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Assessment of Commercial Network RTK User Positioning Performance over Long Inter-Station Distances

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Abstract

The paper provides an assessment of the performance of commercial Real Time Kinematic (RTK) systems over longer than recommended inter-station distances. The experiments were set up to test and analyse solutions from the i-MAX, MAX and VRS systems being operated with three triangle shaped network cells, each having an average inter-station distance of 69km, 118km and 166km. The performance characteristics appraised included initialization success rate, initialization time, RTK position accuracy and availability, ambiguity resolution risk and RTK integrity risk in order to provide a wider perspective of the performance of the testing systems.

The results showed that the performances of all network RTK solutions assessed were affected by the increase in the inter-station distances to similar degrees. The MAX solution achieved the highest initialization success rate of 96.6% on average, albeit with a longer initialisation time. Two VRS approaches achieved lower initialization success rate of 80% over the large triangle. In terms of RTK positioning accuracy after successful initialisation, the results indicated a good agreement between the actual error growth in both horizontal and vertical components and the accuracy specified in the RMS and part per million (ppm) values by the manufacturers.

Additionally, the VRS approaches performed better than the MAX and i-MAX when being tested under the standard triangle network with a mean inter-station distance of 69km. However as the inter-station distance increases, the network RTK software may fail to generate VRS correction and then may turn to operate in the nearest single-base RTK (or RAW) mode. The position uncertainty reached beyond 2 meters occasionally, showing that the RTK rover software was using an incorrect ambiguity fixed solution to estimate the rover position rather than automatically dropping back to using an ambiguity float solution. Results identified that the risk of incorrectly resolving ambiguities reached 18%, 20%, 13% and 25% for i-MAX, MAX, Leica VRS and Trimble VRS respectively when operating over the large triangle network. Additionally, the Coordinate Quality indicator values given by the Leica GX1230 GG rover receiver tended to be over-optimistic and not functioning well with the identification of incorrectly fixed integer ambiguity solutions. In summary, this independent assessment has identified some problems and failures that can occur in all of the systems tested, especially when being pushed beyond the recommended limits. While such failures are expected, they can offer useful insights into where users should be wary and how manufacturers might improve their products. The results also demonstrate that integrity monitoring of RTK solutions is indeed necessary for precision applications, thus deserving serious attention from researchers and system providers.

Keywords: Network RTK, Positioning performance, Long Inter-Station Distances

1. Introduction

Global Navigation Satellite System (GNSS) based Real Time Kinematic (RTK) technology has dominated real time precision applications over the past decade. Applications such as surveying, mobile mapping data acquisition and machine automation for precision agriculture, mining and construction have all benefited greatly from both real time and centimetre level positioning capability. Despite these benefits, network RTK services delivered in regional areas of Australia are often economically unjustifiable due to the sparsely distributed population and the reduced size in potential user base compared to urban areas (Higgins, 2008).

The Cooperative Research Centre for Spatial Information (CRCSI) funded research Project 1.04 on "Delivering Precise Positioning Services in Regional

Areas" (2007-2010) has been carried out to investigate enabling technologies to support the deployment of network-based RTK services in regional areas where low density CORS distributions are desired (Feng et al., 2009). Feng and Li (2008) proved that with use of triple frequency signals offered by the next generation GNSS systems, the inter-station distances can be doubled from the current 70~90km to the future 140 to 180km, to maintain the position accuracy within the centimetre level. Doubling the inter-station distance would effectively reduce the required number of CORS stations to one-fourth to provide a similar coverage area. In additional to the initial savings in the hardware and installation of reference stations, there are further savings in the ongoing costs of communications, network maintenance and other operational requirements. However, none of the next generation, triple frequency GNSS systems will be fully operational within the next 5 years and in the meantime, users will have to rely on dual frequency receiver network-based RTK systems. Three questions being considered are:

- How well do current commercially available network RTK systems perform over CORS networks with extended inter-station distances?
- What are the potential problems that might occur if the commercial RTK systems are used outside the maximum recommended inter-station distance limit?
- Do the commercial RTK systems' adequately indicate these problems and failures if any?

Performance assessment of current network RTK services over the recommended inter-station distances in the range of 50 to 70km have been previously conducted, with various results experienced under different testing conditions (Buick, 2006, Edward et al. 2009, Kim, 2004). In theory, user performance criteria are a function of several factors including: the number of satellites visible, occupation time, observation conditions, obstructions, baseline length (or inter-station distance), environmental effects, bias interpolation techniques, base and receiver noise levels and multipath conditions etc. In realisation and practice, performance assessment may further be complicated by the type of network RTK solutions available, such as Virtual Reference System (VRS) and Master-Auxiliary (MAX) concepts. An examination of commercial network based RTK GNSS services in Great Britain for land surveying have shown similar results for both SmartNET and VRS NOW solutions, with an achievable accuracy of approximately 10-20 mm level in horizontal and 15-35 mm level in vertical (one sigma) with filters applied to remove solutions with large instrument-reported quality measures (CQ indicators) and DOP values (Edward et al., 2009). Additional single or double window averaging is suggested to further reduce the effect of individual coordinate solution variations. While the suggested filters and window averaging strategies may work well for land surveying, they may not be applicable for the precision agriculture, construction or other kinematic applications.

In this paper, we experimentally examine the performance of commercial network RTK precise positioning solutions with networks that have inter-station baseline distances equal to or larger than the standard recommended length (50 -70km). In the following section, we first present a review of two commercial RTK concepts, Trimble's Virtual Reference Station (VRS) and Leica's Master-Auxiliary (MAX), and their claimed performance. This includes a discussion on assessment criteria in general about the RTK performance of commercial systems. In section 4, we outline the test methodologies adopted in the field experiments. Then in section 5, the results are analysed and evaluated against the assessment criteria defined in section 3, including initialization success rate, initialization time, RTK accuracy, availability, ambiguity resolution risk and integrity risk.

2. Commercial Network RTK Concepts and Performance Specifications

A RTK network is a distributed set of continuously operating GPS and/or GNSS reference receivers (CORS) that are combined to generate RTK correction solutions for precise positioning use within the area of reference station coverage. These network generated RTK corrections are called network RTK (Geosystem, 2009). Observations taken from each CORS station are streamed to a centralised network processing server on a synchronous basis, where the network RTK software, such as Trimble GPSNet or Leica GNSS Spider can be used to generate RTK corrections from ambiguity-fixed double difference phase measurements. Both corrections and observations are typically transmitted to the rover in the standard Radio Technical Commission for Maritime Services (RTCM) format using radio broadcast or via wireless network. The rover position is then computed using the received RTCM messages and the local observation for the same epoch to derive the user position. The maximum inter-station distance for the RTK network is typically limited to 50 to 70 km, depending on the capability of the network-based ambiguity resolution software used.

