FIGURE 1 Galileo constellation and occupation status of orbital slots (RAAN: right ascension of the ascending node, May 9, 2017). Source: ESA

HOW GALILEO BENEFITS HIGH-PRECISION RTK

What to Expect with the Current Constellation

THIS ARTICLE DEMONSTRATES the benefits of Galileo integration for high-precision real-time kinematic (RTK) through representative case studies, considering baseline length, multipath impact and tree canopy. The results confirm usability of the current Galileo constellation in high-precision RTK applications and show improved availability, accuracy, reliability and time-to-fix in difficult measuring environments. Plus, Galileo-only RTK positions are compared with GPS-only and GLONASS-only solutions.

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Until now, based on simulated and observed data, the benefits of Galileo (**FIGURE 1**) for high-precision RTK have been investigated in single-base RTK and network RTK solutions. Building on the results of previous studies that frequently employed theoretic analysis and simulation, we present the benefits of Galileo for high-precision RTK based on real observations from the current Initial Operational Capability (IOC) satellite constellation. Using up-to-date real-time corrections including Galileo, we analyze the performance of network RTK under different measuring conditions with respect to availability, accuracy, reliability and time-to-fix.

To achieve the maximum interoperability with other GNSS constellations, all the Galileo signals in the E1 and E5 band, i.e. E1, E5a, E5b and AltBOC (alternative binary offset carrier), are used for positioning in the latest proprietary firmware and receivers (see "Manufacturers" section for details). The Galileo E1 signal is overlapped with the GPS L1 signal at a center frequency of 1575.420 MHz,

whereas the Galileo E5a and GPS L5 signals are overlapped at 1176.450 MHz. As far as BeiDou is concerned, the E5b frequency of Galileo corresponds to the B2 frequency of BeiDou-2 at 1207.140 MHz. The AltBOC signal is also supported in order to benefit from its superior performance in multipath suppression. The availability of more than two frequencies is beneficial for ionospheric modeling, which plays an important role in ambiguity resolution on the fly. In addition, multi-frequency RTK provides more immunity to temporary interruption of GNSS signals caused by interference or by site-specific effects like multipath. When forming linear combinations, the incorporation of multi-frequency signals enhances flexibility and robustness, where the mathematical correlations introduced by including the same signal in different linear combinations of the same type need to be handled properly in RTK algorithms.

By enabling the tracking of Galileo satellites in the aforementioned firmware, the Galileo signals will be used in different RTK position types by default, including navigation position, phase-aided differential code position, extended RTK (xRTK) position and RTK fixed position. When compared to a standard RTK fix, an xRTK fix is provided at a slightly lower accuracy level, but with higher availability in difficult environments such as urban canyons and dense canopy. In terms of RTK correction data formats, Galileo is included in the standardized RTCM v3 MSM format and in the proprietary 4G format. To use Galileo in network RTK, the real-time products provided by network correction services need to include Galileo as well. In the latest version of a proprietary GNSS network software, Galileo is used in network processing to provide RTK corrections via the individualized master-auxiliary (iMAX) method and the virtual reference station (VRS) method in the RTCM 3.2 MSM formats.

RTK PERFORMANCE CHARACTERISTICS

Multi-constellation and multi-frequency GNSS RTK is a complex real-time process, aiming to provide cm-level positioning accuracy with as few as possible data epochs for variable user kinematics and even in difficult measuring environments. Therefore, RTK performance characteristics need to be carefully selected to be able to evaluate the system as a whole and to address users' concerns in their applications. The following parameters are used in this article to assess the benefits of Galileo for high-precision RTK:

Satellite usage. Number of satellites used in RTK fixed solutions with an elevation cut-off angle of 10°;

Availability. Percentage of RTK fixed positions relative to all positions obtained during a time period;

Accuracy. Deviation of RTK fixed positions from ground
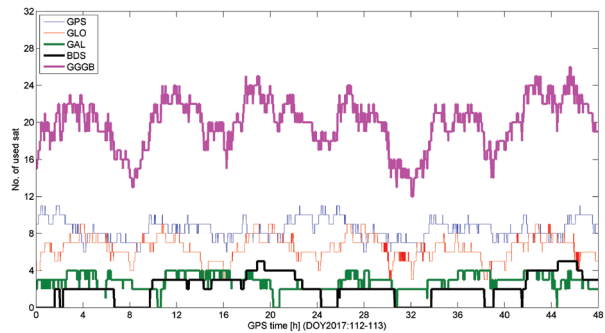
FIGURE 2 Number of satellites used in RTK fixed positions with GGGB under open sky (iMAX, RTCM v3 MSM, baseline length: 2 km, GGGB: GPS+GLO+GAL+BDS, DOY: day of year).

