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Using Multiple Reference Station GPS Networks for Aircraft Precision Approach and Airport Surface Navigation

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Abstract. The use of multiple real-time reference stations (RTK Networks) for positioning during the aircraft's precision approach and airport surface navigation is investigated. These existing networks can replace the proposed airport LAAS systems and have the advantage of improving coverage area. Real-time testing of the proposed technique was carried out in Dubai, UAE, with a helicopter and a small fixed-wing aircraft using a network known as the Dubai Virtual Reference System (DVRS). Results proved the feasibility of the proposed approach as they showed that cm to sub-meter positioning accuracy was achieved most of the time. For some periods, only meter-level positioning accuracy was available due to temporary breaks in reception of the network carrier-phase corrections. Some solutions to improve availability of the corrections are discussed. It is also proposed to integrate the GPS with an IMU. The inertial system aids positioning during periods when the corrections are lost, as well as providing attitude information. The GPS and IMU systems were integrated using a decentralized adaptive Kalman filtering technique. The measurement noise covariance matrix and the system noise matrix are adaptively estimated, taking the aircraft dynamics changes into account. Tests of the integrated system show that it has a good overall performance, and navigation at categories III and II can be achieved during short outages of RTK-GPS network corrections.

Key words: Global Positioning, Airborne Navigation, Wide Area Networks, Adoptive Systems, INS

1 Introduction

Interest in the use of Global Navigation Satellite Systems (GNSS) as a main source of navigation reference is increasing. The system employed for such a purpose should be capable of meeting the strict requirements of air navigation in terms of accuracy, availability, integrity, and reliability. At present, the accuracy requirements for all flight categories up to precision approach are summarized in Table 1 (Whelan, 2001). The accuracy requirement for Category I can be achieved most of the time using wide area differential systems such as the American "WAAS", the European "EGNOS", and the Japanese "MSAS". To meet the most demanding accuracy for categories II and III, which involve the final and precision approach phases of flight, more accurate systems are needed. The American Federal Aviation Authority (FAA) has undertaken the development of a navigation augmentation system based on GPS in the form of a Local Area Augmentation System (LAAS). This LAAS is designed to enable precision approach navigation within the airport area. It includes at least four reference GPS receivers located at each airport. GPS measurements are collected from the four reference stations and processed in real time in a control computer. Next, GPS differential corrections are sent to aircraft to compute their locations for navigation at the sub-meter level of accuracy. Corrections are provided via a Very High Frequency (VHF) radio link from a ground-based transmitter. LAAS preliminary test results have generally demonstrated accuracy of less than 1 meter in the horizontal and vertical axes. However, the percentage of system availability is still under evaluation to see if it can meet the FAA requirements. The cost of establishing LAAS for major airports is also expected to be significant.

Tab. 1 Positioning accuracy requirements for all flight categories

	horizontal	**vertical**
Category I	17.1 m	4.1 m
Category II	5.2 m	1.7 m
Category III (precision approach)	4.1 m	0.6 m

This study proposes the use of Real-Time Kinematic (RTK) multi-station reference networks, as an alternative to the airport LAAS, to aid accurate positioning of aircraft during precision approach, takeoff and airport surface navigation. The feasibility of this approach, the problems experienced in practice and possible methods for improving the overall performance are investigated in this paper. The investigation is carried out on a typical RTK network, bearing in mind that the presented results are dependent, to some extent, on the network design and operational features.

2 Using the multi-station RTK networks for airborne navigation

GPS RTK multi-station reference systems were originally developed for surveying applications. The basics of this type of reference systems are discussed in Enge et al. (2000), Raquet & Lachapelle (2001), Hu et al. (2003) and El-Mowafy et al. (2003). In principle, observations from multiple reference stations covering a large area are gathered and processed in a common network adjustment at a central processing facility and measurement corrections are computed. The corrections are optimized for the coverage area to account for distance dependent errors. A single rover GPS receiver receives these measurement corrections from the control centre of the network and uses the corrections to estimate its position in real-time accurate to the cm-level with fixed integer carrier-phase ambiguity resolution, or to the sub-meter level with a float solution. Currently, the RTK network approach is mostly used in static or kinematic ground applications. In this study, the use of these networks in airborne navigation is considered, where the rover receiving the network corrections is mounted on the aircraft to determine its positions during flight.

2.1 Advantages of Using RTK Networks in Airborne Navigation

The main advantages of using multi-station reference RTK networks for precise airborne navigation can be summarized as follows:

- Due to the fact that multi-station reference networks usually have an area of coverage that extends to several tens or hundreds of kilometres, each network can cover more than one airport, including small airports, unlike the airport LAAS. In addition to airport navigation, the system can be used in search and rescue operations, emergency landing, road traffic control from the air, as well as emergency response.

