GPS+GLONASS RTK: Making the Choice Between Civilian and Military L2 GLONASS

Frank Boon, Jean-Marie Sleewaegen, Andrew Simsky, Wim De Wilde, *Septentrio NV, Belgium*

BIOGRAPHIES

Frank Boon is head of the Research Department at Septentrio. He received his M.Sc. in Aerospace Engineering from Delft University of Technology. His research interests include high-precision position and attitude algorithms and sensor fusion.

Dr. Jean-Marie Sleewaegen is currently responsible for the GNSS signal processing, system architecture and technology development at Septentrio Satellite Navigation. He received his M.Sc. in Electrical Engineering in 1995 and his Ph.D. in 1999 from the University of Brussels. He received the ION Burka award in 1999.

Dr. Andrew Simsky holds a Ph.D. in Physics from the University of Moscow, Russia. He is working as a senior GNSS scientist at Septentrio in Leuven, Belgium. His research interests include differential and standalone navigation algorithms and performance analysis of GNSS receivers and signals.

Wim De Wilde received a M.Sc. in Electrical Engineering from the University of Ghent, Belgium. Upon graduation, he joined the research team at Alcatel Bell. Since 2002 he has worked as an R&D engineer at Septentrio. His area of research includes digital signal processing, multipath mitigation and receiver design.

ABSTRACT

After several years of moderate activity, the GLONASS constellation has undergone significant maintenance. Currently, 16 satellites are present, resulting in a valuable surplus for positioning accuracy and reliability. More interestingly, the GLONASS constellation is now almost fully based on GLONASS-M satellites, which feature L2CA, an open-access civilian code on L2, while GPS currently still supports L2C on a limited number of satellites.

Because old GLONASS satellites did not transmit L2CA, the military L2P signal was the only choice for dual-frequency receivers, which was simplified by the fact that on old satellites L2P was data-less. The new GLONASS-M satellites transmit civilian open-access L2CA signal, while the transmission of the L2P of GLONASS-M is complicated by a navigation message with undocumented contents and structure. Receiver designers have two choices: either deal with the increased complexity of L2P tracking or consider a transfer to the use of L2CA.

Because, to our knowledge, nothing has yet been reported about the structure of the navigation message on GLONASS L2P, we have undertaken our own investigation which resulted in the values of 250 bps for the bit rate and 4s for the frame periodicity. The knowledge of the bit rate is in principle sufficient for the code and phase tracking, although the aiding by CA code is necessary for the resolution of half-cycle phase ambiguity, which is a requirement for RTK applications.

Preliminary performance analysis of code and phase noises has shown that although L2CA code is predictably noisier than L2P code, its overall performance shall be sufficient to ensure reliable use in phase-based GPS/GLONASS applications. The fact that the use of L2P requires behind-the-scene manipulations and is without official guarantee compels receiver designers to tune their future receivers to the use of GLONASS L2CA.

INTRODUCTION

At the time of writing (September 2008), there are 16 satellites in the GLONASS constellation. Of these 16 satellites, 13 are modern GLONASS-M satellites and only 3 are older first-generation GLONASS satellites. Of these 3, only 1 is still in operation. It is expected that all first-generation GLONASS satellites will be decommissioned within a few months.

One of the major differences between GLONASS and GLONASS-M satellites is that the latter transmit an open civilian CA code on the L2 frequency band. The fact that almost all active satellites are of the GLONASS-M type makes GLONASS the first GNSS constellation offering large-scale civilian dual-frequency access.

The major benefit of the new civilian code on L2 is that it is backed by the official GLONASS ICD [1]. With the first-generation GLONASS, access to L2 was only possible through the classified P-code (referred to as the L2P signal in this text), with no publicly available ICD. L2P was officially "not recommended for non-authorized users" [1]. Despite the lack of ICD for the GLONASS P-code, the characteristics of that code have been determined independently [3], rendering it possible for civilian receivers to provide dual-frequency GLONASS measurements, though with no guarantee of continuity of service. The decoding of L2P was simplified by the fact that the signal was data-less.

