The road data acquisition system MoSES – determination and accuracy of trajectory data gained with the Applanix POS/LV

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KEY WORDS : GPS, INS, kinematic surveying system, trajectory uncertainty, mobile mapping

ABSTRACT
System performance of the kinematic surveying system MoSES has been studied under excellent GPS coverage as well as with simulated GPS gaps of various lengths. The uncertainty of photogrammetric measurement alone has been proved to be less than 0.1 cm RMS. Finally, the accuracy of the survey system has been evaluated along a test loop on the university campus, representative of the typical Middle European environment, where GPS positions can be obtained for only 55% of the time travelled. The stereo cameras on the vehicle captured a large number of control points along the test loop. The resulting uncertainty for object determination is 0.3 m RMS for Northing and Easting and 0.5 m for height. The evaluation shows the quality of the trajectory obtained by an Applanix POS/LV and estimated with the Applanix POSPac software.

1 INTRODUCTION

Since completion of the kinematic survey system KiSS® (Caspary 1997; Heister 1995), a new kinematic road data acquisition system called MoSES (Mobile Road Mapping System) is under development at the Institute of Geodesy of the University FAF (Fig. 1). The aim of this multi-sensor measurement system is to capture 3D coordinates and attribute data for all relevant objects within a corridor 20-30 m to the left and right of the route travelled. Based on a van, MoSES is able to collect data at a speed of up to 70 km/h. The recorded data is processed post-mission to get optimum results. A pair of digital cameras, which are part of the system, acquires topographical data. The external orientation for georeferencing the digital images is provided by the Applanix POS/LV position and orientation system, combining IMU, DGPS and DMI measurements of high accuracy.

2 MOBILE ROAD MAPPING SYSTEM (MOSES) - SYSTEM ARCHITECTURE

MoSES basically consists of two subsystems, each comprising a variety of sensors (see Fig. 2) :

- trajectory subsystem, with Applanix POS/LV 420 as the core, and aiding sensors like digital barometer, additional DMI and inclinometer
- object data subsystem, currently with two CCD cameras, color video and a laser scanner

Fig. 1 : The MoSES road data aquisition system

The whole system is managed by a central controller, which logs all sensor data to a hard disc for post-mission processing and performs real-time integrity checks and accuracy estimations. A GUI continually informs the operator on the state of the system. The GPS - PPS (pulse per second) - signal, generated by the receiver, together with GPS time information is used to synchronise all sensors and to time-tag the data with an uncertainty of less than one millisecond.

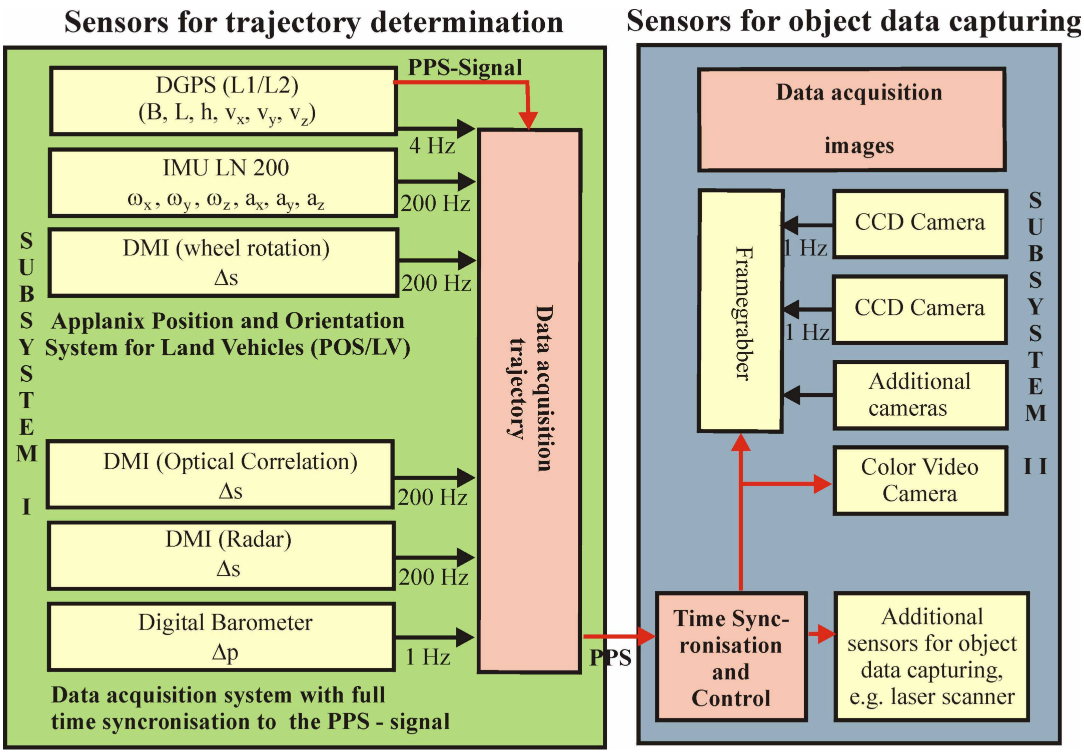

Fig. 2 : Data acquisition MoSES

3 POSITION AND ORIENTATION SYSTEM FOR LAND VEHICLES (POS/LV)

The Position and Orientation System for Land Vehicles (POS/LV) is intended to provide a full navigation solution for a land vehicle in applications such as road surveying, road profiling or roadside surveying. Such applications typically require accurate and continuous position and orientation data in geographic locals where GPS satellite reception is poor or only intermittently available. POS/LV uses strapdown inertial navigation, Kalman filtering, GPS, GPS azimuth measurement (GAMS) and a Distance Measurement Indicator (DMI), to provide position and orientation data that have a high bandwidth, excellent short-term accuracy and minimum long-term errors. The system provides dynamically accurate, high-rate measurements of the full kinematic state of the host vehicle. POS/LV operates at highway speeds, provides continuity of all data and data accuracy during GPS dropouts, and can provide motion compensation information to other sensor systems onboard the host vehicle. The trajectory data for the MoSES system is processed post-mission using the highly developed Kalman filter post-processing software, called POSPac.

