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Carrier-phase Ambiguity Success Rates for Integrated GPS-Galileo Satellite Navigation

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Abstract High-precision Global Navigation Satellite System (GNSS) positioning results are obtained with carrier phase measurements, once the integer cycle ambiguities have been successfully resolved. During the last decade much experience has been gained on fast and precise positioning with GPS as a dual-frequency system. The modernization of the GPS and the advent of Galileo will together lead to a truly multi-frequency civil GNSS, enhancing the capability of resolving the carrier phase ambiguities. In this paper the ambiguity success rates will be presented for different measurement scenarios and different GNSSs (e.g. modernized GPS, Galileo, integrated GPS-Galileo), emphasizing the role played by multiple frequencies and the number of satellites tracked.

Key words Carrier-phase ambiguity resolution, success rates, integrated GPS-Galileo

1 Introduction

The future availability of multi-frequency Global Navigation Satellite Systems (GNSSs) has resulted in high expectations with respect to improved performance. One development is that GPS will be modernised with a civil code on the L2 signal (L2C) and a third frequency, L5. Furthermore, the European GNSS, Galileo, will be operational in 2011. An overview of the available signals is given in table 1. A viable question is then: what will the new frequencies bring us? And how to choose the appropriate system and frequencies?

This study aims at answering these questions. For that purpose, the future performance of GPS and Galileo has been analysed based on the success rate of carrier phase ambiguity resolution [1] [2], since a high success rate is a prerequisite for precise and reliable positioning. The success rates have been computed for different scenarios, with GPS, Galileo and their combination. The success rates for instantaneous ambiguity resolution for a whole day were computed based on the GPS Yuma almanac of GPS week 328 with 28 healthy satellites, and the full nominal Galileo constellation of 30 satellites. Three different locations are considered, one at the equator, one at 70ºN, and one at 30ºS. The vertical tropospheric delays are estimated, and hence included as an additional unknown parameter in the model. It is assumed that these vertical delays can be mapped to slant delays using a simple mapping function. In order to deal with the ionosphere the ionosphere-weighted model is used. The baseline length was set to approximately 15, or 100 kilometres.

The outline of this paper is as follows. In section 2 the impact of the frequency choice on the success rates is analysed. The impact of the satellite constellation is studied in section 3. A performance comparison of GPS, Galileo en combined GPS+Galileo and the different frequency choices is made in section 4.

Table 1. Overview of future GPS and Galileo frequencies and services.

Frequency		**GPS**	**Galileo**			
Band	[MHz]	Open	Open	Commercial	Public Regulated	Safety of Life
L1	1575.42					
L2	1227.60					
L5 / E5a	1176.45					
E5b	1207.14					
E6	1278.75					

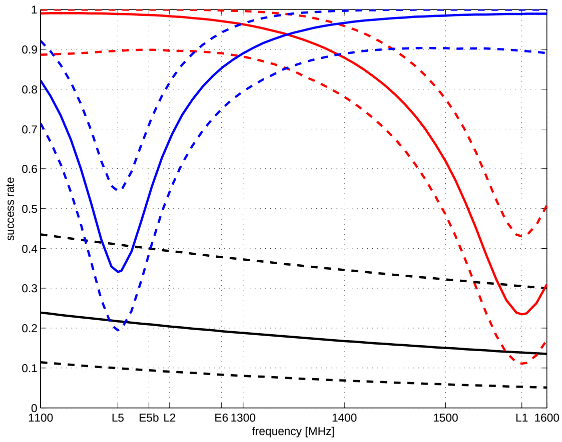

Figure 1. Mean, minimum and maximum success rates in a 24-hour period with Galileo based on instantaneous ambiguity resolution. 1-frequency (graphs at lower end of figure); 2-frequency with one frequency fixed to L1 (graphs with minimum at L1); 2-frequency with one frequency fixed to E5a/L5 (graphs with minimum at L5);.

2 The impact of frequency choice

Figure 1 shows the effect of the frequency choice on the success rates obtained with Galileo at the most Northern location. The mean, minimum and maximum success rates during the day are shown for the 1-frequency case, the 2-frequency case with one frequency fixed to L1, and the 2-frequency case with one frequency fixed to E5a. These frequencies were considered, because they will be used by both GPS and Galileo (in the open service).