There have been several RTK techniques developed over years, two of which have been dominating the current markets in Australia, being Virtual Reference Station (VRS) and the Master-Auxiliary concept (MAX). A variation on MAX is the individualized Master-Auxiliary (i-MAX) approach. The main differences between these methods lie with the manner in which network corrections are interpolated and transmitted to the rover.

The VRS technique requires rovers firstly to connect and then submit their current uncorrected point position to the service which is then used by the server as the location where the VRS is generated. The network processing server interpolates network corrections at this VRS location, based on the surrounding physical network stations using proprietary algorithms. The correction is then transmitted back to the rover in RTCM (or proprietary) format to be processed using a standard single-base RTK algorithm to obtain the corrected precise position for the rover (Retscher, 2002, Janssen, 2009).

On the other hand, the Master-Auxiliary (MAX) correction utilises the Master-Auxiliary Concept (MAC) philosophy where the rover performs the network correction interpolation using the full network information. Firstly, the phase measurements from all reference stations are reduced to a common ambiguity level by removing the integer ambiguity for each satellite-receiver pair at the network processing server (Euler et al., 2005). Thus, integer ambiguities are cancelled when double differences are formed. Corrections for the rover are formed and transmitted using a RTCM 3.1 network message using corrections from a subnet of the network, one station is denoted as the master and the others are referred as auxiliary reference stations. Only the corrections of the master station are transmitted in full, while corrections for the auxiliary station are differenced from the master corrections and only residual corrections are transmitted in order to reduce the transmission volume size. Finally, the rover interpolates the received network corrections to derive corrections at its location to resolve its ambiguities and determine its position (Janssen, 2009).

It should be noted that, unlike VRS where the rover software treats the VRS the same as a single station correction stream, the MAX approach requires specific software at the rover to handle the Max corrections. Therefore, for rover equipment not supporting MAX RTK messages, individualized Master-Auxiliary (i-MAX) correction can be used to provide individualized correction transmitted in a conventional single-base format. This approach is similar to VRS technique where the network RTK corrections are interpolated by the server. However with i-MAX the corrections are applied to the master station rather than a virtual station before being transmitted to the rover (Brown et al., 2006).

3. RTK Performance Characteristics

There are no standard criteria commonly used for the assessment of the RTK performance but GNSS manufactures provide some rover performance specifications in their description of RTK products. Typical specifications provided include receiver noise level, initialisation time and reliability, horizontal and vertical RMS accuracy and part per million (ppm) values for distance related errors in single-baseline RTK operations. Some modern receivers also specify RTK accuracy against latency and sample rates of solutions. In addition, there have been quite a number of publications reporting performance analysis results by manufacturers, independent researchers or users. Table 1 summarises the manufacturer supplied performance specifications and reported performance results from several experiments.

Table 1: Manufacturer RTK performances specifications and experimental results

Receiver type	Source	Initialization	Accuracy
Trimble 5700	datasheet	Typical time < 10 seconds Typical reliability > 99.9%	Horizontal: 10 mm + 1 ppm RMS Vertical: 20 mm + 1 ppm RMS
Trimble R5	datasheet	Typical time < 10 seconds Typical reliability > 99.9%	Horizontal: 10 mm + 1 ppm RMS Vertical: 20 mm + 1 ppm RMS
Trimble R8	datasheet	Typical time < 10 seconds Typical reliability > 99.9%	Horizontal: 10 mm + 1 ppm RMS Vertical: 20 mm + 1 ppm RMS
Leica GX1230	datasheet	Typical time < 8 seconds Typical reliability > 99.99%	Horizontal: 10 mm + 1 ppm RMS Vertical: 20 mm + 1 ppm RMS
Leica GX1230	Edward (2008)	N/A	Horizontal: 10 – 20 mm Vertical: 15 – 30 mm
Leica GX1230	Brown et al. (2006)	Typical time < 1 min	Horizontal: N/A Vertical: 30mm
Leica GX1200	Aponte et al (2008)	N/A	Easting: 12.7mm Northing: 30.8mm Vertical: 32.3mm

Apart from the manufacturer specifications which assume normal or favourable observational conditions, RTK rovers may also output quality indication parameters that may be used to evaluate the system performance in real time. One of the indicators offered on Leica hardware, referred to as Coordinate Quality (CQ), is computed at the rover using ambiguity-fixed double differenced measurements. It provides an overall indication of the quality of the phase observations, the satellite geometry, environment conditions and relative accuracy on the GPS/GNSS measurements performance relative to each other at the particular time (Leica

Geosystems, 2009). CQ is derived such that it is a root mean square of coordinate errors according to how much the computed position deviates from the true position. In this computation, empirical assumptions such as correlation between L1 and L2 phase measurements and weighting between code and phase measurements are used.

In certain cases, Edward et al. (2009) reported that CQ indicator reflected reasonably well the actual performance of the rover using both Trimble VRS and Leica SmartNet MAX systems. However, under challenging conditions (e.g. severely limited satellite visibility, large distances or height differences to surrounding CORS stations, or multipath); both network RTK solution types may give over-optimistic CQ values by a factor of 3-5 especially in the height component.