The POS/LV system comprises an Inertial Measurement Unit (IMU), Distance Measurement Indicator (DMI), two GPS antennas with choke rings, an embedded L1/L2 GPS receiver and a second embedded L1-only GPS receiver. In addition to the real-time embedded software that runs on POS/LV, the graphical user interface software LV-POSView and the post-processing software POSPac, both of which run on a standard Windows^{TM}-based computer, are part of the POS/LV solution. Therefore, it is possible to use the POS/LV navigation solution in real-time or to log data to a standard PC Card disk for post-processing using POSPac to obtain a much more accurate result.

A functional block diagram of POS/LV is shown in Figure 3.

The strapdown inertial navigator solves Newton's equations of motion, which describe the

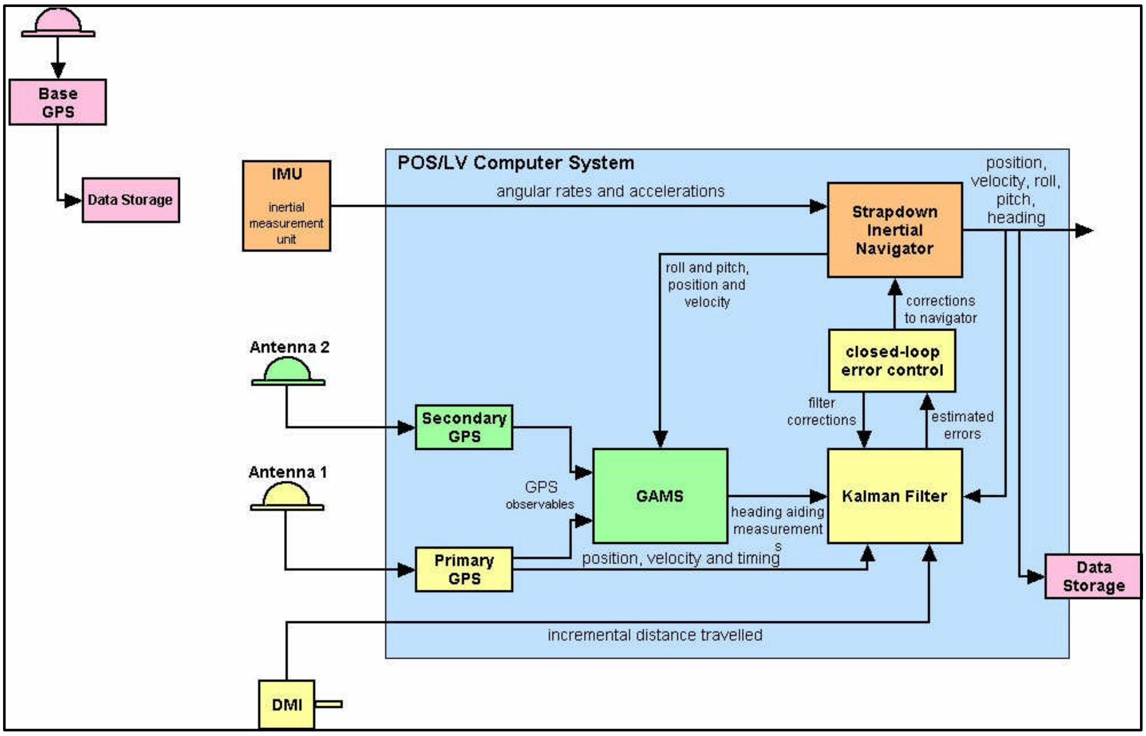

Fig. 3 : POS/LV Functional Block Diagram

position, velocity and attitude of the IMU on an approximately ellipsoidal earth that rotates in space. The inertial navigator computes velocity in a locally level navigation frame from accelerations and angular rates resolved in the IMU's body frame. The navigation frame is the mathematical equivalent of a level stabilized platform. The inertial navigator computes position as the polar coordinates of the navigation frame with respect to the earth frame. These coordinates are lattitude, longitude and altitude above the reference ellipsoid that defines the nominal shape of the earth. The Kalman filter is a key component of an aided inertial navigation algorithm. It performs the two key functions of estimation and noise reduction. The Kalman filter estimates the inertial dynamics of a noisy system based on measurements of the system's outputs and a model of the system's dynamics. The Kalman filter attenuates the noise, which corrupts the system's output data. The closed-loop error controller provides an interface between the inertial navigator and the Kalman filter. The error controller takes the Kalman filter estimated errors and and uses them to generate corrections to both the inertial navigator and the Kalman filter. One property of an aided inertial terrestrial navigator is that the heading error is only weakly observable if the vehicle is stationary or moving at constant velocity. POS/LV addresses this problem by employing GPS azimuth aiding, using two GPS receivers and a software module called the GPS Azimuth Measurement Subsystem (GAMS). With GAMS, the Z-gyro bias is callibrated, allowing an order of magnitude improvement in heading error under all dynamic conditions and at any geographic latitude.