truth with a higher degree of accuracy, where the ground truth can be determined by means of a total station or by post-processing long-term GNSS data;

Reliability. Percentage that the position error (with respect to ground truth) is less than 3 x coordinate quality (CQ) indicator;

Time to Fix. Time needed to regain an RTK fixed solution after losing ambiguity fix provided that GNSS signal tracking is not interrupted.

OPEN-SKY CASE STUDY

The open-sky case study was performed in the Heerbrugg testbed. Two receivers were connected to a single antenna via a four-way antenna splitter. One receiver received four-system iMAX corrections in the RTCM v3 MSM format over a short baseline of 2 km, whereas the other received RTK data of the same type over a long baseline of 116 km. By considering different baseline lengths, the open-sky experiment focused on the usability of the current Galileo constellation in GNSS RTK under normal conditions. Two days of 1-Hz GNSS data were investigated with respect to satellite usage and positioning accuracy.

Using different combinations of GNSS to analyze the short baseline data — GPS+GLO (GG), GPS+GLO+BDS (GGB) and GPS+GLO+GAL+BDS (GGGB) — the mean numbers of used satellites are 15, 17 and 20, respectively, where the elevation cut-off angle was set to 10°. On average, three Galileo satellites contribute to RTK fixed solutions. For the four-system combination GGGB, **FIGURE 2** shows the satellite usage for each individual system over the two-day period. It can be seen that for a short baseline of 2 km, a maximum number of four Galileo satellites can be used for positioning. In fact, during 80.3% of the whole test period, the number of Galileo satellites used in RTK fixed solutions is equal to or greater than the number of BeiDou satellites used.

Number of used Galileo satellites n	Short baseline (2 km)	Long baseline (116 km)
n = 0	1.9	15.0
n = 1	0.4	0.6
n = 2	28.8	41.0
n = 3	40.7	30.4
n = 4	28.2	13.0
n ≥ 2	97.7	84.4
n ≥ 3	68.9	43.4

TABLE 1 Probability [%] that n Galileo satellites are used in RTK fixed positions with GGGB during the two-day period of the open-sky experiment (iMAX, RTCM v3 MSM, GGGB: GPS+GLO+GAL+BDS).

TABLE 1 provides statistics on Galileo satellite usage in case of GGGB for different baseline lengths. As would be expected, the number of Galileo satellites used decreases with an increasing baseline length. In approximately 41% of the cases, three Galileo satellites are used in the short baseline test, whereas two Galileo satellites are used in the long baseline test. Moreover, the probability that no Galileo satellites are involved in a four-system combined solution grows significantly from 1.9% to 15.0% as the baseline length increases from 2 km to 116 km. The probability that only one Galileo satellite is used under open sky is relatively small, amounting to around 0.5%. This is reasonable since no benefits for high-precision RTK are expected in this particular situation. Regarding the short baseline case, there is a 97.7% probability that at least two Galileo satellites are used for positioning, whereas this probability decreases to 84.4% in the long baseline case.

In terms of positioning accuracy, **FIGURE 3** compares the 3D errors from analyzing the long baseline data with different GNSS constellations. Regarding the entire two-day period illustrated in **FIGURE 3A**, the integration of BeiDou (GG vs. GGB) and Galileo (GGB vs. GGGB) results in higher position repeatability with more consistent errors. For a selected period of 12 hours, **FIGURE 3B** highlights the advantages of Galileo in reducing large 3D errors from 6–8 cm to 3–4 cm, where two or three Galileo satellites are used in case of GGGB.

MULTIPATH CASE STUDY

In this case study, a GNSS smart antenna was set up in a location with strong multipath effects, where GNSS signals were obstructed and reflected

|	Total (3D)	Horizontal (2D)	Height (1D)
GGB	0.080	0.028	0.075
GGGB	0.035	0.016	0.031
Improvement	56.3%	42.9%	58.7%

TABLE 2 Root mean square errors [m] of RTK fixed positions under strong multipath (VRS, RTCM v3 MSM, GGB: GPS+GLO+BDS, GGGB: GPS+GLO+GAL+BDS).

