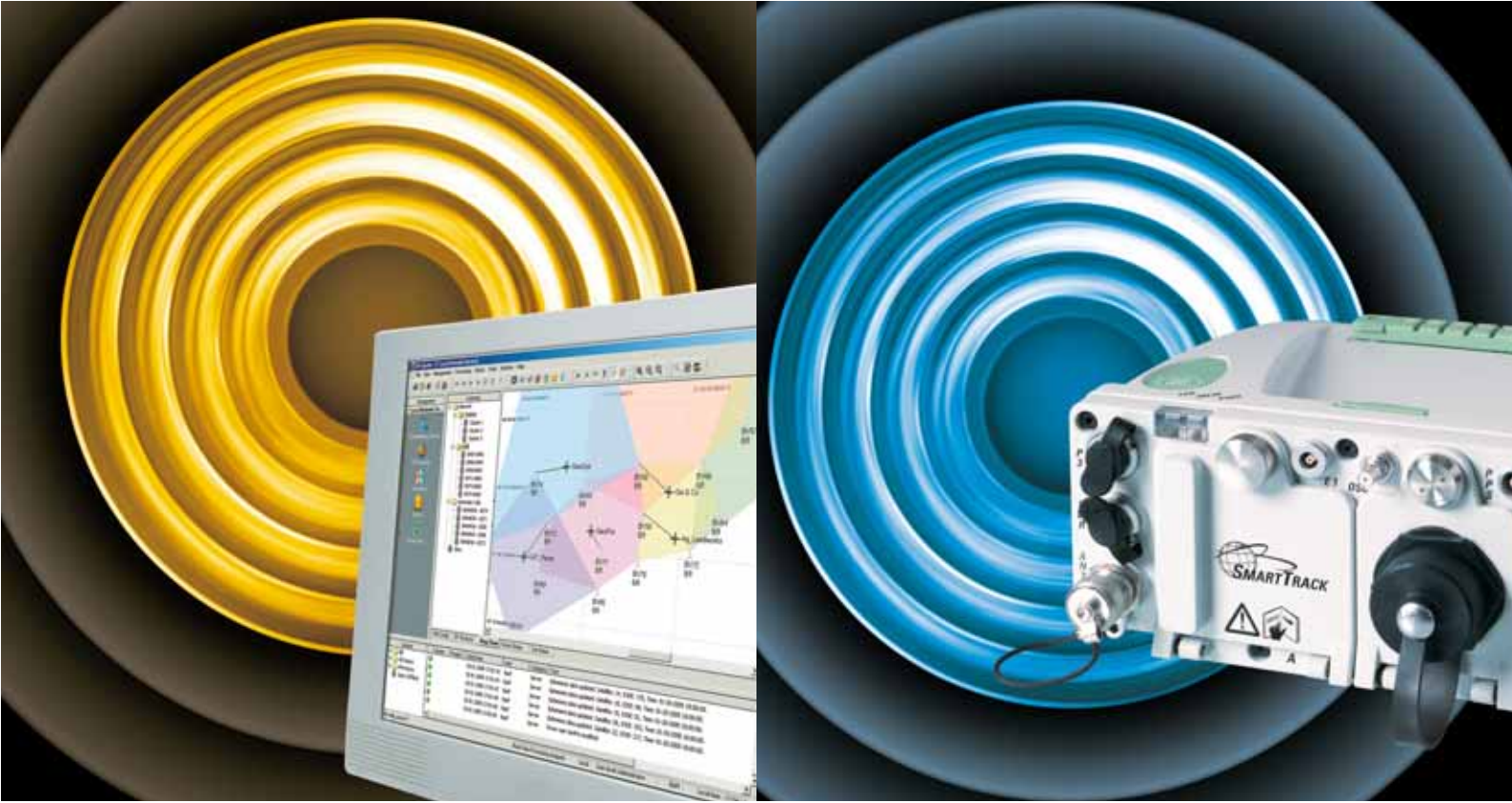


Leica Geosystems Networked Reference Stations



Take it to the MAX!

