A Novel GNSS Aiding Approach in GNSS/INS Integration for Challenging Environments

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Abstract: A novel GNSS-INS coupling approach is presented for challenging environments, such as those encountered in mobile mapping applications. The approach, called SIGIL, was developed by Septentrio, a GNSS manufacturer and iXBlue, an Inertial System manufacturer. It is aimed at mitigating some of the limitations of RTK in difficult environments and takes advantage of one of the main benefits of tight/deep coupling, namely aiding the GNSS filtering. SIGIL aiding is expected to improve the performance of the ambiguity fixing and allow better quality control of the GNSS measurement. This is confirmed with results of field test campaigns using the SIGIL aided RTK engine. It is shown that in difficult areas with SIGIL aiding the receiver is capable of providing more RTK fixed availability and higher accuracy.

BIOGRAPHIES

Dr. Richard Deurloo holds a M.Sc. in Aerospace Engineering from Delft University of Technology in the Netherlands and a Ph.D. in Surveying Engineering from the University of Porto in Portugal. He is currently a GNSS/INS research engineer at Septentrio in Belgium. His main interests include high-precision GNSS and GNSS/INS integration algorithms for difficult environments.

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Ir. Jean-Baptiste Lacambre holds a M.Sc in Telecommunication Engineering from the Ecole Nationale Supérieure d'Electronique, Informatique and Radiocommunication de Bordeaux (France). Before joining iXBlue, he worked as a signal processing engineer in the biomedical field. He is now an Inertial Navigation System research engineer, mainly focused on the GNSS/INS coupling for high precision application.

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1 INTRODUCTION

Position and attitude determination systems are expected to function in more and more challenging environments with increasing performance requirements. A good example of an application that requires high performance, typically cm-level accuracy for the position and 0.01°-level accuracy for the attitude, is mobile mapping. Mobile mapping systems rely on the geo-referencing of data from various sensors, such as LiDARs, sonars, radars, or video that are mounted on moving platforms and are typically operated in challenging environments, such as urban canyons. To achieve the high level of performance and availability these systems use an Inertial Navigation Systems (INS) aided by a RTK GNSS receiver (Jekeli, 2001).

In such systems the INS relies on the unbiased RTK GNSS solutions to correct the navigation parameters (position, speed, attitude, and sensor errors). But in difficult environments buildings and foliage may reflect or hide satellite signals and impede the GNSS receiver from accurately computing its position. The INS can compute navigation solutions in the absence of a GNSS signal, but only for a limited period of time (typically a few seconds to a few minutes, depending on the grade of the inertial sensors and the precision required). After that, it needs external information from the RTK GNSS receiver.

RTK relies on the correct estimation and integer resolution (fixing) of the carrier phase ambiguities to achieve centimeter precision. In challenging environments it is difficult to reliably determine these ambiguities. In some cases this may lead to either the absence of a fix (no integer resolution) and a lower precision, or a wrong integer resolution (a so-called wrong fix) that results in a biased and misleading position. In case the GNSS solution is misleading (e.g., wrong fix), the INS solution will become biased too, resulting in reduced performance.

A proper coupling of the GNSS and INS processes is the key to mitigate the respective limitations of each technology and to offer the optimal accuracy and reliability to the user. Various approaches and algorithms can be found in the literature to achieve such integration, ranging from a basic cascading of the decentralized GNSS and INS Kalman filters (loose coupling) to more complex single hybrid GNSS-INS filters (close coupling or tight coupling) and direct aiding of the GNSS tracking loops by the INS data (deep coupling).

In this paper, a novel GNSS-INS integration algorithm is presented for the challenging environment of mobile mapping applications. The approach, resulting from the collaboration between a GNSS receiver manufacturer (Septentrio) and an INS manufacturer (iXBlue) is called SIGIL: Septentrio-iXBlue GNSS Inertial Link. The approach aims at providing the main benefit of a close/tight coupling approach, namely aiding the GNSS filtering, while keeping the limited complexity of decentralized filters used in loose coupling. Such a separation of concerns has the added advantage of allowing each company to focus on its core competence.

In the next sections, we will first review the advantages and drawbacks of traditional GNSS-INS coupling methods and describe the novel SIGIL approach. This is followed by a more detailed discussion of the possible benefits of the new aiding approach for the GNSS receiver. Then, based on the results of various field test campaigns, we will show that the SIGIL-aided GNSS receiver is able to provide a higher availability of more robust RTK fixed positions with a higher accuracy and reliability in conditions typical for mobile mapping applications. The assessment is done by looking at the RTK availability and accuracy.

2 COUPLING APPROACHES

2.1. Traditional coupling

The fusion of the INS and GNSS data stream is typically achieved with a Kalman filter. But various coupling approaches are possible (Grewal, 2007). The type of coupling determines the complexity of the fusion and the advantages that can be gained.

The simplest integration is so-called loose coupling (Figure 1). In this approach, the GNSS positioning filter and GNSS/INS data fusion filter are kept decentralized and cascaded. The GNSS positioning filter processes the GNSS measurements at a low update rate (typically 1Hz) and provides a position solution. The GNSS/INS data fusion filter combines the GNSS position solution with the INS position solution that is computed by integrating high rate INS data (typically 200Hz) to provide an optimal solution for the position and inertial sensor errors. The result from the GNSS/INS data fusion filter is typically fed back into the INS motion integration to prevent error growth over time and aid in the drift mitigation of the INS position solution.

