Establishment of Dubai Virtual Reference System (DVRS) National GPS-RTK Network

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Key words: DVRS = Dubai Virtual Reference System, Geoid, GPS, FKP, RTK

SUMMARY

The Survey Section of the Planning and Surveying Department has now implemented the latest technology for professionals engaged in the fields of Surveying and Construction Engineering. Recent technological advances, both in GPS Survey & digital data, have made it possible to obtain accurate positioning and design data in real time. These changes introduce many new opportunities and exciting challenges to the surveying discipline within today's construction engineering sector. The Survey Section has reinforced its objectives in technology development by establishing the "*Dubai Virtual Reference System*" (DVRS). This represents the latest concept in the field of Global Positioning Systems (GPS).

DVRS consists of five continuously operating Base Stations provided by Swiss instrument manufacturer LEICA, and are located in different sectors of the Dubai Emirate. The Control Room, with a central Server, is situated in the Survey Section offices within the main Dubai Municipality building in Deira. All five stations are continuously receiving GPS data and are linked to the Central Server by dedicated telephone lines. These lines continuously transmit the data to the control unit (Control Central Server), where data is processed, and corrections transmitted to the end-users, as they require.

All GPS continuous operating Base Stations in the network send on-line raw GPS data via permanent connection (Modem lines) to the Control Central Server. Here, data is processed by a software system called GNSMART, produced by Geo++, of Germany. GNSMART performs all quality checks, computes ionospheric, tropospheric and satellite orbit errors, and delivers the corrections to the end-users. Employing a GPS 'Rover' unit, users can directly start survey work anywhere in the Dubai Emirate. When the GPS receiver is operated, it calculates its position to within a few meters and transfers this information to the Control Reference Station via GSM (Mobile) in NMEA format. The Control Central Server sends back valid correctional data to the user in RTCM format. This defines the user's actual position. This complete task is effectively achieved at the 'press of a button' in the field. Such real-time kinematic GPS technology enables work to be carried out within the entire network coverage area, with homogeneous absolute position to centimetre accuracy.

A multiple GPS reference station approach is superior to a conventional RTK single baseline approach, as it allows for "network-based" homogeneous positioning solutions with centimeter accuracy. The DVR System has already been subject to stringent testing, which found that the expected accuracy to be in the order of 2-3 cm in planimetry, and 3-5 cm in altimetry.

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1. CLASSICAL GPS

Global Positioning System (GPS) technology is a fast and accurate method of determining the location of any point of interest anywhere on earth at any time during the day or night. The technology collects and processes signals from GPS satellites in orbit around the earth to determine the location of points of interest on the ground.

Surveying with single frequency measurement is called "static" mode GPS surveying. Some single frequency systems can collect data in static or Kinematics mode, but the rate of data collection cannot be compared to that produced by dual frequency systems. If the single-frequency unit loses its signal when operating in kinematic mode, it takes some time to re-initialize before survey work can begin again.

GPS Dual frequency system requires post-processing when operating in static or "fast static" mode. In Real Time Kinematics (RTK) GPS, the positional data are displayed and recorded immediately. Sub-centimeters to millimeter level accuracies (both horizontal and vertical) are obtainable with both single and dual frequency technologies. To obtain latitude, longitude, and elevation for new point, both systems need to occupy a number of existing established points. Considerable skill, training, and expertise are required to operate either type of system effectively.

The idea GPS all-differential positioning techniques are to correct bias errors at one location with estimated bias errors at a known position. A reference receiver, or base station, computes corrections for each satellite signal for all satellites in view. GPS receivers require software that can apply individual pseudo-range corrections for each Space Vehicle (SV) prior to computing a position solution.

1.1 Literature Review

Real-Time Kinematics (RTK) GPS is now widely used for surveying and other precise positioning applications. The classical RTK technique requires that GPS data be transmitted from a single reference receiver to one or more roving units. Algorithms in the mobile unit combine the reference station data with measurements from the roving receiver to resolve the integer ambiguity required to calculate precise ranges from the GPS carrier phase measurements. The process of ambiguity resolution is often referred to as “initialization”.
RTK can provide centimeter position accuracy, but the accuracy and reliability of the standard RTK solution decreases with increasing distance from the reference station. This limitation on the distance between the roving GPS receiver and the RTK base station is due to

the systematic effects of ephemeris, tropospheric and ionospheric errors (Wübbena, et al.,1996).
These systematic errors result in reduced accuracy and increasing initialization time as the distance between base and rover increases. This phenomenon is becoming increasingly evident as we approach a maximum in the cycle of solar activity.

