Galileo-Only Cadastral Survey

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SUMMARY

The European Global Navigation Satellite System (GNSS) Galileo has declared the initial services starting December 15th, 2016. The content of the open services and the expected availability and accuracy are described in a service definition document. Anticipating on the Galileo open service, the Dutch Cadastre has upgraded its network of GNSS stations with hardware capable of tracking Galileo stations and equipped its surveyors with Galileo-ready hardware. Using the data from the upgraded network of Galileo enabled GNSS stations, we explored the possibility of using Galileo as a stand-alone system, e.g. without the support of the other GNSS systems GPS, GLONASS and BeiDou, for Real-Time Kinematic (RTK) surveying. The duration of the test was from the declaration of initial services until July 31st 2019. The goal of this activity was to demonstrate the Galileo capability of the GNSS network and the GNSS user hardware.

This contribution describes how the experiment of the Galileo-only RTK was setup as post processing activity and how we used the results to plan and execute a Galileo-only RTK survey at the site of the Galileo Reference Centre in October 2019. The results show how the availability of Galileo-only RTK solution has improved over time mainly due to increased number of satellites, from a few time slots per day with 11 available satellites in December 2016 to almost full availability with 22 operational satellites in July 2019. Also the stability and repeatability is shown for the availability of the RTK solution. Finally results of an actual survey, what we believe is the first stake out of a Cadastral boundary in October 2019 using Galileo-only, are presented.

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1. INTRODUCTION

1.1 Galileo

Galileo is the European Global Navigation Satellite System (GNSS). Galileo has made significant progress in recent years: twenty-six Galileo satellites are now orbiting the Earth, a significant part of the supporting ground station infrastructure has been deployed, and the European GNSS Agency (GSA) has assumed the role of the Galileo Service Provider. With the Declaration of Galileo Initial Services on the 15th of December 2016 [GSA (2016a)], the transition of Galileo from the testing and deployment phase to a system in service has started, and Galileo is now ready to be used. The system is interoperable with GPS and thus can be used both in combination with other GNSSs but also as a stand-alone independent GNSS. The exact content of the (initial) open services and the expected availability and accuracy are described in the Galileo - Open Service - Service Definition Documents (OS-SDDs). The initial open services [GSA (2016b)] did not contain a definition for the positioning service, however the update of the he Galileo OS-SDD in May 2019 the stand-alone positioning service is officially available [GSA (2019a)].

1.1.1 Galileo Reference Centre (GRC)

To support the Galileo service phase, the GSA has established a new service facility called the Galileo Reference Centre (GRC) in Noordwijk, the Netherlands. The primary mission of the GRC is to provide the GSA with an independent means for monitoring and evaluating the performance of the Galileo services and quality of the signals in space [Buist et al. (2017)] [Buist et al. (2018)]. It is fully independent of the system and of the operator with respect to both the technical solution and operations. The GRC also provides service performance expertise to the Galileo Programme, support to investigations of service performance and service degradations and archiving of relevant service performance data over the operational lifetime of the system. Where feasible, the GRC assesses the compatibility and interoperability between Galileo and other GNSS. In addition to its stand-alone capabilities, the GRC integrates data and products from cooperating entities from the EU Member States, Norway and Switzerland (MS)

1.1.2 Galileo for Cadastral Surveying

Galileo targets a wide range of GNSS applications in the GNSS market, which is defined as *'Activities where GNSS-based positioning, navigation and/or timing is a significant enabler of functionality'* in the GNSS Market report of the European GNSS Agency (GSA) [GSA (2019b)]. For the last decade, the usage of GNSS in Cadastral surveying has become one of the most used positioning techniques because of the high accuracy required for land mapping and determination of legal land boundaries. Also, partly thanks to the appearance of new constellations, including Galileo, which has greatly increased the availability of GNSS

satellites. In fact, cadastral services account for almost 50% of the total GNSS revenues in the geomatics segment, in terms of GNSS device shipments, closely followed by mapping and construction. While GNSS is an integral part of land surveying and mapping procedures in most of the European Countries, the final solutions are typically offered as a hybridisation of GNSS with other techniques such as traditional topographic measurements or more novel methods like laser scanning, all based on high-precision real-time kinematic (RTK) techniques.

Beneficial to surveying applications are the Open Services signals on the E1, E5a and E5b frequencies and an unencrypted signal on E6 [GSA (2019c)], which provides users access to 3 frequencies with observation (code and carrier-phase) data. These signals can be used for precise RTK surveying in combination with GNSS augmentation services, but also for the planned free-of-charge Galileo High Accuracy Service (HAS), which is foreseen to provide a target accuracy of 20 centimetres [GSA (2019b)].