4 DATA PROCESSING

A library of programs has been developed for post-mission data processing. It is based on rigorous statistical methods, leading to optimum results, and forms two software suites (Fig. 4).

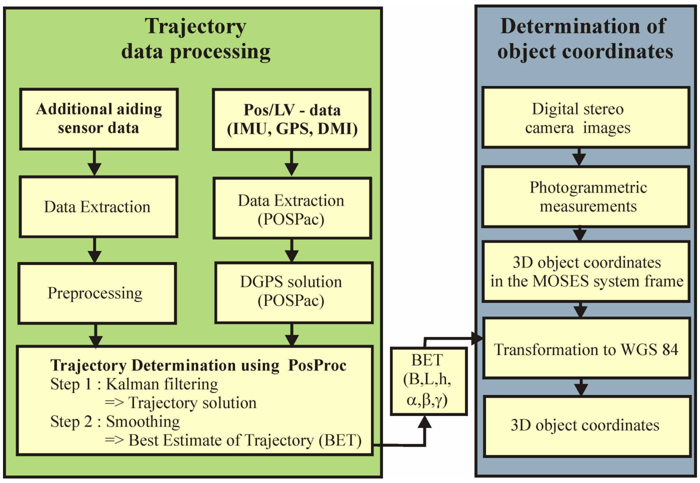

Fig. 4 : Processing of the captured data

4.1 TRAJECTORY DETERMINATION

Aiding sensor data can complement the trajectory sensor data gained with APPLANIX POS/LV. The POSPac software package consists of three main parts:

- data extraction software,
- GPS post-processing software, which determines the necessary DGPS trajectory solution,
- The POSProc filter software containing a strapdown navigator, a Kalman filter and a Bryson-Frazier smoother, which together compute the Best Estimate of Trajectory (BET) blending all data (Scherzinger 1997).

The POSProc Kalman filter can deal with up to 90 states and 23 observables. The configuration, which is employed for processing the MoSES data, captured on highways typical for central Europe, contains 25 states.

4.2 OBJECT COORDINATE DETERMINATION

The second suite of post-mission programs is dedicated to photogrammetric object determination using the calibration and orientation parameters for the cameras. The results of the photogrammetric measurements (Klemm 1997) are local 3D coordinates of all objects of interest within 50 meters distance from the van (Fig. 5). The time required for these measurements depends on the number of objects to be determined in each pair of images. The coordinates are transformed to the WGS-84 coordinate frame using the estimated trajectory parameters for the exterior orientation of the digital cameras. Further transformations to a user coordinate frame may follow.

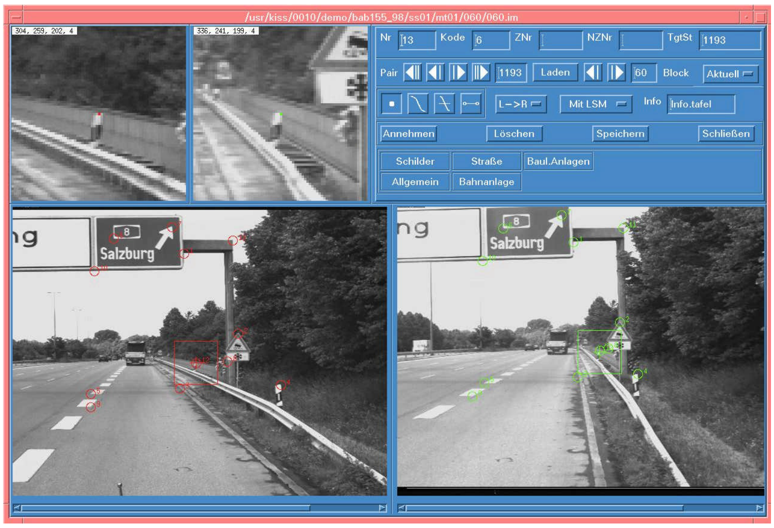

Fig. 5 : Survey of objects along a highway

5 SYSTEM PERFORMANCE

The uncertainty of object coordinates determined by the kinematic surveying system MoSES, depends on the uncertainty of trajectory determination and of photogrammetric measurement. The standard deviation of the photogrammetric object measurements is relatively constant and is expected to be less than 10 cm, depending on the distance of the object and shape of the point of measurement. The main effect on the system performance is the uncertainty of the estimated trajectory parameters. The standard deviation of these parameters varies broadly due to GPS reception conditions.

To evaluate the uncertainty of trajectory parameters, derived from Applanix POS/LV, and the standard deviation of object coordinates, the following investigations are necessary :

a.) Evaluation of the trajectory uncertainty resulting from simulated GPS-outages of different lengths (Section 5.1)

b.) Analysing object coordinate uncertainties resulting from photogrammetry (Section 5.3)

c.) Test of the MoSES system by photogrammetric coordinate determination of known control points and evaluation of trajectory under difficult GPS reception conditions (Section 5.4)

5.1 TRAJECTORY DETERMINATION FOR A LAND-BASED SURVEY SYSTEM

The main problem of trajectory determination is the absence of continuous availability of GPS. To illustrate the conditions, test data was collected driving a typical route near Munich (Fig. 6). GPS coverage is affected by topography, e.g. trees close to the road, houses etc. The GPS statistics (Fig. 7 and 8) show, that trajectory determination in the Middle European environment has to cope with frequent GPS outages lasting up to 120 seconds. Especially difficult for trajectory determination are those GPS outages, which are interrupted by very few GPS fixes of possibly minor accuracy. In the test shown, only in 53% of the travelling time, GPS positions could be obtained.

