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USING THE VIRTUAL REFERENCE STATIONS (VRS) CONCEPT FOR LONG-RANGE AIRBORNE GPS KINEMATIC POSITIONING

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ABSTRACT

In this paper, the potential of long-range kinematic GPS positioning with a multiple reference station (MRS) network for airborne applications is discussed. A novel method of creating Virtual Reference Stations (VRS) is proposed for post-processed airborne GPS kinematic applications, which is called the modified semi-kinematic VRS method (MS-VRS). The purpose of the VRS is to generate data from real GPS observations made by the MRS network, resembling that of a non-existing (virtual) reference station situated close to the project area, so that the commonly used methods for short-range kinematic GPS data processing can be used to determine the position of the aircraft. During the initial phase, the VRS of the MS-VRS method refers to a fixed position according to the aircraft's initial approximate position, and the corrections are applied according to the aircraft's trajectory. The MS-VRS method differs from the conventional VRS method and semi-kinematic VRS method (S-VRS) in that when the aircraft's current approximate position is more than 10 km from the initial VRS position, a new VRS is created. The MS-VRS data can be generated in RINEX format, so that it can be processed using any kinematic GPS post-processing software. Using a simulated kinematic test with static data, the MS-VRS method showed a 12.1 to 47.6 percent improvement in the three coordinate components with respect to the conventional single reference station (SRS) approach. Tests and analysis with real airborne GPS data are presented in some detail using a MRS network and flight test data in Norway. The results indicate that centimetre-level accuracy can be achieved based on the proposed MS-VRS method, which is superior to the S-VRS method, with improvements of 11.4 to 47.4 percent in terms of standard deviations of the coordinate domain.

KEYWORDS. Long Range Airborne GPS. Kinematic Positioning. Virtual Reference Stations.

INTRODUCTION

In recent years, there has been increasing demand for airborne GPS positioning, which provides precise position information for many engineering applications and scientific investigations, such as photogrammetric aerotriangulation without ground control [**1**],[**14**], airborne remote sensing [**1**],[**2**],[**19**], airborne laser systems for precise topographic mapping [**7**], geophysical and oceanographic exploration [**9**],[**25**]. Generally, it is agreed that many of the atmospheric and satellite-related errors cancel when processing the reference and rover station data, so that conventional kinematic GPS positioning can provide the ability to determine the trajectory of an aircraft with respect to a fixed base station to a precision of several centimetres for a rover-base separation less than 10 km [**7**], [**8**],[**10**],[**13**].

However, for long-range airborne GPS positioning, the distance between the aircraft and its reference station can easily reach more than 10 km. As such, the assumption of

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error cancellation degenerates and the performance of the system degrades. Moreover, decorrelated positioning errors, such as ionospheric and tropospheric effects, limit the ability for centimetre-level kinematic positioning [**2**],[**4**],[7],[**9**],[**26**].

More recently, multiple reference station (MRS) networks are being installed in many countries worldwide to extend the operational limits of high-precision GPS, and different approaches to take advantage of the availability of MRS have been developed e.g., [**3**],[**6**],[**11**],[**17**],[**18**],[**20**],[**21**],[**24**]. Airborne GPS positioning with the corrections from a MRS network also showed a significant accuracy improvement when compared to differential GPS (DGPS) processing using individual stations [7],[**9**],[**25**]. Kjorsvik et al. [**14**] show that sub-decimetre positioning of airborne sensors can be achieved by using a MRS network. A number of researchers showed similar results when operating in a MRS network e.g., [**15**], [**19**], [**22**].

An efficient method of utilizing corrections to the network users for real-time or post-processing kinematic positioning is the Virtual Reference Station (VRS) concept. During the past few years, the use of the VRS concept has been proposed by many research groups as a more feasible approach for relaying network correction information to the users e.g., [**12**],[**14**], [**18**], [**20-23**].

This study focuses on investigating the post-processed VRS method for airborne GPS kinematic applications based on a MRS network. This paper begins with a brief discussion of the relevant methodology. This includes a review of the VRS method and a modified semi-kinematic VRS method (MS-VRS) proposed herein. Some results of simulated kinematic positioning and real airborne kinematic GPS data in Norway are then analysed in detail. Finally, conclusions and proposals for future work are presented.