1.2 Limitations of Classical RTK Surveying

The restriction in range of classical RTK is due not only to the systematic errors described above but also, in many cases, to the range of available radio telemetry solutions. In practice this means that a temporary RTK base station must be established close to the work area, often at a location that does not provide any physical security or continuous power supply. Each time such a temporary reference station is established there is an opportunity to introduce an error in the reference station co-ordinates that will be transferred into the position calculated by the rover RTK receiver. Such an error can easily go undetected when using a single base station. In addition to the potential for introducing errors, productivity of the surveyor is lost each time the base station has to be set up at different reference station.

2. GPS NETWORK

The concept of GPS Network Reference Stations allows us to eliminate/reduce systematic errors in reference station data, i.e. allows to increase the distance to the reference station for RTK positioning while increasing the reliability of the system and reducing the initialization time. The GPS Network Reference Stations requires continuous modem line connections between the control center and all reference stations. Data is transmitted continuously to the center. The center will calculate and transmit optimized Radio Technical Commission for Maritime Services (RTCM) correction messages and transmits it to the users.

Permanent GPS reference stations making it possible to receive RTK (Real Time Kinematics) correctional data everywhere. This means centimeter precise measurements in real time. By establishing an adequate number of GPS stations and allocating data access to the reference stations via mobile phone using Global System for Mobile phones (GSM) data modems, they can offer correction data throughout the region of interest. All the GPS reference stations in a network send "on-line" raw GPS data via permanent connections to a super-computer housed in a secure Control Center. In this way all GPS observations can be gathered and weighted to the user’s advantage. This solution gives the following advantages:

Uniform precision of the entire network, or in other words, no additional constants due to increased distance from the individual reference stations (a well-known problem in traditional GPS RTK surveying).

- Single correction data from the entire network.
- Safety and reliability to enhance the quality of GPS measurements.

The Control Center of super computer takes care of the following numerous tasks:

- Import of raw data and quality assurance routines

- Storing of RINEX data
- Correction of antenna phase center wandering
- Modeling and estimation of systematic errors
- Calculation of correction data in RTCM format for the users
- Transmission of data to users in the field

There exist many Networking approaches where GPS signals corrections can be send to mobile rover in the field for Real Time Psositioning.

2.1 Virtual Reference Station

An RTK rover located near the center of several reference stations would be affected by systematic errors if using any one of these reference stations. If, however, measurements from all these reference stations are combined, a model of the geometric and atmospheric errors over the area can be determined and a VRS can be created adjacent to the rover's location, dramatically reducing the systematic errors.

2.1.1 Virtual Reference Station (VRS) Technique

A pre-requisite of the virtual reference station (VRS) concept is the need of a duplex communication link between a node of the reference station network and the rover. The rover has to transmit its approximate coordinates to the network, which then interpolates from the state information a reference data stream VRS_{ij}^{k} for the given position. The data relates to the observation space ref Wübbena et. al (1996):

$$\overleftarrow{X}_{VRS} = \vec{X}_j$$

$$VRS_{ij}^{k} = CPR_{ij}^{k} + f(FKP_{i}^{k}, \Delta\varphi_{ij}, \Delta\lambda_{ij}, \Delta h_{ij}) + \Delta T_{\text{mod}\,el,ij} \qquad (1)$$

Equation (4.20) contains a tropospheric term $\Delta T_{\text{mod}\,el,ij}$, which describes the difference between the tropospheric delay models used in the network processing on the original reference station and the virtual reference station. Due to the RTCM definitions, the reference station may not correct for tropospheric errors. This is in general a reasonable restriction, because it avoids the problem of using inconsistent models for reference station and rover, while the rover is responsible to compute corrections for both sides. This, however, requires the knowledge of the reference station coordinates at the rover. Since the only coordinates the rover knows about are originating from the RTCM data stream, the rover does only know the coordinates of the VRS. Hence, the rover cannot compute the tropospheric correction for the real, but only for the VRS. In consequence, the network has to apply the tropospheric correction between real and virtual reference station. And here there is again the problem of possible inconsistency, if it is done with a different model than the rover applies.

In the VRS concept, the coordinates (in RTCM message type 3) are changed to VRS location, hiding the true reference station completely from the rover. One disadvantage of the VRS concept is, that for a kinematic rover continuously updated approximate coordinates have to be used for the VRS computation (moving reference station). Today, most rover systems cannot handle a kinematic reference station. A system reset is performed, if the VRS coordinates are changing, which will result in frequent initialization of ambiguities. In practice, the VRS position therefore does not change. However, this implies that distance dependent errors will be present in the rovers solution once it starts to move away from the virtual reference.

Typically, some irregular physical effects occur, which can hardly be determined by a reference station network with given station distances. In this context, the reference station network can be considered as a limited number of monitoring stations or sensors with a certain and restricted spatial capability. The errors may arise from local troposphere or turbulent ionospheric conditions. Even if these higher order errors cannot be determined by the reference station network, it is obvious that their magnitude is a function of distance from the next true reference station.