An introduction to the philosophy and technology behind Leica Geosystems' SpiderNET revolutionary Network RTK software and algorithms

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Introduction

Leica Geosystems continues to be the class leader in GPS surveying with their fast and highly reliable 30km conventional RTK using SmartTrack and SmartCheck technology. In its role as industry leader in precision GPS, Leica Geosystems has been for many years actively researching, promoting and realising network RTK solutions and working towards an industry standard for network RTK corrections. It is in this role that Leica Geosystems has developed and driven the Master-Auxiliary Concept (MAC), the future of networked RTK and the basis for the forthcoming RTCM 3.0 network correction message standard. The Master-Auxiliary corrections (MAX) are compact and efficient to transmit to the rover, but also robust and flexible. The Master-Auxiliary Concept overcomes all of the weaknesses of the previous approaches that have been used until now by giving the rover the capability to derive the maximum benefit from the information provided by a reference station network even over a broadcast/one-way communication medium. In conjunction with this new standard, Leica Geosystems is proud to announce the Leica GPS Spider 2.0 software with its revolutionary new network RTK module SpiderNET, which draws on the latest zero-difference processing techniques to take the Master-Auxiliary Concept to the MAX: maximum reliability, maximum performance, maximum flexibility and maximum security.

The Basics of Network RTK

The motivation behind using multiple reference stations in a network for GPS corrections is to model and correct for distance-dependent errors that reduce the accuracy of conventional RTK or DGPS positions in proportion to the distance from a rover to its nearest reference station. It is well known that the most significant sources of error affecting precise GPS positioning are the ionosphere, troposphere and satellite orbits. These error sources may be categorized in two groups: dispersive and non-dispersive. The ionosphere is a dispersive error because the magnitude of the resultant error is directly related to the frequency of the ranging signal (L1, L2, L5). The influence of the ionospheric error on different frequencies in the L-band used by satellite navigation systems is well understood. The ionosphere, which is subject to rapid and localised disturbances, is the main restriction on the station density in a reference network. The troposphere and orbit errors are classified as non-dispersive because they are not frequency-dependent and have an equal effect on all ranging signals used by current (and proposed) satellite-based global navigation systems. The aim of a reference network is to model and estimate these error sources and provide this net-

work correction information to rover users so that they may derive positions with a higher accuracy than with conventional RTK. Until the release of RTCM 3.0, there will have been no official internationally accepted standard for network RTK corrections. Prior to the release of RTCM 3.0, two approaches, namely those making use of area correction parameters and 'virtual' reference stations, were adopted by the user community as interim measures, both of which have serious flaws in their concept and methodology. Some of the problems with these approaches are listed below.

Problems Common to VRS and FKP:

1. The modelling performed by the network software, which is proprietary and unknown to the rover user, greatly influences the information that is provided to the rover. The outcome of this is that not all of the relevant error information is provided to the rover prohibiting it from using the optimal processing techniques (algorithms, models, interpolation) for the application. The fact that proprietary information is transmitted means that the corrections are not standard and therefore biased towards a particular brand of rovers.
2. The use of RTCM 2.3 as the data format for the existing approaches is inefficient, particularly for area correction parameters. The VRS and FKP approaches do not conform to the philosophy of RTCM's industry standard formats because the messages contain modelled data and not raw data as specified by RTCM. More importantly, proprietary, non-standardised messages are used to transmit part of the information. For area correction parameters most of the message is transmitted in proprietary messages.

Problems Unique to VRS:

1. Two-way data links are required between the network computation centre and the user, making access to the correction service costly for both the user and the service provider. Duplex communications also have the downside of limiting the number of simultaneous users who are able to receive the corrections from the network.
2. The rover is forced to reinitialise its position fix once it has travelled more than a certain distance from its initial position because the 'virtual' reference station must be moved to maintain the quality of the network corrections.
3. An arbitrary number of reference stations, typically three, which is determined by the reference station software, are used to calculate the corrections for the

rover. This restriction limits the ability of the system to adapt to the prevailing atmospheric conditions by using an appropriate number of reference stations to, for example, model larger scale atmospheric activity. Such a constraint also influences the robustness through its impact on the network geometry and the sensitivity to data outages. If even one of the three stations is unable to provide data to the network, the network software must search for another suitable reference station and reset the calculation of correction for the user. During this search process, no network corrections are available to the rovers which impacts their productivity in the field.

