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Virtual Reference Station Systems

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Biography

Dr. Herbert Landau, is Managing Director of Trimble Terrasat and Director of GPS Algorithms and Infrastructure software in Trimble's G&E Division. He received his Ph.D. in Geodesy from the University FAF Munich, Germany in 1988. He has many years of experience in GPS and has been involved in a large variety of GPS and GLONASS developments for high precision positioning systems and applications.

Dr. Ulrich Vollath, received a Ph.D. in Computer Science from the Munich University of Technology (TUM) in 1993. He is Senior Manager of the department of kinematic positioning and real-time systems of Trimble Terrasat.

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Introduction

High accuracy Real-Time Kinematic Positioning with GPS is one of today's most widely used surveying techniques. But, the effects of the ionosphere and troposphere, which create systematic errors in the raw data, restrict its use. In practice, these mean that the distance between a rover (mobile) receiver and its reference station has to be quite short in order to work efficiently.

In some countries GPS reference station networks exist, and provide data to individual users. For RTK, due to the need for short distances between reference and rover, the networks need to be very dense. Although of sufficient density for good DGPS, some national networks are just not dense enough to provide complete coverage for RTK. There are gaps in the coverage. The situation is worse during periods of high solar activity, such as in the first few years of the new Millennium, since these periods have extremely high atmospheric disturbance.

The use of a network of reference stations instead of a single reference station allows to model the systematic errors in the region and thus provides the possibility of an error reduction [1], [2], [3], [4], [5],. This allows a user not only to increase the distance at which the rover receiver is located from the reference, it also increases the reliability of the system and reduces the RTK initialization time. The concept can be used not only to set-up new networks, but also to improve the performance of old, established networks. The network error correction terms can be transmitted to the rover in two principle modes:

1. A Virtual Reference station mode as described below. This mode requires bi-directional communication. The basic advantage of this mode is that it makes use of existing RTCM and CMR standards implemented in all major geodetic rover receivers and thus is compatible with existing hardware.
2. A broadcast mode, in which the error corrections due to atmospheric and orbit effects are transmitted in a special format, which requires changes of rover receiver hardware or additional hardware to convert the non-standard format to a standard RTCM data stream before used by the rover.

In the following we will describe in detail the Virtual Reference Station idea first and then comment the current status of broadcast format implementations.

The Virtual Reference Station Concept

The "Virtual Reference Station" concept is based on having a network of GPS reference stations continuously connected via data links to a control center. A computer at the control center continuously gathers the information from all receivers, and creates a living database of Regional Area Corrections.

These are used to create a Virtual Reference Station, situated only a few meters from where any rover is situated, together with the raw data, which would have come from it. The rover interprets and uses the data just as if it has come from real reference station. The resulting performance improvement of RTK is dramatic.

The implementation of the VRS idea into a functional system solution follows the following principles. First we need a number of reference stations (at least three), which are connected to the network server via some communication links.

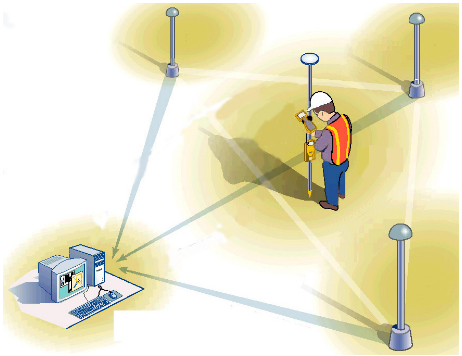

Fig. 1 Network Sketch

The GPS rover sends its approximate position to the control center that is running GPSNet. It does this by using a mobile phone data link, such as GSM, to send a standard NMEA position string called GGA. This format was chosen because it is available on most receivers.

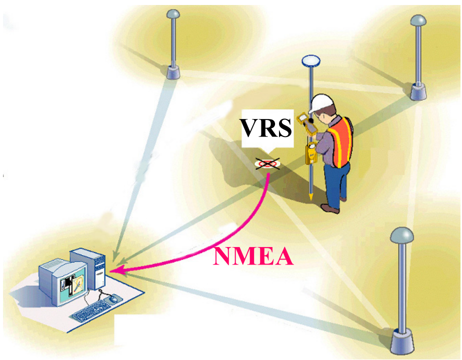

Fig. 2 Rover transmits NMEA message for VRS position to the network server

The control center will accept the position, and responds by sending RTCM correction data to the rover. As soon as it is received, the rover will compute a high quality DGPS solution, and update its position. The rover then sends its new position to the control center.