- RTK networks provide cm to decimetre positioning accuracy even in the case of malfunctioning of some stations, particularly for dense networks. This situation is however more critical in airport LAAS due to the low number of receivers used.

- Compared to LAAS, no significant additional infrastructure cost is involved as the hardware and software of the GPS-RTK networks are available in most developed countries and the establishment of new networks is currently underway (or planned) in different regions worldwide.

- RTK networks can give better runway utilization by improving airport surface navigation. They can also enhance air traffic management by increasing dynamic flight planning.

2.2 The DVRS Network as an Example

The feasibility of using real-time reference networks to provide precise positioning navigation information for aircrafts is examined in this study. A network known as the Dubai Virtual Reference System (DVRS), located in Duabi, UAE, was used for this investigation. The focus was on various aspects of aircraft navigation including precision approach, takeoff and airport surface navigation. For accurate determination of aircraft heights from the ground using GPS-derived ellipsoidal heights, a recently established accurate geoid model for Dubai was utilized. The Dubai geoid model was developed from varying data sources, mainly: gravity measurements, a digital elevation model (DEM), orthometric heights and GPS-observations at levelling benchmarks.

The DVRS network consists of five active reference stations, with baseline lengths varying between 23.4 km and 90.8 km. The main software used in the processing of the DVRS data utilizes the area parameter method (FKP) to estimate and represent the state of individual GPS errors in real time. All stations of the network are processed simultaneously using un-differenced observables. Therefore, all error components including clock errors are estimated. The state vector ($\vec{X}$) used in the Kalman filtering process can be given as:

$$\vec{X} = (\vec{x}_i\, ,\ N_i^s\, ,\ \delta t_i\, ,\ \delta t^s,\ \delta\vec{O}^s\, ,\ \delta T_i^s\, ,\ \delta I_i^s\, ,\ \delta M_i^s\,)^T \quad (1)$$

where $\vec{x}_i$ is the position vector, δt_i and δt^s denote the receiver and clock errors, N_i^s is the ambiguity, $\delta\vec{O}^s$, δT_i^s and δI_i^s represent the distance dependent errors (the orbital, tropospheric, and ionospheric errors respectively), and δM_i^s is the multipath error. To compute its position, the rover receiver sends its approximate position via a cellular modem to the network control centre where computations are carried out for each user. The estimated network measurement corrections, mainly the distance dependent errors, are interpolated for a virtual reference station (VRS) close to the rover position and instantly sent to it. The predicted distance dependent error term (δ_i) at the VRS position (i) from the reference station (j) with respect to the satellite (s) can be expressed in the functional form:

$$\delta_i = f(\mathrm{FKP}_j^s, \Delta\phi_{ji}, \Delta\lambda_{ji}, \Delta h_{ji}) \tag{2}$$

where Δ is the differential operator, ϕ, λ, and h denote the latitude, longitude and height respectively, and FKP_j^s represents the FKP computed error. The corrections at the VRS station (VRS_{ji}^s), which are used to correct the observations at the rover receiver, can be expressed as follows:

$$\mathrm{VRS}_{ji}^s = \mathrm{CR}_{ji}^s + \delta_i + \Delta T_{ji} \tag{3}$$

where CR_{ji}^s denotes the corrected carrier phase observations of the reference station computed from the network solution, and ΔT_{ji} represents the difference in tropospheric modeling between processing of the network at the reference station and processing of the virtual reference station. For in-depth mathematical formulation of this method, interested readers may refer to Wübbena et al. (2001). Previous testing of the DVRS system for kinematic ground surveying showed that system positioning accuracy was typically 1-2 cm in planimetry and 3-5 cm in altimetry (El-Mowafy et al., 2003).

2.3 Concerns and Recommendations in Using the DVRS Network for Airborne Navigation

When applying the VRS technique to airborne navigation, the aircraft rover receiver uses a ground VRS station. The drawback is that continuously updated approximate coordinates have to be used for the VRS computation. This is similar to having a moving reference station. A system reset should thus be frequently performed when the VRS coordinates are changing, which will result in frequent initialization of the carrier-phase ambiguities. Therefore, it is preferable to keep the VRS location for the longest possible range and apply appropriate extrapolation. This can, however, affect the performance of the system. In addition, the duplex communication approach used for the DVRS network puts a restriction on the number of users, as this number is limited by the ability of the control centre to simultaneously perform calculations for different users. As this number grows, extended latency in receiving the corrections may result.