4. The virtual reference station approach represents the network to the rover as a single reference station. Thus in the end the rover still has a single baseline solution, albeit with a much shorter baseline length. However, misleading the rover in this way also denies it the opportunity to fully realise the increase in accuracy and reliability possible with a true network solution. It also limits the ability of the rover to do quality and integrity monitoring.
5. In some jurisdictions there are legal issues if the GPS correction data is not directly related to a real reference station. Georeferencing GPS corrections or observations to virtual reference stations is neither traceable nor repeatable.

In light of these and other limitations of existing approaches to network corrections, Leica Geosystems has driven the development and adoption of the Master-Auxiliary Concept within the RTCM Special Committee 104.

The Master-Auxiliary Concept

Overview

In September 2001, Leica Geosystems together with Geo++ presented a paper titled "Study of a Simplified Approach in Utilizing Information from Permanent Reference Station Arrays" (Euler et al., 2001) to the RTCM SC104. This paper contained a proposal for a standard for network correction messages that would overcome the problems of the existing approaches. Leica Geosystems has been pushing since 2001 for a standard for network RTK, which would be a benefit to the whole surveying industry. The master-auxiliary proposal put forward by Leica Geosystems and Geo++ has since undergone small refinements based on input from other manufacturers. At the time of writing the master-auxiliary network messages are the only fully documented proposal for network RTK messages under consideration by RTCM SC104 and have remained in their current form for over one year. Just as NTRIP was in use prior to its acceptance as a standard, RTCM 3.0 network messages are already available with the Leica GPS Spider reference station software and the Leica System 1200 GPS family. Official acceptance and release of the standard is pending the completion of an interoperability test sanctioned by RTCM and currently in progress between the major manufacturers.

The fundamental concept of the proposed approach was to transmit all relevant correction data from a reference network to the rover in a highly compact form by representing ambiguity levelled observation data as correction differences of dispersive and non-dispersive data. This approach was to become known as the Master-Auxiliary Concept (MAC) and is the basis for the RTCM 3.0 Network RTK messages. A condensed version of this paper was presented at ION GPS 2001 and won the Best Presentation Award for its session. A subsequent paper (Euler et al., 2002) expanded on the concept and demonstrated the superiority of this approach over other proposals and the existing inferior approaches, in terms of throughput, possibility for non-standard data content and the distribution concept. A significant improvement in the quality of corrections compared to conventional RTK was demonstrated leading to proportional improvement in ambiguity resolution and positioning accuracy (Euler and Zebhauser, 2003; Euler et al., 2004).

Basics of the Master-Auxiliary Concept

A fundamental requirement of Master-Auxiliary Concept is that the phase ranges from the reference stations are reduced to a common ambiguity level. Two reference stations are said to be on a common ambiguity level if the integer ambiguities for each phase range (satellite-

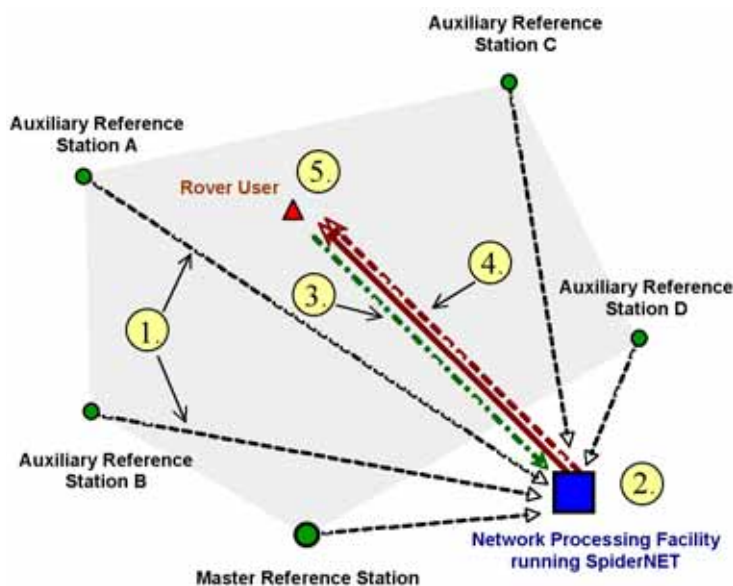
receiver pair) have been removed (or adjusted) so that when double differences are formed the integer ambiguities cancel. The main task of the network processing software is to reduce the ambiguities for the phase ranges from all reference stations in the network (or sub-network) to a common level. With this task done, it is then possible to calculate the dispersive and non-dispersive errors for each satellite-receiver pair and for each frequency.