Frequency band		L1		L2	
Code		CA	P	CA	P
Old GLONASS (3 sats)	Chip rate, mcps	0.5	5	No signal	5
	Data rate, bps	50	50		No data
	Frame, sec	30	10		
GLONASS-M (13 sats)	Chip rate, mcps	0.5	5	0.5	5
	Data rate, bps	50	50	50	250
	Nav frame, sec	30	10	30	4

Table 1. Summary of currently observed GLONASS signals.

Besides the introduction of L2CA, GLONASS-M also brought another surprise to the GNSS community: the L2P signal is transmitted with an undocumented navigation message, making the tracking both more difficult and less reliable. In the next section, some characteristics of the new L2P signal are presented, based on signal analysis done at Septentrio.

THE NEW GLONASS-M P-CODE MODULATION

In the first-generation GLONASS satellites, the P-code on the L1 carrier (L1P) is modulated by a navigation message clocked at 50 bits per second (bps) as described in [4], while the P-code on L2 has no bit modulation. In fact, for these satellites, L2P appears to be a data-less signal, similar to the so-called "pilot" tone in Galileo and modernized GPS signals.

GLONASS-M satellites still transmit a 50-bps navigation message on L1P, but L2P unexpectedly started to become modulated by a new type of navigation message, at a bit rate larger than the common 50 bit-per-second. This lead to tracking problems on virtually all receivers designed back in the period where only first-generation GLONASS satellites were active. Already in the end of 2007, a significant reduction of the number of observations had been reported in GLONASS tracking networks, see e.g. IGSmail#5667 [2].

To our knowledge, there is no specification of that new L2P navigation bit encoding in the public domain. The following presents some important characteristics we have been able to determine from logging the signal during several weeks spread in the period from January to August 2008.

The L2P spreading code itself is still the same as the one disclosed in [3]. What is new is that a fast navigation bit modulation has been added. If the navigation bit sign is 0, or if there is no navigation bit modulation, the genuine P-code is transmitted. If the navigation bit is 1, the inverted P-code is transmitted instead.

To decode the navigation bits, the receiver correlates the P-code with a local replica over the bit period and checks the sign of the end correlation value. Conceptually, a positive sign means that the navigation bit was 0, or that there was no bit modulation. A negative sign means that the bit was 1. If the correlation is done over a time longer than the duration of a navigation bit, the correlation amplitude will decrease. This fact can be used to deduce the bit duration.

By correlating the P-code signal over different intervals, it rapidly became clear that the new GLONASS L2P navigation bits have a duration of 4 ms, i.e. the bit rate is 250 bps. The navigation bit modulation is not continuous. This is illustrated in Figure 1, which shows the sign of the L2P navigation bit modulation (+1 if "0" is transmitted or -1 if "1" is transmitted) decoded every 4 ms over a period of about 3000 seconds from one of the GLONASS-M satellites. The sign of the bit modulation is +1 during the periods without bit modulation, and randomly switches from +1 to -1 in periods with bit modulation active. At the scale of the figure, the individual bits are not visible. In the example of the figure, one can identify a first period of intermittent bit modulation (up to t=2400s), followed by a long period of continuous modulation (from t=2400s to 3200s). After t=3900s, the bit transmission is turned off.

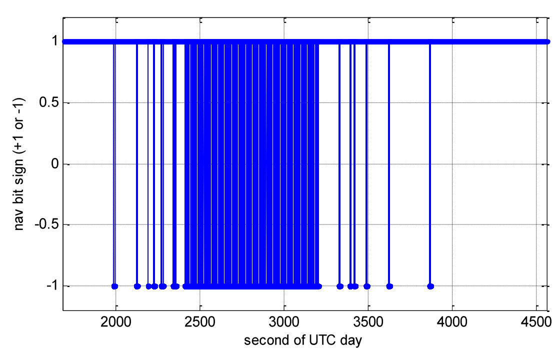

Figure 1. Example of L2P navigation bit transmission.