Performance evaluation based on the above specifications and characterises provided by a RTK system still does not provide a complete perspective. Feng and Wang (2008) suggested additional parameters for more comprehensive performance assessment. In this analysis, we consider the additional parameters as follows:

- ***RTK Availability*** is defined as the percentage of time during which the RTK solutions are available at a certain accuracy using the ambiguity-fixed and/or ambiguity-float phase measurements. For instance, 2xRMS values for position accuracy given in the performance specifications of each RTK system imply their RTK availability of 95%. Comparing the RTK locations obtained at a surveyed location, the RTK availability can measured easily after mission.
- ***Ambiguity Resolution (AR) Risk*** is defined as the probability that incorrect integers are fixed but being undetected in the ambiguity resolution process. As a result, the RTK system most likely generates incorrect solutions with errors beyond several centimetres. The reliability indicator for initialisation given in the commercial RTK system, such as more than 99.9%, imply the AR risk of less than 0.1%. This assessment will reveal more specifically what the commercial RTK system can actually achieve.
- ***RTK Integrity*** relates to the confidential level that can be placed in the information provided by the RTK system. Integrity concepts are widely used in aviation navigation. It includes the ability of a navigation system to provide timely and valid warnings to users when the system must not be used for the intended operation. While RTK positioning is currently used for non-safety critical applications, it is still desirable for the RTK system to provide performance indicator that can inform users when the actual positional errors of the RTK solutions have exceeded Horizontal/Vertical Protection Levels (HPL/VPL). ***RTK Integrity Risk*** is therefore defined as the probability that the system claims its normal operational status while actually being in an abnormal status, e.g., the ambiguities being incorrectly fixed and positional errors having exceeded the given HPL/VPL. The risk probability excludes the cases when these abnormal operations are automatically detected and the system claims its abnormal status. In later analysis, we attempt to examine the suitability of using the CQ indicator as the performance indictor for this RTK integrity measurement, although the CQ indicator was not necessarily designed to reflect the RTK integrity concerns.

4. Test Methodologies

4.1 Reference station configuration

To enable testing of the effects of inter-station distances, three triangle networks were configured within the coverage from a combination of SunPOZ CORS and the CRCSI Test Network CORS in South-East Queensland (SEQ) region as shown in Fig. 1. The small blue triangle (referred to as Tri#1 and using WOOL, GATT and BDST) has an average inter-station distance of 69km, which represents the largest triangle size recommended for operational networks using commercially available software. The blue triangle therefore represents the baseline performance against which we can compare the performance using larger triangles. The yellow and red triangles (Tri#2 and Tri#3 respectively) have a mean inter-station distance of 118 and 166km respectively and each have sides that are approximately twice and three times of the typically recommended maximum size.

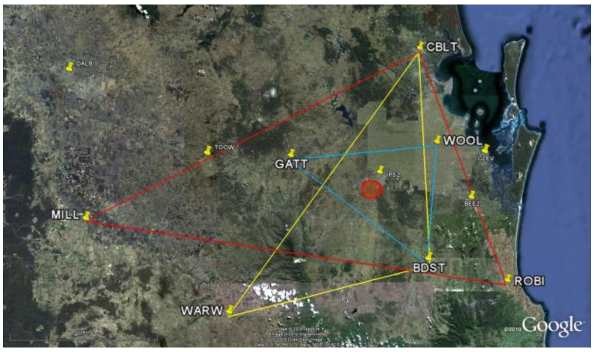

Figure 1: Combined SunPOZ and the CRCSI test network in SEQ with 3 test triangle networks

Both the Leica Spider and Trimble GPSNet network RTK software were used to generate RTK corrections (via the SmartNet Aus and DERM SunPOZ services respectively). Both sets of software were configured to allow rover connections to what would appear to be separate and independent networks, each at the density of the blue, yellow and red triangles. This was done by creating separate cells in the software with separate NTRIP mount points.

4.2 Rover testing configuration

In general network RTK performance should be more representative at the centre of the triangle because the corrections are generated at an equal distance from all three physical CORS sites. The shaded red circle in Figure 1 represents approximately the centre of all three triangles. Therefore, tests were conducted at 5 permanent survey marks across the blue triangle and in the vicinity of the shaded red circle to enable rover performance to be assessed at the centre of all three triangles.

Figure 2 shows the equipment setup used during the test. Three Leica GX1230 GG RTK Rover receivers were connected simultaneously to a single AX1202 GNSS antenna using an antenna splitter. This was done to ensure each rover solution was using exactly the same set of observables and subject to the same potential error sources, e.g. if multipath was present all rovers were subjected to the same level of multipath. Three rover receivers were configured and connected to the NTRIP mount point for the blue, yellow and red networks respectively. The data communication method used for the rovers were 3G modems on the Telstra NextG service. This was chosen as a suitable communication option for the testing as it is typical of what a user would use in a real project.

Figure 2: Leica Rovers used during the test. Each is connected with individual NextG modem and to a common GNSS antenna via the splitter.

Four solution types were generated for each of the three triangles:

- i-MAX: Leica Spider via SmartNet Aus;
- MAX: Leica Spider via SmartNet Aus;
- VRS: Leica Spider via SmartNet Aus (referred to hereafter as LVRS);
- VRS: Trimble GPSNet via SunPOZ (referred to hereafter as SVRS);

Ten RTK initializations were performed for each of the three rovers for each of the four solution types and at each of the five permanent survey marks. All initializations were triggered simultaneously and the initialization time was recorded along with RTK solutions each second for 60 seconds following the receiver reporting that the ambiguities were fixed. After each initialization, all three rovers were then disconnected from the network RTK message and allowed to settle for 1 minute to ensure complete loss of the previous solution before re-initialising. The same operations were repeated and the results were logged in real-time with i-MAX, MAX and both the Leica and Trimble versions of VRS and across the set of three different network sizes.

The procedure at each permanent mark involved 10 initialisations and 60 seconds of solutions with each of the 4 solution types and for each of the three rovers simultaneously connected to the three different triangles. That entire procedure was then repeated at each of 5 permanent survey marks located within the shaded red circle, but over different time sessions.

5. Results and Analysis

The RTK rover performance for each of the four solutions between different triangle sizes is evaluated in terms of following parameters:

- Initialisation success rate and initialization time, also being referred to as Time to Ambiguity Fix (TTAF), where a successful initialization is defined in this instance as the rover receiver being able to report a fixed solution within 8 minutes after the initialization is triggered;
- RTK accuracy and availability in both horizontal and vertical components;
- Ambiguity resolution risk as defined in section 3. Since there was no access to the integer ambiguity information, we make an assumption that solutions with an error larger than 10cm in horizontal and vertical and 15cm in 3D were caused by incorrect ambiguity resolution;
- RTK integrity by examining the CQ indicator provided by the Leica GX1230 GG rover against the accuracy.