To reduce the volume of data to be transmitted for a network, the Master-Auxiliary Concept sends full correction and coordinate information for a single reference station, referred to as the master station. For all other stations in the network (or sub-network), known as auxiliary stations, correction differences and coordinate differences are transmitted. This differenced information, which is calculated between the master and each auxiliary station, is numerically smaller and can thus be represented in the messages with a smaller number of bits. The correction difference information may be used by the rover simply to interpolate the error at the user's location or to reconstruct the full correction information from all reference stations in the network (or sub-network). Thus the Master-Auxiliary Concept fully supports simplex communication media with no loss of positioning performance noticed at the rover. The bandwidth required to transmit the data is further reduced by splitting the corrections into two parts: dispersive and non-dispersive. As mentioned previously, the dispersive error is directly related to the frequency of the signal and the non-dispersive error is the same for all frequencies. Since the frequency-relationship for the ionospheric error is known, it is possible to represent the full

correction for all frequencies (L1, L2, L5) with these two values. Additionally, as the tropospheric and orbit errors are known to change only slowly with time, therefore the non-dispersive component does not need to be transmitted at as a high rate as the dispersive error, which can further reduce the bandwidth needed to provide network corrections to the rover.

The Master-Auxiliary Concept gives the rover the flexibility to perform a simple and efficient interpolation of the network corrections or a more rigorous calculation depending on its processing capabilities. The Leica GX1230 RTK rover has a high performance processing unit and is able to maximise the potential of the master-auxiliary network corrections by using sophisticated error modelling techniques.

The master reference station does not need to be the nearest reference station to the user, though it may be preferable, since it is used simply for data transmission purposes and plays no special role in the computation of corrections. If for some reason data from the master station are no longer valid or available then one of the auxiliary stations can assume the role of the master station. At all times, the RTCM 3.0 master-auxiliary network corrections are related to real reference stations and are therefore fully traceable. The data flow and basic steps for a rover using master-auxiliary corrections are shown in Figure 1. Note also that since the full observations for the master station are transmitted, a rover is still able to compute a single baseline solution with the correction data even if it is not able to interpret the network messages.



1. Transmission of raw observation data from the reference stations to the network processing facility.
2. Network estimation process including **Ambiguity Resolution** to reduce the stations to the common ambiguity level.
3. (Optional) NMEA GGA position received from the rover at the network processing facility. The most appropriate reference stations are chosen for the rover based on its location.
4. Formation and transmission of RTCM 3.0 network message using **Corrections** for the Master station and **Correction Differences** for the auxiliary stations.
5. Computation of high accuracy rover position using the full information from the reference network.