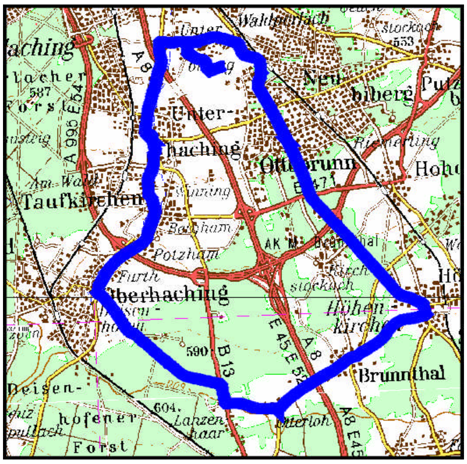

Fig. 6 : Test area near Munich

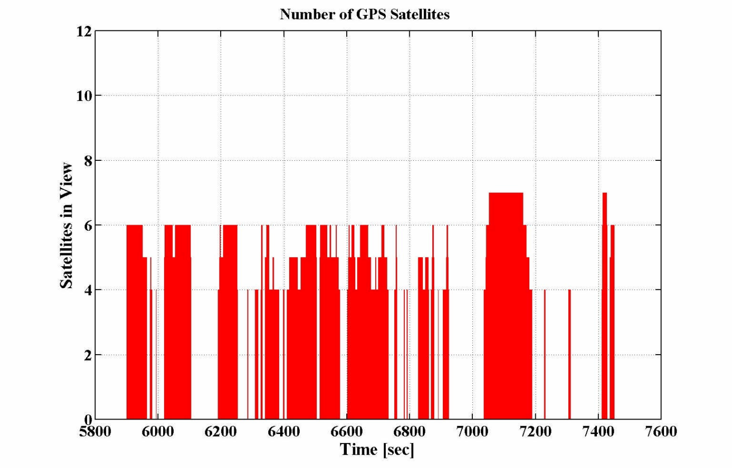

Fig. 7 : Satellites in view

Continuous GPS availability of duration sufficient to calculate an OTF solution is below 20% of the time travelled. There are only two periods with more than 150 seconds of uninterrupted GPS coverage.

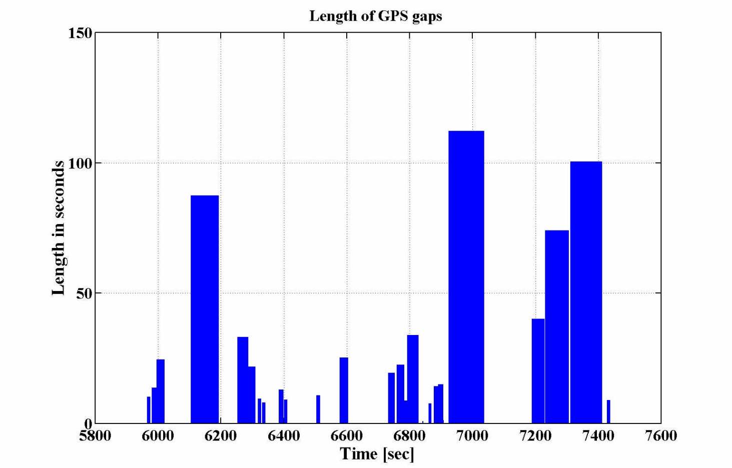

Fig. 8 : Length of GPS gaps

The Applanix software POSProc performs Kalman filtering and smoothing (Fig. 4). To verify the appropriate tuning of the Kalman filter and the weighting of measurements, filter performance was tested under well-defined conditions. The following test setup was used :

1.) Each test route was travelled under full GPS coverage, so that a DGPS On - The - Fly solution could be obtained. The resulting BET trajectory was used as a reference. Position uncertainty is less than 3 cm RMS.
2.) The same trajectory data was processed except for GPS position and velocity information in periods of various length (simulated GPS-outages).

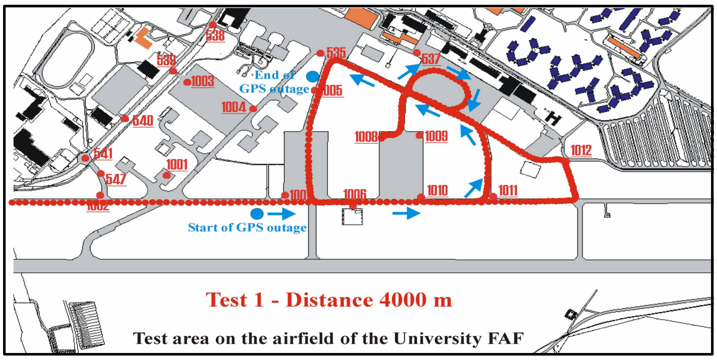

Fig. 9 : University test area - Test 1

The differences between the results of 1.) and 2.) show the filter performance. The tests were carried out at the university test loop.

The Test 1 (Fig. 9) example includes a simulated GPS-outage of 100 seconds, while the van was driving with a maximum speed of 60 km/h, which caused angular velocities up to 30°/s. The results are shown in the following figures and tables.