With only one frequency it is obviously best to choose a low frequency. That is because then the wavelength is longer. However, the effect of the longer wavelength also implies a larger ionospheric effect. So, for longer baselines it may be better to use a higher frequency, whereas for shorter baselines it will be even more beneficial to use a low frequency (ionospheric effect is cancelled out anyway). With two frequencies it is important to choose the frequencies far apart if possible. Of course choosing the frequencies close together would allow for a very long wavelength of the wide-lane combination (almost 10 meters with E5a - E5b). However, the narrow-lane still has to be resolved and it has been shown that the success rate is not increased using the wide- and narrow-lane combinations [3] [4]. Hence, the results in the figure are the best one can get. Note the difference in the results when one of the frequencies is either fixed to L1 or to E5a.

3 The impact of the satellite constellation

The nominal GPS constellation is built up of 24 satellites divided over six planes and orbiting the Earth at an altitude of approximately 20,000 km. The orbital inclination is 55º. For a long time the actual number of satellites is higher, and that is not expected to change. Here, the 28-satellite constellation of December 2005 is used.

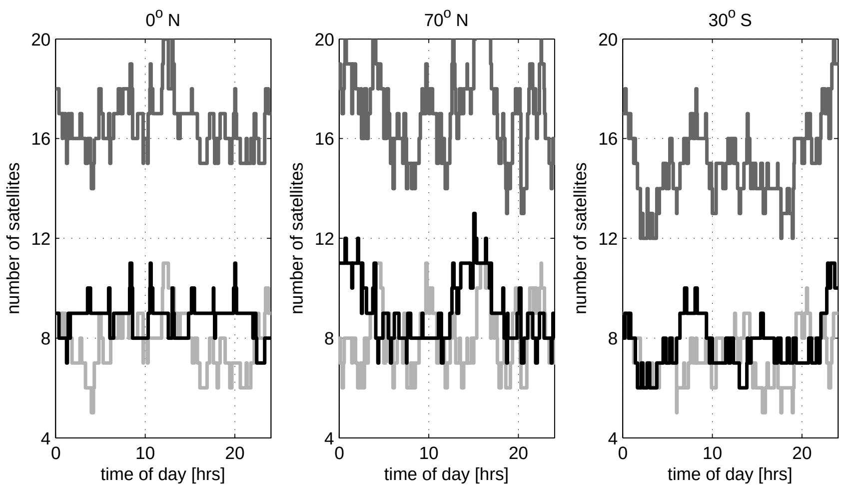

Figure 2. Number of satellites for GPS (light grey), Galileo (black), and combined GPS-Galileo.

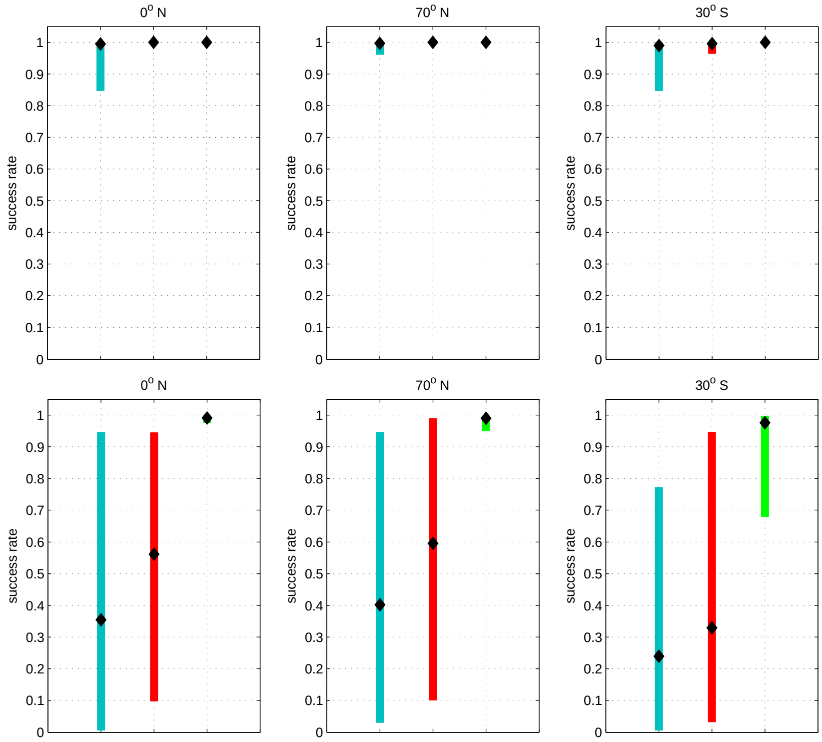

Figure 3. Mean (dots), minimum (bottom of bars) and maximum (top of bars) single epoch success rates during the day with GPS (left) and Galileo (centre) and integrated GPS-Galileo (right) , all based on L1 + L5 frequencies at three locations.
Top: ~15 km baseline. Bottom: ~100 km baseline.