METHODOLOGY

This section is intended to an overview the VRS data generation approach, along with a proposed MS-VRS method. A more detailed description of the VRS approach is given in [**12**],[**20**],[**22**].

Overview of VRS data generation

The main idea behind the VRS concept is to reduce or eliminate the residual double-differenced errors for long-range baselines processing, and combine the observations of several reference stations in such a way that an optimum set of observations of the VRS is obtained. Hence, the commonly used methods for short-range baseline kinematic data processing can be used to determine the position of a long-range rover in real-time or post-processing modes [**12**],[**14**],[**20**],[**22**],[**23**].

In order to create VRS from the observations of the MRS network of real reference stations, several processing steps have to be performed. The first step is to resolve the double-differenced carrier-phase ambiguities among stations in the network epoch-by-epoch. After the double-differenced ambiguities associated with the reference stations have been fixed to their correct values, the correction coefficients for the rover can be generated from the residuals in L1 and L2 carrier-phase measurements on a satellite-by-satellite, epoch-by-epoch basis. Then, the corrections are computed for the rover according to its approximate position.

In the next step, VRS data for user receivers are generated. In order to generate VRS data as though there was a reference station at the user's location, the carrier-phase and code pseudo-range observations from a master reference station have to be displaced geometrically and improved by applying the corrections of the network according to user's approximate position, i.e. the VRS position. The rover's approximate position can be obtained from absolute (single point) C/A-code-positioning. The VRS data is generated in RINEX format, so that it can be processed using any post-processing software.

MS-VRS method

The VRS concept was initially developed for static users or users moving through fairly small areas [**6**],[**12**],[**20**]. In such conditions, one approximate user position (i.e., one VRS) is sufficient for the process. For airborne GPS positioning, however, the rover is moving over longer distances. Wanninger [**22**] suggests a semi-kinematic VRS method (S-VRS) to extend the concept of static VRS to that of kinematic positioning. As illustrated in Figure 1, the area correction parameters (FKP – a translation from German) are applied according to the rover's trajectory, but this method fixes the VRS position. Due to the nature of the airborne GPS task, the typical lengths of baselines being processed may reach many hundred kilometres. It is therefore necessary to frequently update the approximate position and the VRS should be also moved along the rover's trajectory. As such, the S-VRS method is not applicable to large-area kinematic positioning.

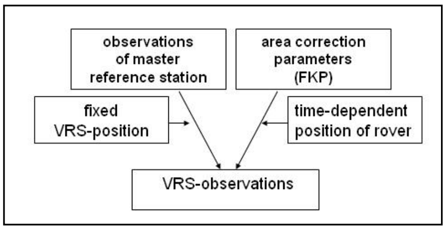

Fig. 1. Generation of the S-VRS data (adapted from [**22**])

Therefore, a MS-VRS is proposed in this paper for long-range airborne post-mission GPS kinematic applications. As shown in Figure 2, during the initial phase, the VRS refers to a fixed position according to the rover's initial approximate position, and the corrections are applied according to the rover's trajectory. Unlike the conventional VRS and the S-VRS methods, when the rover's current approximate position is more than 10 km from the initial VRS position, a new VRS is created. For post-processing, the MS-VRS data can be generated in RINEX format. Another modification to the S-VRS method is that the FKP (area correction parameters) are replaced by the network correction coefficients.

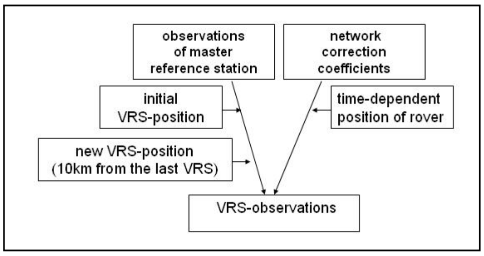

Fig. 2. Generation of the MS-VRS data

TEST RESULTS AND ANALYSIS

Simulated kinematic positioning accuracy

A simulation experiment has been conducted to test the performance of the VRS method by comparing the results with those obtained using a conventional single reference station (SRS) approach. Five static GPS stations in Norway form a network (Figure 3). The stations were equipped with dual-frequency Trimble MS750 receivers and TRM41249.0 antennas. The stations HONE, ARNE and SAND are taken as reference stations. The stations OSLS and SORH are "rover" stations, where the data from them is treated as if they were kinematic data. The resulting kinematic positions are compared, epoch-by-epoch, to the centimetre-level known positions of these sites.