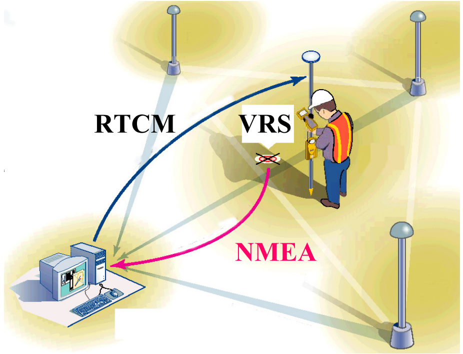

Fig. 3 Network server transmits RTCM correction stream for VRS position

The network server will now calculate new RTCM corrections so that they appear to be coming from a station right beside the rover. It sends them back out on the mobile phone data link (e.g.GSM). The DGPS solution is accurate to +/-1 meter, which is good enough to ensure that the atmospheric and ephemeris distortions, modeled for the entire reference station network, are applied correctly.

This technique of creating raw reference station data for a new, invisible, unoccupied station is what gives the concept its name, “The Virtual Reference Station Concept” [2], [3]. Using the technique, it is possible to perform highly improved RTK positioning within the entire station network.

Network RTK With A Broadcast Format

As pointed out above the VRS technique is only working properly with bi-directional communication like GSM/GPRS etc. For radio solutions a one-directional broadcast solution with a special format is required. Unfortunately there is currently no internationally standardized network format, which could be used for this. The RTCM committee is currently discussing and evaluating several proposals for a network broadcast format, but no receiver manufacturer has currently implemented such a format [6], [7]. The SAPOS committee in Germany had decided to standardize on a very simple linear description of error components also called area network corrections (FKP). This proposal is now one of the standard formats used in Germany in addition to the VRS technique. The FKP format is using the RTCM 2.3 message 59 description to come up with a special message including the linear correction parameters to approximate the error behavior in the neighborhood of a physical reference station. This implementation of a broadcast message has its limitations. It will serve as a good solution for a moving rover in the neighborhood of a station. However, if the rover moves too far from the station the errors will increase and the system will need to change the reference station to a station nearby the actual rover position. Currently the use of the SAPOS FKP RTCM 59 message was only implemented by a few receiver manufacturers, i.e. it has not yet been accepted as a quasi standard (Trimble has implemented support for this message in the 5700 and 5800 rovers).

Server Software

Each reference station is equipped with a receiver, antenna, power supply and modem through which it communicates to the control center.

The computer at the control center, which runs a network server software like Trimble's GPSNet is the nerve center of the concept. While connected to all the receivers in the network, it performs several major tasks including:

- Raw data import and quality check
- RINEX and compact RINEX data storage
- Antenna phase center corrections (relative and absolute models supported)
- Modeling and Estimation of systematic errors
- Generation of data to create a virtual position for the rover receiver
- Generation of an RTCM data stream for the virtual position
- Transmission of RTCM data to the rover in the field
- Generation of the SAPOS FKP broadcast network correction stream

The network server software also performs a continuous computation of the following parameters by analyzing code and carrier phase observations:

- Multipath errors
- Ionospheric errors
- Tropospheric errors
- Ephemeris errors
- Carrier phase ambiguities for L1 and L2

When performing this task the software makes use of the full network information, rather than using only a local subset of the reference station network.

Using the computed parameters, the server will re-compute all GPS data, interpolating to match the position of the rover, which may be at any location within the reference station network. By doing that, the systematic errors for RTK are reduced considerably.

Error Interpolation

When interpolating the errors for the Virtual Reference Station within the server software the errors are interpolated from the residuals of the surrounding reference stations based on a special interpolation technique. In Trimble's GPSNet we are using a weighted linear approximation approach and a least squares collocation approach. The interpolation technique allows to interpolate (user 1) but also extrapolate (user 2) (Fig. 4).

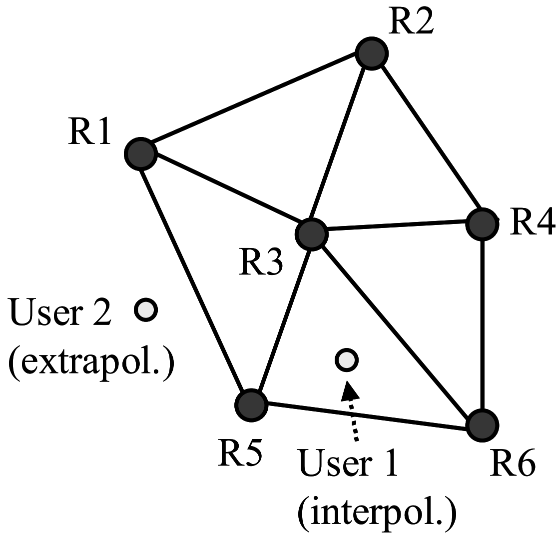

Fig. 4 Interpolation and Extrapolation

GPSNet Software Set-up

The GPSNet software is provided in three major modules:

1. The basic module GPSNet allows the data collection from reference stations, detection and correction of cycle slips, QA/QC analysis and raw data storage in RINEX format. It also provides a module for generation of RTCM messages to mobile users.
2. DGPSNet is an extension of the basic module GPSNet allowing the reduction of error sources like atmospheric and orbital effects and multipath. It is targeted for DGPS users and includes the generation of RTCM messages 1,2,3,9 supporting L1 C/A code differential positioning. The precision of these solutions ranges from sub-meter to 2-3 decimeters depending on the type of mobile receiver used.
3. RTKNet is the Trimble VRS solution for RTK users and is an extension to the basic GPSNet module. RTKNet provides the same kind of formats like DGPSNet plus the RTCM messages 18, 19,20,21 and 22, 23, 24 and the CMR/ CMR+ formats.

Typical Vrs Hardware Set-up

The control center is continuously communicating with the reference stations and receives raw data with an update rate of 1 Hz. It also controls the receivers.

Different methods can be used to transfer the data from the remote stations to the control center.

- Continuous analog or digital modem lines may be used. This method requires a modem at the reference station site and in the control center. The modem in the control center may be connected to the PC serial port directly using RS232, but if several reference stations are to be connected, a router such as CISCO 3640 can be used. The router will forward the data via Local Area Network to the control center computer. It is extendable with respect to the number of supported lines, and this allows an almost unlimited number of data lines to be available. The PC running GPSNet receives its data via IP protocol from the CISCO router. The remote stations are identified via IP port numbers.
- Frame Relay connections may be used. Although these are not always available in telephone networks, it may be the best transfer method to choose, especially over longer distances. In this case, the reference station requires a converter for the RS232 data stream. In the case where only Frame Relay is used, a more simple router such as CISCO 2500 can be used in the control center. In this configuration each remote station has its own IP address and the router at the center only translates from Frame Relay to LAN and vice versa.
- The data may be also transferred via the Internet using a DSL or other access. In that case the serial interface protocol of the receiver has to be converted to a TCP/IP protocol. This can be achieved by a local PC or a comserver.

In each case, the data can come directly from the receiver, or via GPSBase, Trimble's autonomous reference station software.

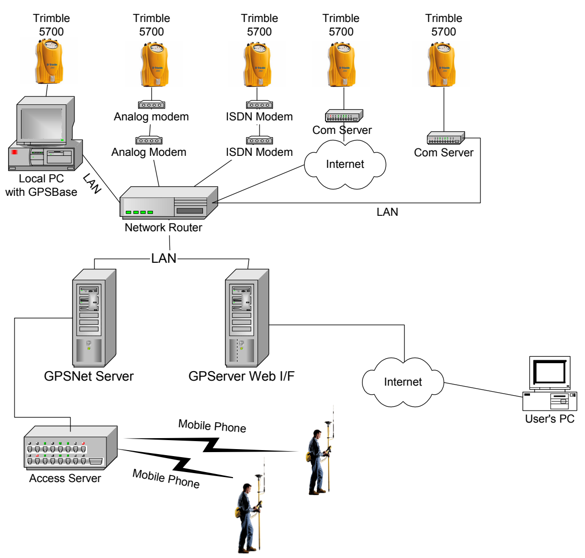

Fig. 5 Typical VRS system set-up

The RTCM message is transferred to the rover via a mobile phone network such as GSM, or other digital mobile phone services like GPRS. An alternative communication medium is CDPD in the US.

A dial access server such as a CISCO AS 5300 handles the incoming calls. This allows all rovers to use the same phone number to connect to the system. The access server will provide an IP connection to the GPSNet software resulting in both its registration within the system, and the creation of RTCM data for that rover. The access server can be extended to handle increased volume of parallel incoming calls.

Typical Field Set-up Procedure

On a typical field session, the following set-up procedure is performed.

1. After starting the local receiver in real-time positioning mode, the user dials into the Virtual Reference Station Network service via a mobile phone capable of data transmission. This is normally done using one central phone number available for a whole state or country.
2. When the caller is successfully authenticated, the local receiver sends a navigation solution of its current position as a rough position estimate to the computing center.
3. After receiving the rough position estimate, the computing center creates a Virtual Reference Station at this location.
4. A continuous data stream of reference data generated for the Virtual Reference Station position is sent to the field user receiver. This can be done in RTCM or other real-time formats like CMR2.