These problems can however be alleviated in the implementation phase of the system in aviation by using a one-directional communication method. In this case, one or two ground transmitters (repeaters) at the airport will be established; they will receive the reference-station measurement corrections from the control centre on-line and send them to the aircraft by means of, for instance, VHF modems. The receiver on board the aircraft will then be responsible for interpolating the corrections at its location and processing the measurements to estimate its position. Thus, the rover can independently use its own interpolation and processing models, and no restrictions exist on the number of users. For faster and continuous prediction of the corrections at the rover location, it is recommended that the software computes a particular set of aviation corrections sent to the airport transmitters, emphasizing the airport area with a preset radius (e.g. 30-40 km). The current architecture of the DVRS communication with the user can, however, be kept to serve ground-based surveying applications. Hence, both types of communication can be used to serve different applications (aviation and surveying), using the same infrastructure of the real-time reference stations.

The establishment of ground transmitters at the airport can also improve the current availability of the corrections to the rover receiver, as breaks in receiving such corrections frequently take place. Another recommendation is to integrate GPS with an inertial system. More details will be given in a following section.

Since the proposed system is based on the use of satellite measurements, the integrity of the system and continuous reception of the corrections are primary concerns. These items should be continuously monitored, and methods such as RAIM should be implemented to warn the pilot against any deficiency in the system. Other concerns in the use of RTK networks in airborne navigation include:

- Due to the high dynamics involved in airborne navigation, a high update rate of sending the corrections is needed compared with that implemented for land applications, which is usually 5-70 seconds for current networks. This rate has a direct impact on the Time-To-First-Fix of phase ambiguities, and thus on the overall positioning feasibility and accuracy (El-Mowafy, 2004).

- The format of GPS measurement corrections should be standardized to ensure that the system is independent of any single receiver manufacturer. The use of the RTCM standard for RTK multiple reference stations v3.0 is thus recommended, see Euler et al. (2004).

- The need to ensure the security of the reference station locations: these stations should be safe and unreachable by the public in order to prevent possible tampering.

- The possibility that the airport authorities share control of the system with surveying authorities is recommended.

3. Testing the DVRS system for Airborne Navigation

3.1 Test Description

The use of the DVRS network for aircraft navigation in the airport area was evaluated by conducting several flight tests. Two types of aircraft were used for this purpose, a helicopter and a small fixed-wing airplane. In these tests, aircraft positions (planimetric + height) were determined using a dual-frequency GPS rover receiver (Leica SR530) equipped with a DVRS GSM modem capable of receiving the DVRS corrections. The GPS/DVRS rover receiver collected both the GPS and the correction data during the aircraft takeoff, enroute flying, landing and airport surface navigation. The data were processed in real time at one-second intervals. On the other hand, the DVRS reference stations collected data at five-second intervals. Processing of their RTK network corrections was also carried out at this interval. Thus, the corrections were interpolated in time for the rover receiver to compute the measurement corrections at the one-second interval. The satellite window during testing was generally normal, and 6 to 8 satellites were observed at any moment, giving Dilution of Precision (PDOP) values ranging from 1.4 to 3.7 at the rover receiver locations. The GPS data were also stored in the receiver's internal memory for further post processing testing and analysis after being integrated with the data from the DVRS reference stations.

In the helicopter test, the GPS and GSM antennae were rigidly mounted on an arm approximately 0.9 m long extending outside the helicopter. The arm was attached to a frame rigidly fixed inside the helicopter. No arm vibration was experienced during flight testing. For better GPS as well as GSM signal reception, the GPS antenna was mounted high on the arm for better visibility of the sky, while the GSM antenna faced down. This architecture was designed only for testing purposes. Figures 1 and 2 show the system installation on the helicopter, and the test trajectory. For the fixed-wing aircraft test, the GSM antenna was installed inside the aircraft, which is acceptable for GSM communication. Figures 3 and 4 show the fixed-wing aircraft and the test trajectory respectively. Both tests were carried out over the city of Dubai.