Table 2. Standard deviations of undifferenced observations.

	L1	L5
code [cm]	20	10
phase [mm]	1.3	1.0

The Galileo constellation will be built up of 30 satellites (27 + 3 spares), divided over three planes at an altitude of approximately 23,200 km. The orbital inclination will be 56º.

Figure 2 shows the number of satellites during the day with GPS, Galileo and combined GPS+Galileo for the three locations. Table 2 gives an overview of the standard deviations assigned to the code and phase observations on each frequency. The standard deviations were chosen equal for GPS and Galileo. In this way, the differences in the success rates are only due to the different satellite constellations.

Figure 3 shows the success rates with dual-frequency GPS, Galileo and their combination using the L1 and L5 frequencies. The bars show the range of values that the success rates take during the day, the dots show the mean values. Note that over a longer time period, the mean success rates with Galileo can be different, because the repeat period of the constellation is 10 days, whereas for GPS it is one day. However, it was verified that the values here are representative (only very small deviations).

Obviously, the success rates are higher with the Galileo constellation. From Figure 2 follows that the number of satellites is generally higher than with GPS, and never below six, whereas with GPS the number of satellites may drop to five and is never higher than eleven. With combined GPS+Galileo the success rates are always very close to one thanks to the large number of satellites. The figure also shows that the constellations are more beneficial at high and low latitudes.

In order to study the impact of the satellite constellation further, the single epoch success rates obtained with Galileo have been computed as function of the number of satellites in view. The long baseline of 100 km was considered here. The results are shown in the top panels of Figure 4. It follows that the number of satellites is the main factor affecting the success rates. The mean success rate for each location is namely approximately the same for the same number of satellites. However, geometry does play a role, since even with the same number of satellites, the success rate may still take a range of values. This range is small if the number of satellites is small, in that case the success rates will always be low. The range will also be small if the number of satellites is high, since then the success rate will always be high.