Figure 1:
Generation of master-auxiliary corrections (MAX) for a rover

Common Misunderstandings About the Master-Auxiliary Concept

1. It is a drawback that data from only a subset of the network is transmitted. In a large network the rover will be too far from many of the stations to benefit from their contribution. Transmitting data from these stations is just a waste of bandwidth. Intelligent software like GPS Spider chooses the optimal set of reference station data to send to the rover.
2. It is a drawback that only a snapshot of the ionospheric and geometric errors are sent. Since the actual error information is available in the master-auxiliary corrections, the rover can directly calculate the error at its position and, therefore, does not need time for its error models to converge. High accuracy positioning is possible from the moment the first set of corrections are received.
3. It is preferable to send the state-space vector to the rover. The state-space vector contains estimates of the error sources based on certain proprietary mathematical models that are unknown to the rover. A simplistic interpolation method is then used to generate the corrections for the rover's location and applied to its single baseline solution. With the master-auxiliary approach, the ambiguity-levelled observations, which contain the actual atmospheric and geometric error observed at the reference stations, are transmitted to the rover. The rover is then able to compute a true multiple baseline solution using all relevant error information. Since the full error information is available to and used by the rover, there are no adverse effects from not knowing what models the reference station software has applied to the data.
4. With Master-Auxiliary Concept the master station will be a long way from the rover. With two-way communications GPS Spider will always choose the closest reference station to be the master. With one-way communications the rover user can choose which correction service to connect to and thereby ensuring that a cell with the nearest master station is used. Thus the master will always be close to the rover and, hence, will be tracking the same satellites.
5. Accuracy will be compromised because reduced update rates are used. Update rates of 1Hz are supported for both the master station observations and the dispersive and non-dispersive errors. Update rates for the dispersive and non-dispersive errors, can be configured to be

slower than 1Hz to conserve bandwidth. Having a slower update rate (of say 2s or 5s) for these errors will not significantly impact on the accuracy of the rover's position.

6. The bandwidth of the network messages is very high. Sending 1Hz master data and 2s dispersive and non-dispersive error information is more efficient than 1Hz VRS with RTCM 2.3 for a typical set of up to 8 stations.
7. If the network is unable to fix ambiguities, then the rover will not get corrections. The master-auxiliary corrections contain the full observations for the master station, so a rover is still able to compute a single baseline solution if the correction differences are not available or not valid. With two-way communications GPS Spider will always use the closest reference station as the master.

Spidernet

Overview

The Leica GPS Spider software has been designed from the ground up as a flexible, powerful, modular and secure reference station software that can be tailored to the needs of large and small, simple and complex reference station networks. Introduced in Leica GPS Spider 2.0 is the SpiderNET network RTK processing kernel. SpiderNET uses the latest in zero-difference processing algorithms to deliver outstanding reliability and performance. SpiderNET has gone through extensive testing and tuning with numerous datasets from around the world to ensure high standards of performance even during periods of high ionospheric disturbance and when there are large height differences between reference stations. A variety of real time data input formats are supported including Leica LB2, RTCM and various third party raw data formats. A full range of correction formats are supported for single site corrections including RTCM 3.0, RTCM 2.x, Leica, CMR and CMR+.

The Leica GPS Spider software consists of five key components: the Site Server, the Network Server, the Cluster Server, the RTK Proxy Server and the Spider User Interface. Each server can run on a together on a single computer or separately on multiple computers. The Leica GPS Spider architecture is scalable and permits the network processing to be distributed across a number of computers to reduce the computational burden. The flexible and distributed architecture also makes it possible to build redundancy into the system to ensure the network service operates with the highest possible reliability. Multiple CPU computers are supported to fully leverage today's advanced computing technology.

Network Processing Algorithm

The SpiderNET kernel was designed and developed specifically to conform to and harness the power of the new RTCM network correction message standard. SpiderNET boasts state-of-the-art processing algorithms to maximise the benefit of network RTK for the rover in the field. For estimation of the relevant parameters, including network ambiguities and atmospheric models, SpiderNET uses zero-difference code and carrier phase measurements in an mathematically optimal observation based Kalman filter. This approach has a number of benefits over the traditional double-difference based processing strategies. By processing with undifferenced observations, SpiderNET increases the amount of data available, reduces the sensitivity of the system to data outages and enables more effective estimation of atmospheric and other errors. This approach also avoids the use of linear combinations of GPS observables, such as the well known wide-lane and ionosphere-free combinations, which magnify measurement noise and multipath. SpiderNET updates at 1Hz and is continuously processing to ensure network corrections are available whenever a rover user connects.