Fig. 1 System instillation for the helicopter test

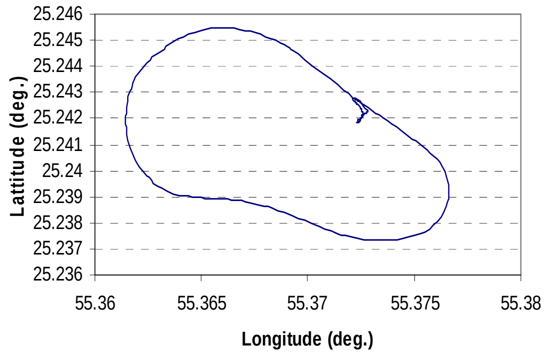

Fig. 2 Trajectory of the helicopter test

Fig. 3 Testing using the fixed-wing aircraft

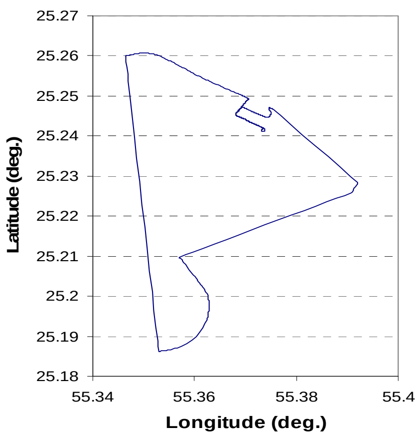

Fig. 4 Trajectory of the fixed-wing aircraft test

3.2 Test Results

Figure 5 shows the helicopter test results, illustrating the flying height and the 2-D and height positioning accuracies achieved during testing. At the beginning of the test and after an initial warming up period of less than 20 seconds, the phase ambiguities were successfully fixed. Thus, positioning accuracy was feasible at the cm level before starting the engine. The DVRS corrections were continuously received during takeoff until reaching the required height (first dashed region in Figure 5), which was approximately 145m. During the major part of the enroute flying time, the DVRS corrections were continuously received. However, during most of the landing phase the DVRS corrections were lost, but were regained after the helicopter landed (second dashed region in Figure 5). This can be mainly attributed to the use of GSM signals in sending the DVRS data, and partially to changes in the helicopter dynamics. In addition, due to changes in the VRS positions, initialization of the phase-ambiguities was often carried out. The change in error values from the decimetre to the cm level, which can be observed at some instances in the figure, can be ascribed to reaching a fixed ambiguity solution after a float solution. In general, during the two marked periods, the ambiguities were resolved as integers and the average positioning accuracy, represented by coordinate standard deviations, was 0.022 m in the planimetric 2-D positions and 0.034 m in height.

One can, however, note that the highest accuracies needed in airborne navigation corresponding to category III, which are 4.1 m for 2-D positioning and 0.6m for height determination, can generally only be achieved with a float ambiguity resolution. For instance, for the helicopter test, during the periods where the DVRS corrections were received but the ambiguities were resolved in a float solution, the positioning accuracy was at the sub-meter level, as shown in Table 2. This accuracy was on average 0.322 m for the 2-D positioning and 0.539 m for height determination. However, when the DVRS signals were not received, the 2-D positioning and the height errors were increased to more than 3.5 m, which are only suitable for navigation at category I, i.e. during the enroute flying.

Tab. 2 Average positioning accuracies (m)

	Helicopter test		**Fixed-wing aircraft test**	
	2D (E&N)	Height	2D (E&N)	Height
fixed solution	0.022	0.034	0.016	0.028
float solution	0.322	0.539	0.263	0.525
all test periods	0.484	0.642	1.107	0.831

Figure 6 shows the results of the fixed-wing aircraft test. In this test, the DVRS corrections were available during airport surface navigation and manoeuvring to the runway, in addition to the periods of takeoff, reaching the designated height, landing and parking, which are shown in the dashed areas in the figure. The DVRS corrections were, however, lost during flying for some periods. This can also be attributed to the use of GSM signals as the means of communication with the DVRS centre, which might result from changes in the aircraft dynamics as clearly seen from the top figure. This result, together with the outcome of the helicopter test, shows that accurate positioning using RTK network corrections in real-time is feasible during the critical phases of takeoff, landing, and airport surface navigation. However, the use of GSM signals for sending the RTK network corrections is not efficient and other methods are needed. The average 2-D and height positioning accuracies achieved during the fixed-wing aircraft test are given in Table 2. As with the helicopter test, when receiving the DVRS corrections and initializing fixed phase measurement ambiguities, the average 2-D and height positioning accuracies were at the cm level, as they were 0.016 m and 0.028 m respectively. When phase ambiguities were solved in a float solution, these accuracies were 0.263 m and 0.525 m. Both cases are sufficient for positioning in all phases of flight, including category III. When the DVRS corrections were lost, the 2-D and height positioning errors were more than 4 m, which can be only used for category I of navigation.

To compare results of the RTK network approach for this particular application with the standard double differencing technique, the phase data of the rover receiver stored in its internal memory were processed in a post-mission mode referenced to one of the DVRS network reference stations. This was possible since the tests were carried out at a distance of approximately 6 km from this station and the flight paths were within a range of a few kilometres. Precise IGS orbits were used. When comparing the results of positioning obtained by the DVRS real-time multi-station reference network with the post-mission positions, the 3D differences were within the range of a few millimetres to a few centimetres when the phase ambiguities were fixed. In general, the discrepancies were less than 7 cm.