1.2 GNSS Infrastructure in the Netherlands

The Dutch Cadastre, in collaboration with Rijkswaterstaat and Delft University of Technology (DUT), is responsible for the GNSS infrastructure of the Netherlands. This infrastructure consists of a three level hierarchy [Van Willigen and Salzman, (2002), De Bruijne et al. (2005) and NSGI (2016)]. The Active GNSS Reference Network for the Netherlands (AGRS.NL) is the first order network and is used for the Dutch realization of ETRS89 and ITRS and scientific research. Data of the AGRS.NL is freely available as files (RINEX) and real-time streams (NTRIP/RTCM) through the GNSS data centre of DUT. The second order network is a densification of the AGRS.NL for RTK applications. The densification is realized by commercial GNSS service providers and an independent densification for the Netherlands Positioning Service (NETPOS) of Kadaster and Rijkswaterstaat. NETPOS observation data is freely available in file format (RINEX), since September 7th 2019 (Kadaster (2018). The third order consists of a network of passive benchmarks spread over the country.

Anticipating on the availability of the Galileo open services, the Dutch Cadastre has upgraded its network of GNSS stations of the AGRS.NL and NETPOS networks, with hardware capable of tracking Galileo stations and equipped its surveyors with Galileo-ready hardware. To avoid the dependency on a single hardware provider for the correct implementation of signal tracking and the robust and uninterrupted service provision of the GNSS infrastructure, different receiver makes were selected for the upgrade. The current status of GNSS receiver brands available at the GNSS stations is shown in Figure 1. The data from the AGRS.NL and NETPOS networks is provided to the GRC as part of Member States contributions.

Using only a few additional Galileo satellites increases the availability of a correct RTK fixed as shown in [Odijk et al. (2012)]. To verify the implementation of Galileo in user hardware of Kadaster, experiments were carried out using a combined GPS/Galileo RTK configuration already in 2015 and 2016. However testing the possibility of using stand-alone Galileo RTK with augmentation data from Kadaster was not straightforward due to the limited number of available satellites. To actually plan a survey using Galileo only, an experiment was setup to predict the Galileo-only RTK availability at any time.

The Galileo-only RTK availability and experiment are described in section 2 and the Galileo-only cadastral survey which is possible to plan using the outcome of the experiment is described in section 3. Section 4 discusses the results of the experiment and survey.
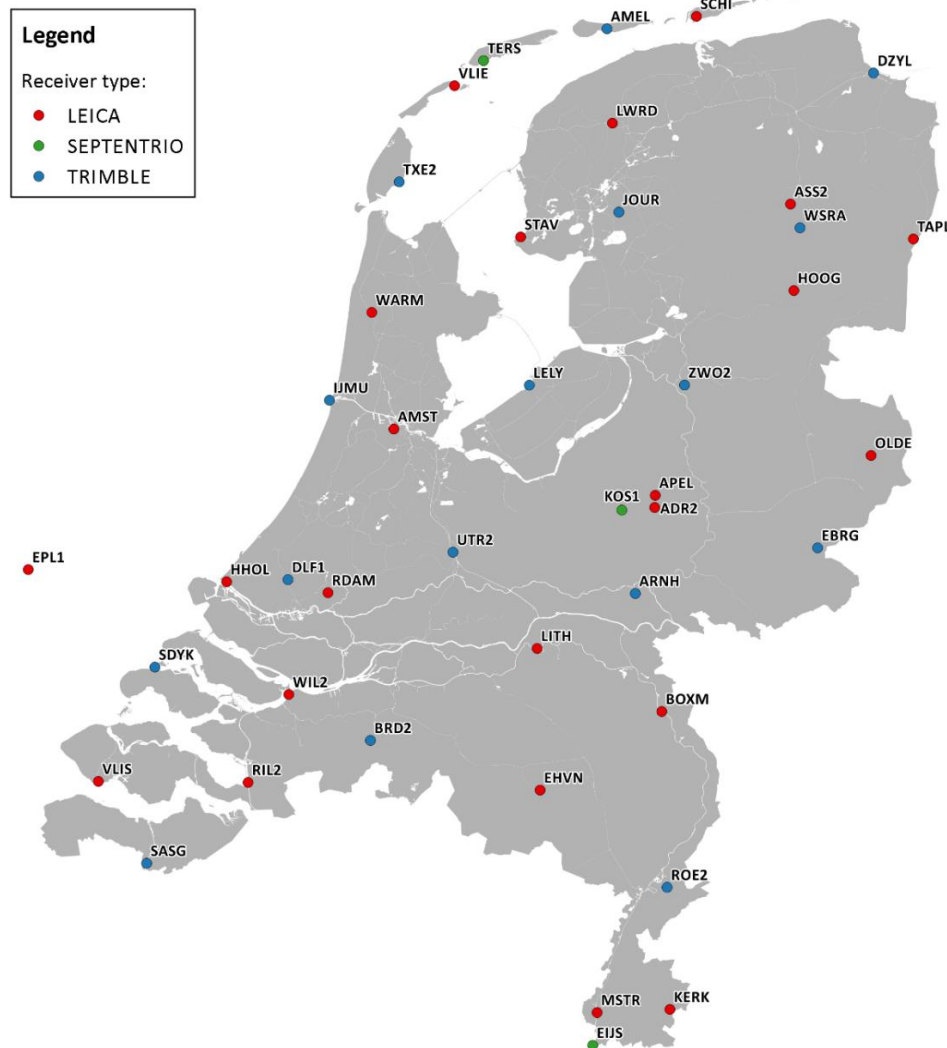