In addition to the network ambiguities, the Kalman filter is used to estimate deterministic ionosphere and troposphere models, satellite and receiver clocks and satellite orbits. Stochastic models for the ionosphere and satellite clocks are also used to ensure that the errors are modelled with the highest possible fidelity. Predicted precise orbits from the IGS, AIUB or other organisations may also be used to further refine the solution. With all parameters of the state-space vector estimated in a single filter, SpiderNET offers a true network solution and not a multiple-baseline solution like other software.

For ambiguity resolution, SpiderNET uses the well known and well accepted LAMBDA (Teunissen, 1994) method. Consistent with the SmartCheck technology integrated in the Leica GX1230 RTK rovers, SpiderNET continually re-verifies the ambiguities to ensure that they are fixed with the highest possible reliability.

Networks, Clusters and Cells

For practical reasons, processing of the network and dissemination of the master-auxiliary corrections is based on a tiered system of networks, clusters and cells. A network is a collection of reference stations that are to be combined for the generation of network corrections. A cluster is a sub-network of stations that are processed together to achieve a common ambiguity level. For small networks, the entire network may be contained in one cluster. For larger networks, where computational overhead is an issue, several clusters may be required so that the processing may be distributed over several computers. Individual sites within the network may be in more than one cluster allowing overlap between clusters (see Figure 2). Each cluster in the network may or may not be on the same integer level. A cell is a selection of sites from a cluster consisting of one master station and a number of auxiliary stations and which is used to generate master-auxiliary corrections (refer to Figure 3).

Since SpiderNET processes all data together in a single filter, every site in the cluster is reduced to the same ambiguity level. For the user this means that there is no artificial and restrictive limit of three reference stations imposed as with other approaches, therefore easily allowing the optimum number of reference stations to be used in the determination of the network corrections for the rover. Using five or six reference stations for the network corrections can improve the network geometry for the rover and help to estimate larger scale atmospheric effects. Also, by using more than three reference stations, the rover will not lose its fix if one reference station drops out of the solution as a result of unreliable communication links or other issues. The inherent flexibility of the Leica GPS Spider solution enables new modules to be added in the future for extensions such as orbit improvement and meteorology in addition to support for modernised GPS and Galileo.

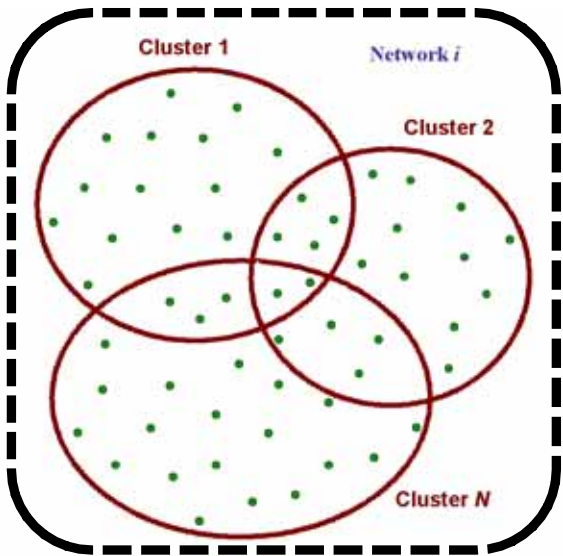


Figure 2:
A reference network comprising a number of clusters.

Master-Auxiliary Corrections (MAX)

For broadcast communication mediums, pre-defined cells, which may be created manually by the network operator, can be used to transmit master-auxiliary corrections, known as MAX, to the rovers. The rover user can connect to the correction service that is most relevant for their geographic location. Depending on the size of the network, multiple cells can be defined to optimise the transmission of data by reducing the number of stations that are contained in the correction messages.

In the case of two-way communications, Leica GPS Spider will automatically select the optimum sites for the cell used to generate master-auxiliary corrections for each rover. This correction service is referred to as Auto-MAX. By choosing the most appropriate cell configuration, Auto-MAX corrections minimise the bandwidth required to transmit the corrections. The master station is always chosen as the station nearest to the rover. The auxiliaries are chosen from the surrounding stations to provide the best possible set of corrections for the rover's position. With Auto-MAX even the largest reference networks can be fully serviced with a single communication channel.