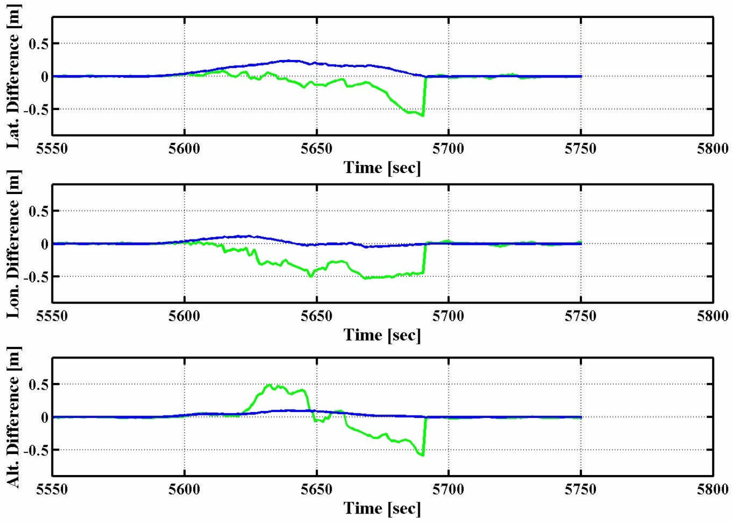

Fig. 10 : Test 1 : Coordinates with and without simulated GPS-outage after filtering and after smoothing

Maximum differences between coordinates with and without outage

	Kalman	BET
Δ_{lat} [m]	-0.61	0.24
Δ_{lon} [m]	-0.53	0.11
Δ_{h} [m]	-0.59	0.10
Δ_{roll} [°]	0.03	0.01
Δ_{pitch} [°]	-0.02	0.01
$\Delta_{heading}$ [°]	0.09	0.02

Table 1 : Test 1

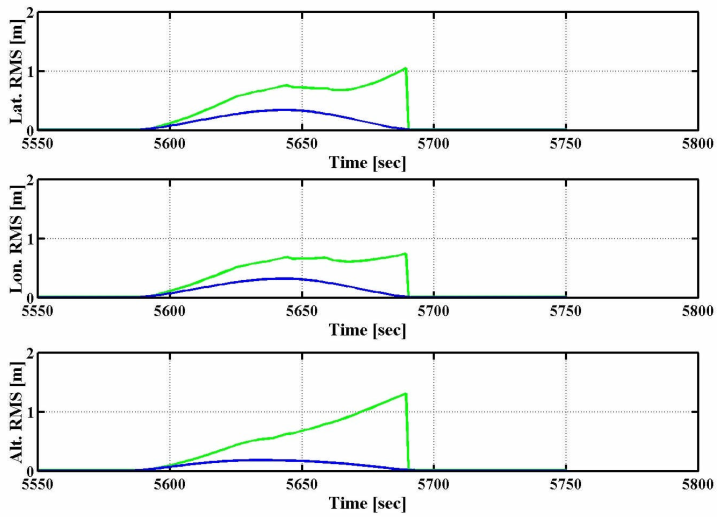

Fig. 11 : Test 1: RMS values with and without a simulated GPS-outage of 100 seconds length filtered and smoothed

Maximum RMS values

	Kalman	BET
σ_{lat} [m]	1.06	0.35
σ_{lon} [m]	0.75	0.33
σ_{h} [m]	1.32	0.19
σ_{roll} [°]	0.03	0.01
σ_{pitch} [°]	0.03	0.01
$\sigma_{heading}$ [°]	0.15	0.05

Table 2 : Test 1

The position differences show the typical error behaviour of a Kalman filter. Without GPS, the IMU sensor data is only aided by the odometer (DMI). Due to small estimation errors in the filter states, the position starts drifting. The resulting difference to the reference trajectory does not exceed 0.6 m for each coordinate (Fig. 10). This is a considerably accurate result. In this test, the GPS-outage of 100 seconds is equivalent to 640 m without GPS. The position errors are greatly reduced by the Bryson-Frazier Smoother. The remaining differences are less than 0.3 m. In contrast to position, roll, pitch and heading are almost not affected by the GPS-outage (Table 1). The RMS error values for the angles (Table 2) are representative for the uncertainty normally achieved by the POS/LV. They do not change during the simulated GPS gap. The sensors for attitude estimation are obviously long-time stable.

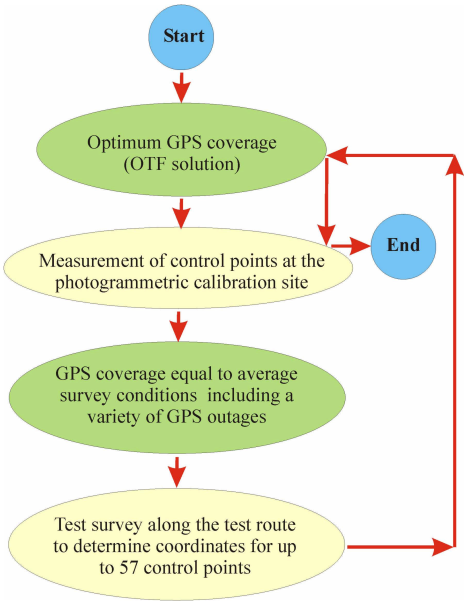

Fig. 12 : Test 2 with the MoSES

The RMS error values for the position (Figure 11 and Table 2) are two to three times larger then the differences to the reference solution (Figure 10 and Table 1). This is an important test result, showing that the RMS-output of the filter is a conservative estimate of the true uncertainty.

5.2 TEST 2 WITH THE MOSES

A reliable estimate of the uncertainty of object coordinates, determined with the MoSES system, was derived from Test 2 combining kinematic road survey with the photogrammetric determination of coordinates of a large number of control points (Fig. 12 and 13).
The test area on the university campus (Fig. 13) offers a variety of GPS reception conditions ranging from dense tree coverage and urban canyon to sections subjected to multipath effects. The test loop is 5 km long. Start and end point are located at the photogrammetric calibration site.