	Total (3D)	Horizontal (2D)	Height (1D)
GGB	88.2	87.9	88.3
GGGB	95.5	95.6	95.5
Improvement	7.3	7.7	7.2

TABLE 3 Reliability [%] of RTK fixed positions under strong multipath (VRS, RTCM v3 MSM, GGB: GPS+GLO+BDS, GGGB: GPS+GLO+GAL+BDS).

by the surrounding buildings (**FIGURE 4**). This test setup simulates the use case that a user measures a point near a building with degraded GNSS signal reception, even at high elevation angles. The default elevation cut-off angle of 10° was applied. The receiver received four-system VRS corrections in the RTCM v3 MSM format, where the distance to the physical reference station was approximately 200 m. Three hours of 1-Hz GNSS data were analyzed with respect to accuracy, reliability and time to fix.

FIGURE 5 illustrates the 3D errors from multi-GNSS RTK with and without Galileo (GGGB vs. GGB), along with the number of used satellites. Regarding the periods marked with dashed rectangles, the inclusion of two or three Galileo
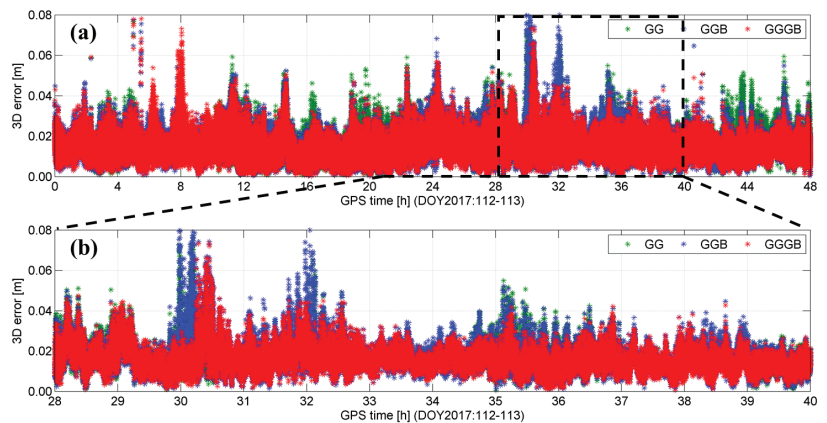
FIGURE 3 3D errors of RTK fixed positions under open sky (iMAX, RTCM v3 MSM, baseline length: 116 km, GG: GPS+GLO in green, GGB: GPS+GLO+BDS in blue, GGGB: GPS+GLO+GAL+BDS in red, DOY: day of year) (a) Entire two-day period, (b) Selected 12-hour period (28−40 h).

satellites (**FIGURE 5B**) leads to significant improvements in positioning accuracy at the few cm to dm level (**FIGURE 5A**). By comparing the empirical cumulative distribution function (CDF) of the 3D errors, the probability that 3D error is within 5 cm increases from 70% to 85% if Galileo is used, even with a maximum number of three satellites.

TABLE 2 and **TABLE 3** provide the root mean square (RMS) errors and reliability of RTK fixed positions from the multipath experiment, respectively. By using Galileo in high-precision RTK, the 3D RMS error is significantly reduced by 56.3% in this case study, from 0.080 m (GGB) to 0.035 m (GGGB). When compared to the horizontal components, the height RMS error shows a larger relative improvement of 58.7% due to Galileo integration. The reliability reflects the consistency between the actual position error with respect to ground truth and the CQ indicator estimated based on mathematical models in RTK algorithms. As shown in Table 3, the 3D reliability improves by 7.3%, from 88.2% (GGB) to 95.5% (GGGB), where the increases for the horizontal components and height are comparable.

The time to fix (TTF) was determined by constantly re-initializing RTK once an ambiguity fix was gained. During the whole period of repeatedly resetting the RTK filter, the GNSS signals were tracked continuously without interruption. A total of 765 TTF values were obtained with GGB, whereas 1,128 TTF estimates were available with GGGB. The significantly larger number of the TTF samples from GGGB indicates higher availability of RTK fix if Galileo is used. **FIGURE 6** shows the statistical distribution of TTF with respect to Galileo integration. As can be seen in the empirical CDF in **FIGURE 6A**, it takes shorter time for GGGB to regain an ambiguity fix. As an example, GGGB
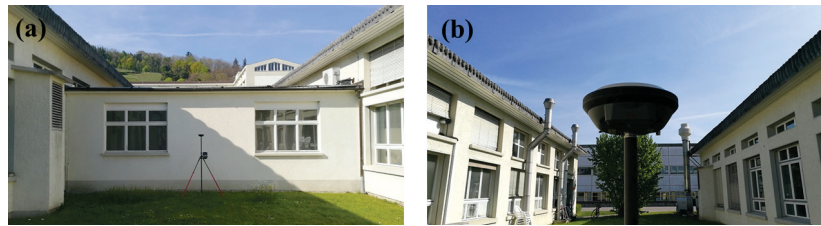