The MAX corrections contain the full information from the cell and therefore provide the maximum level of accuracy and reliability for the rover. With MAX, the network operator has the ability to transmit corrections using both two-way and broadcast communication technologies.

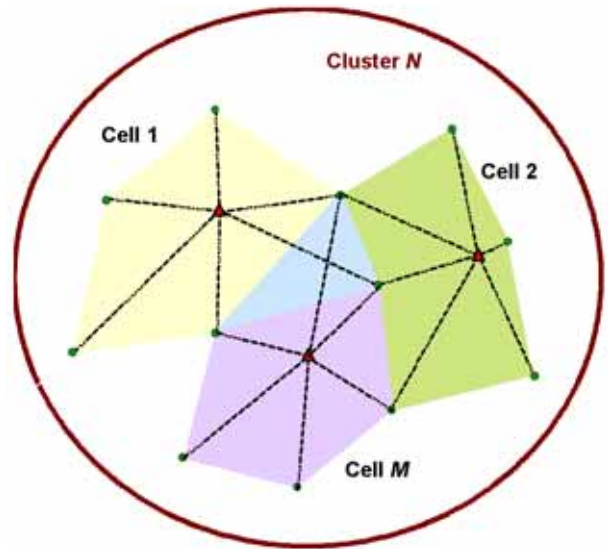
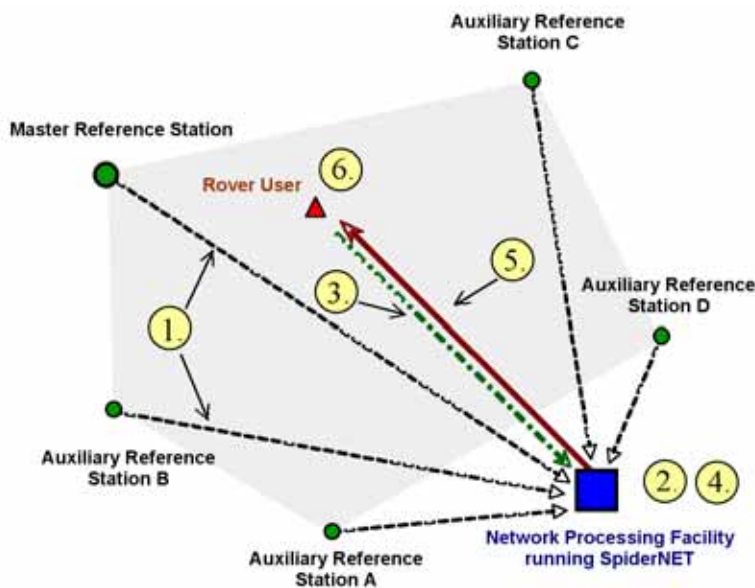


Figure 3:
A cluster providing master-auxiliary corrections to several rovers, with each rover using an appropriate cell based on its location.

Individualized Master-Auxiliary Corrections (i-MAX)

In order to support earlier model rover receivers that are not able to interpret the RTCM 3.0 Network RTK messages, Leica GPS Spider is able to produce individualized master-auxiliary corrections, known as i-MAX. These i-MAX corrections require two-way communications and may be transmitted in the RTCM 2.3 and RTCM 3.0 formats. Unlike other approaches, i-MAX uses a real reference station as the source for the network corrections so there is consistency and traceability for the corrections received by the rover. The interpolation performed in Leica GPS Spider for the i-MAX corrections is the same as that used in the Leica GX1230 RTK rovers when positioning using master-auxiliary corrections. As such, rover performance using i-MAX is comparable to that of a rover that fully supports master-auxiliary corrections. The data flow and basic steps in the use of i-MAX by the rover user is shown in Figure 4.