Thus, if the rover knows the reference station position(s), it can take into account these higher order errors and improve its own RTK models, e.g. by stochastic ionospheric modeling. If the rover knows only the VRS position, it has no chance to do such kind of improvement. It should be mentioned that there are different types of VRS depending on the type of networking model. A VRS derived from the observation space (*OSP*-VRS) shows different behavior than a VRS derived from a state space model (*SSP*-VRS). This results from the fact, that a *SSP*-VRS is much less affected by current individual reference station errors than the *OSP*-VRS ref. Wübbena 2001.

Since the state vector is the result of a continuously running filter, the influence of station dependent errors reduces, the more redundancy (number of stations and satellites) is available in the network. A similar filtering in the observation space can only be done with arbitrary models and is therefore less effective. Especially the non- depressive part of the signal is much smoother if derived from state information than from the observation state.

2.2 Area Corrections Parameters (FKP) Technique

One way of representing the additional corrections for the distance dependent errors is a polynomial parameterization to describe the influence for any rover position in a certain area. Depending on the temporal and spatial variation the orders of the representation must be defined. The RTCM standard currently limits the correction data to be formulated in the observation space, which means, that modified GPS observable must be used. The area correction parameters (commonly called FKP), are the most flexible and suitable way to represent the state. FKP can be assumed for this discussion as a representation of the full state space information. FKP are more or less simplified to reduce the required bandwidth for transmission or the complexity to apply it at the rover. The state has to be transferred to the observation space, because most rover systems are currently not capable to handle any state space information. The FKP allow the prediction of the distance dependent error term for the approximately known rover position:

$$\Delta\delta\hat{D}_{ij}^{k} = f(FKP_i^k, \Delta\varphi_{ij}, \Delta h_{ij}) \quad (2)$$

This can be done independently from the network processing, as only the rover coordinates and satellite information are required. It is a major advantage, that FKP can be distributed by broadcast media, which is requested by most service providers. The FKP do not contain absolute tropospheric information, but gradients of the troposphere. The tropospheric effect for a reference station can therefore be figured out and applied correctly to the data by the rover.

The dimensions of networks and the coverage of distribution media often make a linear FKP representation sufficient. The coverage of a linear FKP model is then centered to a real reference station, and the FKP describe the horizontal gradients for the geometric and ionospheric signal components in the observation space (Figure 2.2).

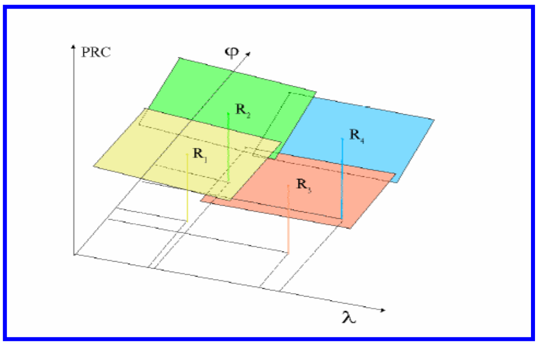


Figure 2.2: Linear FKP planes for four reference stations

3. PROBLEM STATEMENT

There are multiple objectives for the establishments of Dubai Virtual GPS Reference System(DVRS) network, such as follows:

- Real Time Kinematics (RTK) applications
- Differential Global Positioning System (DGPS) applications
- Realisation and continuous improvement of the International Terrestrial Reference Frame (ITRF)
- Realisation and continuous improvement of the Dubai Emirate Special Reference Frame
- Absolute sea level determination
- Monitoring of the deformation of the earth
- Facilitate the studies on the ionospheric model and the determination of the atmospheric water vapour content
- Application for the geodynamic and scientific studies
- Combination of the GPS derived ellipsoidal heights with a precise geoid model to replace conventional leveling.

3.1 Establishment of Dubai Virtual Reference Network

The Dubai Virtual GPS Reference System (DVRS) consists of five permanent GPS stations Figure3.1 and a Central Processing Centre for the processing and distribution of GPS data. This project is carried out by the Survey Section of the Dubai Municipality. The five permanent GPS stations within DVRS are continuously tracking all visible satellites. They were designed and constructed over the 2001 fiscal year. This network of permanent GPS stations will form the Zero-order geodetic network for the Dubai Emirate and connected to the ITRF epoch 2000. In all these permanent GPS stations, Leica receivers were installed. The GPS receivers will telemetry the data to the Central Processing Center via a GSM media at a measurement interval of 1 second. The core product of the DVRS is the data collected from the permanent GPS stations:

- Daily 24-hour GPS carrier phase and code observations, on both frequencies, for all satellites in view
- GPS navigation messages and status information.

The products that could be derived are:

- Highly precise GPS satellite ephemeris
- Earth rotation parameters
- Ionospheric and atmospheric information
- Coordinates and velocities of the permanent GPS stations.