The advantage of the loose coupling approach is the low complexity and the separation of the GNSS and GNSS/INS data fusion process, avoiding among others the risk of error propagation. However, the GNSS positioning filter does not benefit from the fusion with the INS, since no feedback of the improved solution is provided.

In more advanced coupling approaches, such as tight and deep coupling, there is only a single centralized GNSS/INS data fusion filter (Figure 2). In these approaches the GNSS receiver provides pseudorange, carrier phase and Doppler measurements directly to the data fusion filter.

One of the main advantages of tight and deep coupling is the fact that data fusion is possible with only a few GNSS measurements and that the INS is therefore aided by the GNSS even when there are insufficient satellites for a GNSS-only solution. In addition, the GNSS can now also benefit from the fusion. The improved integrated solution allows better fault detections and ambiguity fixing of the GNSS measurements and thus mitigates the limitations of RTK mentioned in the introduction. In deep coupling the corrected INS solution is also used to aid the tracking loops of the GNSS receiver.

Although tight and deep coupling increase the availability for the end-user, it requires a concentrated effort on both the GNSS and INS design from the manufacturer(s). It also results in a significantly increased complexity leading to real time limitation and lower post-processing speed.

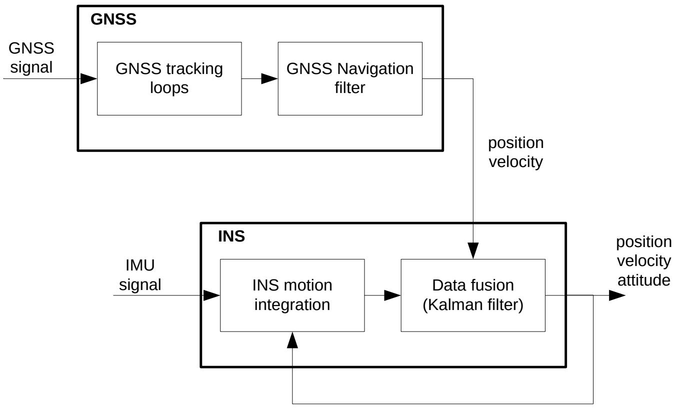


Figure 1. Traditional loose GNSS-INS coupling

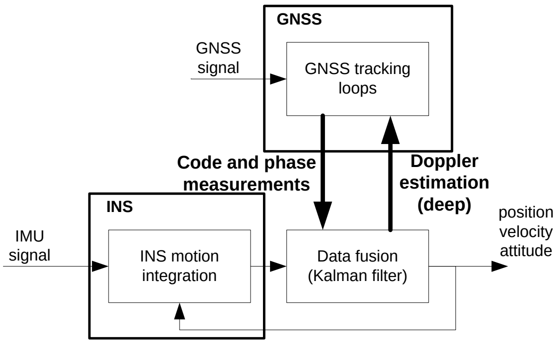


Figure 2. Traditional tight/deep GNSS-INS coupling

2.2. Novel coupling

The novel approach presented is aimed at mitigating the limitations of RTK and can be seen as an extension or enhancement of loose coupling. The approach takes advantage of one of the main benefits of tight/deep coupling, namely aiding the GNSS filtering, while keeping the low complexity and decentralized filters of loose coupling. This is possible with the addition of a dedicated interface, called SIGIL, to allow the GNSS receiver to benefit from the high rate, high short-term precision INS data. SIGIL allows for separate development of the INS and GNSS components and still takes advantage of the mutual aiding and feedback.

In Figure 3 the high level architecture of the closed loop SIGIL-based design is given. The SIGIL-based GNSS/INS coupling uses position variations computed by the INS between GNSS solution epochs. Since this position variation is precisely computed by the INS, the GNSS receiver can forego its own motion assumption and instead use a significantly more accurate prediction based on integrated INS data. This means that, similar to the loose coupling, the GNSS receiver provides high-precision PVT (position, velocity, and time) information to the INS. But with SIGIL the INS motion integration also provides high-precision integrated INS data to the GNSS receiver. The aim is to increase the availability, accuracy and reliability of the GNSS aiding to the INS, which can then provide more accurate aiding to the GNSS. The processes reinforce each other.

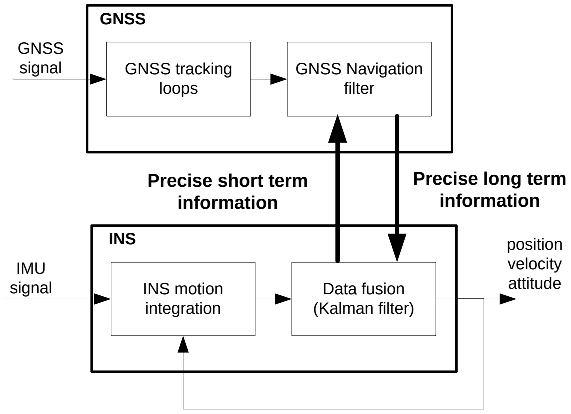


Figure 3. SIGIL-based approach

3 SIGIL AIDING BENEFITS

It is clear from the previous section that SIGIL is expected to aid the GNSS filtering. The main advantage is that the SIGIL-based position prediction used in RTK has a much lower covariance. This leads to:

1. a significantly reduced and more accurate search space of the carrier phase ambiguities;
2. robustness against biased GNSS measurements due to more reliable quality control.

An improvement of the ambiguity search space is expected to result in a shorter time to fix the partial ambiguities and thus a more reliable and robust RTK fix position under adverse conditions. This allows the GNSS receiver to transmit a more accurate RTK solution to the GNSS/INS data fusion filter in the presence of measurement outliers. Furthermore, with more reliable quality control the GNSS receiver is able to keep the fixed ambiguity solution for a longer time. In other words, with SIGIL the GNSS receiver is able to provide a higher availability of more robust fixed solutions with a higher accuracy and reliability in difficult conditions.