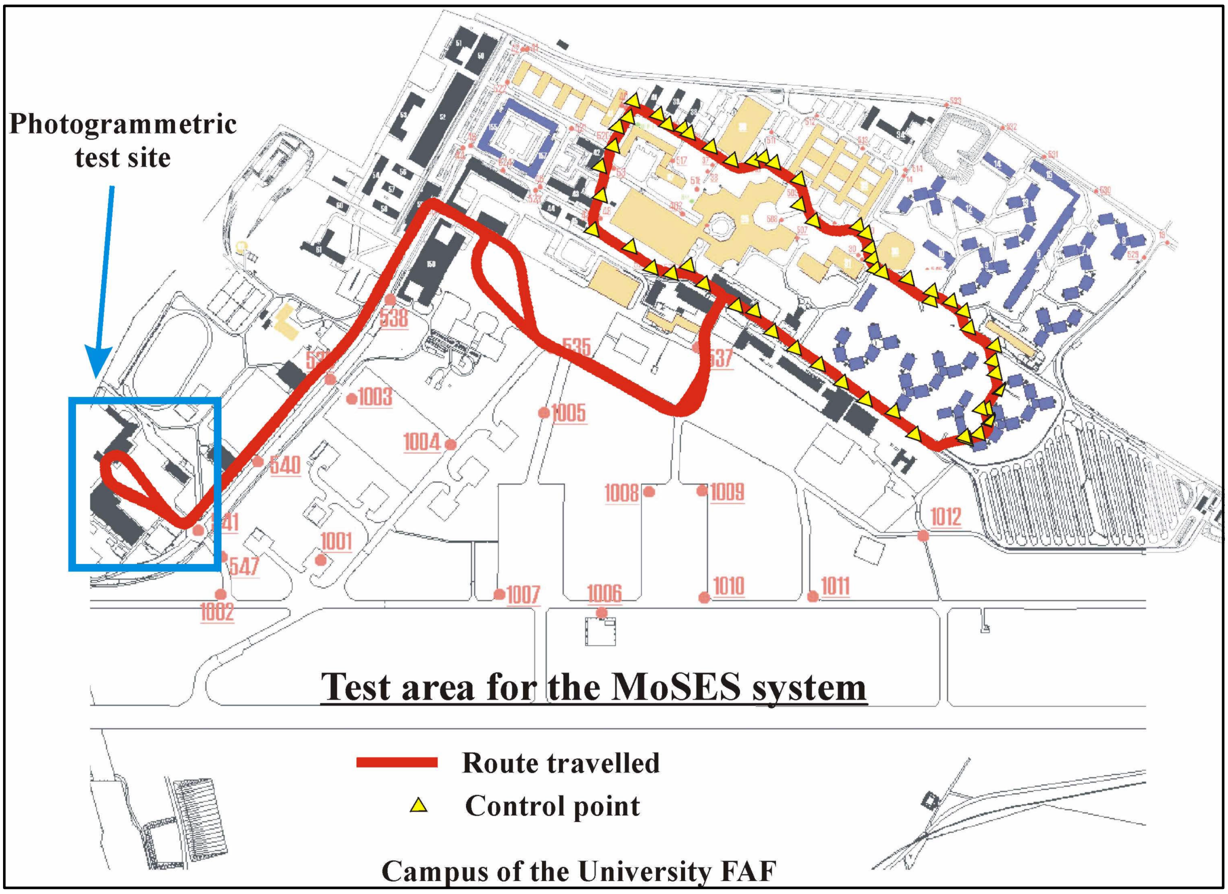

Fig. 13 : Test route of Test 2

Along Test 2 route, coordinates for 57 control points were determined (Fig. 13). These are typical objects to be captured by the MoSES such as streetlights, signs, information boards and so on. On the test route, only GPS fixes of poor quality could be obtained (Fig. 15).

5.3 UNCERTAINTY OF PHOTOGRAMMETRIC COORDINATE DETERMINATION
A smaller, nearly constant contribution to object coordinate uncertainty is caused by photogrammetric measurement errors. As long as the calibration and orientation parameters for the digital cameras are constant, the uncertainty of photogrammetric measurement depends mainly on the distance between object and vehicle. The test results shown here were obtained at distances of less than 30 m. Before and after driving Test 2, the system captured images of the calibration wall.

Fig. 14 : Photogrammetric calibration site with 105 control points

Due to very good GPS coverage, the trajectory in this part of the test was based on an OTF solution leading to an uncertainty better than 5 cm RMS. The images were taken while the vehicle was standing or driving at low speed. The photogrammetric coordinates of a large number of control points were determined several times. Table 3 shows the standard deviation of the result.

	Before Test 2	After Test 2
σ_N [m]	0,08	0,08
σ_E [m]	0,04	0,06
σ_D [m]	0,03	0,04

Table 3 : Standard deviation of the photogrammetric control points

The following conclusions can be made:

1.) The photogrammetric measurement uncertainty for object coordinates is less than 10 cm for North and East coordinates and less than 5 cm for height.
2.) The coordinates were determined before and after driving the Test 2 route. The results are the same. This verifies that the photogrammetric calibration and orientation parameters are stable and well determined.
3.) Table 3 shows the object coordinate uncertainty that can be achieved with the MoSES, if a GPS OTF solution is available.

5.4 EVALUATION OF THE POS/LV TRAJECTORY ON TEST 2 ROUTE
The route of Test 2, located on the university campus, leads through an environment where (Fig. 16) only in 55% of the time travelled GPS positions could be obtained, and many of these have minor accuracy (Fig. 15). The GPS quality factor indicates that the appropriate weighting of the positions for the Kalman filter is not obvious.