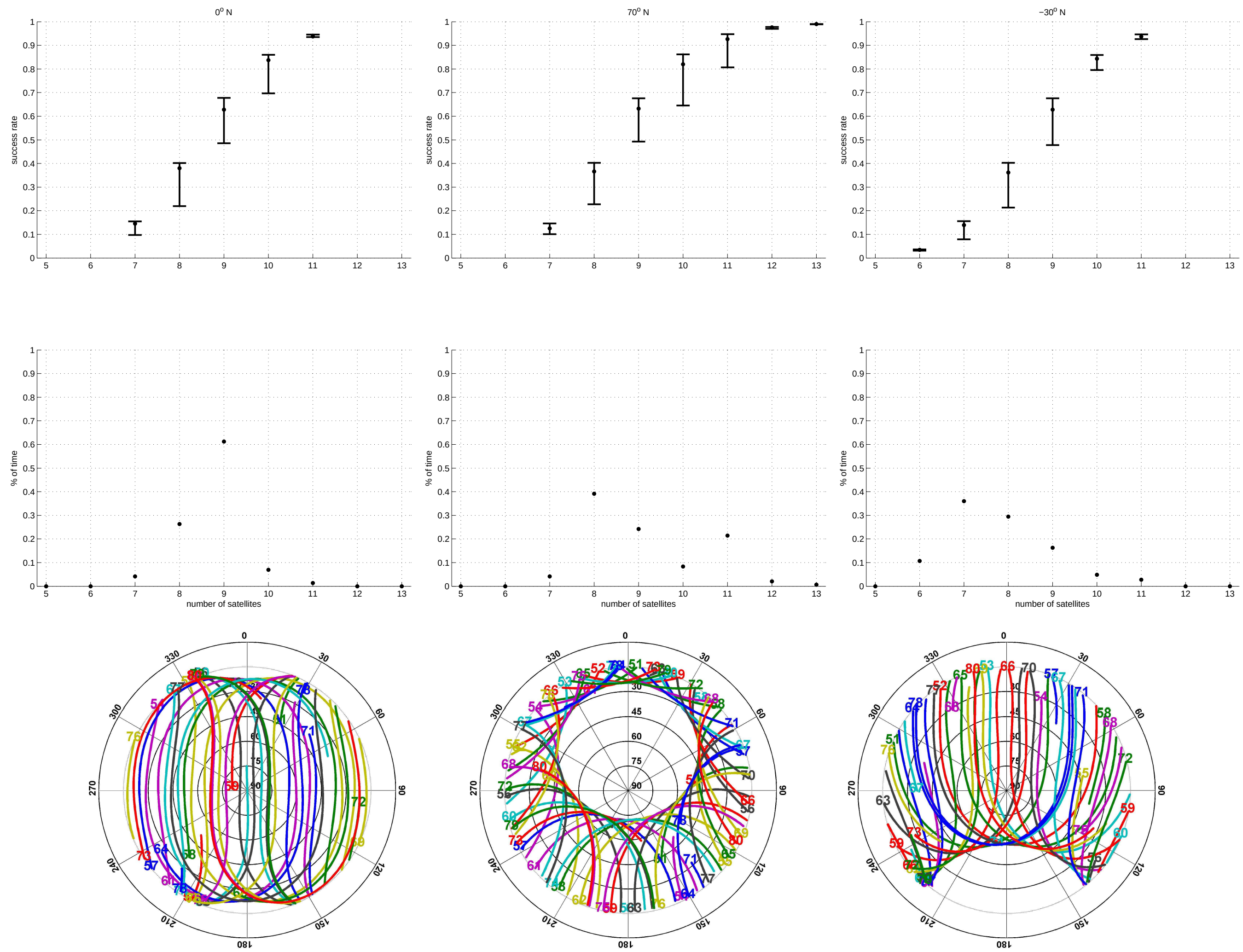

Figure 4. Mean (dots), minimum and maximum success rates as function of the number of satellites with Galileo L1+L5 (top); Percentage of time in 24h period that number of satellites is visible (centre); Skyplots (bottom).

Figure 4 also shows the percentage of time in a 24h period that a certain number of satellites is visible. This is highly dependent on the latitude, which becomes clear from inspection of the skyplots, shown in Figure 4 as well. Close to the equator, satellites can be seen almost everywhere in the sky. At high latitudes, however, there is a hole. The reason is that the orbital inclination is 56˚, so that the satellites do not fly over high latitude regions. Still, satellites at low elevations are visible which are 'on the other side' of the Earth. Therefore, the number of satellites is generally higher than at mid-latitude regions, where no satellites are visible at low elevations in the South at the Southern hemisphere, or in the North at the Northern hemisphere. The difference in number of satellites is clearly visible in Figure 2.

It should be mentioned that the results with GPS are very similar; the mean success rates as function of the number of satellites are approximately the same. But since the satellite geometry is different, the ranges of values for a certain number of satellites are somewhat different.

4 Performance comparison

Figure 5 - Figure 7 show the results for GPS and Galileo and their combination with nearly all possible frequency choices. The bars show the range of values that the single epoch success rates take during the day, the dots show the mean values. Table 3 gives an overview of realistic standard deviations (in the future that is) assigned to the code and phase observations on each frequency.

If we compare the results of the GPS frequency combinations, it follows that the L1+L5 combination is somewhat better than the L1+L2 combination, since the mean and maximum values are somewhat higher. On the other hand, the minimum values can be much lower. Using 3-frequency GPS gives better results, as expected, although the improvement is marginal if we take into account that we want the success rate to be very close to 1.