3.1. SIGIL-Based Ambiguity Fixing

Figure 4 shows an example of one of the challenging urban environment that was encountered during testing of SIGIL (Section 4). In this type of environment the low number of available signals and the GNSS measurement biases result in a low accuracy of the RTK ambiguities. In addition, frequent signal interrupts prevent ambiguity convergence, reducing the opportunities for reliable ambiguity fixing.

The availability of high accuracy INS information on short term intervals has a significant impact on the RTK ambiguity estimation and fixing process. Provided that the receiver is able to achieve sufficient confidence in recent ambiguity fixes, a new carrier phase can be included into the position solution almost instantaneously as initial ambiguity variances are typically well below the half cycle level. This usage of the INS information has great benefits for a partial ambiguity fixing engine where satellites can be validated individually (Meerbergen, 2010).

The accuracy of the initial float ambiguity scales with the quality of the INS chosen for the integration. The high-quality fiber optics gyro (FOG) IMU that is used in the INS from iXBlue has a drastic impact as illustrated by Figure 5. The search space for the L1 and L2 ambiguity of a reacquired satellite is significantly reduced and in addition more accurate.

Figure 4. Challenging urban environment

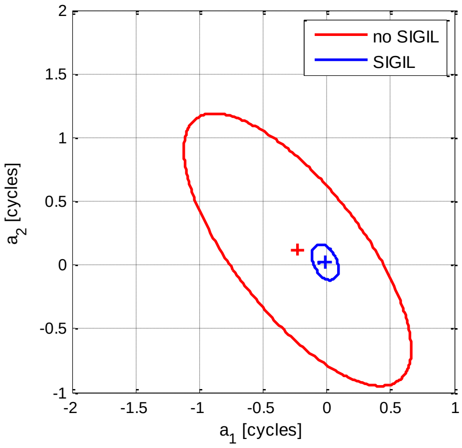


Figure 5. Impact of SIGIL aiding on the ambiguity covariance

Figure 6 shows this effect over time for the area shown in Figure 4. The upper graph shows the ambiguity accuracy of the aided solution over time; the unaided accuracy is shown in the lower graph. Note the difference in vertical scale: the aided ambiguities are well below half a cycle while the unaided engine has ambiguities with an accuracy of up to 10 cycles.

To avoid the risk of contaminating the INS solution with incorrectly fixed ambiguities, the individual partial fixes are tested against the complete set of ambiguities (both fixed and float) using hypothesis testing.

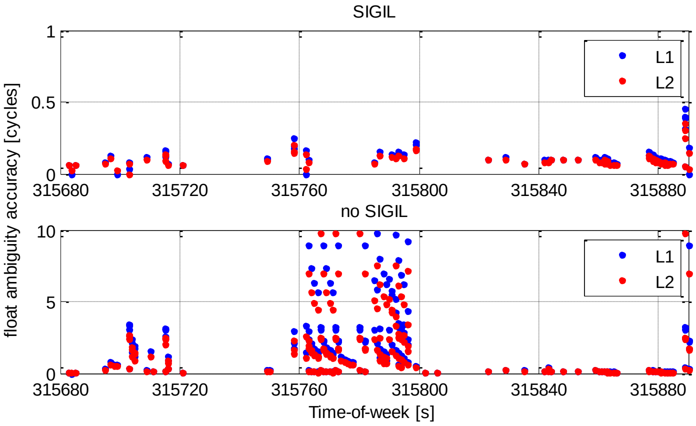


Figure 6. Impact of SIGIL aiding on the ambiguity accuracy

3.2. SIGIL-Based Quality Control

Without INS aiding we rely on the redundancy of GNSS measurements for quality control. Measurement biases will be absorbed into the position solution unless sufficient redundancy and/or an accurate online colored noise model are available. Both of these prerequisites are difficult to achieve in the challenging urban environments. The redundancy of satellites obtained by combined use of the GPS, GLONASS and BeiDou constellations is an enormous improvement compared to a decade ago, allowing a constant stream of at least 5 to 6 satellites in narrow streets. Unfortunately it is still insufficient to continuously provide a comfortable redundancy level for the GNSS positioning engine. With INS aiding we have more reliable information for quality control and redundancy is less of an issue and quality control becomes more robust.

In contrast to intuition, the measurement residuals of an INS aided positioning engine will increase as illustrated by the schematic illustration in Figure 7 where a vehicle drives from top to bottom along a building. The GNSS-only solution, as a least-squares result, will be biased because all input GNSS measurements are biased (e.g. by multipath). The INS-only solution however is stable on the short term and insensitive to the environment. Combining these two paths will hence lead to higher residuals. In a loosely coupled system the integration filter will simply weight both solutions. The SIGIL aided filter on the other hand is able to scan the GNSS measurements for biases and outliers, using an accurate description of the short term IMU noise.

This behavior is confirmed when analyzing the carrier phase residuals for both the aided and the unaided RTK engine in the challenging environment indicated in Figure 4. These residuals are shown in Figure 8. The lower graph (unaided) exhibits sections where all phase residuals are nearly zero. This is unrealistic considering the urban environment with both signal fading and multipath effects. The upper graph (aided with INS data) shows the expected behavior where the carrier phase measurements exhibit a time-invariant error behavior. Note that the number of satellites is not significantly different between the aided and unaided solution, indicating that the near-zero residuals are not caused by zero-redundancy effects.