The periods with navigation bit transmission are not synchronous on the different satellites: each GLONASS-M satellite appears to transmit navigation bits at different and seemingly random times.

We have also tried to identify some repeating known pattern in the intermittent bit stream, in the hope to find an equivalent of the GPS "preamble". As will be explained later, such repeating pattern is essential to ensure proper full-cycle carrier phase recovery.

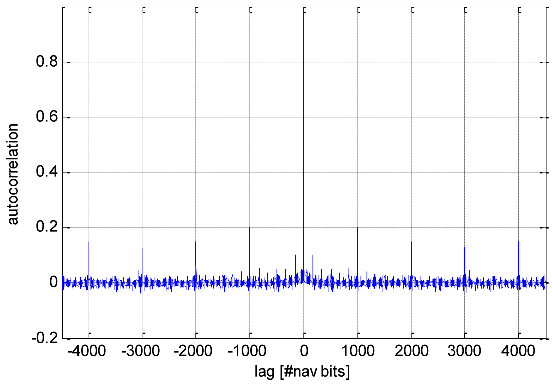

Figure 2. Autocorrelation of the L2P navigation bit stream.

To this end, we have computed the autocorrelation function of the bit stream. If some bit pattern is repeating at regular interval in the stream, it would give rise to regularly-spaced peaks in the autocorrelation function. Figure 2 represents an example of such autocorrelation function, obtained over 100000 bits. Peaks are clearly visible at lags multiple of 1000 bits, which indicates that a pattern is repeating every 1000 bits, i.e. every 4 seconds. We have observed such characteristics in all the data sets we have recorded.

This observation suggests that the L2P message is composed of frames having a duration of 4 seconds. This hypothesis is also supported by the fact that all short transmission periods appear to start and to end at multiple of 4 s in the GLONASS time scale (UTC). For instance, Figure 3 represents a magnification of Figure 1 around t=1984s. It is visible that the transmission starts at GLONASS time 1984s and ends at time 1988s. As a side note, the transmission in Figure 3 is composed of 3 short bursts. The presence of such triple burst has been often observed, but not always.

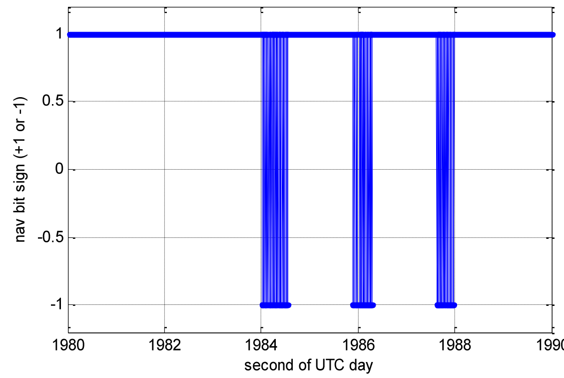

Figure 3. Example of a short L2P navigation bit transmission.

A more in-depth analysis revealed that a couple of bits around the 4-second boundaries (in the GLONASS time scale) appeared to always have the same value. For example, the bits transmitted during the 4-ms interval starting at multiple of 4 seconds in the GLONASS time scale appear to always be 0. The same applies to the 3 last bits of any 4-second interval. We have regularly checked this from January to August 2008 without finding any exception. Whether these seemingly fixed bits can be used as some kind of "preamble" is not clear. In the absence of official ICD, there is no guarantee that bits that appear to remain constant over a period of 8 months will remain constant in the long term.

TRACKING THE NEW L2P SIGNAL

Even with the knowledge of the bit modulation of the L2P navigation message, the tracking of the new L2P signal suffers from limitations with respect to the first-generation GLONASS.

