COMPARISON OF KINEMATIC PARAMETERS OF A MOVING VEHICLE BY GNSS MEASUREMENTS AND INERTIAL/GPS NAVIGATION SYSTEM

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ABSTRACT:

The kinematic survey with GNSS measurements has known a good diffusion in Italy especially after the new Italian laws about road cadastre. The Laboratory of surveying of Perugia University has deepened the aspect of the road axis survey with GNSS measurements. The analysis has started from a kinematic survey with GNSS measurements at a sampling rate up to 20 Hz. The survey has been performed with three GNSS static receivers beside the surveyed road, and a rover mounted on the roof of a car. All the redundant results (one for each fixed station) have been checked and statistically filtered with semi-automatic procedures. In the next step it has been installed on a van a combined inertial-GNSS measurement system, with a GPS receiver able to process OMNISTAR-HP corrections. It has been possible to compare the solutions in terms of kinematic parameters (coordinates and velocities) from the IMU-GPS system with the same elements derived from GNSS measurements only. A further analysis has concerned the van orientation obtained by means of four GNSS antennas compared with the data deriving from the IMU-GPS system. The vehicle heading is computed from the two GNSS antennas fore and aft on the vehicle axis. Other two antennas are located on the left and right side of the van roof and contribute to both positioning and orientation.

1.INTRODUCTION

The Italian law about road circulation (Codice della Strada) requires since 1992 that the institutions and agencies owning or managing public roads provide themselves with a "Road Cadastre", that is a catalogue, an inventory of all public roads in the country. A further law (D.M. LL. PP. 1/6/2001) states that on a middle to long term the new Road Cadastre has to be coordinated with the existing Land and Building Registration.

The Road Cadastre has compulsorily to contain the geometric elements of the roads and relative pertinences, as the permanent equipments and facilities connected to the traffic exigencies.

The law imposes the road axis to be surveyed as a sequence of points with 1 meter accuracy on the N, E coordinates. For the road axis longitudinal profile, the accuracy of the absolute orthometric heights with respect to the national vertical datum has to be less than 5 meters. The relative height accuracy has to be less than 10 centimeters on 10 meters distance, that is, the slope accuracy has to be less than 1%. The maximum error on the road width has to be less than 10 centimeters.

The law permits to use existing maps, with the only condition that such maps are referred to the national grid. No prescriptions are given about the techniques to be used: as a consequence, a number of variants of Mobile Mapping System (MMS) have been developed expressly for road survey.

MMS are multi-sensor systems integrating in a single platform some navigation/positioning devices with data acquisition sensors of different natures. Initially developed for mapping applications, they are now currently used for many other surveying purposes, also thanks to the contemporary growth of hardware, software and surveying instruments.

The acronym MMV (Mobile Mapping Vehicle) refers to a MMS for multiple applications on a terrestrial vehicle (car, van…).

The data acquisition segment of a MMV for Road Cadastre can be built up with many types of sensors:

– CCD still cameras with a geometric accuracy depending on the sensor resolution; they have completely replaced film cameras, so digitalization is no more necessary;
– video cameras (BW, RGB, IR) and panoramic cameras;
– laser scanners and profile meters for the survey of the surfaces surrounding the vehicle; in particular, for the analysis of the road surface roughness;
– radar and ultrasonic sensors;
– other sensor types for particular applications.

The positioning devices have been introduced in MMS to solve the problem of the exterior orientation of images without GCPs (Ground Control Points) or block adjustment procedures. In MMVs they are used for the georeferencing of all data acquired and, specifically in Road Cadastre applications, for the road axis survey.

For such purpose are generally used GNSS sensors in kinematic mode. If the integer ambiguities are correctly fixed, stable and reliable solutions in terms of positions and velocities can be obtained.

While performing the survey, the moving vehicle can run up against accidental or permanent obstacles obstructing the satellite visibility. For this reason, the MMV are generally also equipped with an inertial sensors platform (IMU = Inertial Measurement Unit), which in such circumstances is capable to supply for short periods position and orientation data replacing the satellite based positioning system. But inertial measures are subjected to a time drift effect that soon leads the solution to diverge from the right position (with a good satellite visibility a GNSS device periodically controls the drift of the inertial sensor of a IMU). Thus, GNSS and IMU integrate each other

in such way that limited sky visibility cannot be tolerated for a long time.

MMVs are also equipped with odometers for direct distance measurement.

Synchronization and data storage devices are also fundamental in any MMS platform, considering the relevant quantity of data being acquired by the multi-sensor system on board.

Different kinds of vectors (cars, vans, motorcycles, airplanes, helicopters, ...) are equipped with MMS depending on applications:

- road vehicles: road cadastre, 3D city models, survey and positioning of infrastructures;
- railway vehicles: control and monitoring of tunnels, survey of level crossings;
- airplane or helicopter: laser scanning, aerial photogrammetry, local surveys in impervious or inaccessible areas;
- walking operator: urban survey with camera and/or laser range finder georeferenced with GNSS sensor.

2. KINEMATIC SURVEY OF A ROAD STRETCH WITH GPS/GLONASS RECEIVERS

One of the lacks of the MMS is the relevance of systematic errors with sensors like INS and odometers, together with the low redundancy of the usual kinematic GNSS technique: with only one base station there is in practice no possibility of control. The GNSS positioning data have no redundancy, while their importance is fundamental for the other devices composing the platform.

Our experience has consisted in the survey of a road stretch of about 7 kilometers, with an antenna placed on the center of the moving car roof, and three base stations located approximatively at the start, the middle and the end of the test run (figure 1). The run has been covered five times in going and return. All the instruments (fixed stations and rover) had the same characteristics: Topcon Legacy-E-GGD receivers and Legant antennas, enabled to the acquisition in double frequency of GPS and GLONASS signals with a 10 Hz sampling rate.