Figure 1: Locations of GNSS stations and used receiver brands at Kadaster operated GNSS stations

2. ASSESMENT OF GALILEO-ONLY RTK AVAILABILITY

To assess the availability of Galileo-only RTK for any moment an experiment was setup using a single baseline between two GNSS reference stations. The data was processed using the RTKLIB open-source software [Takasu and Yasuda (2009)] using Galileo only. This section describes the processing configuration, Galileo satellite availability and observation data availability in more detail. The last subsection shows the RTK availability.

2.1 Single baseline experiment

2.1.1 RTK setup

The open-source RTKLIB software was used to process the 1Hz interval observations from the two selected GNSS reference stations. Modifications were made to the RTKLIB software to handle the different Galileo navigation message types for all frequencies in-line with Galileo SDD and to be able to process the signals on the E1, E5a and E5b frequency simultaneously. The key settings for the processing strategy are shown in Table 1.

Table 1: Key processing options for RTKLIB, options are explained in [Takasu (2013)]

Setting	Value
Processing mode	Kinematic
Frequencies	Dual-Frequency (E1, E5a)
Solution type	Forward
Elevation mask	13 degrees
Ionosphere model	Klobuchar
Troposphere model	Saastamoinen
Ambiguity resolution mode	Fix and Hold
Ratio test threshold	3
Phase precision	0.01 m + 0.01 m / sin(Elevation angle)
Code precision	100 * Phase precision

The processing engine was set in kinematic and forward mode using only data that would have been available in real-time, for example no navigation messages were used that became available after the epoch to be processed. The observations were a-priori corrected for atmospheric delays using the available ionosphere and troposphere models in RTKLIB, the recommended NeQuick model for Galileo [GSA (2016c)] is currently not implemented in RTKLIB. The observation data was split in session of 15 minutes length. The sessions were processed independently from other sessions. With this configuration the processing can be considered as if it was a real-time RTK algorithm.

2.1.2 Galileo satellite availability

The experiment started when the initial services for Galileo were declared available in December 2016. At this time 11 satellites were available. At the end of the experiment in July 2019, 22 satellites were available. Figure 2 (top) shows the increase of available satellites in time. The Galileo constellation has a repetition period of 10 sidereal days, this means that every 9 days, 23 hours and 20 minutes solar time a user observes the same Galileo satellite geometry. Figure 2 (bottom) shows the average available number of Galileo satellites above 13 degrees elevation in Apeldoorn from December 2016 until July 2019. Each column of this graph shows a 10 sidereal day period, the graph nicely shows the repeatability of the number of visible satellites as a result of the recurring satellite geometry over time and the increase when more satellites become available.
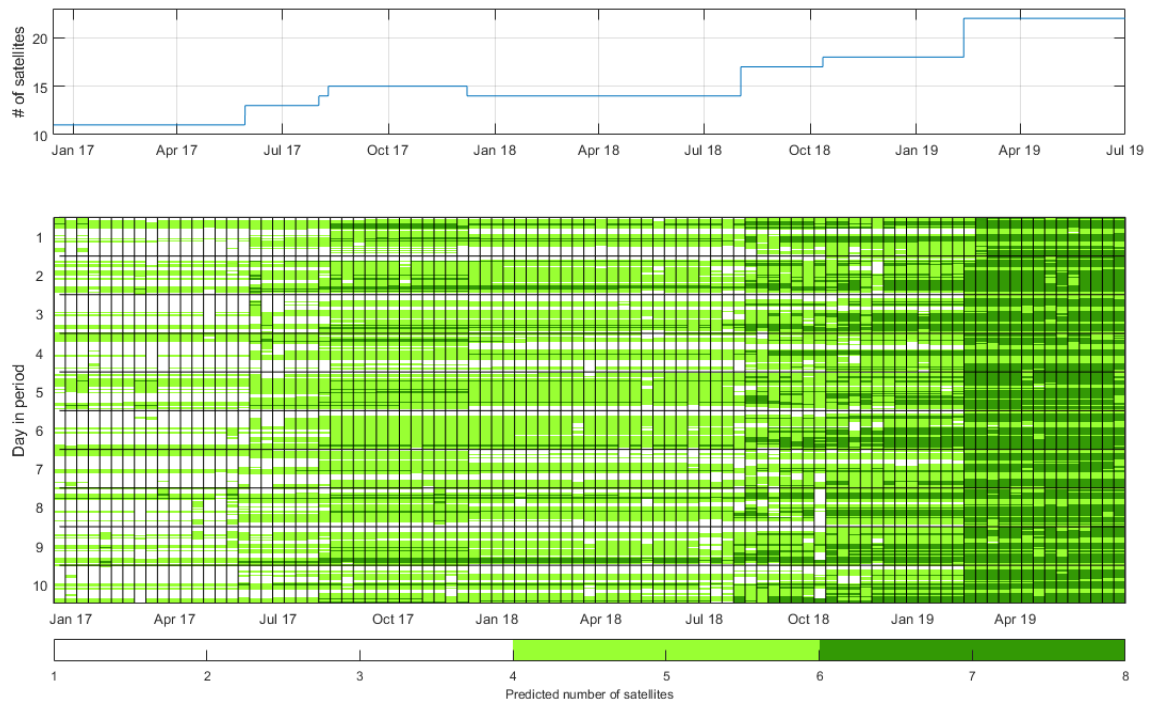
Figure 2: Available Galileo satellites in orbit (top) and predicted number of available Galileo satellites above 13 degrees elevation in Apeldoorn, the Netherlands (bottom) for December 2016 until July 2019.