Firstly, the mere presence of the data modulation, even if it would be perfectly characterized, impairs the tracking performance with respect to a data-less case. This effect has been extensively documented in the context of Galileo and modernized GPS, both of which will combine a data-less and a data-bearing signal on the same carrier. In short, a data-less signal offers significantly better performances in terms of tracking noise, tracking thresholds and cycle slip resistance.

Secondly, and more importantly, the fact that the navigation bit frames are undocumented makes it unreliable to produce carrier phase observables with integer cycle ambiguity. The inherent tracking ambiguity of a data-bearing signal is half a cycle. This ambiguity can be fixed to a full cycle provided at least a few bits of the navigation frame are known a priori. This is the case in GPS CA for instance, where a known pattern of 8 bits (the so-called "preamble") is repeated every 6 seconds.

With GLONASS-M L2P, the results reported in the preceding section tend to show that there are bits repeating every 4 seconds. However, as discussed, in the absence of an official ICD, relying on this result is dangerous and not recommendable.

Another way of recovering the full cycle ambiguity of GLONASS L2P is to use the civilian L2CA signal, which is transmitted in quadrature of the L2P signal. If the receiver is able to track both L2CA and L2P signals in parallel, the carrier phase from the L2CA tracking can be used to resolve the half-cycle ambiguity of L2P. In fact, L2CA aiding seems to be the only reliable way of recovering the full-cycle ambiguity of the L2P carrier phase. However, this requires to dedicate two tracking channels to GLONASS-M L2, one for L2CA and one for L2P, which is a significant increase in the receiver complexity.

In summary, the introduction of a navigation bit modulation on the L2P signal painfully demonstrated that the usage of GLONASS P-code is at user's own risk. After all, this should not be a surprise for a signal that has never been authorized for civilian uses. The good news is that all GLONASS-M also transmit a civilian CA code on L2, offering access to the L2 band in a well-documented manner.

The remaining of this paper focuses on comparing the performances of a receiver that would use the P-code on L2 and a receiver that would use the CA code on L2.

The results are based on data recorded with Septentrio's AsteRx2 receiver, which has the ability to track both L2P and L2CA in parallel. This allowed to reliably resolve the full cycle ambiguity of L2P as explained above.

L2CA vs L2P OBSERVABLES

Figure 4 represents the carrier-to-noise ratio difference between the L2CA and L2P signals, measured over a period of about 2 hours. Different colours correspond to different GLONASS-M satellites. It is apparent that the L2CA signal benefits from about 2 dB of additional carrier power. This is a significant advantage in terms of tracking noise and signal availability.

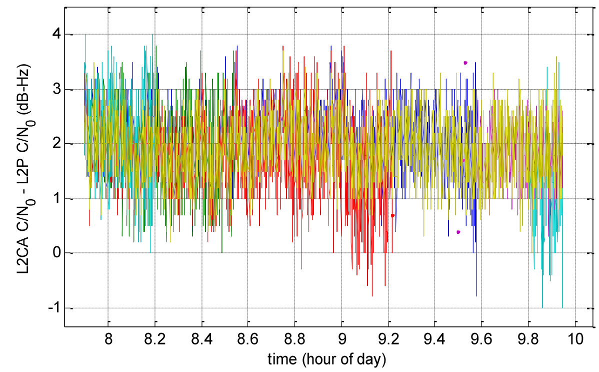

Figure 4. Carrier-to-noise ratio difference between L2CA and L2P.

In terms of code tracking noise (including multipath), it can be expected that the P-code performs better than the CA code, due to its higher chipping rate. This is confirmed by Figure 5, which shows the multipath and thermal noise error over all GLONASS-M passes during a full day, in a static data recording on Septentrio's rooftop in Leuven, Belgium. The standard deviation of the error over all these passes is 0.6 m for L2CA and 0.5 m for L2P.