FIGURE 4 Test setup in a strong multipath environment in Heerbrugg (rover: GS16, antenna height: 1.8 m) (a) View from the south, (b) View from the north.
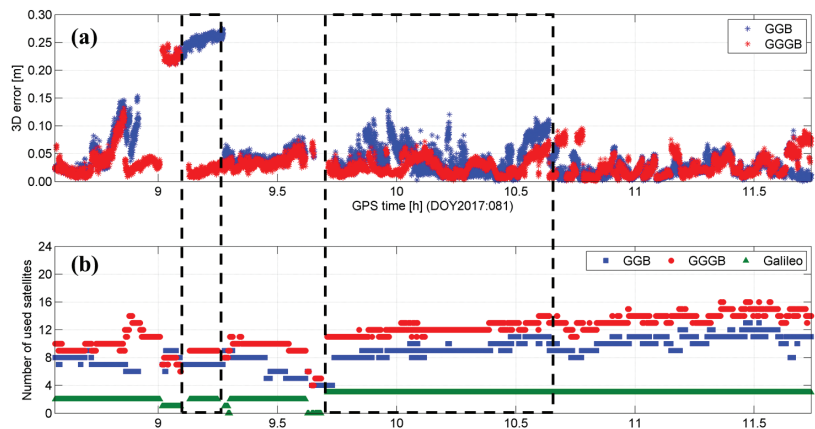

FIGURE 5 Impact of Galileo integration on RTK positioning accuracy under strong multipath (VRS, RTCM v3 MSM, GGB: GPS+GLO+BDS in blue, GGGB: GPS+GLO+GAL+BDS in red, DOY: day of year) (a) 3D errors of RTK fixed positions, (b) Number of used satellites (Galileo in green).
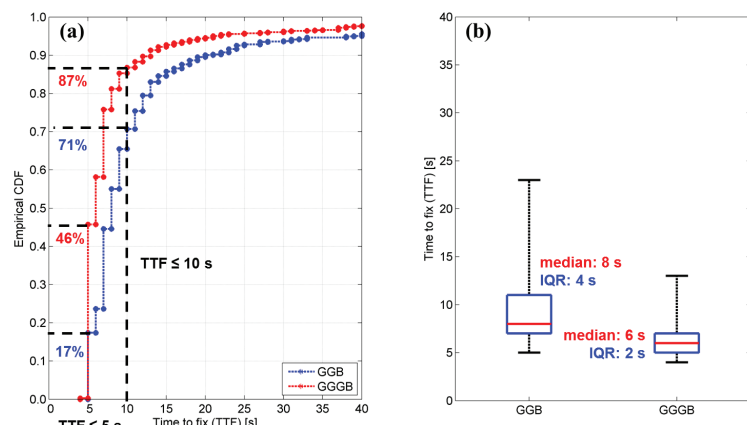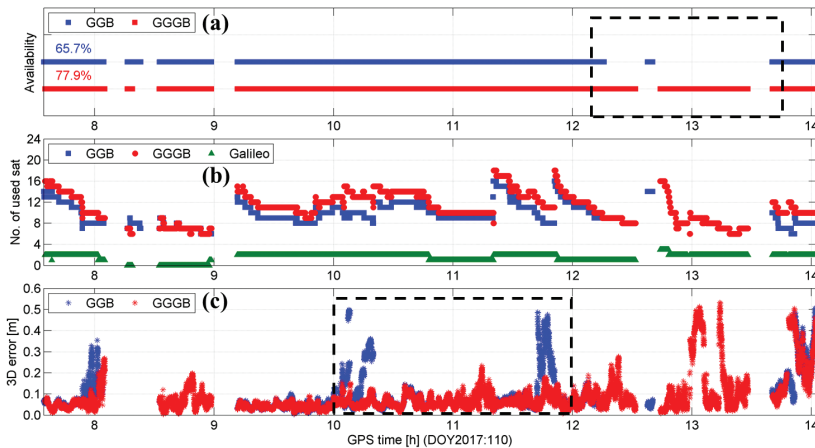