Operating Reference Station Networks

The presented concepts are implemented in a number of reference station network installations since up to 4 years on a worldwide basis. Many experiences with operation and performance were made during this time. The following table gives an overview of some existing installations of Virtual Reference Station Networks by Trimble.

Tab. 1 Overview on existing VRS installations

Network	Location	Stations
SAPOS Bavaria	Germany	44
SAPOS Hessen	Germany	28
SAPOS BaWü	Germany	36
SAPOS Thüringen	Germany	24
SAPOS Sachsen	Germany	19
SAPOS NRW	Germany	34

ASCOS/Ruhrgas	Germany	120
BKG	Germany	20
Swissat	Switzerland	23
Swiss Topo	Switzerland	29
BEV	Austria	5
LE34	Denmark	26
OC GIS Vlandeeren	Belgium	40
SWEPOS	Sweden	56
Tampere	Finland	4
Lennen Puhelin	Finland	8
Statens Kartverk	Norway	6
Bysat Cz	Czech Rep.	4
Shenzhen	China	4
NGDS	Japan	200
Jenoba	Japan	200
NCDOT	USA	5
MnDOT	USA	6
QBR Queensland	Australia	5
Bay Area Network	USA	10
Colorado Network	USA	10
Christchurch	N. Zealand	6
Munich Test Network	Germany	42

Sample Networks

In the following we are showing some examples of network installations in Europe and Asia. For example Denmark is using a Trimble solution with Trimble reference station receivers and Trimble network server software GPSNet. RTCM corrections are transmitted to the users in the field via GSM.

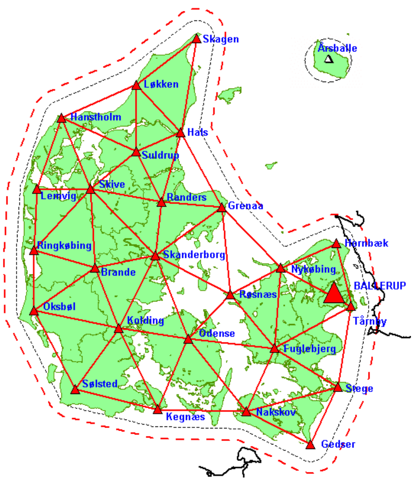

Fig. 6 VRS Network in Denmark

Another Trimble network was set-up in Switzerland by the Swisstopo organization; again Trimble receivers are used and have proven to provide excellent performance since the start of the VRS system in 1999.

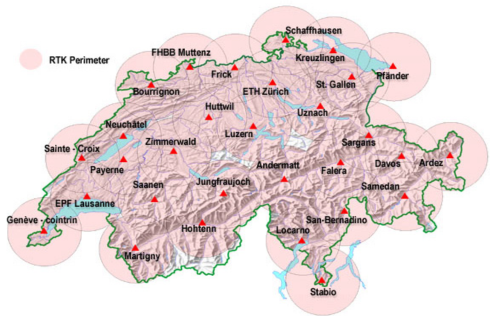

Fig. 7 VRS Network in Switzerland by Swisstopo

In the German SAPOS system the largest area is covered by the Trimble VRS networking solution. Currently six major states have decided to use the Trimble solution. Besides these public German organizations a private organization has started to provide a Germany-wide service. This company ASCOS is belonging to the Ruhrgas AG, the largest gas provider in Germany, and is currently using a VRS solution from Trimble to operate 120 reference stations.

Fig. 8 Coverage of ASCOS VRS Network in Germany

Ascos/Ruhrgas is primarily targeting the utility management market and wants to serve all companies doing pipeline and cable GIS surveying. Their business plan is based on the investigation that we have more than four million kilometers of gas, drinking water, wastewater, phone of electricity lines, which require surveys. ASCOS estimates that approximately 3 % of these lines have to be surveyed every year.

Currently two independent and competing organizations are operating a 200-station network with Trimble VRS software. The Japanese Geographical Survey Institute

(GSI) makes the receiver data from the 200 reference stations available. All the stations are equipped with Trimble 5700 receivers.