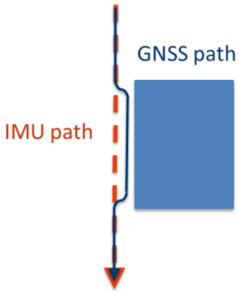


Figure 7. Mismatch between the INS and GNSS path

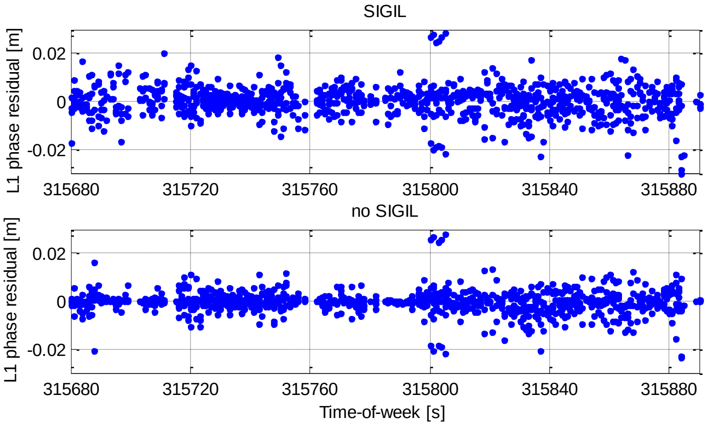


Figure 8. Impact of SIGIL aiding on the phase residuals

4 RESULTS AND DISCUSSION

A number of field tests were conducted to evaluate the SIGIL approach in various environments. SIGIL has been implemented in the iXBlue ATLANS-C INS which contains an iXBlue IMU50 core and a Septentrio AsteRx3 receiver. In addition, a post-processing tool has been developed for which Septentrio's GNSS processing library (PPSDK) is integrated into iXBlue's DELPHINS post-processing suite.

In the sections below we present results from 3 tests (Figure 9):

- Open-sky: a test conducted in June 2013 in the open-sky conditions of Plaisir near Paris, France (1 hour 10 min).
- Saint Germain: a test conducted in March 2014 in a challenging urban environment of Saint-Germain-en-Laye near Paris, France (1 hour 45 min).
- Plaisir: a test conducted in March 2014 in a variety of environments (open-sky, urban, forest) between Marly-le-Roi and Plaisir near Paris, France (2 hour 45 min).