5.1 Initialisation success rate

First of all, the RTK rover claimed initialization success rate and initialization time results with respect to network sizes and RTK solution types are presented in Table 2. As will be shown later on, the successful initialization attempts still contain some degrees of AR risk or probability of incorrect integer ambiguity resolution. The four solution types examined for the test are Leica i-MAX, MAX, and VRS (denoted as LVRS) and Trimble VRS (denoted as SVRS). It is to be noted that if a fixed solution is not achieved within 8 minutes of initialization, it is considered to be a failed initialization attempt. The average TTAF is obtained by averaging over the five permanent survey marks. To simplify the table, the three different networks (blue, yellow and red) are denoted as Tri#1, Tri#2 and Tri#3 respectively.

Table 2 shows the initialization success rate and initialization time averaged over the five permanent survey marks and results summarized with respect to the four different solution types and the three network sizes. It can be seen that the MAX solution has outperformed the other three solution types in terms of the percentage of claimed successful initializations. One of the results noted is that the two MAX approaches (i-MAX and MAX) achieves 94% and 100% of claimed success rates (out of 50 initialization attempts) with the large triangle network. This is significantly better than the two VRS approaches where the similar values of 82% and 84% were achieved. These differences between VRS and MAX are to be expected because as triangle size increases the MAX approach is effectively a single station solution compared to the synthesised VRS being based on distant stations and thus appearing as very noisy data to the rover. Even so, it is noted that TTAF recorded for the MAX approach is also the slowest at an average of 142.79 seconds compared to 82.46, 72.73 and 129.5 seconds for IMAX, LVRS and SVRS respectively.

Table 2: Initialization success rate and initialization time

	% of Successful Initialization	Average Initialization Time (sec)
IMAX_Tri#1	98%	53.87
IMAX_ Tri#2	90%	85.42
IMAX_ Tri#3	94%	108.1
MAX_ Tri#1	94%	135.6
MAX_ Tri#2	96%	125.94
MAX_ Tri#3	100%	166.8
LVRS_ Tri#1	96%	54.83
LVRS_ Tri#2	94%	81.11
LVRS_ Tri#3	82%	100.26
SVRS_ Tri#1	100%	90.24
SVRS_ Tri#2	96%	136.04
SVRS_ Tri#3	84%	162.48
Result Summary w.r.t Solution Types		
IMAX_Sum	94%	82.46
MAX_Sum	96.6%	142.78
LVRS_Sum	90.6%	78.73
SVRS_Sum	93.3%	129.59
Result Summary w.r.t Network Sizes		
Tri#1_Sum	97%	83.64
Tri#2_Sum	94%	107.13
Tri#3_Sum	90%	134.41

The averaged initialization success rate and TTAF results against the different network sizes show that the initialization failure rate is roughly doubled and tripled compare to the small triangle, which is of the maximum recommended triangle size. The failure rates increased from 3% for the small triangle (Tri#1) to 6% and 10% for the middle and large triangles (Tri#2 and Tri#3) respectively.

Server logs from the SunPOZ Trimble GPSNet software reveal that in some cases the corrections may be sent in RAW format instead of a VRS solution. In such cases, raw RTK correction data from the closest single station in the triangle are sent to the rover for operating in single base station RTK mode. The distance to the closest station is 36.7, 47 and 70km for the small, middle and large triangle network respectively. Table 3 shows the number of successful initialization attempts and the number of VRS and RAW corrections sent from the Trimble VRS solution for the three triangle networks. VRS corrections failed to form on 7 and 10 occasions for the middle and large triangle respectively. We note that the type of corrections sent by the server was not shown on the Leica rover during the tests, meaning that the rover was unable to distinguish whether single-base or network RTK corrections were used. It should be noted that the software supplier wisely allow solutions to be set to prohibit raw mode so that corrections are not provided to the rover when a VRS solution is unable to be formed. However, that setting was not used here in order to allow testing outside of normal conditions.

Table 3: RTK correction sent from SunPOZ Trimble GPSNet

	# of Success Initialization Attempts	# of VRS correction from server	# of RAW correction from server
SVRS_ Tri#1	50	50	0
SVRS_ Tri#2	48	41	7
SVRS_ Tri#3	42	32	10
SVRS_Sum	140	123	17

5.2 RTK accuracy

The accuracies of the four RTK solutions are summarized in Table 4 with respect to the three network sizes in the horizontal, vertical and 3D components. For example, the accuracy achieved for the i-Max solution with the standard network configuration (Tri#1) in horizontal plan is 2.98 cm at 68% (1σ) and 9.91cm at 95% (2σ) level respectively. In general, the two VRS approaches (LVRS and SVRS) achieved better accuracy for the standard network compared to the MAX and i-MAX results. However, that result is reversed with the large triangle and the two VRS solutions degrading more quickly than the MAX and i-MAX solutions as the triangle size increased. Additionally, vertical accuracies observed in all cases are larger than the horizontal accuracies as expected.

Results achieved for all of the four solution types over the standard triangle are approximately 20 ~ 30 mm rms in horizontal and 40 ~ 50 mm rms in vertical. In the case of large triangle network, RTK accuracy performances are slightly degraded to approximately 30mm rms in the horizontal. However, greater degradations are seen in the vertical direction with variations between 50 ~ 100 mm rms. Since the solutions may be obtained in single-base station mode, we compared these results with specified accuracy in the RMS and part per million (ppm) values for Leica GX1230 GG rover receiver, which are 10mm + 1ppm for the horizontal and 20mm + 1ppm for the vertical. These translate to 46, 57 and 80 mm in the horizontal, and 56, 67, 90mm in the vertical, for distances of 36.7, 47 and 70km to the nearest reference station in the networks. The results indicated a good agreement of error growth in both horizontal and vertical components with the accuracy as specified in the RMS and part per million (ppm) values by the manufacturers.

Figure 3 shows the accuracy verses the accumulated probability of Leica SmartNet VRS solution for the large triangle network (Tri#3) in the East (top left), North (top right), Height (bottom left) and 3D (bottom right) direction. It can be noticed that large errors of up to 1 m in the North, East and Height component and 2.4m error in 3D exists. These highly inaccurate solutions appear to be caused by incorrect integer ambiguity resolution solutions. A possible reason could be that the RTK software in the rover fails to identify unfixable ambiguities or has output ambiguity-floated position solutions. On the other hand, we do notice that Figure 4 show the position errors of MAX solution for large network only grow to around 0.25 m in North, East and Height components 0.3 in 3D. This indicates the MAX RTK solution may have handled the effects of error growth due to increase of inter-station distances more effectively.