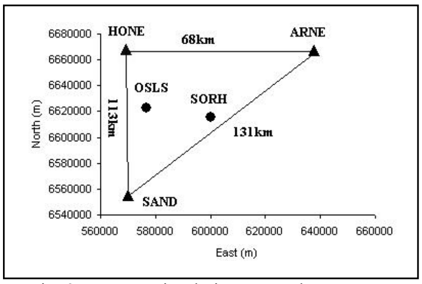

Fig. 3. Norway simulation network

In this test, the time span from 08:25 to 09:25 (GPS time) on May 8th 2002, with a sampling rate of 1 Hz is selected. The VRS data for the "rover" are generated in RINEX format according to the approximate position of the "rover" from the simulated network, using the post-mission VRS software developed at Curtin University of Technology. The UNB3 models [**5**] with Niell mapping functions [**16**] are used in the software to compute the *a priori* troposphere delay. Final precise orbits from the IGS service were adopted, and the satellite elevation cut-off angle is set at 10 degrees.

The VRS data were generated for the OSLS station (75 km "rover" distance relative to the master station ARNE), and the SORH station (68 km "rover" distance relative to the master station SAND), respectively. For the purpose of the comparison, solutions were also obtained by SRS kinematic positioning relative to the respective master station using the raw data. The kinematic processing results using the VRS and SRS methods are shown in Figures 4 and 5. The coordinate components' error values (external accuracy) are computed by differencing the estimated position from the known position in the EUREF89 datum (UTM North Zone 32).

Table 1. Summary statistics of kinematic position accuracy by using the SRS and the VRS methods (unit: metres)

Test Point	Coord. Comp.	STD			Mean		Max		Min	
		SRS	VRS	*Imp(%)*	SRS	VRS	SRS	VRS	SRS	VRS
SORH	North	0.036	0.026	*27.8*	-0.139	-0.018	-0.093	0.027	-0.182	-0.119
	East	0.021	0.011	*47.6*	0.137	0.004	0.173	0.028	0.092	-0.02
	Height	0.047	0.038	*19.1*	-0.157	-0.035	-0.086	0.056	-0.224	-0.151
OSLS	North	0.037	0.022	*40.5*	-0.146	-0.017	0.178	0.042	0.125	-0.116
	East	0.026	0.014	*46.1*	-0.126	0.012	-0.076	0.016	-0.176	-0.046
	Height	0.033	0.029	*12.1*	0.192	-0.041	0.258	0.03	0.125	-0.105

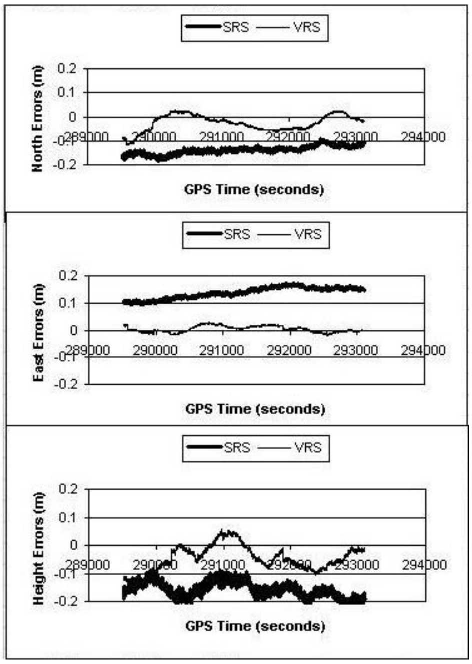

Fig. 4. SORH station kinematic position accuracy by using the SRS and the VRS methods