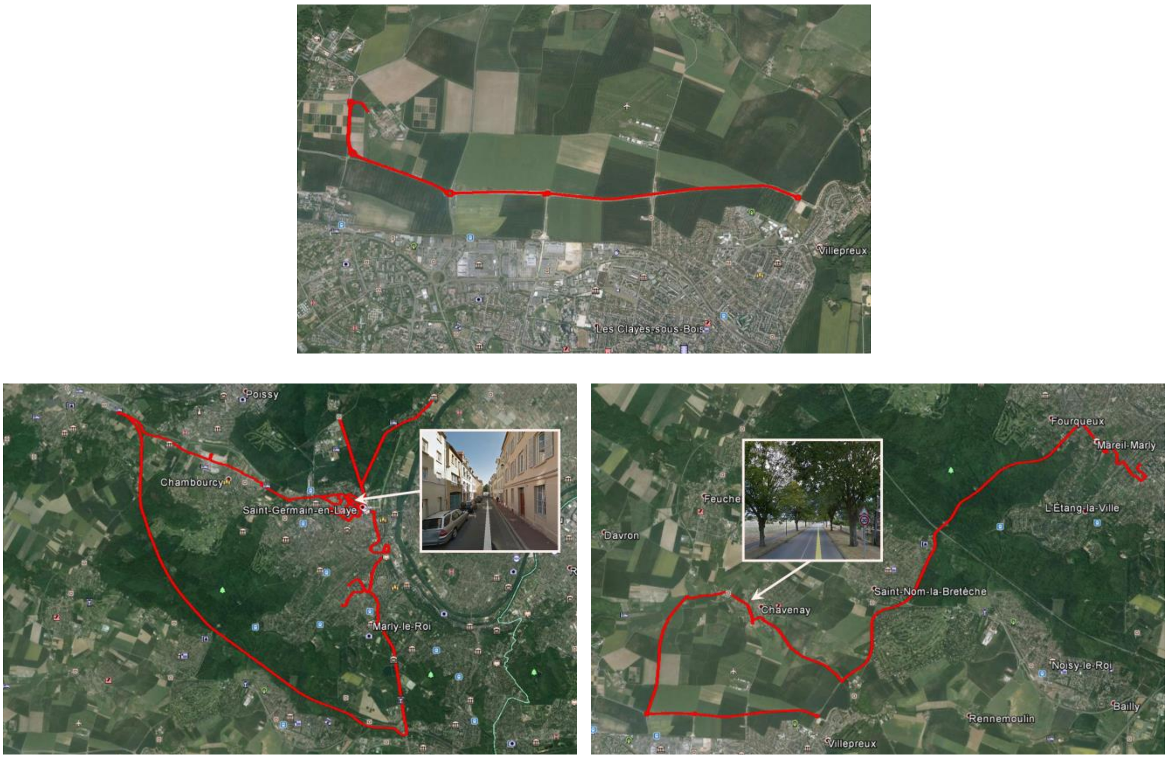
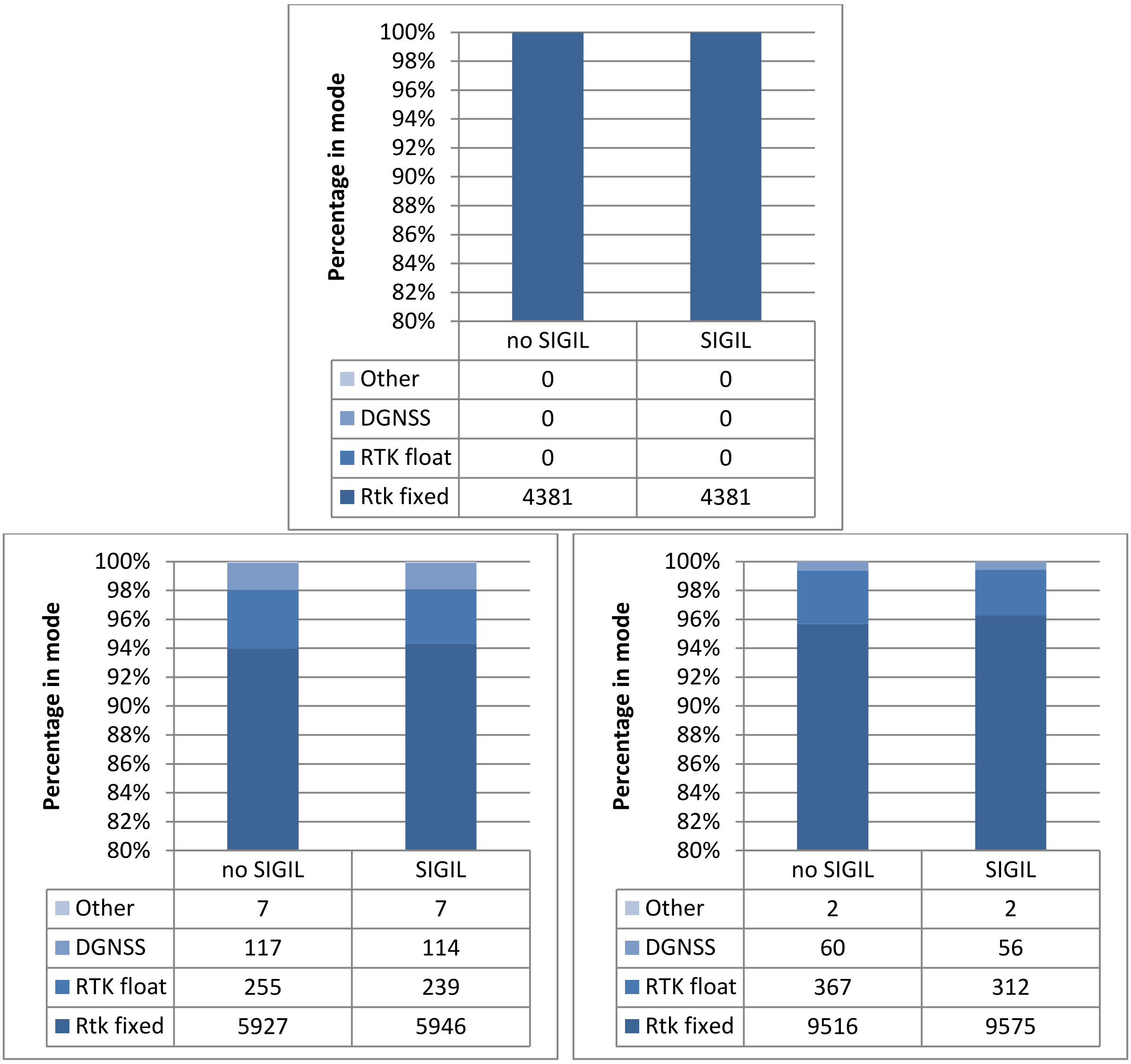


Figure 9. Trajectories of the open-sky (top), Saint Germain (left), and Plaisir (right) tests (courtesy of Google Earth).

For each of the tests we compare the performance of the RTK solutions with and without SIGIL aiding. The performance is evaluated based on RTK availability and accuracy. A higher grade INS from iXBlue was available during the tests to serve as a reference. For the first test an iXBlue LANDINS was used; in the last 2 tests an iXBlue MARINS was used. Both the LANDINS and MARINS receive PVT updates from a Trimble receiver. However, the reference was computed in post-processing with DELPHINS using the INS data together with the GNSS data from both the Septentrio and Trimble receivers.



	no SIGIL	SIGIL
Other	0	0
DGNSS	0	0
RTK float	0	0
Rtk fixed	4381	4381

	no SIGIL	SIGIL
Other	7	7
DGNSS	117	114
RTK float	255	239
Rtk fixed	5927	5946

	no SIGIL	SIGIL
Other	2	2
DGNSS	60	56
RTK float	367	312
Rtk fixed	9516	9575

Figure 10. Mode availability for the open-sky (top), Saint Germain (left), and Plaisir (right) tests.