Table 4: Statistic results of RTK accuracy (cm)

	2D (N-E) Stat.		1D (H) Stat.		3D (N-E-H) Stat.	
	Error @ 68%	Error @ 95%	Error @ 68%	Error @ 95%	Error @ 68%	Error @ 95%
IMAX_Tri#1	2.98	9.91	4.71	14.58	5.95	17.08
IMAX_Tri#2	2.70	8.02	8.33	18.28	9.43	20.83
IMAX_Tri#3	2.94	8.11	5.10	31.96	6.50	33.47
MAX_Tri#1	2.65	5.77	5.02	15.33	5.41	15.91
MAX_Tri#2	3.09	7.73	8.29	18.37	8.68	20.34
MAX_Tri#3	3.18	6.60	6.30	31.09	7.30	33.21
LVRS_Tri#1	1.82	6.16	4.08	9.68	4.82	10.73
LVRS_Tri#2	2.48	11.43	5.04	22.78	6.26	23.63
LVRS_Tri#3	3.07	90.31	5.41	89.78	6.76	127.07
SVRS_Tri#1	1.88	4.01	3.81	10.15	4.43	10.32
SVRS_Tri#2	1.90	23.65	6.87	32.81	7.95	32.84
SVRS_Tri#3	3.00	97.18	10.77	67.63	11.43	162.57

5.3 RTK availability

Table 5 shows the statistical results of RTK availability, which is defined as the percentage of time during which the RTK solutions are available at a particular accuracy. For example, results of i-Max with the standard network (Tri#1) shows 54%, 79.7% and 90.4% of the solutions are within 2cm, 4cm and 6cm respectively of the true coordinates. Similarly, the VRS based approaches show a better performance with the standard network and the performances degrade quickly as the inter-station distance increases. Overall, at least 90 % of the horizontal solutions and 75% of the vertical solutions are within 6cm for any solution type when the standard 69km triangle (Tri#1) is used. The ability to achieve 6cm decreases to 86% in horizontal and 46% in vertical for the middle triangle (Tri#2) and 79.9% in horizontal and 48.6% in vertical for the large triangle (Tri#3) where the mean inter-station distances are 118km and 166km respectively.

5.4 Ambiguity resolution risk

Due to the lack of integer ambiguity information from the rover receivers, we analyse the ambiguity resolution risk level by deeming failed solutions as those that are in error by more than 10cm in horizontal and vertical and 15cm in 3D. These thresholds can be thought of as 5σ values for a user requirement of 2cm and 3cm RMS. Failures to meet these thresholds are most likely to be due to use of incorrectly fixed ambiguities or unstable floating ambiguity solutions. Referring to the definition of AR risk in section 3, measuring the AR risks the error thresholds is a rough estimation, perhaps including the effects of ambiguity-floating solutions.

For each solution type and each triangle size, Table 6 lists the total number of samples which have solution outputs and the number of samples and percentage that contain errors more than the 10 cm horizontal and 15cm 3D thresholds. The results show that both VRS solutions have a low ambiguity resolution risk with 1% and 0.2% over the standard network, whereas the risks for i-MAX and MAX are 7.9% and 6.1%. Additionally, it is also observed that the risk is significantly increased for the larger networks, up to 25% for SVRS over the large triangle network. This type of failure occurred in all of the testing systems and AR risk should be taken seriously by users and manufacturers.