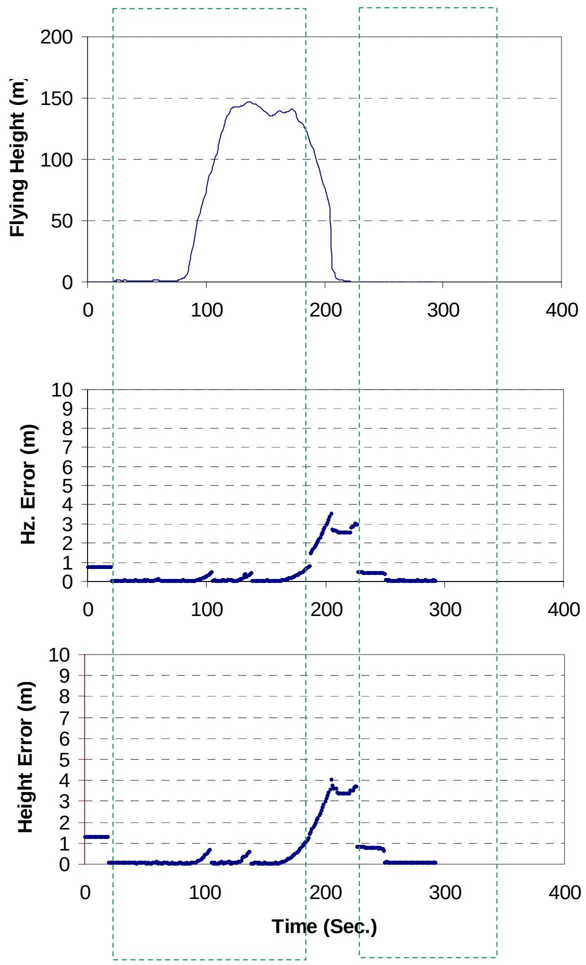

Fig. 5 Helicopter test results

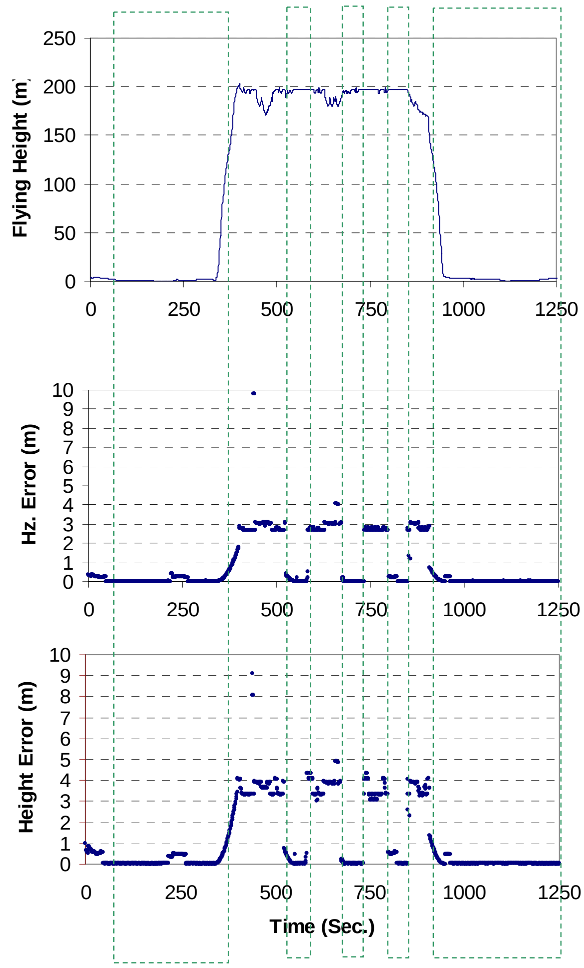

Fig. **6** Fixed-wing aircraft test results

4 Integration with the INertial system

4.1 Integration and Estimation Methodology

One method to increase the availability of the positioning accuracy at the required level is to integrate GPS with an Inertial Measuring Unit (IMU). Thus, for the same tests given above, the GPS/DVRS system was integrated with an IMU running simultaneously, with the purpose of bridging positioning outage by the Inertial Navigation System (INS) of the IMU during short breaks in reception of network corrections. The data of both systems were recorded for post mission processing and analysis. For testing purposes and due to hardware availability, a Honeywell tactical-grade (medium accuracy) IMU system of approximately 1-10 degrees/hour gyro drift was used. For simplicity, the GPS/INS integration was carried out in a decentralized loose coupling scheme. In this approach, the GPS and IMU (INS) filters ran independently in parallel. The GPS filter used the rover data and the corrections received from the multiple-reference station network as an input to the filter. The states are given in Equation (1), which includes the rover's position, phase ambiguities and measurement errors. The state vector of the INS comprises the misalignment, position, velocity, gyro drifts and accelerator biases. Positions determined from the GPS filter and velocity estimates were used as an update to the INS filter. Since real-time processing was required, no bridging algorithms such as backward smoothing were applied.