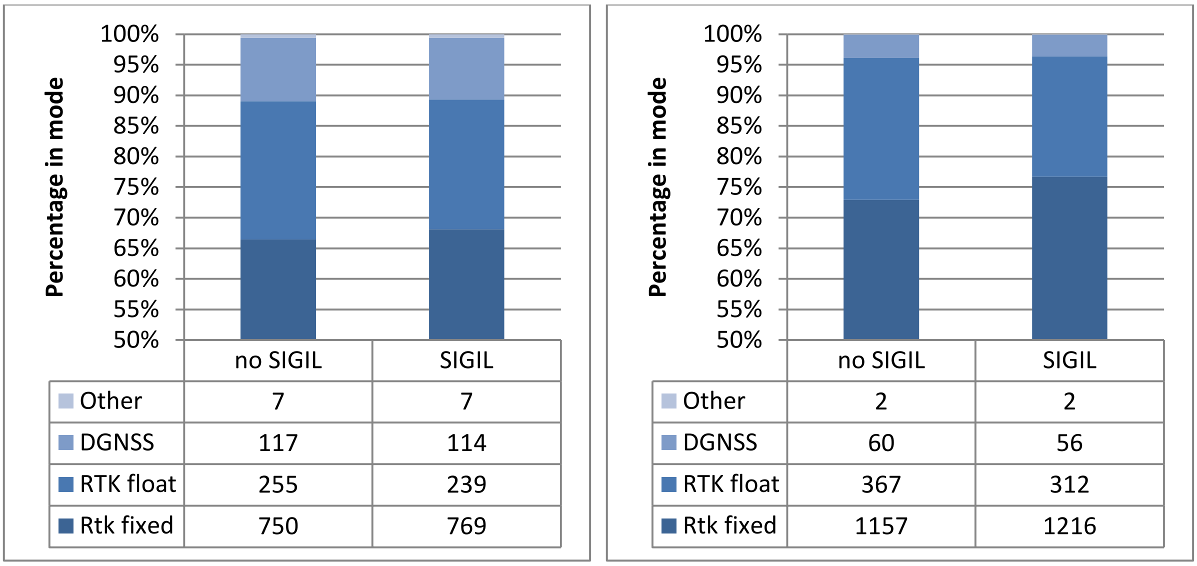
4.1. RTK availability

The availability of different solution modes of the tests is shown in Figure 10. The results marked with “SIGIL” are obtained with the novel INS aiding; the results marked with “no SIGIL” are obtained without INS aiding as in traditional loose coupling. Here the availability of each mode is defined as the percentage of epochs in that mode compared to the total amount of valid GNSS solution epochs.

It can be seen that the RTK availability for all tests is already high without SIGIL aiding, even in the most challenging test: 100% for the open-sky test, 94% for the Saint Germain test, and 96% for the Plaisir test. With SIGIL aiding this increases by 0.32% and 0.62% for the latter two tests. Although the RTK availability has indeed increased, the effect is limited. This is to be expected, as SIGIL aiding is expected to benefit only the more difficult areas.

When we focus on only the difficult sections of the Saint Germain and Plaisir test, we see the benefit of SIGIL aiding more clearly. This is shown in Figure 11. The RTK availability increases by 2.5% for the Saint Germain test and 5.1% for the Plaisir test.

Note that the availability in RTK float and RTK fixed together remains similar in the tests. However, with SIGIL aiding the fixed availability increases, confirming the expected impact of the SIGIL approach on the ability to retain a fixed solution and to quickly fix reacquired satellites. It is shown in the next section that the accuracy of the RTK solution with SIGIL aiding also increases.



	no SIGIL	SIGIL
Other	7	7
DGNSS	117	114
RTK float	255	239
Rtk fixed	750	769

	no SIGIL	SIGIL
Other	2	2
DGNSS	60	56
RTK float	367	312
Rtk fixed	1157	1216

Figure 11. Mode availability for the difficult sections in the Saint Germain (left), and Plaisir (right) tests.

4.2. RTK Accuracy

To assess the benefit of SIGIL aiding on the quality of the fixed RTK GNSS positions, the accuracy of the solutions is computed. At each RTK fixed epoch the distance is computed to the trusted reference derived from the higher grade INS system. For the resulting set of distances the 75% to 99% percentile errors are computed.

The 3D error percentiles are shown in Figure 12 for the all three tests. The corresponding 75%, 90%, 95% and 99% percentiles are show in Table 1. There is a reduction of the P95 and P99 3D error. This is to be interpreted as a reduction in amount and size of outliers.

The percentiles for the difficult areas are shown in Figure 13 and Table 2. Note that the 3D errors in the difficult sections are larger than that of the full data set. This is to be expected. In challenging conditions the solution noise will be higher. In addition, outliers are more likely to occur in difficult areas and their percentage will be higher. However, SIGIL aiding is able to significantly reduce the P99 3D error: in the Saint Germain test by 32% and in the Plaisir test by 40%. This confirms that the SIGIL approach not only increases the availability of the RTK fixed solution, but also increases accuracy through better quality control.

To illustrate a specific case, we focus on 2 representative points of interest, which have been indicated in Figure 9. We examine the RTK horizontal and vertical errors compared to the trusted reference in function of time (Figure 14 and Figure 15). The uncertainty of the reference is superimposed to indicate how much the reference trajectory can be trusted at each epoch. The SIGIL aided RTK solution is compared with the unaided RTK solution. Note again that the unaided RTK solution is the solution used in a traditional loosely coupled approach.

In the example from the Saint Germain test a horizontal outlier is removed around time-of-week 470580 s, while at the same time the number of (good) RTK fixed epochs is increased. In the Plaisir example RTK fixed availability is increased around time-of-week 483610 s and a outlier is removed at 483662 s.