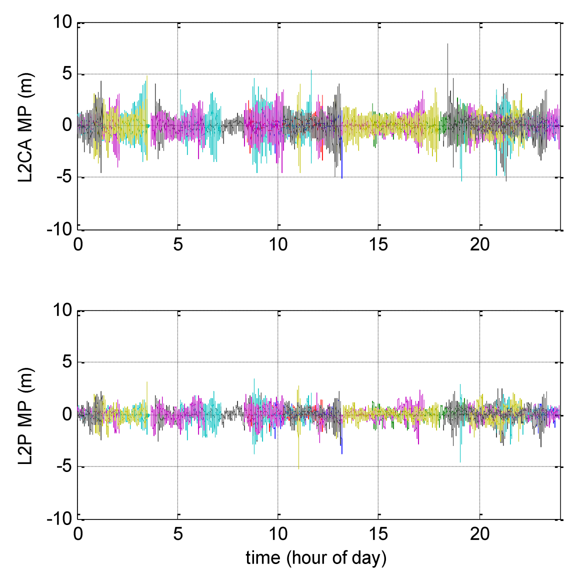

Figure 5. Multipath and thermal noise on L2CA (upper panel) and L2P (lower panel), for all GLONASS passes within one day (colors identify satellites).

Further inspection of the data reveals that the main advantage of the L2P resides in the suppression of high-frequency multipath component, as can be seen in Figure 6. The low-frequency errors appear to be of the same magnitude on L2CA and L2P. This result is not unexpected and is in line with comparable results obtained when comparing Galileo MBOC vs. BOC modulations [5].

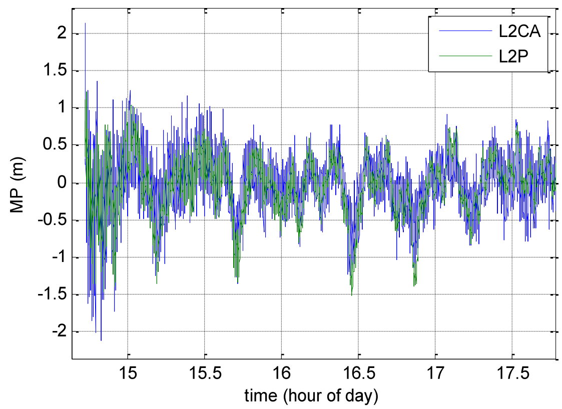

Figure 6. Multipath and thermal noise on L2CA and L2P for one of the satellites shown in Figure 5.

In order to compare the noise on L2P carrier phase (Φ_{L2P}) and L2CA carrier phase (Φ_{L2CA}), we have computed the first-order time derivative of (Φ_{L2CA}-Φ_{L1}) and (Φ_{L2P}-Φ_{L1}) respectively, where Φ_{L1} is the L1 carrier phase. The first-order time derivative is a simple way to remove the effect of the ionospheric divergence between the L1 and L2 carriers. Figure 7 illustrates the result for one pass of a GLONASS-M satellite, and is representative of all passes we have analysed. It is apparent that the noise on the L2CA carrier phase is smaller than on the L2P carrier phase. The reason is likely to be found in the larger C/N_0 value of the L2CA signal and in the longer duration of the L2CA navigation bits, allowing a longer predetection time in the L2CA PLL.

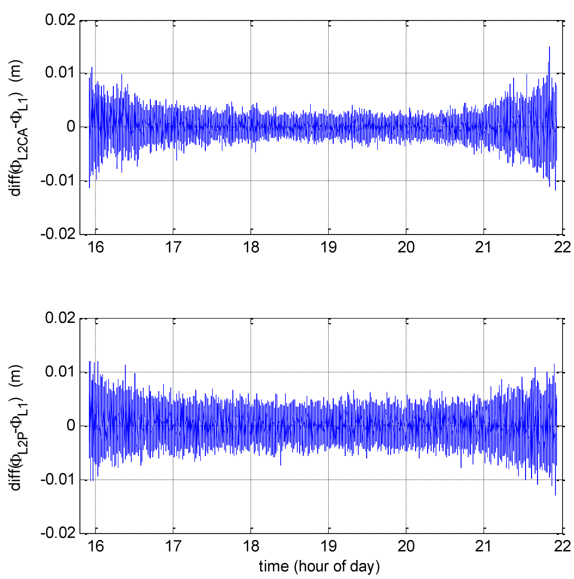

Figure 7. Comparison of L2CA and L2P carrier phase noise.