3.2 Network Design

The listed conditions are minimum conditions consider in designing the DVRS Network: Network coverage of RTK services of whole Dubai Emirates.

- Stable site (minimal local horizontal and vertical movement).
- Stable antenna mount.
- Minimum electromagnetic interference.
- degrees located as far away from the reference antenna as possible and
- located to the north of the reference antenna.
- Adequate security for equipment.
- Receiver and communications hub located inside a building
- Providing protection from weather and elements.
- Antenna located in a minimal Multipath environment.
- Continuous long-term operation.
- Availability of power supplies and telecommunication connection.

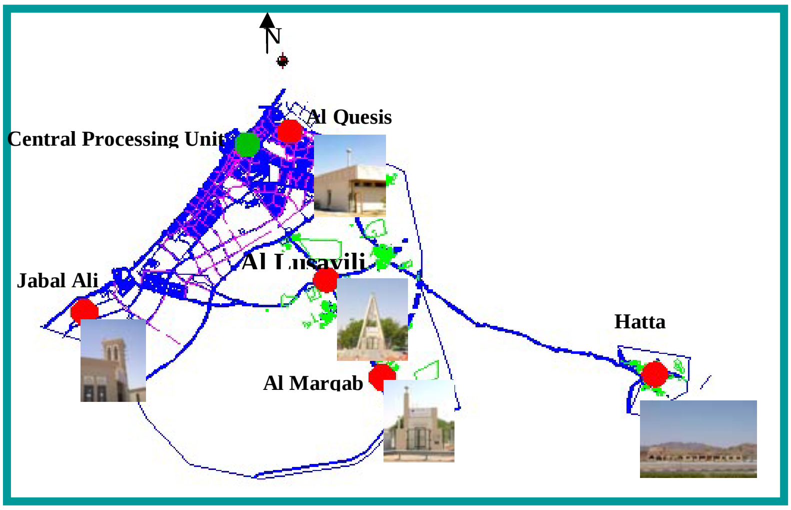


Figure 3.1: DVRS Stations Distribution

3.3 Site Selection

The preliminary planning to select reference stations from the primary existing control stations but due to security and safety requirements we decided to find out locations where security and safety are available in additions to other requirements like securing the location of stations from any future replanning by coordination with planning and road departments. Three Base stations are situated on existing building (Al Quesis, Jabal Ali and Hatta) and the other two stations at Lusayili, Marqab developed and constructed from scratch

3.4 DVRS System Configuration

3.4.1 Hardware Configuration at Reference Station

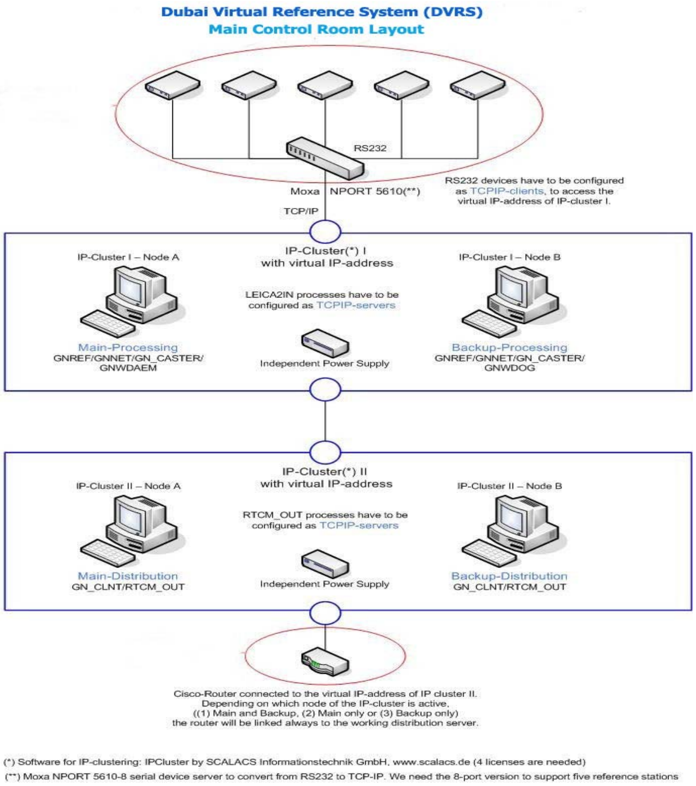
The following hardware configuration at Reference Station are as follows :

- GPS Antenna
  Leica AT 504 choke-ring (Figure 5.4), the system includes an International GPS Service (IGS), |Chock-Ring antenna designed by NASA/ Jet Propulsion Laboratory (JPL) with Multi-Path facility, it was calibrated by Geo++. Also covered by Radom cover for weather protection (Figure 3.4)
- GPS Receiver
  Leica MC 500 (Figure 5.6), 12 channels L1 C/A or P-code.
  12 channels L2 P-code, Full-wave length L1, L2 Carrier Phase.
- Al CATELE MODEMS
  For sending raw data from Base-Station to Main-Control Room through Leased lines

3.4.2 Hardware Configuration at Main-Control Room

Hardware configuration being considered at MCR consist of :
- 3 Personnal computers connected in network.
- MOXA to convert serial port R232 into TCP-IP
- 5 Modems for receiving raw data from 5 RS.
- IPR.
- Router to receive 30 calls simultaneously through IPR.