FIGURE 6 Impact of Galileo integration on time to fix (TTF) statistics under strong multipath (VRS, RTCM v3 MSM) (a) Empirical cumulative distribution function (CDF) of TTF, (b) Boxplot of TTF with median and interquartile range (IQR).

allows ambiguity resolution within 5 s (10 s) with 46% (87%) probability, which is 29% (16%) higher than GGB. Regarding the boxplots of TTF in **FIGURE 6B**, GGGB shows a smaller median

(by 25% from 8 s to 6 s) and a smaller interquartile range (IQR; by 50% from 4 s to 2 s) than GGB, where the IQR is the length of the box. This indicates that the integration of Galileo enables a

FIGURE 7 Test setup under canopy in Heerbrugg (rover: GS10, antenna: AS10).

FIGURE 8 Impact of Galileo integration on RTK availability and accuracy under canopy (iMAX, RTCM v3 MSM, baseline length: 116 km, GGB: GPS+GLO+BDS in blue, GGGB: GPS+GLO+GAL+BDS in red, DOY: day of year) (a) Availability of RTK fixed positions over time, (b) Number of used satellites (Galileo in green), (c) 3D errors of RTK fixed positions.
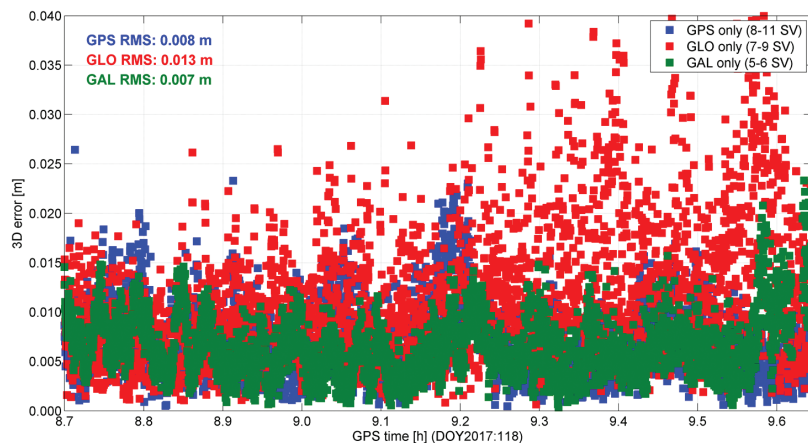
FIGURE 9 3D errors of RTK fixed positions from GPS-only, GLONASS-only and Galileo-only RTK under open sky (single-base RTK, baseline length: 1 m, RTCM v3 MSM, DOY: day of year, RMS: root mean square).

faster ambiguity resolution with more consistent fixing performance.

CANOPY CASE STUDY

In this case study, a receiver was connected to an antenna under tree canopy (**FIGURE 7**), where GNSS signals are blocked, attenuated and reflected, leading to decreased number of observations, low data quality and degraded RTK performance. Under these circumstances, the inclusion of Galileo satellites transmitting multi-frequency signals could be particularly beneficial for high-precision RTK. Using an elevation cut-off angle of 10°, the receiver received four-system iMAX corrections in the RTCM v3 MSM format, where the baseline length was 116 km. A long baseline was intentionally selected as an additional challenge for the RTK system. About seven hours of 1-Hz GNSS data were investigated regarding availability, accuracy and reliability.

FIGURE 8 illustrates the impact of Galileo integration on RTK availability and accuracy under canopy, along with the number of used satellites. As can be seen in **FIGURE 8A**, the inclusion of Galileo improves the availability of RTK fixed positions by 12.2%, from 65.7% (GGB) to 77.9% (GGGB). Moreover, dm-level position errors are largely reduced, as shown in **FIGURE 8C**. The improvements in availability and accuracy are achieved by using up to three Galileo satellites **(FIGURE 8B)**. This demonstrates that the current Galileo constellation in the IOC phase brings considerable benefits to high-precision RTK under canopy conditions.