2.1.3 Observation data availability

The selected GNSS stations are both located in Apeldoorn, the baseline length is about 3.5 km. Table 2 shows metadata for both stations. In this setup station ADR200NLD was considered the rover and the APEL00NLD the base.

Table 2: Station information for GNSS reference stations used in the experiment

Station name	APEL00NLD	ADR200NLD
ETRF2000 Latitude	52° 12' 42.91757''	52° 10' 47.27323''
ETRF2000 Longitude	5° 57' 44.25707''	5° 57' 35.34608''
ETRF2000 Height	115.885	88.289
Receiver type	Leica GR50	Leica GR50
Antenna type	Leica AR25.R4 LEIT	Leica AR20 LEIM
Antenna setup		

Figure 3 shows the data availability from December 2016 until July 2019. For this contribution all data was reprocessed with the same processing strategy. Unfortunately the observation data was lost from April 2017 to June 2017 due to data storage issues, along with small gaps in other periods due to download issues. For example, from January 2019 until July 2019 a systematic trend is visible in the availability which shows the loss of data due to an incorrect download setting. The data loss shows up as a trend in the plot since the y-axis of the figure represents sidereal days, if the y-axis would be represented in solar days it would show up as a straight line. Despite the data losses there is still enough data available to evaluate the availability of the Galileo-only RTK solution over the whole period.
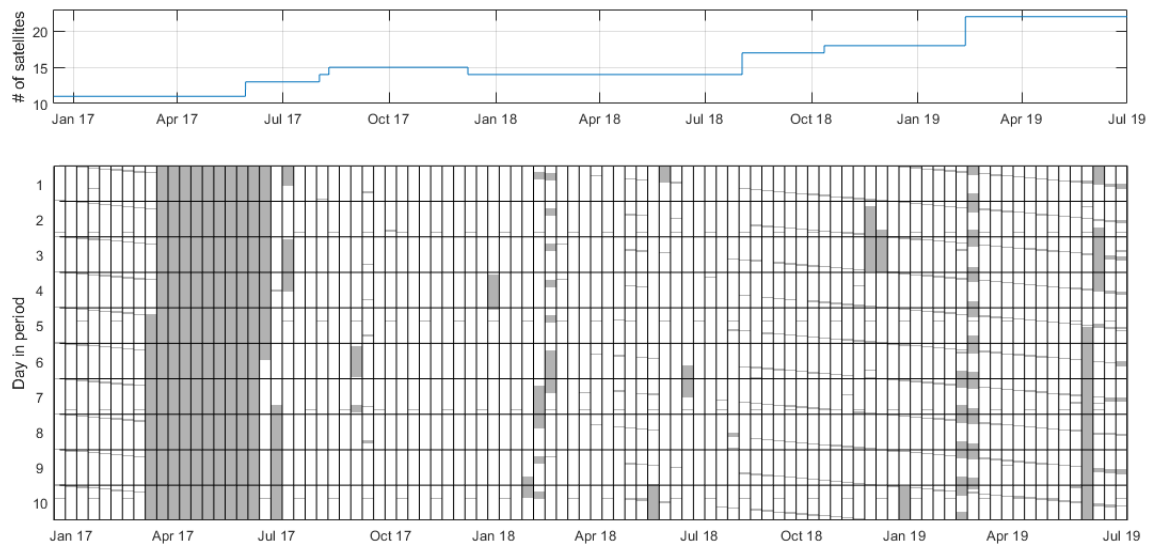

Figure 3: Available Galileo satellites (top) and observation data availability for December 2016 until June 2019(bottom)
Gray indicates data unavailability due to data storage and download issues.