(IP-cluster software function is to make the raw GPS data coming from reference stations avialbel for two PC in Real Time through virtual IP adress)



3.4.3 DVRS Software

The software used in the DVRS is the GEO ++ Software known as Global Navigation Satellite System - State Monitoring And Representation Technique (GNSS-MART) Software (Wübbena, G., A. Bagge, Martin , Schmitz,2001).

GNSS-MART comprises the monitoring system including regional atmospheric effects, together with its presentation and delivery to the user for the purpose of position determination with highest accuracy, reliability and availability, both in real time and by post processing. GNSS-MART consist of the following list of software:
- Reference stations (GNREF) Software

- Communications systems (GNCOM, RTCM_IN, RTCM_OUT) software
- Multi station solutions (GNNET) software
- Real time applications (FKP area corrections, RTCM 2.1) software

The advantages of GNSS-MART could be listed as:

- Capability of Networking with spacing more than 50km to enable position fixing
- with centimeter. accuracy in Real Time and Post Processing.
- Can be used for both GPS and GLONASS systems.
- Error modeling of the system for satellite orbit, ionosphe troposphere.
- Reduction of Multi-Path effects.
- Elimination of Antenna Phase Center variations by antenna calibrations.
- GNNET processes correction signals of several PDGPS reference stations in the RTCM 2.1 format such as they are created by GNREF.
- Communication between the reference stations via modem connection, via transparentnetwork connections (e.g. via Ethernet TCP/IP, ISDN-Routing) or via the normal RTCM-correction data signal (e.g. 2m radio).
- Simultaneous processing of Five reference stations, thus, far-reaching registration of distance dependent errors in satellite orbits, ionosphere, troposphere.
- Definition of correction models and parameters to describe these errors.
- Generation of correction parameters for an extended RTCM,virtual reference stations(VRS),Pseudo Rereference Station (PRS) or Area Correction Parameters (FKP).
- On the mobile station the additional correction parameters make the computation of optimal position dependent correction data possible.
- GNNET increases the redundancy of the overall system by using several reference stations.

3.5 ITRF Connection

In 1995 during the DUREF-95 GPS campaign jointly conducted by Dubai Municipality and IfAG (BKG), GPS observation and computation have been carried out in order to connect the existing Dubai Geodetic Network to the International Terrestrial Reference System (ITRS) ITRF93. Four (4) stations from the DUREF-95 have been re-observed simultaneously with the DVRS stations on 11th May 2002 for six hours. With the connection, Helmert transformation parameters can be derived in order to established the relationship between ITRF93 and ITRF2000 coordinates.

The GPS data was processed using Bernese 4.2 software with the strategy similar to the DVRS permanent stations processing. Five (5) DVRS stations have been processed together with four (4) established triangulation stations (ITRF93) namely ET145, ET228, OBP5 and ET152.

4. ASSESSMENT OF DVRS

The DVRS system is fully tested with regard to its accuracy, speed of operation and optimum utilization of advance technology. It is also successfully implemented in day to day survey activities of DM survey section. It is being used for the various activities in the Department such as demarcation of plots and alignments, providing survey controls, GPS levelling and DTM generation.

The testing of DVR system was carried out at various stages and for the various factors. The system was tested for its positional accuracy and network coverage. A random check for the telephone connection time, correction receiving time and rover initialization time were also being carried out.

4.1 Field Testing of The DVRS

Testing the DVRS network in this study included investigating its availability, absolute and relative accuracy, precision and compatibility of results, reliability, and robustness. In addition, the performance of the network approach against the traditional approach of employing a single reference station was investigated.

4.1.1 <u>Investigating Positioning Accuracy Using the DVRS Network</u>

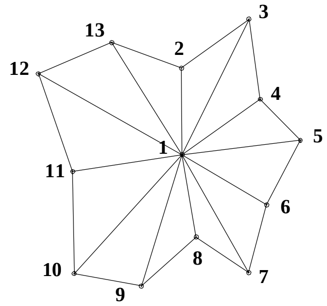
The DVRS availability and general positioning accuracy were first examined at three independent locations, where coordinates of ten points at each location were determined. The first test was performed in an urban area, located a few kilometers away from the (Al Qusies) station. The second test was close to the (Al Lusali) station near to the centre of the network, and the third was on the southern border of the network coverage area, which is approximately 11.53 Km from the nearest reference station. The estimated average standard deviation of point coordinates for the three tests are given in Table 1, which were less than 2 and 3 cm for the 2D and height, respectively.