1. Transmission of raw observation data from the reference stations to the network processing facility.
2. Network estimation process including **Ambiguity Resolution** to reduce the stations to the common ambiguity level.
3. NMEA GGA position received from the rover at the network processing facility. The most appropriate reference stations are chosen for the rover based on its location. The master station is chosen as the reference station closest to the rover.
4. Leica GPS Spider calculates the **network corrections** for the rover and applies them to the observations from the master station.
5. Formation and transmission of RTCM 2.3 or Leica format corrections from the master station.
6. Computation of high accuracy rover position using the reference network.

Figure 4:
Generation of individualized master-auxiliary corrections (i-MAX) for a rover.

Re-Processing

SpiderNET can operate in real time mode for normal network RTK, or in re-processing mode for network testing. In re-processing mode reference sites are simulated using data from previously logged RINEX or MDB files. All functionality in the GPS Spider application, such as network processing, generation of correction streams and logging of data, works in re-processing mode as it would in real time mode making it possible to fully simulate an operating reference network. This is very useful for testing a network configuration before installing all of the hardware infrastructure and for tuning the processing to local conditions.

Security Concept

The Leica GPS Spider security concept has been integrated into the software architecture from the design stage and was not added as an afterthought as is the case with existing systems. The security concept effectively separates the network operation and computation from the data dissemination thereby protecting the key infrastructure as well as sensitive user and billing information associated with the centralised RTK service.

The key component of the Leica GPS Spider security concept is the RTK Proxy Server. The RTK Proxy Server is situated outside the firewall and is used to provide the correction data to the users either directly, using for example NTRIP or TCP/IP, or via an access router. Communication between the network processing module (the Network Server) and the RTK Proxy Server may only be initiated by the Network Server.

All sensitive information such as user and billing information is stored in a database behind the firewall and not on the RTK Proxy Server or the access router, as is the case with competitor systems. Thus any hacker who manages to gain access to the RTK Proxy Server (which is normally open on the Internet) would not be able to access confidential information or other parts of the system. With Leica GPS Spider, it is a simple matter to protect the network operation and user information from hackers, and at the same time minimise issues in integrating the system into existing IT infrastructure and procedures.

Data Distribution, User Management and Billing

Leica GPS Spider supports communication over NTRIP, TCP/IP, serial, radio, GSM, GPRS, CDMA and modem in addition to access routers, which may be used to interface ISDN lines and other communication technologies. Leica GPS Spider provides an advanced centralised RTK service that can distribute corrections from single and nearest sites with the same flexibility and security as it can for network corrections.

Authentication, Authorization, Accounting and Auditing (AAAA) are fully integrated in Leica GPS Spider in a centralised, secure and easy to use manner. The network operator is able to specify which single site or network correction streams each user is able to access. Each connection by the user is logged and stored in a XML machine-readable connection log. Authentication based on telephone number, NTRIP, IP address and NMEA GPUID are supported.

Conclusions

The GPS Spider software from Leica Geosystems represents the next generation of network RTK. GPS Spider has been designed from the ground up to use the latest in GPS processing and software technology and is optimized for the new Master-Auxiliary Concept, the basis of the forthcoming RTCM 3.0 standard for network RTK corrections. The Master-Auxiliary Concept is not just a new data format, rather a whole new second-generation approach to network RTK that addresses all of the shortcomings of previous approaches. In the Master-Auxiliary Concept the rover is given all of relevant information on the ionospheric and geometric errors observed by the reference network and is able to utilize this information in an optimal way. The rover is no longer restricted to simplistic interpolation methods used by VRS but is able to do true multiple-baseline positioning. The optimal zero-difference processing kernel of SpiderNET combined with the strong security concept and comprehensive user management and billing features of GPS Spider ensure that your reference network achieves the highest return on investment and rover user satisfaction.

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Whether providing corrections from just a single reference station, or an extensive range of services from a nationwide RTK network – innovative reference station solutions from Leica Geosystems offer tailor-made yet scalable systems, designed for minimum operator interaction whilst providing maximum user benefit. In full compliance with international standards, Leica's proven and reliable solutions are based on the latest technology.

Precision, value, and service from Leica Geosystems.

When it has to be right.

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