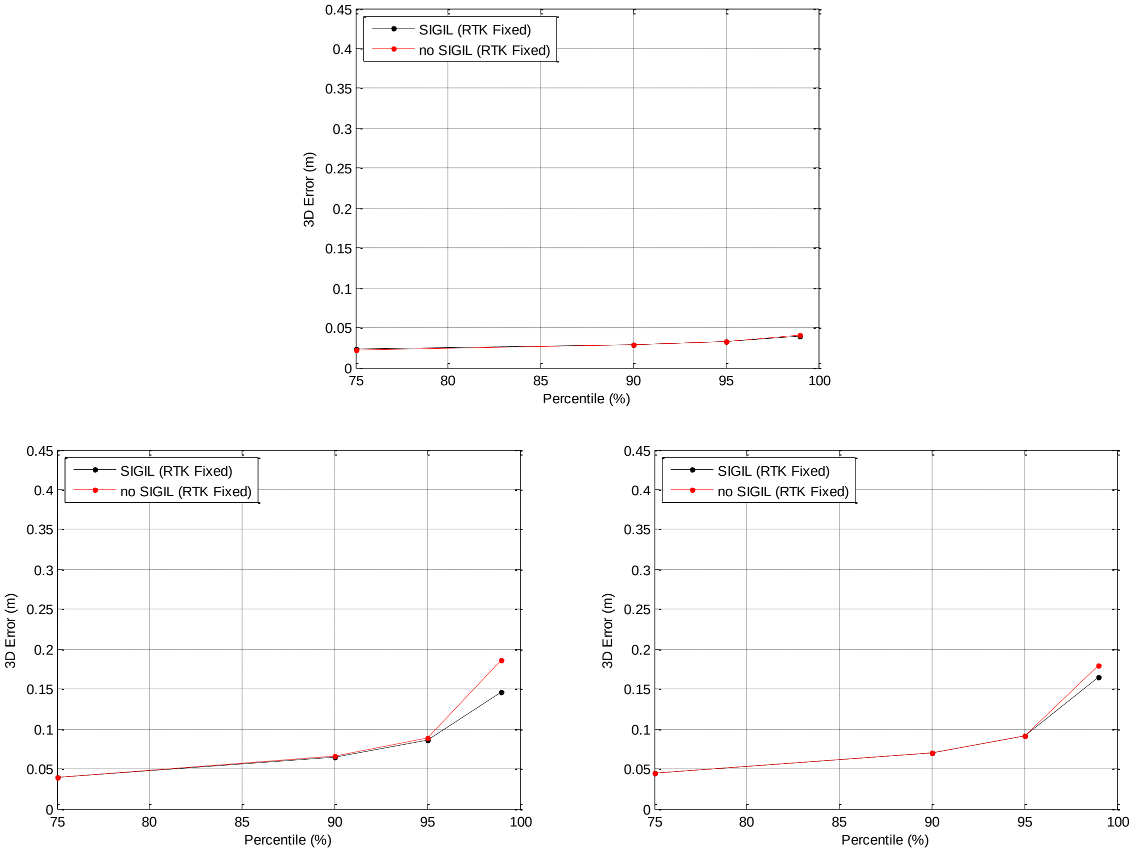


Figure 12. RTK fixed 3D error percentiles for the open-sky (top), Saint Germain (left), and Plaisir (right) tests.

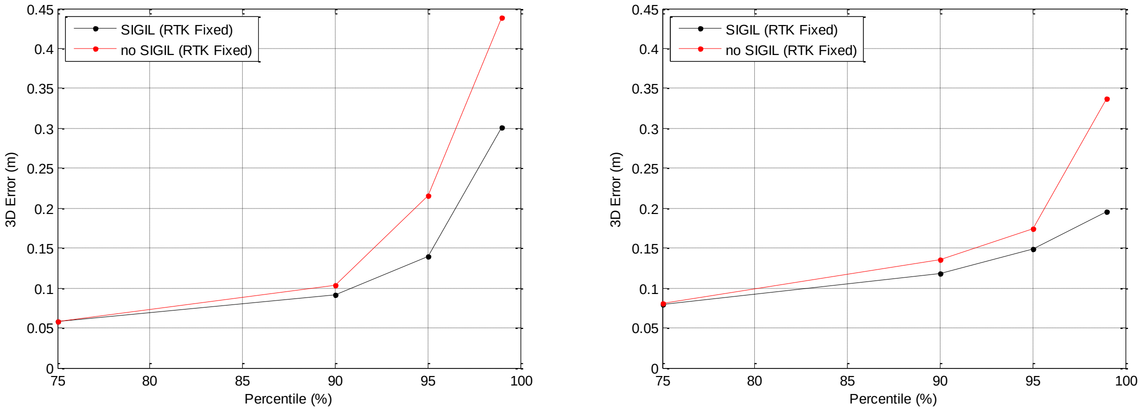


Figure 13.RTK fixed 3D error percentiles for the difficult sections in the Saint Germain (left), and Plaisir (right) tests.

Table 1. RTK fixed 3D error percentiles for the open-sky, Saint Germain, and Plaisir tests.

Error percentile (cm)		P75	P90	P95	P99
SIGIL (RTK fixed)	Open-sky	2	3	3	4
	Saint Germain	4	7	9	15
	Plaisir	4	7	9	16
no SIGIL (RTK fixed)	Open-sky	2	3	3	4
	Saint Germain	4	7	9	19
	Plaisir	4	7	9	18

Table 2. RTK fixed 3D error percentiles for the difficult sections in the Saint Germain and Plaisir tests.