	□□	□□	□**h**
Al Qusies Test	0.019	0.016	0.024
Al Lusali Test	0.012	0.007	0.032
Border Test	0.009	0.012	0.026

Table 4.1 Average coordinate standard deviations at different locations within the network (m)

To test the network absolute and relative accuracy, a set of 13 with distances ranging between 18.875m and 36.968m were established approximately 9.2 km away from the ‘Al Qusies’ control station. The layout of the test points is illustrated in Figure 4.1 Their coordinates have first been determined using a total station to an accuracy of less than 1 cm based on a least-squares adjustment approach integrating the angular and distance measurements. After that, the point coordinates were estimated in real time using the DVRS data. Three independent surveys were carried out with time spacing of 1-2 hrs to allow for significant changes in satellite geometry and atmospheric conditions. The PDOP values ranged from 1.9 to 3.92.

The absolute (external) accuracy of the DVRS coordinates estimation is expressed as the differences between results of the DVRS survey and the total station. The differences are estimated taking the total station results as the reference. The 3D (spatial) differences ranged between 0.81cm and 3.61 cm. The estimated differences at each point for the three tests are illustrated in Figure 4.2



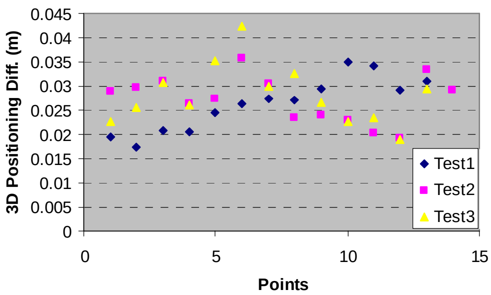


Figure 4.1 Layout of the test points **Figure 4.2** 3D external accuracy of the DVRS

The accuracy of relative positioning was evaluated by studying differences between distances derived from the DVRS estimated point coordinates against their precise values, which were independently determined using a calibrated stainless steel measuring tape. Figure 4.3 depicts the values of distance discrepancies. Table 4.2 shows their average and maximum values as well as their standard deviations. As can be seen, the differences were within 1 cm for the three tests, and the maximum discrepancy found was 2.2 cm. The standard deviations ranged from 0.4 cm to 2.2 cm.

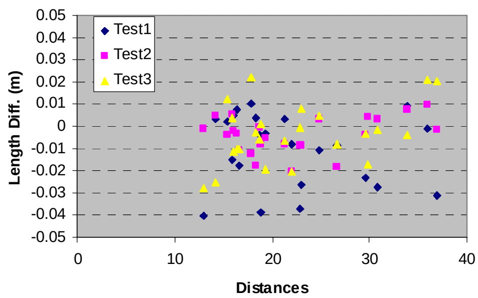


Figure 4.3; Differences in length computation

	Test1	Test2	Test3
Average	- 0.010	- 0.004	- 0.003
Max.	0.010	0.010	0.022
□	0.019	0.009	0.014

Table 4.2 Statistics of distance discrepancies (m)

4.1.2 Testing of Precision and Compatibility of DVRS Results

To test the achievable positioning precision from the DVRS data, the results of the three tests were compared, recalling that they are independent as they were carried out in different times. This comparison would not only test the compatibility of DVRS results, but also indicate system availability at different observing sessions (times). To examine the compatibility of results, discrepancies in coordinate estimation for the 13 test points were computed between the three tests, taking the first one as the reference. Figures 4.4 and 4.5 shows the discrepancies in coordinate estimation between the second and first tests, and between the third and first tests, respectively. The planemetric (E & N) discrepancies were generally less than 5 cm, while the height differences were generally less than 6 cm, although it reached at some instances 10 cm. The average and maximum discrepancy values are given in Table 4.3 The table also gives the coordinate standard deviations (σ) as estimated from the discrepancies