2.2 RTK availability

The data processing resulted in solution files with a length of 15 minutes. For each session the following parameters were computed based on the observation and solution files:

- Number of observation epochs and tracked Galileo satellites for each station.
- Number of tracked Galileo satellites for each station.
- Number of seconds with a RTK Fixed position.
- Average number of Galileo satellites used for RTK Fixed positions.
- Mean, standard deviation and median 3D position error of RTK fixed epochs.

These parameters were stored in a database, after which the analysis was done on the results. Obviously, the fix status of a solution is decided by the processing algorithm. Remember that the results of this experiment are intended to provide information when a successful Galileo only fix can be expected for a surveying session. Therefore, a posteriori an additional criterion was set that a fix was only correct if the 3D position error was below 0.05 metre. The criteria listed in Table 3 were used to identify and distinguish the session results.

Session type	Criteria value
RTK not fixed	Less than 60 seconds with a RTK fixed session
RTK fix false	At least 60 seconds with a RTK fixed solution and a 3D position error larger than 0.05 meter
RTK fix correct	At least 60 seconds with a RTK fixed solution and a 3D position error less than or equal to 0.05 meter

Figure 4 shows an example of a RTK fix correct and RTK fix false solution in December 2016. Both solutions are in float status at the beginning and reach the RTK fix status according to the software algorithm after some minutes. The RTK fix is available for more than 60 seconds, however the median position error for the RTK fix correct session is below 0.05 meter, while it is more than 5 metre for the RTK fix false session.
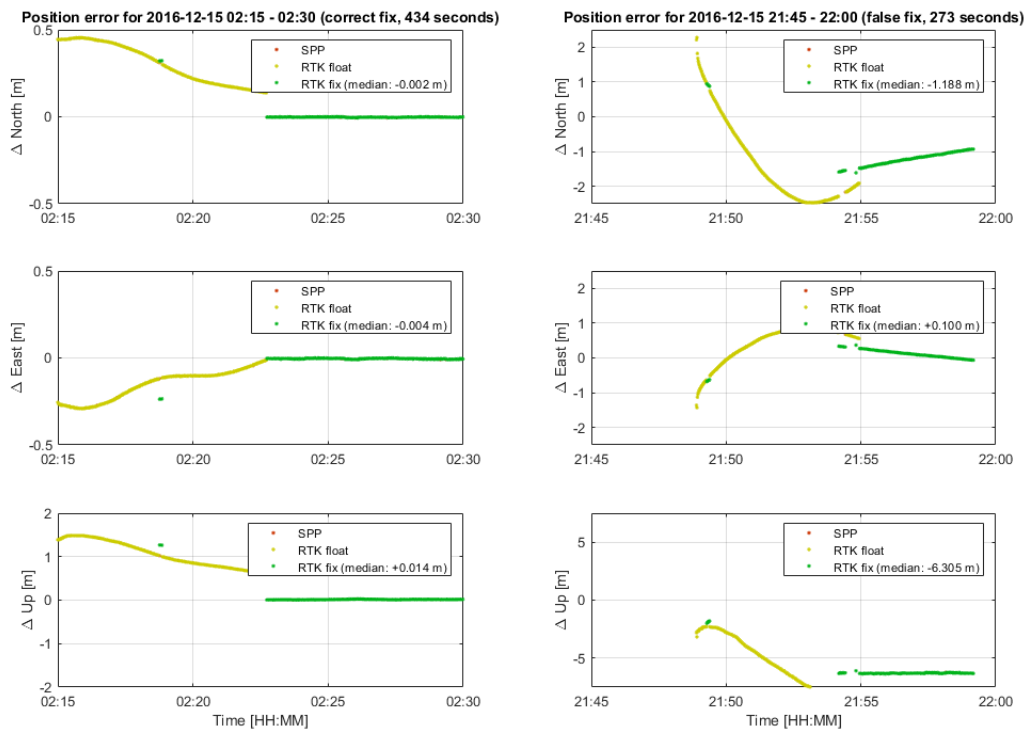