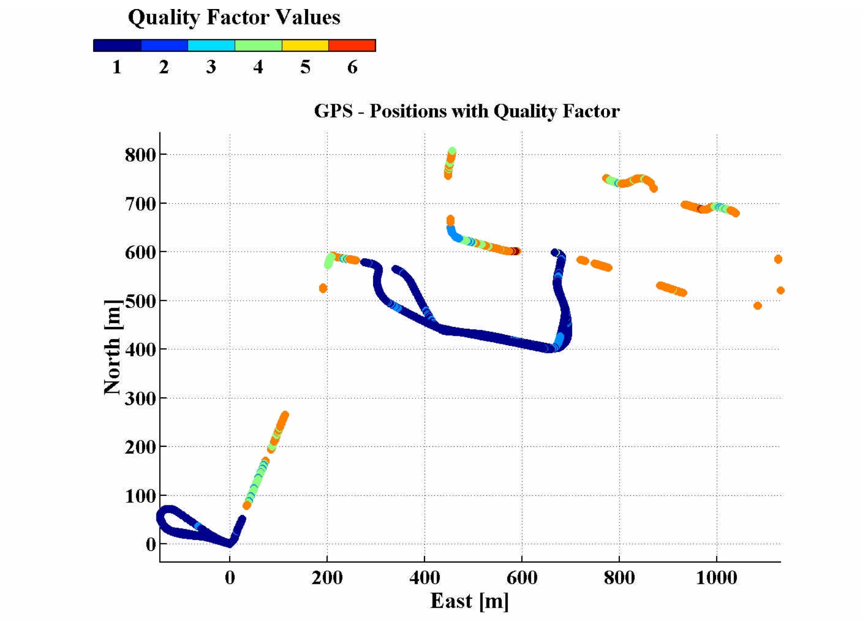

Fig. 15 : GPS positions of Test 2

The RMS error values (Fig. 17) of the filter are less than the values shown in Section 5.1. Based on the computed RMS for the BET solution it can be assumed that the trajectory position uncertainty is equal to, or less than, 20 cm. To verify the object coordinate uncertainty, 46 control points (Fig. 13) were surveyed. The coordinate differences are shown in Figure 18. The resulting coordinate uncertainty is 0.3 m for Northing and Easting and 0.5 m for height (Table 4).

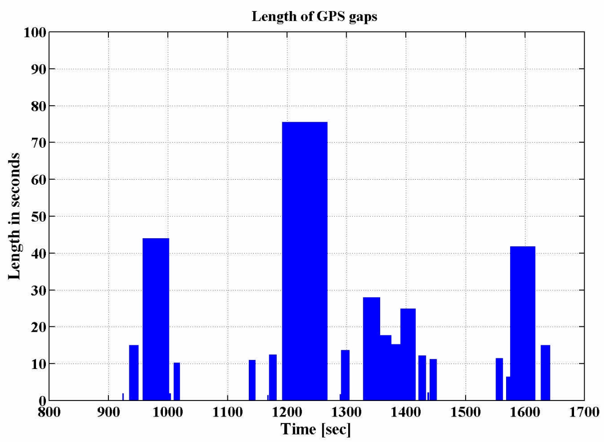

Fig. 16 : Length of GPS-outages

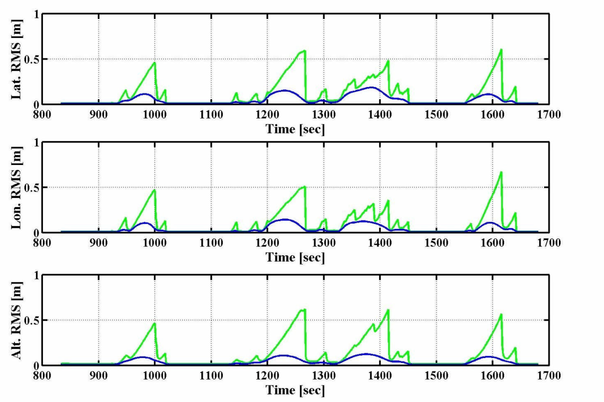

Fig. 17 : POSProc RMS error values of Test 2

This result shows that the desired accuracy of 0.3 m RMS for the MoSES is met even under very difficult GPS conditions. The coordinate error plot (Fig. 18) shows that the errors are not randomly distributed. There is a clear systematic pattern. Poor GPS availability and continuously minor quality of GPS positioning in the control point area (Fig. 15) for a period of 300 seconds (Fig. 16) causes a trajectory shift. Size and direction of the shift vary with time, but adjacent control points in most cases have similar errors. In particular, the northeastern part of Test 2 route shows a systematic shift of about 0.4 m.

	Coordinate error
σ_N [m]	0,28
σ_E [m]	0,26
σ_D [m]	0,49

Table 4 : Standard deviation of surveyed control points

The RMS error values of 0.2 m computed by POSProc are too optimistic, compared with these systematic deviations.