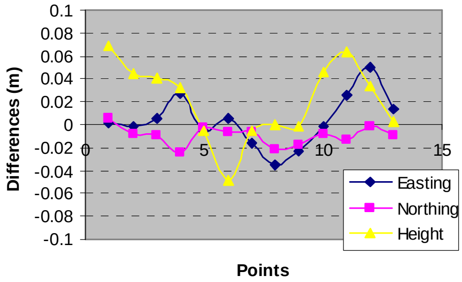


Figure 4.4 Discrepancies between the 2nd and 1st tests

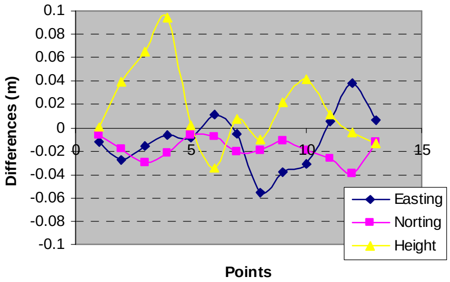


Figure 4.5 Discrepancies between the 3rd and 1st tests

Discrepancies		**E**	**N**	**h**
Test2 – Test1	Average	0.004	-0.009	0.021
	Max.	0.050	0.006	0.069
	□	0.023	0.013	0.040
Test3 – Test1	Average	-0.011	-0.018	0.027
	Max.	0.038	-0.007	0.102
	□	0.027	0.021	0.039

Table 4.3:Statistics of coordinate discrepancies between the three independent DVRS tests (m)

To statistically examine the compatibility and the consistency of internal precision between the three tests, the discrepancies of the results of the second and third tests from the first test were tested using the Fisher (F) test. The test can be directly applied by testing the significance of the difference between any two variance estimates related to two samples of coordinates discrepancies. The ratio of the two sample variances should lie within a specified confidence region, such that ref Wübbena. G., , June 5-8, 2001:

$$F_{df1,df2,0.025} > \frac{\sigma_1^2}{\sigma_2^2} > F_{df1,df2,0.975} \qquad (3)$$

Where, σ^2_1 is the estimated variance of the sample that has the larger standard deviation (σ), and σ^2_2 is the estimated variance of the sample that has the smaller value of σ. The confidence boundaries can be evaluated from the tabulated values of Fisher distribution with (∝) probability that can be taken as 95% and (df1 and df2) degrees of freedom corresponding to the first and second samples of position discrepancies, respectively. This gives 2.69 and 0.11 for the upper and lower limits for the test in hand. The spatial (3 D) precision of the three tests, expressed as the average values of the 3D standard deviations of the computed 13 points from the 3 independent surveys, are 0.0264m, 0.0273m, and 0.0282m, respectively. Consequently, the examined ratios for the second and first tests, and for the third and first tests are 1.07 and 1.14, respectively, which lie within the upper and lower boundaries of the compatibility test, thus, passing the test. This means that the three tests are consistent in terms of their internal precision of the final output results. This can also be statistically interpreted that the three tests are statistically compatible (equivalent).

4.1.3 Investigating System Reliability and Robustness

In order to test the DVRS output reliability and robustness, particularly in case of failure of one of the reference stations, a set of ten points were surveyed 2 km away from the ‘Al Lusayli’ reference station using the DVRS RTK data under two scenarios. In the first, the data of all five reference stations including “ Al Lusayli” were incorporated in the computation of the phase measurements corrections. In the second case, the measurements of the “ Al Lusayli” reference station were eliminated in the process of computing the DVRS data, resembling a case of failure of this station. In this case, the nearest control station to the survey area was approximately 25 km away. Usually, in the classical single reference RTK approach, such a case can only be solved using a float ambiguity resolution, leading mostly to a positioning accuracy at the decimeter level. Point coordinates in the case of eliminating the ‘Al Lusayli’ were also processed in two sessions. The first had a low PDOP values (less than 5), and the second had higher PDOP values. The second case represents one of the worst scenarios that can occur while surveying with the DVRS network. Table 4.4 gives the average and maximum coordinates standard deviations in all scenarios.

	All DVRS stations low PDOP			**LSLY is disabled low PDOP**			**LSLY is disabled High PDOP**		
	$\square_E$	$\square_N$	$\square_h$	$\square_E$	$\square_N$	$\square_h$	$\square_E$	$\square_N$	$\square_h$
Average	0.006	0.009	0.019	0.016	0.017	0.038	0.040	0.015	0.080
Max.	0.007	0.011	0.023	0.024	0.022	0.050	0.047	0.02	0.090

Table 4.4 Average coordinate standard deviations for different scenarios (m)

The results of Table 4.4 show the importance of employing the network concept. In the case of incorporating all reference stations, the standard deviations of the estimated point coordinates were generally less than 2 cm. In the second case of ‘failure’ of the LSLY station and under low PDOP values, the standard deviations were slightly larger, but stay at the cm level, where they did not exceed 3 cm for 2D positioning and 5 cm for height determination. Even in the case of high PDOP values, the standard deviations did not exceed 5 cm and 9 cm for 2D and height estimation, respectively. This proves that the DVRS performance is more reliable compared to the classical approach of employing a single reference station. In addition, the system proves to be robust in case of failure of one of its stations.