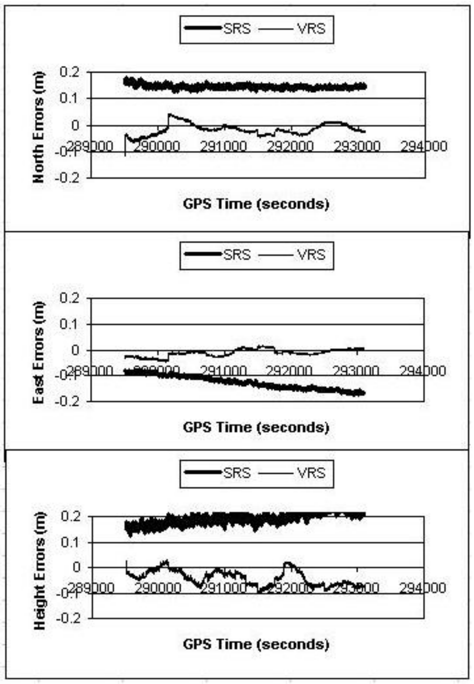

Fig. 5. OSLS station kinematic position accuracy by using the SRS and the VRS methods

The statistics of kinematic position accuracy for the two "rovers" are listed in Table 1. The results illustrate that the standard deviations are at the few centimetres level for the horizontal and ellipsoidal height components, as well as the average errors for the VRS solutions. The VRS method shows an improved accuracy in all three components of the position domain, as compared to the SRS solution. As shown in Table 1, the improvement in the solutions clearly presents the benefits of the VRS method.

Norway Airborne GPS data test

The objective of this test was to verify how much improvement the MS-VRS method achieved relative to the S-VRS method using real airborne data. A one-hour dual-frequency airborne dataset from 08:25 to 09:25 on the same day as the simulation test in the previous subsection was selected from a test flight in Norway, with a data collection rate of 1 Hz (for further details about the whole flight period, see [**14**]). This test used three Norwegian reference stations (SAND, SORH and OE23) to form a network with the sampling rate of 1 Hz. The distance between reference stations varied from 60-70 km. Figure 6 shows the test network and the trajectory of the flight during the selected test period. The VRS data were generated using the S-VRS and the MS-VRS methods, respectively.

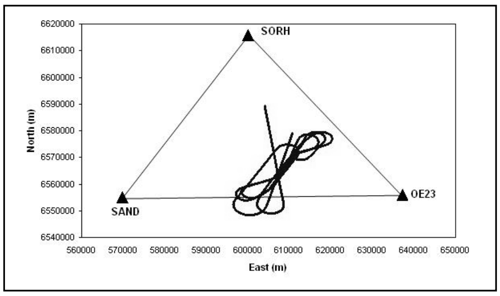

Fig. 6. Flight trajectory and the reference stations network of the selected test data

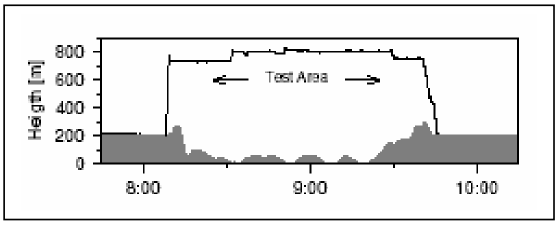

Fig. 7. The height and terrain profile of the test flight (from [**14**])

The reference trajectory was confirmed at an accuracy of several centimetres by comparison with different software and independently determined positions from an aerial triangulation (for further details, see [**14**]). The height and terrain profile of the flight period is plotted in Figure 7. The estimated positions from both the S-VRS and the MS-VRS methods were compared with the reference trajectory. Figures 8a and 8b show the position differences. Table 2 summarises the results of the comparisons conducted during the selected test period.

It can be seen from Table 2 that, in comparison with the solution obtained by the S-VRS method, the standard deviations of north, east and height components are reduced from 0.059 to 0.031m (47.4%), 0.035 to 0.031m (11.4%) and 0.091 to 0.078m (14.3%), respectively, by using the MS-VRS method. The standard deviation in the height component is a factor of 2 to 3 times worse than in the horizontal component. Since the accuracy of GPS positioning is comparatively worse in the height component, it is necessary to pay attention to the accuracy of the height determination. An optimal model for the *a priori* troposphere delay relating to the height should be made in future.