For the purposes of the test, positioning by the INS was mainly investigated during bridging of the GPS positioning outages for the short breaks in reception of network corrections. Figure 7 shows a flowchart of the integration scheme of the GPS/INS adopted during testing. To externally evaluate the performance of the INS positioning during the network correction outages, the rover receiver kept on collecting GPS observations, which were processed in a post-mission mode referenced to one of the DVRS network reference stations to compute position data that were compared with the INS results. Apart from this testing purpose, positioning information can be generally acquired from the IMU in an integrated GPS/INS system to benefit from its high frequency output. In addition, the INS is useful for determination of the attitude information of the aircraft, as well as cycle slip detection and repair, and ambiguity resolution, if a centralized filtering scheme is used.

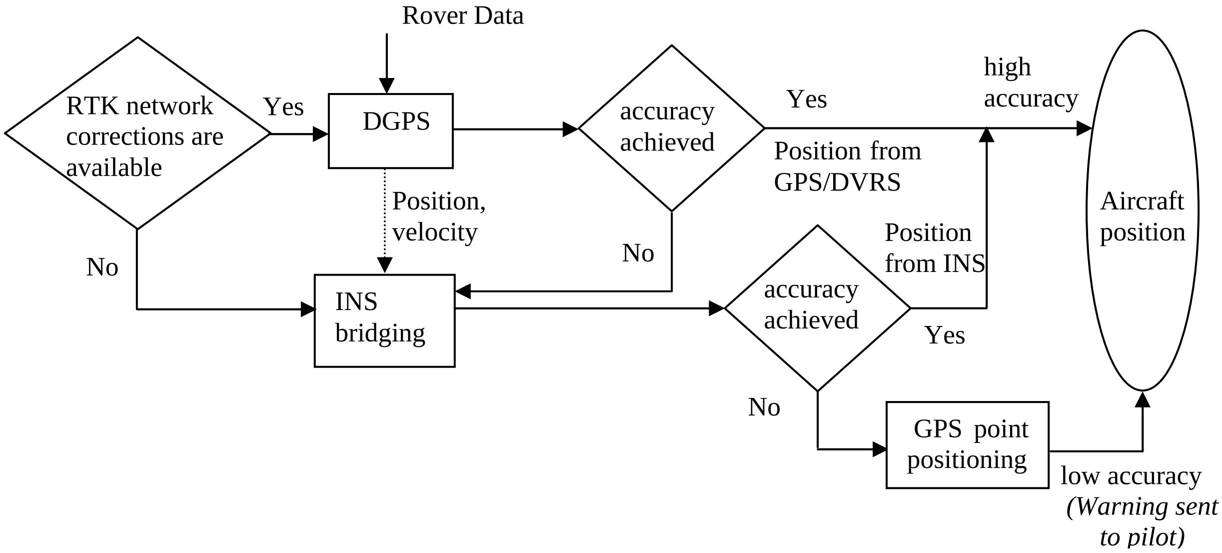

Fig. 7 Flowchart of GPS/INS integration for testing purposes

The mathematical models used in the filtering estimation approach can be written in matrix form as:

Dynamics model: $\dot{S}_i = F_{i,i-1}\, S_i + G\, u_i$ (4)

taking, for simplicity, $\Phi_{i,i-1} = F_{i,i-1}\, dt + I$ (5)

Observation model: $M_i = h(S_i) + e_i$ (6)

where S_i denotes the state vector, M_i is the measurement vector, $\Phi_{i,i-1}$ is the transition matrix, F represents the dynamics matrix, dt is the prediction time interval $(t_i - t_{i-1})$, and e_i represents the measurement noise. G is the design matrix and u_i denotes a forcing vector function, such that the term $(G\, u_i)$ represents the noise of the dynamics model. This model for the INS is described using a first order Gauss-Markov process.

An extended Kalman filtering approach was used to represent the non-linear observation equations, where the filter states become estimated corrections (δ) to an approximate state (S_o) represented as a nominal time varying state updated using filter estimation, such that:

$$\delta = \hat{S} - S_o \qquad (7)$$

The time update (prediction) equations take the form:

$$\delta_{i,i-1} = \Phi_{i,i-1}\, \delta_{i-1} \qquad (8)$$

$$P_{i,i-1} = \Phi_{i,i-1}\, P_{i-1}\, \Phi^T_{i,i-1} + Q_{i-1} \qquad (9)$$

$$K_i = P_{i,i-1}\, H_i^T\, (H_i\, P_{i,i-1}\, H_i^T + R_{i-1})^{-1} \qquad (10)$$

The measurement update (information) equations can be formulated as:

$$\delta_i = \delta_{i,i-1} + K_i\, (\omega_i - H_i\, \delta_{i,i-1}) \qquad (11)$$

$$P_i = (I - K_i\, H_i)\, P_{i,i-1} \qquad (12)$$

where Q and R denote the covariance matrices of the dynamics model and the measurement model respectively. P is the covariance matrix of the filter states, H_i represents the partial derivatives (linearized design matrix) derived from the observation equation, K is the Kalman gain matrix, and ω symbolizes the measurement misclosure.