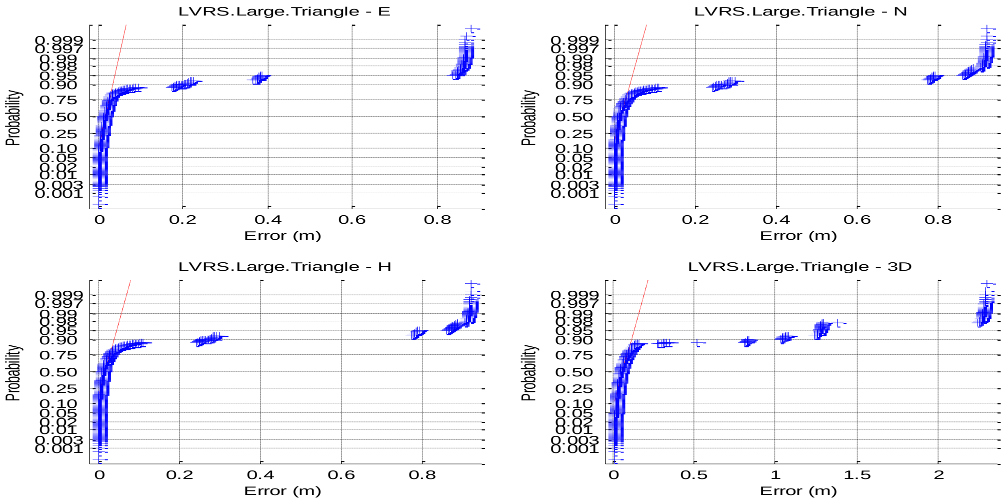

Figure 3: Accuracy of Leica SmartNet VRS solutions for large triangle network

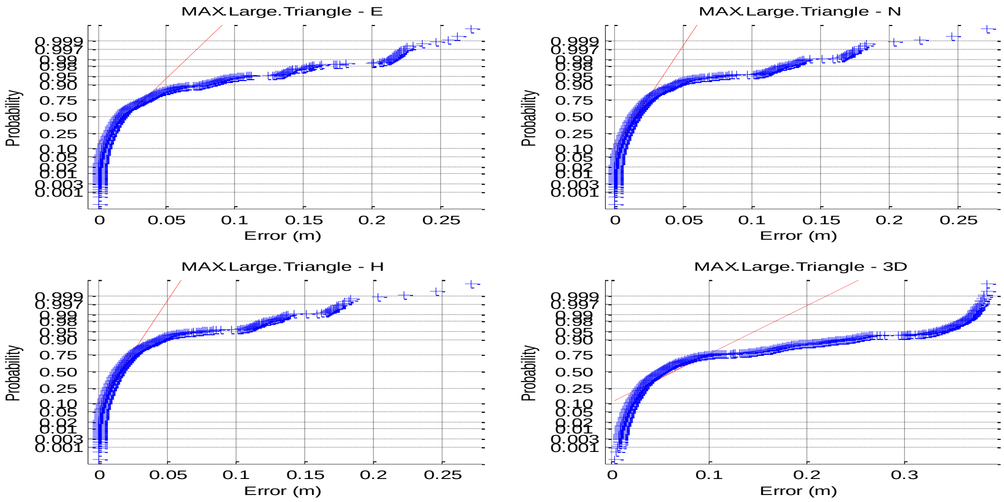

Figure 4: Accuracy of Leica SmartNet MAX solutions for large triangle network

Table 5: Statistic results of RTK availability

	2D (N-E) Stat.			1D (H) Stat.			3D (N-E-H) Stat.		
	Cum. % @ 2cm	Cum. % @ 4cm	Cum. % @ 6cm	Cum. % @ 2cm	Cum. % @ 4cm	Cum. % @ 6cm	Cum. % @ 5cm	Cum. % @ 10cm	Cum. % @ 15cm
IMAX_Tri#1	54.0%	79.7%	90.4%	35.6%	61.2%	77.1%	59.7%	80.7%	92.1%
IMAX_Tri#2	54.8%	81.3%	92.9%	19.0%	32.6%	46.1%	33.4%	71.7%	85.6%
IMAX_Tri#3	47.4%	76.6%	79.9%	33.1%	59.3%	72.3%	61.2%	71.8%	82.0%
MAX_Tri#1	54.0%	86.0%	95.5%	32.0%	56.9%	75.2%	63.4%	87.0%	93.9%
MAX_Tri#2	41.2%	82.2%	93.4%	22.5%	46.0%	58.4%	48.3%	74.2%	89.2%
MAX_Tri#3	41.7%	75.6%	86.8%	28.2%	54.2%	66.8%	51.2%	75.6%	79.9%
LVRS_Tri#1	71.9%	90.6%	94.8%	39.2%	67.2%	83.1%	70.2%	93.6%	99.0%
LVRS_Tri#2	55.3%	81.6%	86.8%	28.9%	56.3%	75.8%	56.1%	88.3%	93.1%
LVRS_Tri#3	49.9%	77.0%	83.0%	28.5%	55.5%	71.2%	56.6%	80.0%	87.2%
SVRS_Tri#1	71.5%	95.0%	98.3%	41.9%	69.9%	81.9%	72.9%	94.2%	99.8%
SVRS_Tri#2	70.7%	89.4%	93.2%	35.3%	58.7%	66.0%	62.1%	74.2%	85.6%
SVRS_Tri#3	46.0%	79.6%	83.5%	17.3%	35.5%	48.6%	38.3%	65.4%	75.0%

Table 6: Ambiguity resolution risk results

	Total Samples	Wrong AR Samples 2D (10cm threshold)	%	Wrong AR Samples 1D (10cm threshold)	%	Wrong AR Samples 3D (15cm threshold)	%
IMAX_Tri#1	3059	150	4.9%	379	12.4%	243	7.9%
IMAX_Tri#2	2763	82	2.9%	300	10.9%	399	14.4%
IMAX_Tri#3	2895	316	10.9%	640	22.1%	522	18.0%
MAX_Tri#1	2880	60	2.1%	330	11.5%	176	6.1%
MAX_Tri#2	2940	115	3.9%	181	6.2%	318	10.8%
MAX_Tri#3	3028	212	7.0%	667	22.0%	610	20.2%
LVRS_Tri#1	2940	27	0.9%	128	4.4%	29	1.0%
LVRS_Tri#2	2760	161	5.8%	186	6.7%	191	6.9%
LVRS_Tri#3	2451	328	13.4%	431	17.6%	313	12.8%
SVRS_Tri#1	3075	0	0.0%	164	5.3%	7	0.19%
SVRS_Tri#2	2882	180	6.3%	354	12.3%	414	14.4%
SVRS_Tri#3	2587	288	11.3%	868	33.6%	647	25.0%

5.5 RTK integrity risk

Next, we examine the RTK integrity risk of the four solutions using the Coordinate Quality (CQ) indicator provided by Leica GX1230 GG rover. Figure 5 shows the 3D CQ plot against the 3D positioning errors across all five permanent survey marks using the i-Max solution in the standard triangle (Tri#1) as an example. Histograms plotted on the right and bottom of the figure show the distribution of 3D CQ values and error in 3D respectively. The red line represents the 1:1 relationship between the two sets of data to reflect the fact that CQ is meant to be an indicator of the position estimate RMS value derived from the true position errors. In an ideal scenario, 68% of solutions (the scattered blue circles) should be to the left of the red line, in the top-left region of the plot. Instead, it can be seen that most of the solutions lie in the lower right region of the plot, indicating that many solutions have actual position errors significantly larger than the CQ indicators. In other words, the CQ indicators supplied by the rover appear to be optimistic when representing the quality of the coordinates obtained.

Figure 6 plots the 3D position error plotted against the 3D CQ indicator for the Leica VRS solution from the large triangle network (Tri#3). There are two regions showing the large position errors around 1.1 m and 1.5 metres while CQ values are 0.06 and 0.003 respectively.

We now examine the CQ indicator alternatively by presenting the ratio of the position error to the CQ value. Table 7 summarizes the percentage of the position errors falling within the ratios of 1, 5 and 10 in the horizontal, vertical and 3D space respectively. The results have indicated that on average the percentages of the horizontal, vertical and 3D position errors falling in 1 CQ are 35.2%, 38.9% and 31.6% respectively, which are far less than the 68% expected from theory. On the other hand, it is also noticed that on average there are over 6.9% of 3D position errors falling outside the 5 CQ bracket. Overall, the CQ indicator provides values that are significantly over-optimistic and not very helpful to represent the quality of derived coordinates, even when the system is operating under normal conditions. Certainly, the CQ indicator as given in the existing system possesses some risk if it is to be used solely as a RTK integrity performance indicator, especially for long baseline positioning.