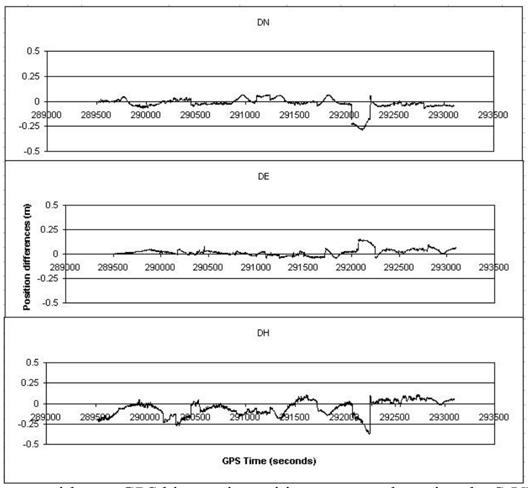

Fig. 8a. Norway airborne GPS kinematic position accuracy by using the S-VRS method

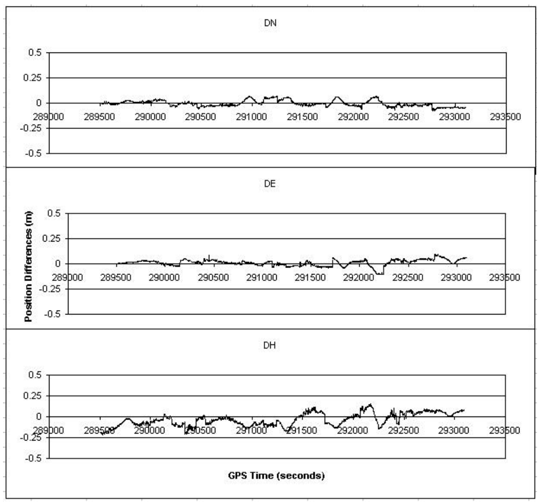

Fig. 8b. Norway airborne GPS kinematic position accuracy by using the MS-VRS method

Table 2. Statistics of the accuracy by using S-VRS and the MS-VRS methods for Norway airborne GPS test

Coord. Comp.	STD			Mean		Max		Min	
	S-VRS	MS-VRS	*Imp(%)*	S-VRS	MS-VRS	S-VRS	MS-VRS	S-VRS	MS-VRS
North	0.059	0.031	*47.4*	-0.022	-0.005	0.066	0.068	-0.288	-0.076
East	0.035	0.031	*11.4*	0.019	0.010	0.151	0.097	-0.043	-0.107
Height	0.091	0.078	*14.3*	-0.056	-0.035	0.111	0.157	-0.375	-0.219

SUMMARY AND CONCLUSIONS

For some airborne GPS positioning, the distance between the aircraft and its reference station can easily reach several hundred kilometres, and as the distance increases, more decorrelated positioning errors (e.g., ionospheric and tropospheric effects) limit the ability for centimetre-level kinematic positioning. Fortunately, the use of a multiple reference station (MRS) network can extend the operational limits for long-range kinematic positioning.

The post-processing VRS concept based on MRS networks is discussed in this paper. A modified semi-kinematic VRS (MS-VRS) technique is used so that the existing standardized data formats and standard commercial kinematic software are capable of working in network mode. Results and analysis using simulation tests show an improvement of 12.1 to 47.6 percent in the three coordinate components by using the VRS method, as compared to the SRS method. Tests with real airborne GPS data demonstrate that 3D-position accuracy of a few centimetres can be achieved with the MS-VRS method. The results obtained in this study reveal the improvements brought about by the application of the MS-VRS method as opposed to the S-VRS method.

However, there is a constant bias error in the vertical component. These errors may be caused by the modelling errors for the tropospheric delay because of the height difference between the base station network and the aircraft. It is suggested to model troposphere more carefully in future to see if further improvement can be made.

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