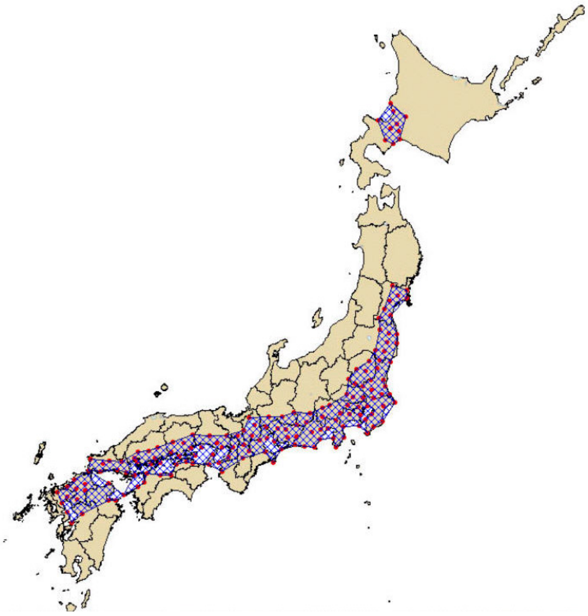

Fig. 9 VRS Network in Japans

The above figure shows the part of the GSI network as a band through Japan, which is operated as RTK VRS networks by the two independent companies JENOBA and NGDS. In the near future GSI is planning to release another 200 stations for VRS operation in Japan for use by private organizations.

Real-time Performance Test

Test Description

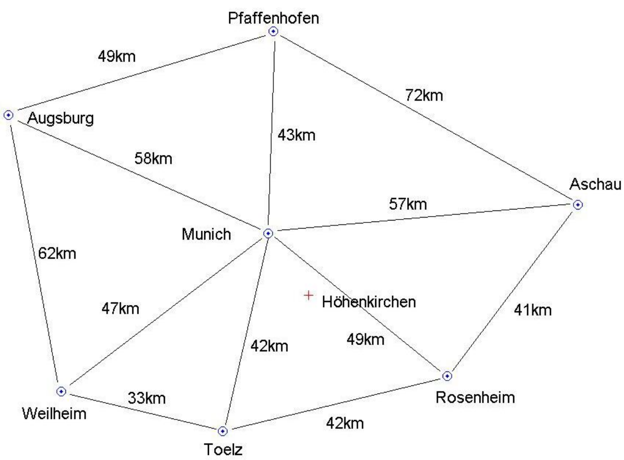

Fig. 10 Munich test network used for RTK evaluation in single-baseline and broadcast network modes.

As a test network, a part around Munich, Germany of the BLVA network of the land surveying authorities in Bavaria has been used. This test-bed is continuously operated for GPSNet software testing and development. The network consists of 7 stations, each station has a dual-frequency GPS receiver and is permanently connected to the Trimble Terrasat office via leased data lines. The network configuration is shown in Fig. 10 including the inter-station baseline lengths.

The Trimble Network RTK software [Trimble, 2002] can be operated in either a VRS or Broadcast mode. The broadcast mode was used for the tests described below.

Four concurrent tests were run over a 40-hour period to evaluate the performance of RTK in single-baseline and network modes. Four Trimble 5700 receivers were connected to the same antenna at the Trimble Terrasat office at Höhenkirchen. Standard single-baseline data was fed from Munich and Toelz into two 5700 receivers, thus giving rise to 16km and 32km baselines, respectively. Network corrections were input to the other two 5700 receivers at Höhenkirchen. One set of corrections was derived from the entire network, while the second correction stream was created without the nearest network station - Munich.

Test Results

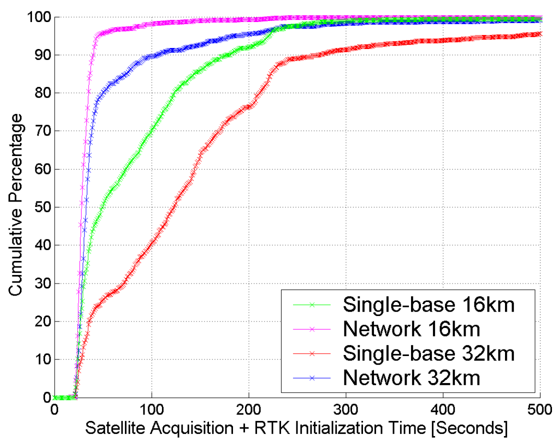

Fig. 11 Cumulative probability of ambiguity resolution for single-base and network modes over 16km and 32km baselines.

Fig. 11 illustrates the cumulative time-to-initialize for the 4 different 5700 receivers. The results of network corrected data provide very noticeable benefits for the time-to-initialize statistics. The 16km baseline with network corrections exhibits the sharpest elbow in figure 15. In other words, the majority of initializations occur within a short period of time. The network-corrected 16km baseline results are comparable to those regularly achieved with single-baseline RTK on lines less than 10km where ionospheric biases are typically small. The 32km baseline with network corrections has the next-best performance. The single-base RTK results for the 16 and 32km lines exhibit the worst initialization times.

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