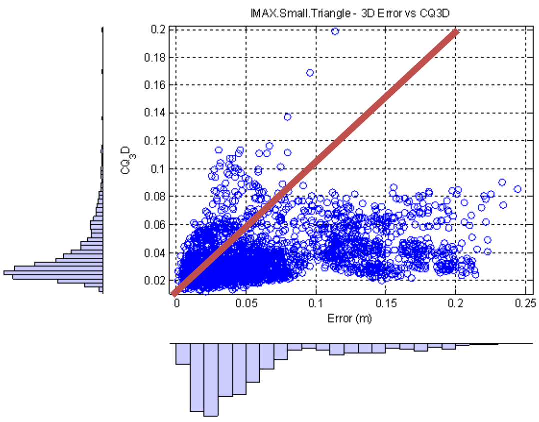

Figure 5: Illustration of 3D position errors plotted against 3D CQ indicator for i-MAX solution from a standard triangle network

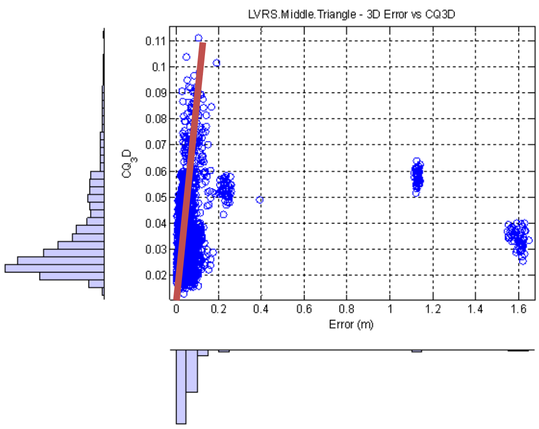

Figure 6: Illustration of 3D position errors plotted againts the 3D CQ indicator for Leica SmartNet VRS solution from the large triangle network

Table 7: Statistic results of CQ ratio in relation to horizontal (2D), vertical (1D) and 3D position estimate error

	2D (N-E) Stat.			**1D (H) Stat.**			**3D (N-E-H) Stat.**		
	1 CQ ratio	**5 CQ ratio**	**10 CQ ratio**	**1 CQ ratio**	**5 CQ ratio**	**10 CQ ratio**	**1 CQ ratio**	**5 CQ ratio**	**10 CQ ratio**
IMAX_Tri#1	35.2%	98.2%	100%	46.8%	95.8%	100%	36.4%	96.4%	100%
IMAX_Tri#2	39.3%	97.2%	100%	25.2%	91.8%	100%	20.9%	93.3%	100%
IMAX_Tri#3	41.7%	94.6%	97.8%	49.8%	96.3%	97.9%	42.8%	96.0%	97.9%
MAX_Tri#1	36.2%	96.1%	100%	38.0%	94.1%	99.5%	28.8%	94.8%	99.8%
MAX_Tri#2	24.4%	94.9%	99.4%	26.1%	91.8%	99.0%	19.8%	92.4%	99.3%
MAX_Tri#3	26.6%	96.4%	99.9%	34.6%	91.5%	100%	24.5%	93.3%	100%
LVRS_Tri#1	41.6%	99.1%	99.7%	47.8%	97.0%	99.5%	42.0%	98.4%	99.7%
LVRS_Tri#2	26.2%	94.2%	95.7%	38.8%	94.7%	97.4%	28.5%	94.8%	95.7%
LVRS_Tri#3	25.5%	87.8%	87.8%	41.1%	87.5%	92.0%	34.4%	86.7%	87.7%
SVRS_Tri#1	44.9%	99.8%	100%	48.5%	98.1%	99.9%	39.7%	99.3%	99.9%
SVRS_Tri#2	43.4%	94.5%	97.9%	40.5%	85.7%	97.3%	36.2%	87.3%	97.9%
SVRS_Tri#3	36.9%	90.6%	92.3%	29.5%	83.7%	96.8%	24.9%	85.1%	92.3%
Average	**35.2%**	**95.3%**	**97.54%**	**38.9%**	**92.3%**	**98.27%**	**31.6%**	**93.1%**	**97.52%**

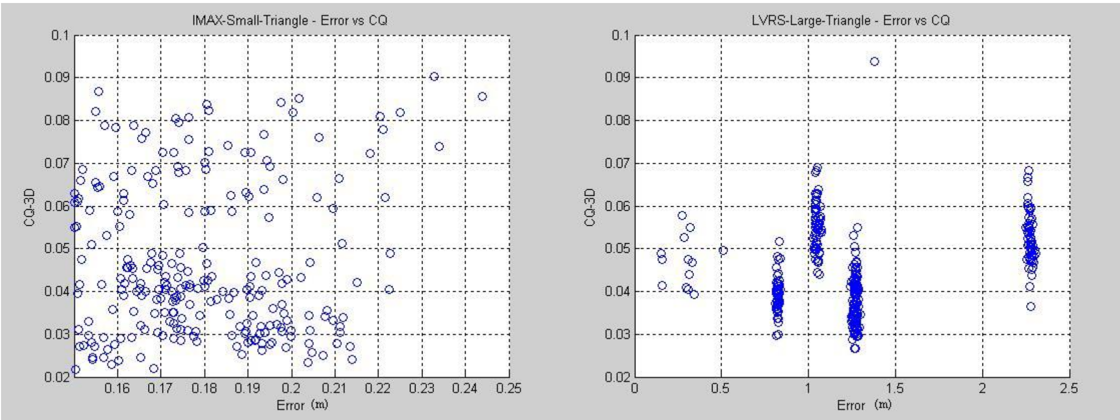

Figure 7: 3D error verse 3D CQ for Leica SmartNet i-Max solution (left) and VRS solution (right)

We further plot the CQ values corresponding to the position errors outside 15 cm error in 3D, which indicates the AR risk in Figure 7, in which the left panel shows the i-MAX CQ values over the standard triangle network (Tri#1), and the right panel shows the Leica VRS solution over the large triangle network. The results further illustrate the over-optimistic nature of the CQ indicators under conditions of standard and long inter-station distances. None of the CQ values adequately represented the true position errors in this analysis or reflected the AR risk.

Overall, the four commercial RTK systems perform well over the test networks with 69.3km, 118km and 166km mean inter-station distances in relation to RTK position accuracy against the specified distance dependent accuracy (i.e. compared to the expected ppm value in the specification sheet). However, these results revealed some common problems where there is a scope for improvement by the systems tested. As shown in Table 6, ambiguity resolution risk of as high as 7.9% is identified when the systems operate with the standard network (mean inter-station distance of 69km) and this risk reached 25% over the large network (mean inter-station distance of 166km). Next, RTK positioning errors as large as 2 metres are identified, showing the RTK software modules in the system probably failed to identify incorrectly solved integer ambiguities or failed to choose ambiguity-floated position solutions. Additionally, the Coordinate Quality (CQ) indicator often provides over-optimistic values, sometimes as much as 10 times better than the actual position error, which is not helpful for mitigating RTK integrity risk. These problems are common to all of the systems tested to different extents and can cause serious problems for some users, especially these requiring high reliability solutions. The assessement results undoubtly indicate the necessarity of monitoring of AR risk and integrity risk of RTK solutions. Although the integrity risk acceptable by most precise positioning users can be much higher than that required by aviation navigation users, the risk level of as high as several percentages may still be difficult to accept by many precision users.