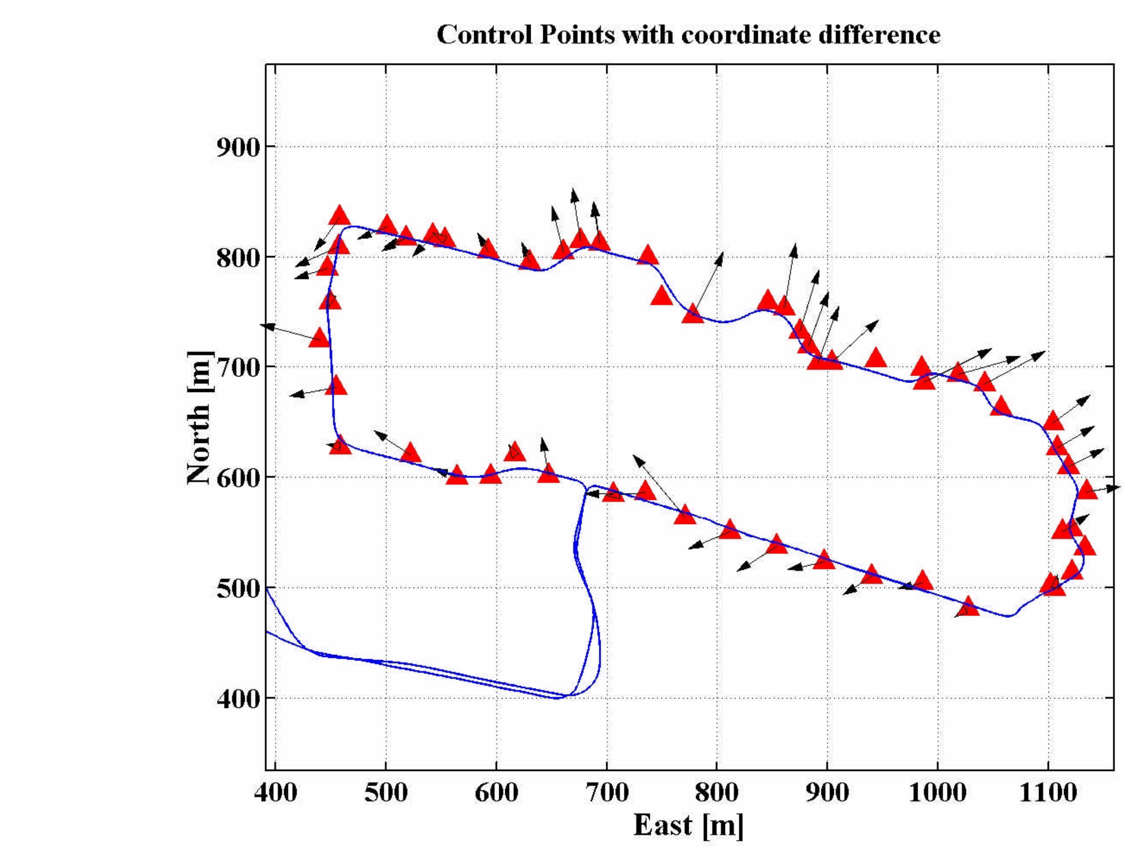

Fig. 18 : Coordinate errors of the control points at a scale of 100:1

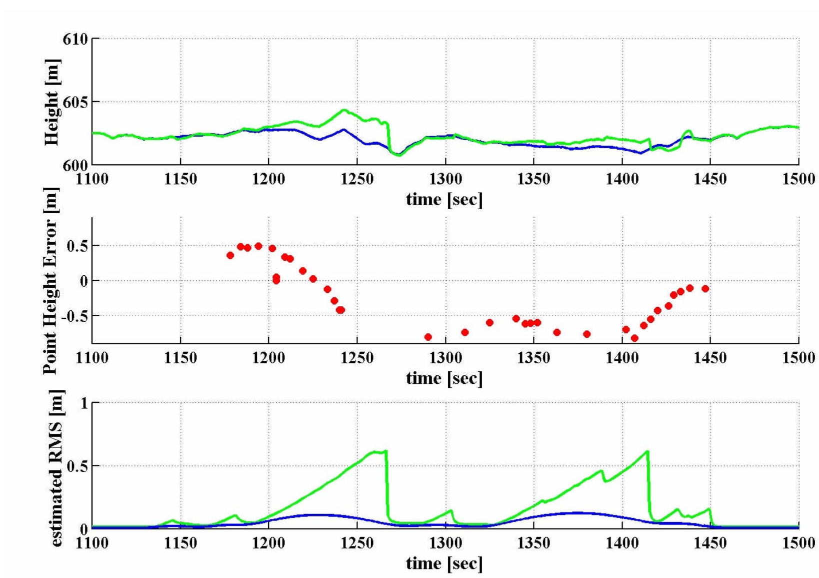

Fig. 19 : Height errors of the control points

The test results show that the error in height is in average two times larger than estimated in the BET solution (Fig. 19). The height channel is always problematic, because it is only GPS aided. Additional barometric data has not yet been used. At poor GPS geometry, the GPS height can some-times be significantly incorrect (Sternberg 2000). This explains the 0.5 m RMS error value for the height.

6 CONCLUSION

The test results show that object coordinates along the route travelled can be determined by the MoSES with a horizontal coordinate uncertainty of 0.3 m and 0.5 m in height even in an environment unfavorable for kinematic GPS. The resulting uncertainty of object coordinates is mainly caused by the standard deviation of the trajectory parameters estimated with the Applanix POS/LV system. The influence of photogrammetry on the resulting uncertainty is below 0.1 m. The POS/LV, along with the efficient post-processing software package POSProc, has proven to be a reliable multisensor system for trajectory determination.

7 OUTLOOK

The evaluation and refinement of the trajectory uncertainty of the MoSES will be continued. It is expected that the new tightly coupled Kalman filter software under development at Applanix will improve results. For the MoSES, in the near future, barometric data will additionally be used to stabelize the height channel.

The development of the MoSES will continue. The implementation of other sensors for road data acquisition is under development as well.

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