For the INS filter, the measurement equations can be formulated as follows:

$$M_i = \begin{Bmatrix} (\varsigma + h)(\phi_{IMU} - \phi_{GPS}) \\ (\xi + h)\cos\phi(\lambda_{IMU} - \lambda_{GPS}) \\ h_{IMU} - h_{GPS} \\ \hline v^n_{IMU} - v^n_{GPS} \\ v^e_{IMU} - v^e_{GPS} \\ v^d_{IMU} - v^d_{GPS} \end{Bmatrix} + e_i \qquad (13)$$

where ζ and ξ are the radii of curvature for the meridian and prime vertical. v^n, v^e and v^d are the velocity components in the navigation frame axes (north, east, down).

The measurement noise matrix can be estimated from:

$$R = \text{diag}\,(\ \sigma^2_{\phi}\ \ \sigma^2_{\lambda}\ \sigma^2_{h}\ \ \ \sigma^2_{v^n}\ \ \sigma^2_{v^e}\ \sigma^2_{v^d}\ ) \tag{14}$$

where σ_{v^n} , σ_{v^e} and σ_{v^d} denote the standard deviations of velocity. The initial position and velocity standard deviations are taken from the GPS solution.

The Q matrix can be calculated from (Shin, 2001):

$$Q = \Phi\ G\ q\ G^T\ \Phi^T\ dt \tag{15}$$

where q is the spectral density matrix computed as:

$$q = \text{diag}\,(\ \sigma^2_{ax}\ \ \sigma^2_{ay}\ \sigma^2_{az}\ \ \ \sigma^2_{\psi x}\ \ \sigma^2_{\psi y}\ \sigma^2_{\psi z}\ ) \tag{16}$$

the σ_a and σ_ψ are the standard deviations of the accelerometers and gyroscopes, respectively.

Both the Q and R matrices play a main role in determining the quality of the estimated states owing to the fact that the predicted states covariance is affected by the Q matrix, while the update measurements covariance is R. The change of these covariance matrices reflects changes in the system dynamics, which represent a major factor affecting the performance of the tactical-grade IMU system. Thus, for medium accuracy IMU, tuning of the Q matrix is crucial to achieve filter stability. Hence, arrangement of the Q and R matrices in an adaptive manner can improve estimation, as they would dynamically reflect the actual situation. Prior field-testing results for a kinematic ground survey showed that the adaptive Kalman filter approach outperformed the conventional approach, both on internal and external bases (El-Mowafy and Mohamed, 2005). It was also shown that the track ability of the adaptive filter for the filter states was much better than that of the conventional filter.

For the above reasons, an adaptive Kalman filtering approach was employed in the processing of the test data. In this approach, the residual sequence η_i was first computed as:

$$\eta_i = M_i - h(S_i) \tag{17}$$

Then, the adaptive formulation of the R and Q matrices followed the following formulations (Mohammed and Schwarz, 1999):

$$C_\eta = \frac{1}{N} \sum_{k=k_0}^{i} \eta_k\ \eta_k^T \tag{18}$$

$$R_i = C_\eta\ + H_i\ P_i\ H_i^T \tag{19}$$

$$Q_i = K_i\ C_\eta\ K_i^T \tag{20}$$

where C_η is the covariance matrix of the residual sequence, and using $k_o = i - N + 1$ as the first epoch inside the estimation of a moving time window of the size (N), which can be taken as 20-30 epochs.

4.2 GPS/INS Integration Results

When breaks in reception of network corrections take place, an extrapolation of these corrections continues for a few seconds; after that GPS solution accuracy deteriorates. As a result, the GPS positions and velocity input are de-weighted in the filter, and the INS works in a stand-alone mode. Thus, the acceptable period of outage in reception of the network corrections is the summation of the extrapolation period of the network corrections, during which the GPS still provides positioning accuracy at the cm to decimetre level, and the time through which the INS positioning accuracy in a stand-alone mode without GPS updates is within the accuracy required for navigation. In the case of regaining GPS observations with network corrections, the time needed to resolve the ambiguities should be included in the GPS positioning outage period. For the tests in hand, an outage in receiving the network corrections occurred after the dashed areas, illustrated in Figures 5 and 6. The INS stand-alone positioning errors grew very rapidly with time in a non-linear form. However, unlike GPS, the tested IMU system has a better height determination accuracy than its horizontal accuracy. This is advantageous for airborne navigation, which is more restricted by the height accuracy. For instance, the maximum allowable height error for category III is 0.6m, while it is 4.1m for the horizontal error.