4.1.4 Comparison with Results of A Single Reference Station for Short Ranges

The achievable positioning accuracy of the network approach against the traditional technique of using a single reference station was next investigated. This was performed by comparing coordinate estimation of the 13 test points, estimated in real time using the DVRS data, with their estimation using a single reference station using the same set of measurements. For the latter case, the “AlQusies” reference station of the DVRS network was used to ensure consistency of the results. The data used were the archived data of the " AlQusies" station and the internally stored dual-frequency phase data of the rover receiver. The data of the reference and rover receivers were processed in the traditional technique in post mission. The rover points were approximately 9.2 km away from the reference station, therefore processing in a single baseline mode to the cm level of accuracy was feasible in general for the first and third DVRS tests. However, due to the large baseline length encountered, and high PDOP values experienced during the second test, post processing of the collected phase results for the second test was unsuccessful. The average standard deviations of point estimation from data of the first and third tests for the single baseline scenario and the DVRS survey are given in Table 4.5. For the former case, the 2D positioning accuracy was usually less than 2.2 cm, while for the height it was less than 5 cm, and its was 11 cm at most. Comparison of the positioning accuracy in the two estimation scenarios show that the DVRS performed better as all of its standard deviations were smaller than their corresponding values computed by using an single reference station except for the Easting coordinate in the first test. Even in this case, the standard deviations of the two techniques were very close. Thus, it can be concluded that, in general, the DVRS has a better positioning performance than using a single reference station for short baselines.

	Single Reference Station			**DVRS**		
	□$_E$	□$_N$	□$_h$	□$_E$	□$_N$	□$_h$
Test1	0.013	0.011	0.034	0.015	0.008	0.031
Test3	0.022	0.016	0.049	0.012	0.010	0.027

Table 4.5: Accuracy Comparison between using a single reference station and the DVRS (m)

To quantify accuracy differences between the two approaches for the tests in hand, discrepancies in coordinate estimation for the 13 points between the DVRS approach and the single reference station processing for test1 and test3 are illustrated in the Figures 4.7 and 4.8, respectively. In general, the differences were less than 5 cm for the planimeteric coordinates and 7.4 cm for the height. The standard deviations estimated from the differences were less than 6 cm for both cases, as given in Table 4.6.

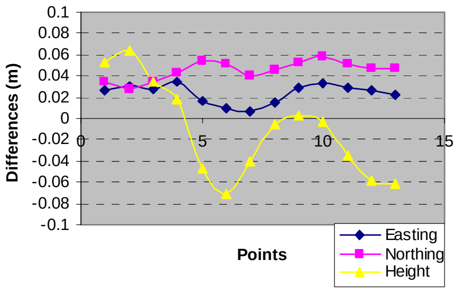


Figure 4.6: Coordinate discrepancies for test1 with single-baseline processing

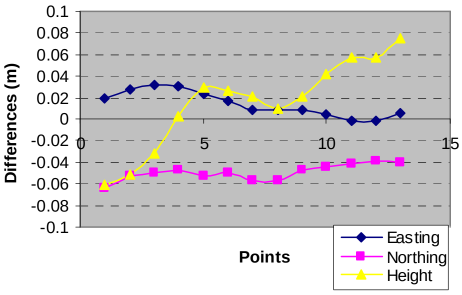


Figure 4.7 Coordinate discrepancies for test3 with single-baseline processing

		E	N	h
Test1	Average	0.024	0.045	-0.012
	Max.	0.035	0.058	0.064
	□	0.026	0.048	0.046
Test3	Average	0.014	-0.049	0.015
	Max.	0.032	-0.039	0.074
	□	0.021	0.055	0.051

Table 4.6: Statistics of coordinate discrepancies between the DVRS and the single-reference (m)

5. CONCLUSIONS

The performance of the Dubai Virtual Reference System (DVRS) has been investigated as an example of the RTK networks. The system absolute accuracy was first tested by comparing the DVRS estimated coordinates for a set of 13 points with their accurate coordinates, which have been previously determined by a precise surveying using a total station. The 3D (spatial) positioning differences between the two techniques, reflecting the DVRS external accuracy, ranged between 0.81cm and 3.61 cm. The accuracy of relative positioning was tested by studying differences between distances derived from the DVRS estimated point coordinates against their precise values. The differences were within 1 cm on the average for the three tests, with a maximum value of 2.2 cm. The standard deviation of the differences ranged from 1 to 2 cm. For the three DVRS tests, coordinate precision were less than 2 cm for planemeteric coordinates, and less than 3 cm for height determination. Different DVRS surveys to the same test points prove to be consistent in terms of their internal precision of the final output results. This can be statistically interpreted that the different tests are statistically compatible. In addition, the system proves to be reliable and robust particularly in case of failure of one of the reference stations. In this case, positioning accuracy at the cm level was feasible for points that are as far as 25 km away from the nearest reference station. Such a case can not be usually solved at that level of accuracy using the classical single reference RTK approach. This shows that the DVRS

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