6. Concluding remarks

An assessment for the performance of the commercial Real Time Kinematic (RTK) services over longer inter-station distances has been carried out as part of a CRCSI research project. The four RTK systems, including i-MAX, MAX, Leica VRS and Trimble VRS systems have been tested using triangle networks with mean inter-station distances of 69km, 118km and 166km. A variety of performance measures including initialization success rate, initialization time, RTK positioning accuracy, RTK availability, ambiguity resolution risk and RTK integrity risk were used to present a comprehensive analysis of the performance of the different approaches to network RTK.

The analysis has shown that the commercial RTK solutions tested over the varying sized networks generally perform satisfactorily against specifications in terms of the initialisation success rates and RTK position accuracy. On average, 90% of initialization attempts can lead to integer fixed solutions even when operating in the large triangle with a mean inter-station distance of 166km, although a high AR risk is also associated with it. That compares quite favourably to the 97% success rate achieved for the standard triangle with an average inter-standard distance of 69km. While initialization is possible over longer distances, TTAF increases accordingly as expected and can reach several minutes. In terms of RTK positioning accuracy and availability, VRS approaches perform better than MAX and i-MAX when operating under the standard triangle network. As the inter-station distance increases to 166km, the RTK uncertainty of the VRS systems can reach as high as 2.5 meters, while the MAX position errors remain within the range of 40cm over the large triangle network.

Despite those promising aspects, the results of this work have also revealed several problems common to all the RTK approaches. Firstly, the probability of solutions with 3D error of more than 15 cm is 7.9% and 6.1%, for i-MAX and MAX compared to 1% and 0.2% for LVRS and SVRS solutions even when operating within the standard triangle network. This probability increased to 18% and 20.2%, for i-MAX and MAX, and jumped to 12.8% and 25% for the LVRS and SVRS solutions, when operating with the large triangle. These errors are most likely due to incorrect integer ambiguity resolution, which has been defined as Ambiguity Resolution Risk in this paper. The Coordinate Quality (CQ) indicator provided by the Leica GX1230 GG rover receivers provide over-optimistic quality indications for the position estimate errors, especially under challenging conditions. Only 25% ~ 40% of the test samples' 3D CQ values reflect the true error, compared to the 68% specified by the manufacturer. In this long inter-station performance assessment experiment, the CQ indicator is often misleading for RTK integrity risk mitigation. These problems that are common to all the systems tested to different extents, can cause serious problems to safety-of-life and liability-critical users requiring requiring highly reliability solutions. The assessement results have clearly indicated the needs for both researchers and manufactures to devote attention to detection and mitigation of the AR risk and integrity risk of RTK solutions.

These systems tested have shown some potential in providing services to regional areas using long inter-station CORS networks. The results have indicated that in areas where there are insufficient users to justify high densities of CORS stations, it may still be possible to offer RTK services using more sparse networks, so long as users can either tolerate the potential risks or can employ some procedures to identify errors due to incorrect ambiguity resolution or other factors. For example, surveying applications may be able to incorporate multiple occupations of points to be coordinated to help identify errors, assuming the longer initialization times can be tolerated. For applications such as construction machine guidance where the rover is moving, error checking using re-occupation approach is less practical and may require more advance fault detection solutions. On the other hand, within denser networks, a node may be removed or disfunctional, perhaps due to failure. That would mean that reference stations are interspaced in excess of the maximum distance recommended by the network software solution provider. Such a sparse network could offer more severely or just slightly degraded performance within that area. The comparison of the performance between the 69.3km and 117.6km cell seperation within this testing, can offer an indication of the level of performance degradation that could be expected within any area of a sparse (70km) RTK network has suffered from the failure of a reference station.

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References

Aponte, J., X. Meng, M. Burbidge, (2008), ***Performance Assessment of a GPS Network RTK Service***, FIG Working Week 2008, Stockholm, Sweden, 14-19 June 2008

Brown, N., I. Geisler, et al. (2006), ***RTK Rover performance using the master-Auxiliary Concept***, Journal of Global Positioning Systems 5(2): 135-144.

Buick, R. (2006), ***RTK base station networks driving adoption of GPS +/- 1 inch automated steering among crop growers***, Trimble Whitepaper.

Edwards, S., P. Clarke, et al. (2008), ***An examination of commercial network RTK GPS services in Great Britian***, report.

Euler, H.-J. (2005), ***Reference Station Network Information Distribution***, Retrieved 30 July, 2010, from http://www.wasoft.de/e/iagwg451/euler/euler.html.

Feng, Y., B. Li, (2008), ***A benefit of multiple carrier GNSS signals: regional scale network-based RTK with doubled inter-station distances***, Journal of Spatial Sciences, 2008,53(1):135-147

Feng, Y. and J. Wang (2008), ***GPS RTK Performance Characteristics and Analysis***, Journal of Global Positioning Systems 7(1).

Feng, Y., Rizos, C., Higgins, M., Lim, S., & Tang, M. (2009), ***Developing Regional Precise Positioning Services Using the Legacy and Future GNSS Receivers,*** Journal of Global Positioning Systems, Vol 8 (1): 17-25

Leica Geosystems, (2009), ***Leica SmartNet UK & Ireland Network RTK User Guide***.

Higgins, M. (2008), ***An Organisational Model for a Unified GNSS Reference Station Network for Australia***, Journal of Spatial Science 53(2).

Janssen, V. (2009), ***A comparison of the VRS and MAC principles for network RTK***, International Global Navigation Satellite Systems Symposium 2009. Gold Coast, Australia.

Kim, D., S. Bisnath, et al. (2004), ***Performance of Long-Baseline Real-Time Kinematic Applications by Improving Tropospheric Delay Modeling***, ION GNSS 17th International Technical Meeting of the Satellite Division. Long Beach, CA.

Retscher, G. (2002), ***Accuracy Performance of Virtual Reference Station (VRS) Networks***, Journal of Global Positioning System 1(1).

Biography

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