Figure 4: Time series of a RTK fix correct (left) and a RTK fix false (right) sessions

Figure 5 shows the fix status for each processed session. No data sessions are shown in grey, RTK not fixed session are white, RTK fixed false session are red and RTK fix correct session are shown in green. As expected the availability is limited in the beginning and increases to the end. The results show nicely that over the whole period the availability has a relation with the available satellites as shown in Figure 2 and is repeatable over the periods where the satellite geometry repeats. From March 2019 it is very likely that a RTK fixed correct session is available at any time.
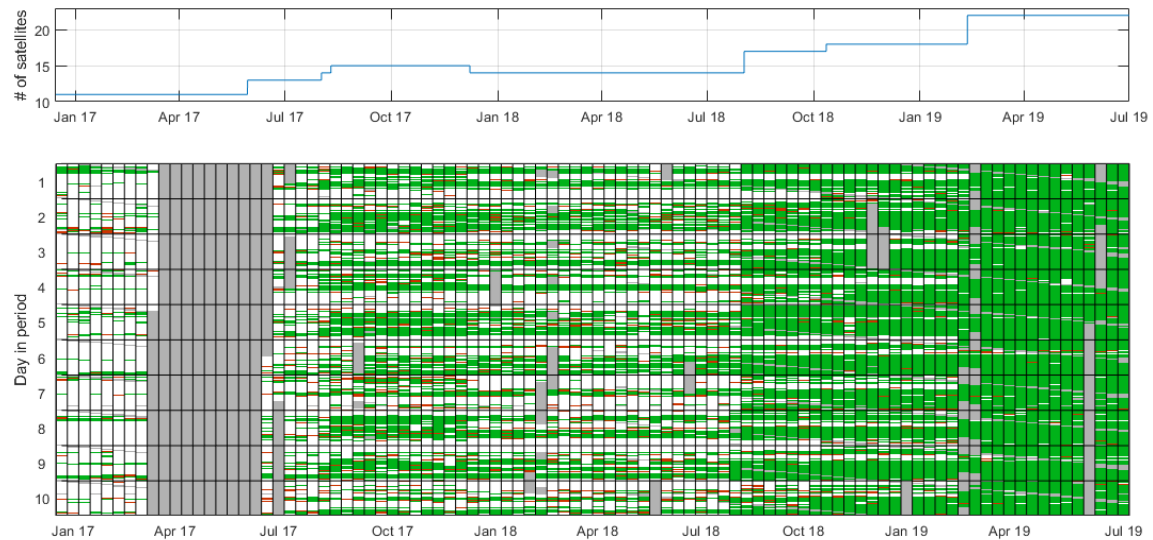
Figure 5: Available Galileo satellites (top) and RTK fix results for December 2016 until July 2019(bottom). Gray indicates data unavailability. White indicates no RTK fix was possible. Red indicated false RTK fixes. Green indicates correct RTK fixes.

3. CADSTRAL GALILEO ONLY SURVEY

3.1 Planning

The analysis of Galileo-only RTK availability shows that the availability of a RTK correct fix session can be predicted in advance. This prediction capability was used to plan an actual cadastral boundary reconstruction. The selected boundary was the property boundary of the GRC in Noordwijk, the Netherlands. After setting a date, October 7th 2019, the results of the RTK availability analysis was used to predict the Galileo-only RTK availability at the time of the planned survey. The epochs with an identical satellite geometry as the time of the planned survey, were computed using the following equation:

$$t_o = t_p - N * 10 * (23 * 60 + 56) * 60$$

Where t_o is the epoch of observation in seconds, t_p the epoch for prediction, e.g. the time of the planned survey, with identical satellite geometry as t_o and N is an integer number of ground repetition periods of the Galileo constellation. Using this relation RTK fixed correct solutions were selected from the solutions with identical satellite geometry on July 9th, July 19th and July 29th was selected. Figure 6 shows the Predicted availability based on these solutions. It shows that between 5 and 8 Galileo satellites are available in the morning, and with the avaiable number of satellites and associated geometry a correct RTK fix is expected to be possible. Using this data, the survey was planned between 11 and 12h AM local time where the availability of 6 to 7 satellites was expected for the RTK solution.
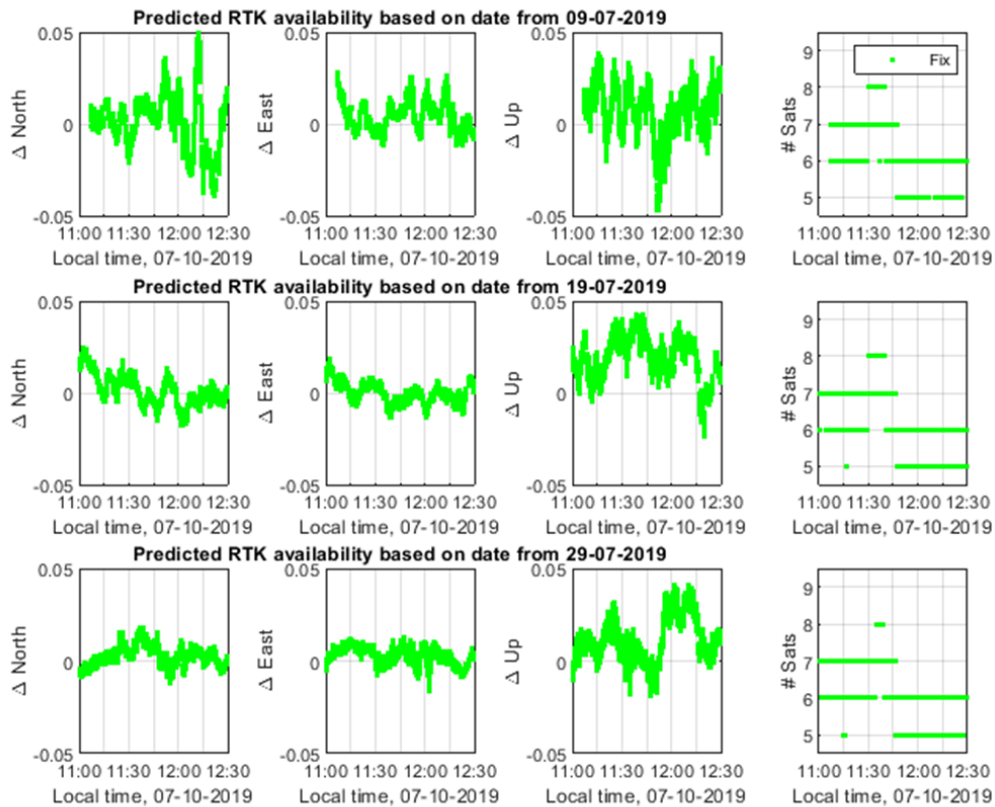
Figure 6: Predicted RTK availability for October 7th, 2019 11:00 - 12:30 local time (GMT+1) from previous RTK sessions with identical satellite geometry.

3.2 Fieldwork

For the actual survey a Leica GS18T Rover was used. The firmware of this Rover allows to disable the tracking of GNSS systems and individual satellites. After deselecting all GNSS systems apart from Galileo it was confirmed that only Galileo satellites were used as shown in Figure 7.
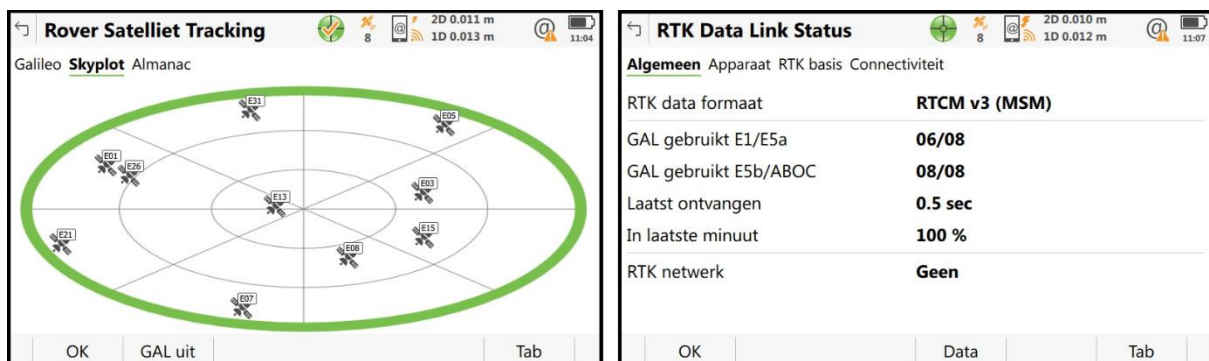

Figure 7: Screenshots of surveying equipment showing that only Galileo is used for the RTK fix.