TABLE 4 and **TABLE 5** provide the RMS errors and reliability of RTK fixed positions from the canopy experiment, respectively. The main factors degrading the RTK accuracy in this case study are not only the canopy environment, but also the long baseline length of 116 km. It can

	Total (3D)	Horizontal (2D)	Height (1D)
GGB	0.114	0.065	0.102
GGGB	0.087	0.062	0.075
Improvement	23.7%	4.6%	26.5%

TABLE 4 Root mean square errors [m] of RTK fixed positions under canopy (iMAX, RTCM v3 MSM, baseline length: 116 km, GGB: GPS+GLO+BDS, GGGB: GPS+GLO+GAL+BDS).

	Total (3D)	Horizontal (2D)	Height (1D)
GGB	92.6	99.2	94.6
GGGB	94.5	99.5	96.0
Improvement	1.9	0.3	1.4

TABLE 5 Reliability [%] of RTK fixed positions under canopy (iMAX, RTCM v3 MSM, baseline length: 116 km, GGB: GPS+GLO+BDS, GGGB: GPS+GLO+GAL+BDS).

be seen in Table 4 that the integration of Galileo leads to a significant reduction of 3D RMS error by 23.7%, from 0.114 m (GGB) to 0.087 m (GGGB). By comparing the 2D and 1D RMS errors, the benefits of Galileo for the height are more dominant than for the horizontal components, which was also observed in the multipath experiment (Table 2). In terms of reliability, only slight (below 2%) increases are visible in Table 5. 116km baseline length and heavy canopy are considered extreme conditions and beyond the standard conditions relevant for specifications. Considering reliability together with availability (Figure 8a), it is encouraging to see that both the RTK performance characteristics are improved in this case study.

GALILEO-ONLY RTK

To optimize the performance of multi-GNSS RTK positioning, the individual systems need to be fully understood and mastered. With a previous firmware release in August 2014, mass-market devices were able to perform GLONASS-only and BeiDou-only high-precision RTK. In 2014 tests, we compared the performance of GPS-only, GLONASS-only and BeiDou-only RTK at different accuracy levels. Considering that Galileo has reached the IOC phase, it is reasonable to assess the Galileo-only RTK performance with the latest firmware.

Due to the limited number of usable Galileo satellites, Galileo-only RTK positioning was carried out in the Heerbrugg open-sky testbed over a very short baseline of 1 m. In addition, the elevation cut-off angle was set to 0° in order to track as many Galileo satellites as possible simultaneously. Two receivers were connected to two choke-ring antennas with good low-elevation tracking

ability. Single-base RTK positioning was performed with four-system corrections in the RTCM v3 MSM format. About one hour of 1-Hz GNSS data was analyzed with a special focus on positioning accuracy.
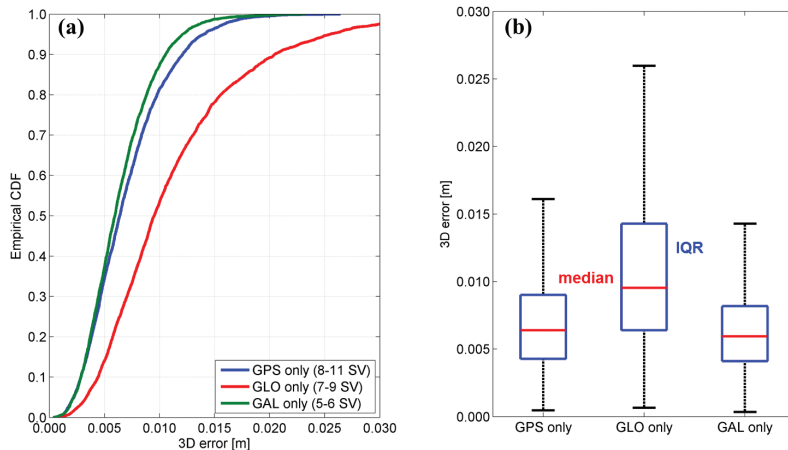
FIGURE 9 shows the 3D errors from GPS-only, GLONASS-only and Galileo-only RTK positioning, where the numbers of used satellites are 8–11, 7–9 and 5–6, respectively. During the test period, only three or four BeiDou satellites were tracked with poor geometry, making BeiDou-only RTK impossible. As the figure shows, the 3D errors from GPS-only and Galileo-only RTK are at a comparable level with similar RMS values, whereas the 3D RMS error from GLONASS-only RTK is almost twice as large as the GPS/Galileo-only case. Note that when compared to GPS-only RTK, almost half as many satellites are used in Galileo-only RTK.