Error percentile (cm)		P75	P90	P95	P99
SIGIL (RTK fixed)	Saint Germain	6	9	14	30
	Plaisir	8	12	15	20
no SIGIL (RTK fixed)	Saint Germain	6	10	21	44
	Plaisir	8	14	17	34

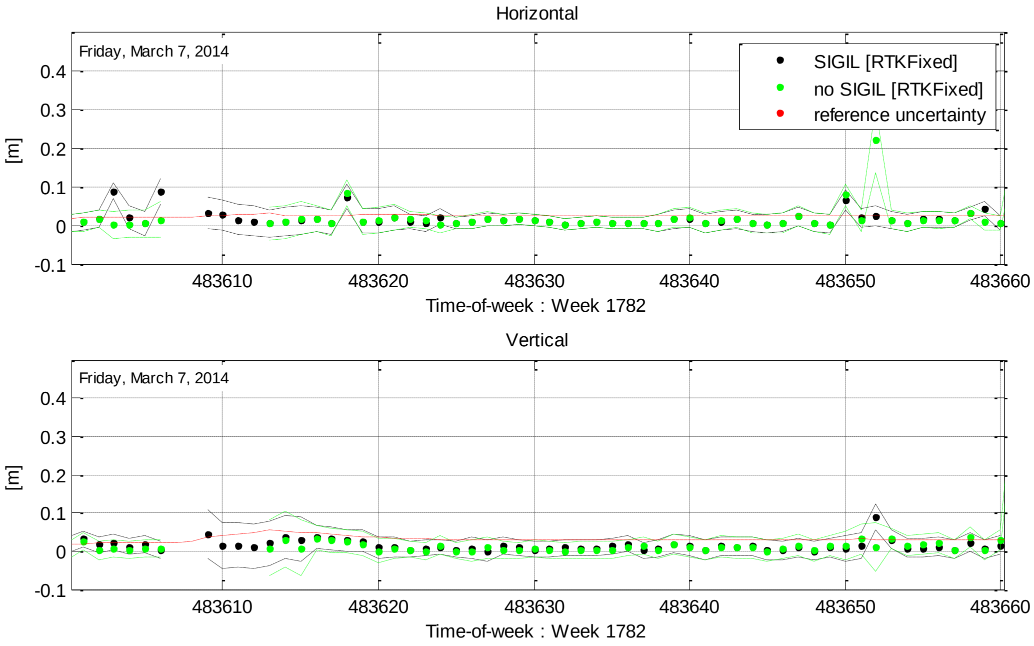


Figure 14. Horizontal and vertical error for the point of interest of the Saint Germain test.

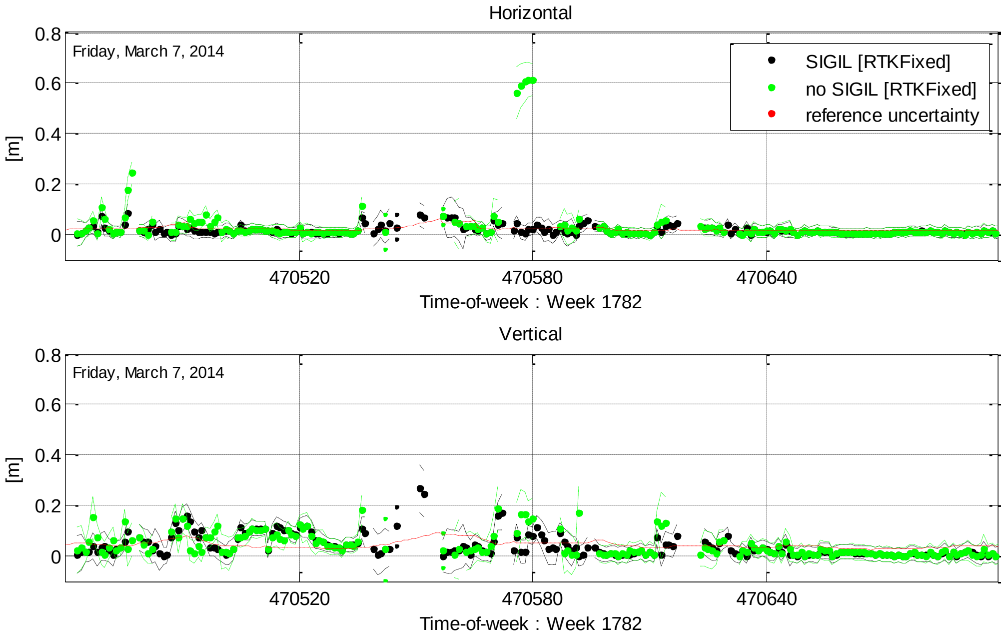


Figure 15. Horizontal and vertical error for the point of interest of the Saint Plaisir test.

5 CONCLUSION

The novel approach presented here, called SIGIL, is aimed at mitigating some of the limitations of RTK in difficult urban environments typically used in mobile mapping applications. The approach takes advantage of one of the main benefits of tight/deep coupling, namely aiding the GNSS filtering. The aiding helps to improve the GNSS solution and in turn provide better aiding to the INS.

With the current full constellations of GPS and GLONASS it is already possible to obtain a high RTK fixed performance, reaching 94%-96% RTK availability even in difficult environments. With SIGIL aiding the RTK fixed performance can be further increased. It was shown that with SIGIL aiding the receiver is capable of providing more RTK fixed availability and higher accuracy.

It is clear that SIGIL is of benefit where it is most needed, i.e. in challenging environments. The SIGIL aided receiver is able to better retain a fixed solution and to quickly fix reacquired satellites. For the two field tests performed in the challenging urban environment the RTK availability is increased by 2.5% and 5.1%.

But not only the availability is increased, the accuracy is of the solution is also increased. With SIGIL aiding better quality control of the GNSS measurements is possible. As a result, the 99 percentile 3D error is reduced by 32% and 40% respectively, confirming the improved outlier detection of the SIGIL aided RTK engine.

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