RTK PERFORMANCE OF L2CA VS L2P

In this section we discuss the factors which influence performance of GPS/GLONASS RTK applications and try to assess possible user impact of replacing of L2P with L2CA. From the user point of view, the performance of RTK applications is affected by (i) the time it takes until a position based on carrier phase with fixed integer ambiguities becomes available and (ii) the positioning accuracy of the carrier phase solution based on integer ambiguities.

The first parameter, time-to-fix, is mainly driven by the availability of a wide-lane combination and the magnitude of pseudorange errors. In the preceding section it has been shown that the GLONASS L2P modulation shows lower multipath errors than GLONASS L2CA. Hence, the RTK based on L1CA-L2CA combination will result in somewhat longer time-to-fix than with L1CA-L2P. However, improvements to the ambiguity estimation and validation algorithms (such as described in [6]) can help to overcome this disadvantage.

The second parameter, positioning accuracy, is a direct function of the carrier phase measurement accuracy: the carrier phase with the lowest noise will result in the best performance. As Figure 7 shows, L2CA carrier phase appears to outperform L2P carrier phase in this respect.

A specific challenge with combined GPS+GLONASS RTK is caused by residual hardware-dependent biases which are present in GLONASS double-differenced combinations of measurements. GLONASS satellites transmit on different frequencies and the pseudorange and carrier phase measurements will have different group delays and phase shifts dependent upon their frequency numbers. These biases shall have influence on the positioning performance [7]. Due to the deviations of the filter response between different receiver units (even of the same manufacturer) the group delays and phase shifts may not cancel as they would do with CDMA-based satellite systems.

The front-end design of the AsteRx2 receiver features linear variation of the phase-shift and group delays with wavelength, which allows for convenient calibration of the biases. The wavelengths corresponding to the different GLONASS frequency numbers are listed in Table 2, relative to the “center” wavelength at frequency number 0. The effect of this wavelength difference on the double-differenced (DD) residuals is proportional to integer cycle ambiguities. In the process of ambiguity fixing, the impact of these biases can be minimized if the values of unknown integer ambiguities are kept artificially small by adjusting the original carrier phase measurement. Once integer ambiguities are known, the biases can be directly computed and compensated for.

fn	**$\lambda_{L1}(fn) - \lambda_{L1}(0)$, cm**	**$\lambda_{L2}(fn) - \lambda_{L2}(0)$, cm**
-7	+0.0461	+0.0593
-6	+0.0395	+0.0508
-5	+0.0329	+0.0423
-4	+0.0263	+0.0338
-3	+0.0197	+0.0254
-2	+0.0132	+0.0169
-1	+0.0066	+0.0085
0	0	0
1	-0.0066	-0.0086
2	-0.0131	-0.0169
3	-0.0197	-0.0253
4	-0.0262	-0.0337
5	-0.0328	-0.0422
6	-0.0393	-0.0506

Table 2. Wavelength differences over the range of frequency numbers referenced to fn = 0.

To compare the performance of the RTK engine with different wide-lane combinations, we present here the DD residuals of both pseudorange and carrier phase measurements with respect to a fixed location. It is worth noting that the conclusions of the preceding section regarding phase noise are based on un-differenced data and do not translate directly into real-time kinematic RTK positioning accuracy. Indeed, latency of the differential corrections of 1-2 seconds, typical for real-time operation, will expose mm-level time variations of measurements caused by satellite clock jitter and other similar factors.