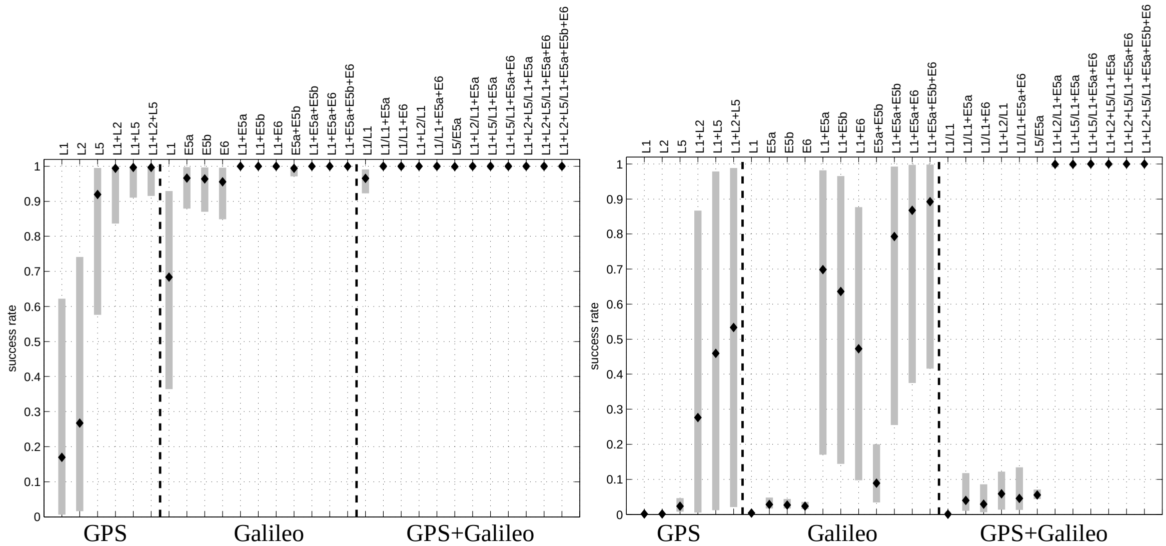

Figure 5. Mean (dots), minimum (bottom of bars) and maximum (top of bars) success rates during the day with GPS and Galileo at 0ºN. Left: ~15 km baseline. Right: ~100 km baseline.

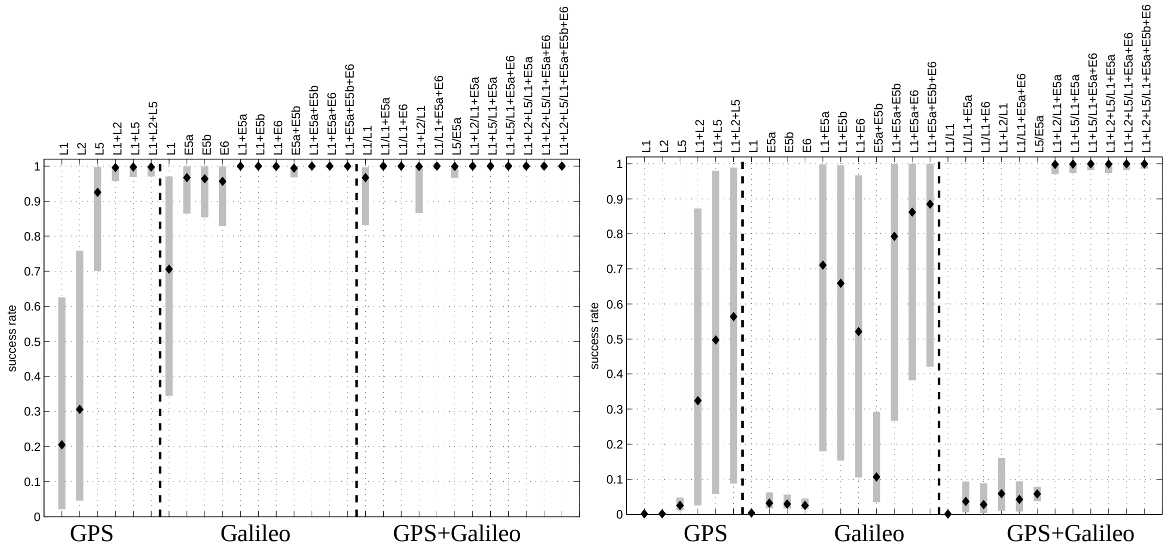

Figure 6. Mean (dots), minimum (bottom of bars) and maximum (top of bars) success rates during the day with GPS and Galileo at 70ºN. Left: ~15 km baseline. Right: ~100 km baseline.