The boundary was staked out by a specialist surveyor of Kadaster using the Galileo-only set-up and following the normal procedures for such cadastral work. After finalizing the boundary reconstruction all staked out points were measured again in network RTK mode, using GPS and GLONASS augmentation data from NETPOS, to verify the results. Figure 8 shows an overview of the boundary and its surroundings and the 2D differences between the measured coordinated using Galileo-only RTK and NETPOS RTK. The differences are at centimetre level which can be expected considering the RTK precision of 1 centimetre and the idealisation precision of about 1 cm of the stake out points.
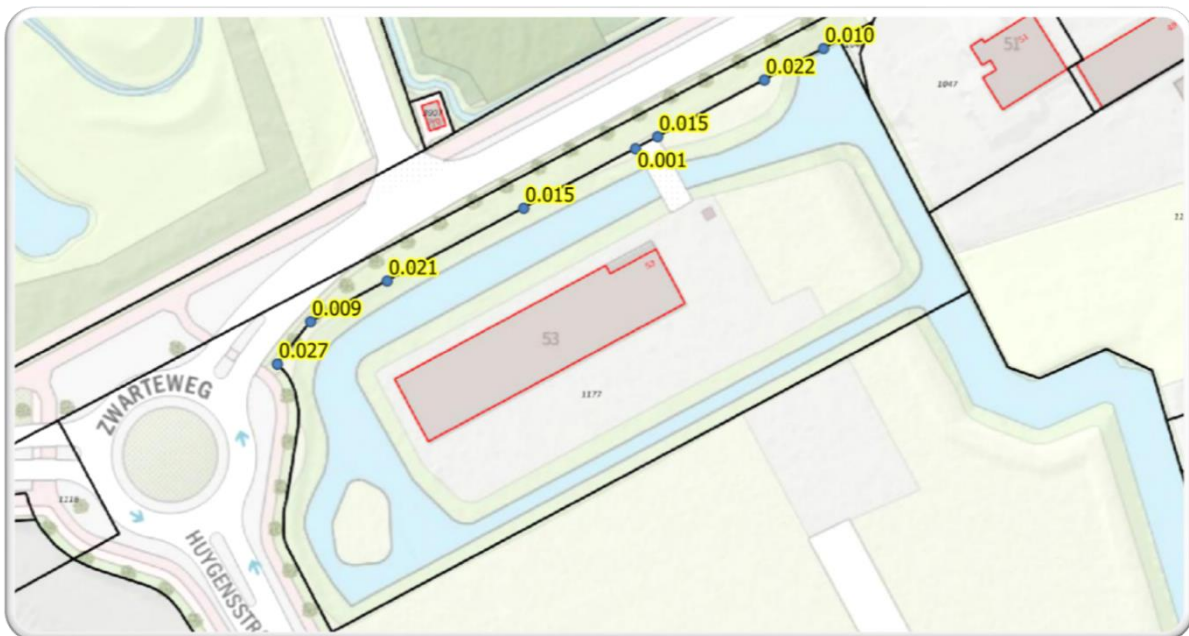

Figure 8: Map showing cadastral boundary (black), staked out points (blue) and differences between Galileo only and NETPOS RTK measurement. Map source: www.opentopo.nl

4. DISCUSSION

This contribution shows how the RTK availability of Galileo-only RTK has increased during the deployment of Galileo. As expected the availability of correct RTK fixes is correlated with the number of satellites. The system can now be used stand-alone for RTK surveying and the availability and reliability will increase when more satellites become available until the full operational constellation status is reached.

The match of the repeatability of the RTK availability and the satellite geometry shows the stability of the system and allows for planning of a successful Galileo-only survey. This was shown by the Galileo-only cadastral boundary reconstruction of the Galileo Reference Center premises by Kadaster on October 7th.

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BIOGRAPHICAL NOTES

Lennard Huisman MSc is an enthusiastic Geodetic engineer, whose expertise is to make things work. His work focuses on coordinate reference systems, real-time GNSS systems and CORS networks. Lennard received his MSc in geodetic engineering from Delft University of Technology in 2004. He has gained working experience in the government, industry, research and education sector in several countries. Lennard is a member of the editorial advisory board of the GPS Solutions journal, has been the (co-)author of more than 20 publications and has given many (invited) presentations at national and international meetings and symposia.

Kees Hoentjen BSc is a studious and creative geodetic engineer with the ability to quickly apply new skills in his work. He obtained his BSC in 2009 for the Utrecht University of Applied Sciences. Kees has wide experience is subsidence monitoring using geodetic techniques and maintaining the GNSS infrastructure, he is currently employed as a GNSS specialist at Kadaster.

Armando Vet is a senior consultant reference systems at Kadaster. He is an experienced surveyor and gained his on-field experience in industry and at Kadaster, he uses this experience as a teacher in the internal education programme for cadastral surveyors. Armando is currently responsible for the procurement of surveying equipment and the stability monitoring of GNSS benchmarks.

Peter Buist received his master degree in the field of aerospace engineering and PhD in field of GNSS from Delft University of Technology. He worked in the Japanese aerospace industry, specialising in particular in GNSS applications for satellites and rockets. After his return to the Netherlands, he worked for Delft University of Technology and the National Aerospace Laboratory (NLR), before joining the European GNSS Agency (GSA) to set up Galileo Reference Centre.

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