Figure 8 shows double-differenced pseudorange residuals for a short-baseline setup. Both the L2P and L2CA residuals are compared to the L1CA residuals. In agreement with the results of the previous section (**Figure 5**), this figure shows the lower accuracy of the L2CA modulation when compared to the L2P. It can be also seen that the noise on L2CA is somewhat higher than on L1CA. This is caused by the lower power of the GLONASS L2 signal, as specified in the GLONASS ICD [1] (see Figure 9).

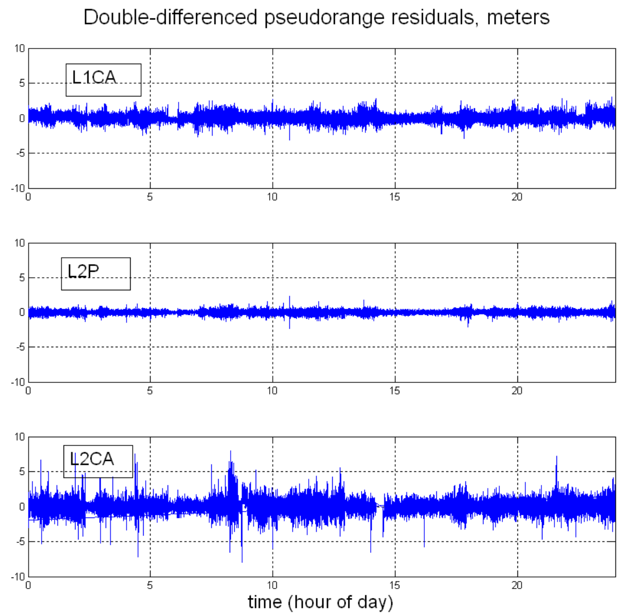

Figure 8. Comparison of GLONASS L2CA and L2P double differenced pseudorange residuals.

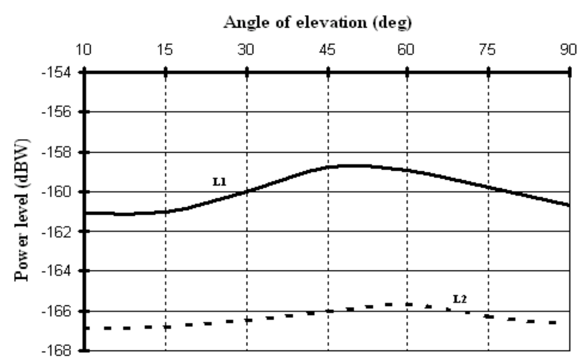

Figure 9. Comparison of GLONASS L1CA and L2CA signal power specification, [1].

Table 3 shows the overall standard deviation of double-differenced pseudorange residuals for each signal for both GLONASS and GPS computed from a day's worth of data. In this data set, the noise standard deviation was 0.77 m for L2CA and 0.21m for L2P. Hence the noise in the L1CA-L2CA combination shall be almost twice that of the L1CA-L2P combination.

system	signal	Residual STD, m
GLONASS	L1CA	0.41
	L2P	0.21
	L2CA	0.77
GPS	L1CA	0.21
	L2P	0.28
	L2CA	0.38

Table 3. GLONASS and GPS double differenced pseudorange statistics.

Figure 10 shows the double differenced carrier phase residuals for the same data set for all modulations. The latency of the differential corrections link was about 1 sec As it can be seen, there is no significant differences between the L2P and L2CA signals.