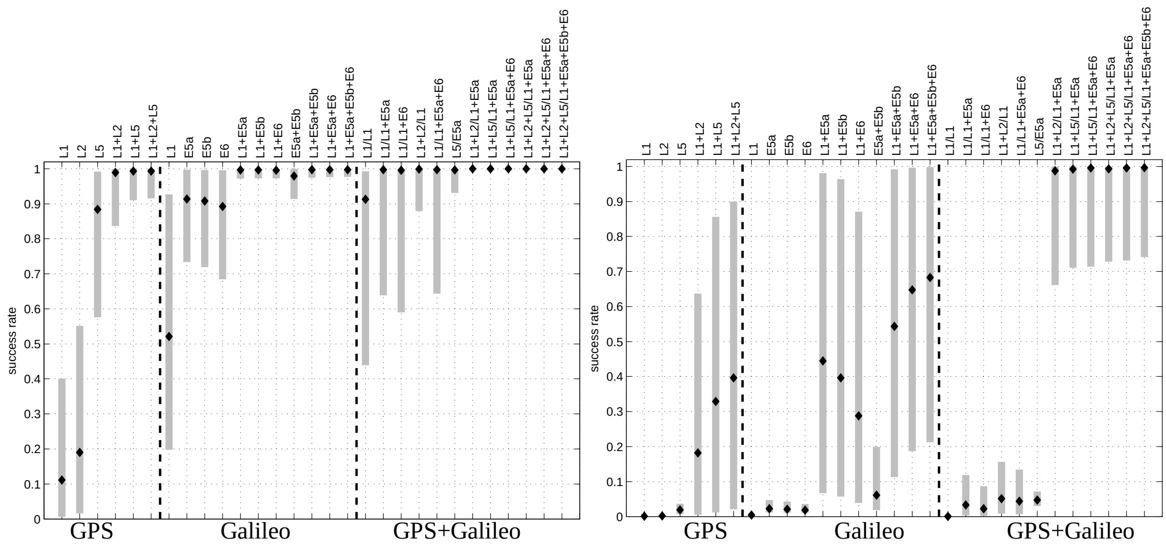

Figure 7. Mean (dots), minimum (bottom of bars) and maximum (top of bars) success rates during the day with GPS and Galileo at 30ºS. Left: ~15 km baseline. Right: ~100 km baseline.

Table 3. Standard deviations of undifferenced observations.

	GPS			Galileo			
	L1	L2	L5	L1	E6	E5a	E5b
code [cm]	15	15	4	7	4	4	4
phase [mm]	1.3	1.3	1.0	1.3	1.0	1.0	1.0

Comparing GPS L1+L5 with Galileo L1+E5a shows the effect of the different constellations and lower code noise on the success rate. For all locations, Galileo provides higher success rates than GPS, but the difference is especially large at the equator. Especially for shorter baselines, Galileo will enable reliable ambiguity resolution at nearly 100% of the time, in contrast to GPS. For longer baselines, the ionosphere modelling will remain the limiting factor.

Using Galileo L1+E6 instead of L1+E5a gives somewhat lower success rates, and a third or fourth frequency gives only marginal improvements. The combination E5a+E5b is not a good choice in terms of the success rate, as became clear from Figure 1 as well. The combination will, however, not be used in practice, but is just included for completeness.

Single frequency GPS results in very low success rates. With Galileo the situation is much improved, due to the lower observation noise and improved geometry of the constellation.

Combined GPS-Galileo shows a tremendous improvement when compared to the individual systems. Especially if at least two frequencies are used for both systems, the mean success rates are equal or very close to one, even with long baselines. The combination GPS L1+L2 / Galileo L1+E5a results in somewhat lower success rates than GPS L1+L5 / Galileo L1+E5a. However, GPS L5 will be available at a later stage, and therefore this combination is a good choice in the mean time.

In conclusion, we can say that Galileo will improve the reliability of ambiguity resolution, and will enable the use of longer baselines. Especially, if we take into account that the code noise for the GPS observations are currently very optimistic. The values used here are thought to be realistic in the future. This means that compared to the current situation, Galileo will even show a larger improvement.

Unfortunately, for long baselines the improvement may not be satisfactory if only one of the GNSSs is used. In that case a larger improvement is to be expected from the availability of more satellites (integrated GPS-Galileo), improved troposphere and ionosphere models, less observation noise, and improved multipath characteristics and mitigation.

5 Summary

In this study the performance of Galileo is compared with GPS and integrated GPS-Galileo. The results are based only on single-epoch processing. It followed that Galileo will offer much improved performance as compared to the current GPS. The performance is even better or at least as good as with triple-frequency GPS, which will not be (completely) available within a short time (~10 years). The results indicate that with Galileo it will be possible to use longer baselines, and that the time-to-fix will become shorter, since the single-epoch results are already much better. The major improvement is to be expected from integrated GPS-Galileo. If two frequencies of both systems are used, instantaneous ambiguity resolution will become feasible even for long baselines. A reason why to use more frequencies is the availability of system integrity information on the Galileo E6 signal, and that more frequencies may be beneficial for error mitigation and quality control.

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