FIGURE 10 displays the statistical distribution of the 3D errors from GPS-only, GLONASS-only and Galileo-only RTK positioning. Regarding the empirical CDF in **FIGURE 10A**, GPS/Galileo-only RTK shows a clearly more favorable error distribution than the GLONASS-only case. Using only GPS or Galileo, the probability that 3D error is within 1 cm is above 80%, which is approximately 30% higher than using only GLONASS. For 3D errors ranging between 5 mm and 1.7 cm, Galileo-only RTK even provides a slightly higher cumulative probability than the GPS-only case. The 3D error boxplots in **FIGURE 10B** illustrate a similar pattern between GPS-only and Galileo-only RTK, which is superior to GLONASS-only RTK due to the significantly smaller median and IQR.

CONCLUSIONS

With the declaration of Galileo Initial Services in December 2016, for the first time ever all GNSS users worldwide are able to use the positioning, navigation and timing information provided by Galileo's global satellite constellation. Upon full system completion by 2020, Galileo will play an important role in high-precision GNSS applications for users around the world. This article showed representative case studies to understand the benefits of the current Galileo constellation for high-precision RTK. In addition to a multi-GNSS solution, the performance of Galileo-only RTK was presented. The main findings from the case studies can be summarized as follows:

- In the open-sky test, with an elevation cut-off angle of 10°, on average three Galileo satellites can be used for high-precision multi-GNSS RTK. This leads to cm-level improvements in coordinate repeatability over a long baseline of 116 km.
- In the multipath case study, the additional use of two

FIGURE 10 3D error statistics from GPS-only, GLONASS-only and Galileo-only RTK under open sky (single-base RTK, baseline length: 1 m, RTCM v3 MSM). (a) Empirical cumulative distribution function (CDF) of 3D errors, (b) Boxplot of 3D errors (IQR: interquartile range).

or three Galileo satellites produces significant enhancements in positioning accuracy at the few cm to dm level, where the benefits for the height component are more significant. Moreover, the integration of Galileo increases the 3D reliability of RTK fixed positions by 7.3% and reduces the median time to fix by 2 s (25%).

- In the canopy experiment, the inclusion of Galileo improves the availability of RTK fixed solutions by 12.2%. Furthermore, dm-level position errors are largely reduced.
- When compared to GPS-only RTK, Galileo-only RTK provides a similar positioning accuracy over a 1-m baseline under open

sky, where almost half as many satellites are used. The 3D RMS error from GLONASS-only RTK is approximately twice as large as the GPS/Galileo-only case.

The promising results achieved through Galileo integration already indicate the very important role of the European GNSS in high-precision, multi-frequency and multi-constellation RTK positioning. During the deployment of the Galileo system, more benefits can be expected in the near future.

ACKNOWLEDGMENTS

The staffs of Leica Geosystems AG (Heerbrugg/Switzerland), Christian Waese and Youssef Tawk, are

gratefully acknowledged for support in setting up the variety of RTK network streams.

MANUFACTURERS

SmartWorx 6.16 of **Leica** *(leica-geo-systems.com)* Viva GNSS is the latest firmware cited and used in these high-precision RTK tests. Leica GNSS Spider 7.0.0 furnished the GNSS real-time corrections. The open-sky case study used two Leica Viva GS10 units connected to a Leica Viva AS10 antenna via a four-way antenna splitter. The multipath case study used a Leica Viva GS16 GNSS smart antenna. The canopy case study used a Leica Viva GS10 receiver and a Leica Viva AS10 antenna. The Galileo-only RTK test used two Leica Viva GS10 receivers and two Leica AR25 choke ring antennas. ◉

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GPS 40 YEARS YOUNG

Working after midnight on July 19, 1977, a Rockwell Collins engineer in Cedar Rapids, Iowa, adjusted a rooftop antenna every five minutes to receive a signal from the world's first GPS satellite. Within a small window of time, the satellite was turned on,

and the message was successfully received and decoded by the team working the six-foot-tall GPS receiver, a two-seater model.

A modern version of the 1977 receiver, the Rockwell Collins GPS-4000S, can process transmissions of up to 10 GPS satellites and two Space-Based Augmentation Systems (SBAS) satellites simultaneously. The GPS-4000S is only 7.87 inches tall.

The Micro GPS Receiver Application Module (MicroGRAM) is only one inch tall, can use data from up to 12 GPS satellites and consumes the least power of any receiver in its class. Other advances include anti-jamming and anti-spoofing technologies crucial to security and efficiency when used within critical military and aircraft operations.