The test results showed that the accuracy requirements for precision approach (category III) were generally achieved within 25-31 seconds of the GPS data outages. This was dependent to some extent on the aircraft dynamics. During enroute flying, the aircraft generally had uniform dynamics, which resulted in a longer positioning outage bridging, while during takeoff and landing, more changes in dynamics took place, which resulted in shorter coverage of outages. In addition, during curved parts of the course, the INS performed less well than during straight flying. Thus, shorter position bridging periods were recorded during curved flying. Overall, for data outages up to 43 seconds, the positioning accuracy achieved was suitable for category II. After that, the vertical positioning error was several meters, which is only suitable for category I of airborne navigation. These results, however, correspond to the used system and may differ for other IMU systems. The performance of the tested INS in the stand-alone mode during positioning bridging of the GPS data outages is shown in Table 3 for the helicopter and the fixed-wing aircraft tests. The average and maximum standard deviations of the planimetric (horizontal) and height components are given for GPS network data outages of 20 seconds and 40 seconds.

Tab. 3 Standard deviations of the INS positioning results during GPS data outages (m)

Period of GPS data outages	Helicopter test				Fixed-wing aircraft test			
	2D (E&N)		Height		2D (E&N)		Height	
	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.
20 seconds	2.635	3.725	0.354	0.582	2.140	3.971	0.310	0.534
40 seconds	4.161	5.103	0.915	1.662	3.651	4.837	0.832	1.388

Although the system hardware used and their integration processing schemes still have room for improvement, this configuration was tested to investigate the feasibility of the presented concepts, namely: using the multiple reference station RTK GPS networks for precision airborne navigation, and the ability of an integrated GPS/INS system to bridge positioning during short breaks in reception of network corrections. Other GPS/INS integration types, including tight coupling with centralized filtering, are currently under investigation. Tight coupling, as compared with loose coupling, is expected to provide a solution for longer data outage periods. Partial GPS data of less than 4 satellites, which only give under-determined solution, can also be used. In addition, the INS can help in detecting and correcting cycle slips, and aiding ambiguity resolution, see for instance Wu (2003). Other studies (e.g. Petovello, 2003) have also shown that the tight integration approach outperforms loose integration approaches in terms of the overall system accuracy, due to the reduced amount of process noise in the tight integration. The duration range of the INS positioning bridging under different operational conditions is also under investigation. However, this will vary according to the quality of the IMU used. For instance, better results can be achieved with higher accuracy systems (navigation grade IMU) compared with the medium accuracy IMU system used in this test.

5 Conclusions and Recommendations

The test results show that the use of RTK multi-station reference networks (e.g. the DVRS network) in precise aircraft navigation is feasible, particularly for the airport area. This new technology can increase the coverage area compared with other GPS-navigation systems, such as airport LAAS, with significant cost reduction. Small airports can thus benefit from this service. For the test flights conducted, the DVRS GSM signals were received during most of the testing periods. The loss of the signals, which took place for some periods, was expected due to the use of GSM signals and changes in aircraft dynamics. During the majority of periods of receiving the DVRS corrections, the phase measurement ambiguities were fixed and the average positioning accuracies were less than 4 cm. The accuracy needed for category III was achieved even with a float ambiguity resolution.

One can see from these results that to achieve the accuracy requirement of all phases of flight using the DVRS system, it is necessary to guarantee continuous transmission of the DVRS corrections in a suitable form for civil aviation. One suggestion to achieve this goal is by establishing ground transmitters at the airport. These transmitters will receive the corrections from the network control centre on-line and send them to the aircraft using, for instance, VHF modems instead of the currently used GSM modems. This can be implemented in the update phase of the DVRS network. A one-way direction of communication from the ground transmitter to the aircraft is recommended. In addition, it is advisable to add one reference station in the vicinity of the airport to enhance correction estimation in this area and act as a backup for the system, such that its corrections can be readily applied in case of any interruption in reception of the signals from the network control centre.

In the final implementation phase, the integrity of the system should be fully ascertained, with systems that can warn the pilot in case of system accuracy and availability deficiency being added as necessary. The security of the reference station locations should also be maintained at the highest levels. In addition, the format of the GPS corrections sent should be standardized so as to be independent of any single receiver manufacturer. This can be achieved by adopting the upcoming RTCM version 3.0 multi-station reference RTK standards.

One way to increase the availability of the positioning data is to integrate GPS with an Inertial Measuring Unit (IMU). Test results with medium accuracy IMU integrated using an adaptive Kalman filtering showed that positioning bridging can give acceptable results for category III and II if breaks in GPS solution availability are less than 40 seconds on average. After this period, without having new accurate GPS position updates, positioning errors grow and reach several meters. This accuracy is only suitable for category I of airborne navigation. However, better results can be achieved if navigation-grade IMU systems are used.

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