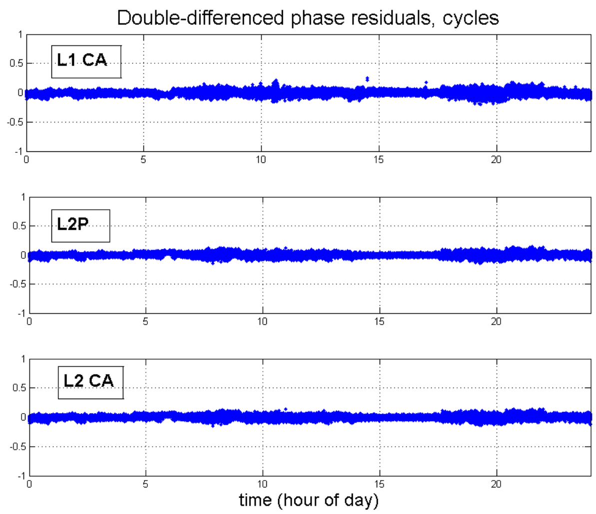

Figure 10. Comparison of GLONASS L1CA, L2CA and L2P double differenced carrier phase residuals.

In summary, the phase noise of the two L2 signals is about the same which shall translate into similar accuracy of the RTK solution with fixed ambiguities. The difference in code noise is quite substantial, but it is somewhat mitigated by the fact that the time-to-fix is affected by the noise of the combination (L1code – L2code) rather than by the noise of the L2 code itself. Future research is needed to see whether efficiency of ambiguity fixing algorithms is sufficient to cope with the increased noise in the L1CA-L2CA code combination versus L1CA-L2P. Simulations of multi-system ambiguity-fixing process [6] indicate that the multipath of this order of magnitude shall not cause significant increase of the time-to-fix.

CONCLUSIONS

GLONASS-M satellites bring two major modifications with respect to their predecessors. Firstly, a civilian signal is made available in the L2 band. Secondly, the legacy military L2P signal is now modulated with a new form of navigation message. The official specification of the new L2P navigation message is not publicly available, but our research indicates a bit rate of 250 bps and a frame duration of 4 sec. Some fixed bits which look like a preamble have been detected. Although the determination of the bit rate allows the tracking of the signal, this sudden change of specification of the L2P signal confirms that the use of L2P is at user's own risk. The only L2 signal, which offers guarantee of continuity to the community of CLONASS users is the civilian L2CA, which should be considered by receiver designers as a replacement of L2P.

The comparison of the tracking performance of the two L2 signals shows that L2P has predictably lower multipath errors than L2CA, while phase noise of both signals is about the same. Our conclusion is that although certain deterioration of time-to-fix with L2CA is inevitable, L2CA is a viable alternative to L2P and can be used in GLONASS RTK algorithms as the main L2 signal.

ACKNOWLEDGEMENTS

The authors would like to thank Stefan Schaer of the University of Berne for the valuable feedback he provided regarding the status of the GLONASS P-code.

REFERENCES

1. GLONASS Interface Control Document, version 5, 2002.
2. http://igscb.jpl.nasa.gov/mail/igsmail/2007/msg00147.html
3. Lennen, Gary R, The USSR's Glonass P-code - Determination and initial results. Proceedings of ION GPS-89, Colorado Springs, CO, US, September 1989.
4. Beser J., Danaher J. *The 3S Navigation R-100 Family of Integrated GPS/GLONASS Receivers: Description and Performance Results.* Proceedings of ION NTM 93, San Francisco, CA, US, January 1993.
5. Simsky A., Mertens D., Sleewaegen, J-M., De Wilde W., Hollreiser, M., Crisci M. *Multipath and Tracking Performance of Galileo Ranging Signals Transmitted by GIOVE-B.* Proceedings

of ION GNSS 2008, Savannah, GA, US, September 2008.

6. Verhagen S., Odijk D., Boon F. and Lopez Almansa J.M, *Reliable Multi-Carrier Ambiguity Resolution in the Presence of Multipath*. Proceedings of the ION GNSS 2007, Fort Worth, TX, US, September 2007.
7. Wang J., Rizos C., Stewart, M.P, Leick A., *GPS and GLONASS Integration: Modelling and Ambiguity Resolution Issues*. GPS Solutions Volume 5, Number 1, July 2001