all GPS-GLONASS processing strategies. Once again, it is important to emphasize that only residuals from solutions with redundancy are considered. In addition, the results presented are limited to those epochs during which the vehicle was in the downtown portion of the test. For the purposes of this presentation an upper GDOP threshold of 10 was set. It is interesting to note that in all cases (assisted HS, standard wide correlator, and commercial survey-grade processing), the relative RMS values of the GPS and GLONASS residuals are about the same. These results indicate that, irrespective of the signal-processing strategy employed, the GLONASS measurements are of a similar quality to the GPS measurements. The number of residuals available is however different between the standard and HS solutions, as the latter produce more measurements and more redundant solutions, hence more residuals. The processing strategy obviously had a significant impact on the availability of redundant solutions as discussed in the previous section. Figure 8A. GPS-GLONASS range residuals comparison: assisted HS-GPS-GLONASS. RMS values and the percentage of solutions used in the histogram are also shown. Figure 8B. GPS-GLONASS range residuals

comparison: standard wide correlator. RMS values and the percentage of solutions used in the histogram are also shown. Figure 8C. GPS-GLONASS range residuals comparison: survey-grade receiver. RMS values and the percentage of solutions used in the histogram are also shown. Figure 9 shows the histograms of the range residuals from GPS-only processing. In this case, the navigation solution is a GPS-only navigation solution, though in the case of the assisted HS receiver the measurements used are identical to those used in Figure 8. Clearly the assisted HS receiver has a greater availability of redundant solutions compared to the standalone receiver, which is to be expected. Also, the assisted HS GPS receiver residuals have a slighter lower RMS than when a GPS-GLONASS implementation was considered, indicating that the navigation solution absorbs more of the measurement errors in this case. Figure 9A. GPS range residuals comparison, assisted HS GPS. Figure 9B. GPS range residuals comparison, commercial standalone HS GPS.

Position Domain Results The final stage of the analysis is a comparison of the trajectories computed using each of the receiver types. While no truth solution was available for this test, a highly filtered navigation solution from the high-sensitivity commercial receiver was used as a nominal reference. This trajectory is shown in black in the following figures. Figure 10 shows the trajectories obtained using standard wide-correlator processing. The position solutions are quite accurate, but the availability is low, namely of the order of 30 percent as shown above. The addition of GLONASS does improve the availability in this case. The accuracy is not significantly improved. In fact it appears that the addition of GLONASS occasionally leads to biases in the navigation solutions, likely solutions with high DOP values. Figure 10. Trajectory obtained with standard wide correlator processing. Figure 11 shows the trajectories computed using the commercial receivers. The survey-grade receiver yields less noisy positions, though the addition of GLONASS does lead to some significant outliers. The position availability is lower as discussed earlier. Similar to the standard wide-correlator processing case, the addition of GLONASS again appears to introduce an error in the solution during some epochs (for example, at a northing of about 500 meters between 100 and 500 meters easting). Figure 11. Trajectories obtained from the commercial receivers. Finally, Figure 12 shows the trajectories obtained from the assisted HS receiver. In this case, the position solutions are significantly less noisy than in previous cases, in addition to being more available. The quality of the GPS-only and GPS+GLONASS results is broadly similar, with perhaps more outliers in the GPS-GLONASS case, due to the reason mentioned earlier. Figure 12. Trajectories obtained using assisted HS GPS-GLONASS processing. In summary, it would appear that the greatest benefit of GLONASS in this test was in the provision of greater redundancy in the navigation solution, in addition to potential better reliability, although the latter remains to be confirmed. With GLONASS approaching full operational capability, it is to be expected that the increased GLONASS constellation will lead to further improvements in terms of availability, DOP, and reliability.

Coherent Integration Time From the preceding analysis it is clear that the assisted HS GNSS processing strategy yielded the best performance. To evaluate the impact of the coherent integration time on performance, the data was re-processed with a coherent integration time of 300 milliseconds (ms), instead of the 100 ms used for the data presented so far. The resulting trajectories are shown in Figure 13. It is interesting to note that increasing the receiver sensitivity in this way does not yield

better navigation performance. In fact, in the urban canyon environment, the major issue is not the signal attenuation (which can be overcome by increased coherent integration) but rather the multipath effect. By increasing the coherent integration time to 300 ms, the receiver becomes more sensitive to dynamics, resulting in poorer navigation performance. Figure 13. Trajectories obtained using assisted HS GPS-GLONASS processing (300 ms integration time).

Discussion High-sensitivity processing in urban canyon environments is a very effective means of improving navigation performance. Given the discussion above, however, it is clear that the performance is not limited by the strength of the received signal, but rather by the effect of multipath and satellite geometry. The advantage of high-sensitivity processing in this case is two-fold. The first advantage over standard tracking techniques is the open-loop nature of HS processing. The time-varying nature of the multipath channel causes significant variation in signal level. This variation can cause traditional tracking loops to lose lock. In fact, the poor performance of the standard wide-correlator strategy in the above analysis can be explained by the fact that the receiver was unable to maintain lock on the satellites in view. Hence no measurements were generated, and no solutions computed. The survey-grade receiver used has advanced multipath mitigation technology, which helped to avoid loss of lock, but may have been tracking non-line-of-sight signals during portion of the down-town test, leading to errors in the navigation solution. The second advantage of HS processing is related to the coherent integration time and the vehicle dynamics. As the receiver antenna moves through the multipath environment, a different Doppler shift is observed on signals coming from different directions. Thus the line-of-sight and multipath components become separated in frequency. A longer coherent integration time increases the frequency resolution of the correlator output (due to the familiar sinc shape). Thus if the line-of-sight is present, and the coherent integration time is long relative to the inverse of the Doppler difference between the line-of-sight and reflected signals, individual peaks become visible in the grid of correlators. This effect can significantly reduce the impact of multipath on the measurements. Figure 14 gives an example of this. Figure 14. Sample correlation function showing two peaks.

Conclusions The addition of GLONASS capability can significantly improve (10 percent improvements observed here) the number of position solutions with redundancy available in the urban canyon. With increasing GLONASS satellite availability, the benefits of using GLONASS will even be greater. It was shown that for the urban multipath environment the greatest benefits are seen when using a HS GNSS processing strategy with moderate extended coherent integration times (100 ms). Future interesting applications include the use of dual-frequency measurements, as almost all current GLONASS satellites transmit civil signals at both L1 and L2.

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Manufacturers The tests used a National Instruments PXI-5661 RF downconverter and digitizer, the PLAN GSNRx as standard wide-correlator receiver, the u-blox Antaris 4 (standalone HS-GPS), NovAtel OEMV-3 (survey-grade GPS/GLONASS), and the PLAN group software receiver GSNRx, as the assisted HS GPS/GLONASS. Cillian O'Driscoll received his Ph.D. in 2007 from the Department of

Electrical and Electronic Engineering, University College Cork, and is currently a post-doctoral fellow in the PLAN Group of the University of Calgary. Gérard Lachapelle is a professor of geomatics engineering at the University of Calgary where he holds a Canada Research Chair in wireless location and heads the Position, Location and Navigation (PLAN) Group. Mohamed Tamazin is a M.Sc. candidate in the the PLAN at the University of Calgary. He holds a M.Sc. in electrical communications from the Arab Academy for Science and Technology, Alexandria, Egypt.

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