Figure 1 – In red the three reference stations. In blue the surveyed points

The employ of the GLONASS satellites has revealed particularly useful to improve the number of available observations, considering the high incidence of sky obstructions (trees, buildings, ...) along the test road.

The coordinates of the three base stations have been computed through the adjustment of a local network including three permanent stations of the Umbria Region/University of Perugia GNSS network (Perugia, Foligno and Todi).

The data acquired have been elaborated with Geogenius® software by Terrasat®; for each run have been computed three different solutions, deriving from the rover data together with each one of the three base stations.

All solutions have been computed using the OTF (On The Fly, rapid ambiguity solution algorithm) option, in single base mode. The rover to base distances are quite short (less than 10 kilometers), thus only broadcast ephemerides have been used.
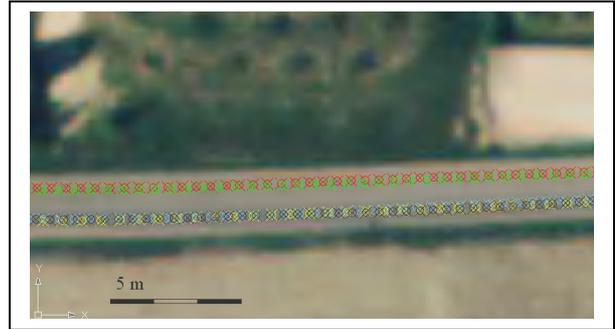

Figure 2 – Particular of some surveyed paths superimposed on a 1:10.000 ortophoto

The values of any parameters (position, velocity, PDOP, satellites number, ...) determined from each solution considering a different base station, have been compared to each other at the same GPS epochs. Considering the relevant amount of data to be analyzed (at 10 Hz, about 3500 epochs for any station/run), some procedures have been implemented for performing in an automatic way on each one of the three solutions the following operations:

- synchronization of the GPS epochs for each one of the different solutions;
- exclusion of the code solutions;
- RMS control: exclusion of the solutions having an RMS bigger than a fixed threshold (e.g.: RMS > 0.2 meters on N, E components and RMS > 0.3 meters on height);
- outliers detection and elimination;
- computation of final averaged positions and reports generation.

The presence of outliers has been evidenced on some positions subsequent to cycle slips, probably caused by an incorrect OTF estimation of the initial phase ambiguities: some positions tend to be shifted, the phenomenon is particularly significant with reference to the distance from the base station (increasing baseline length).

Figure 2 shows a particular of the obtained paths on the two ways of the road and their coincidence, that confirms the final accuracy.

Starting from the positions obtained in the previous phase, the resultant velocity has been computed. In this case, a 1 Hz sampling rate has been chosen, as more appropriate for such analysis. The comparison between the velocities computed by the elaboration software (Geogenius®) by means of the Doppler effect, and those obtained from the derivatives of the positions, suitably filtered in the former phase, shows a better stability of the second ones (figure 3).

Such deepening has been carried out because in road design it is particularly useful to have available such information in

order to understand the behaviour of a driver in relation to the road geometry.
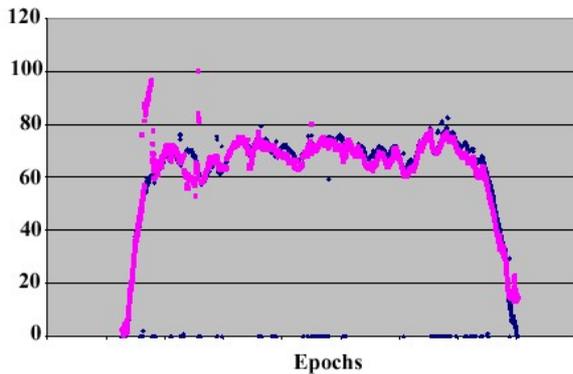

Figure 3 - Velocities (Km/h) computed from positions (blue) vs. velocities estimated by Doppler effect (magenta), for one of the test runs

Figure 4 shows the paths obtained from more drivers (of our car) which describe different trajectories in relation their guide and the road geometry.

Figure 4 – GNSS kinematic survey to study the behaviour of a driver in relation with the road geometry

3.TEST SURVEYS WITH A MMV

In the following phase of the research, a collaboration between the Laboratory of Surveying and the Company Italeco S.p.a. has permitted to test and compare two different positioning systems.
On the roof of a van has been placed a rigid metal frame designed to mount a IMU-GPS platform plus a variable number of GNSS antennas. The IMU-GPS device has been mounted at the center of the frame, and four GNSS antennas (Topcon Legant) have been placed on the four tips of a rumble (fore-aft; left-right). The four antennas have been mounted at the same level through tribrachs and connected to four separate Topcon Legacy GGD-E receivers (figure 5).
The X-axis of the IMU sensor, the centers of the fore and aft GNSS antennas, and the center of the IMU GPS antenna are accurately placed along the longitudinal axis of the van (motion direction). The centers of the left and right GNSS antennas are located along a line perpendicular to the longitudinal axis and passing through the center of the IMU antenna (figure 5).
The four Topcon Legacy receivers are able to acquire double frequency GPS and GLONASS signals at a sampling rate up to

20 Hz. The IMU platform used for the tests is a RT3040 device by OXTS (Oxford Technical Solution). It is composed of three accelerometers, three gyroscopes, a GPS double frequency sensor Novatel OEM-4 with single antenna and differential correction through Omnistar HP. The platform also includes a navigation computer; the operating system is real-time QNX. The main technical specs of the platform are in Table 1. A multifunction cable connects the device to a control computer and permits the input of an odometer (if present), of event markers or 1 pps signal.
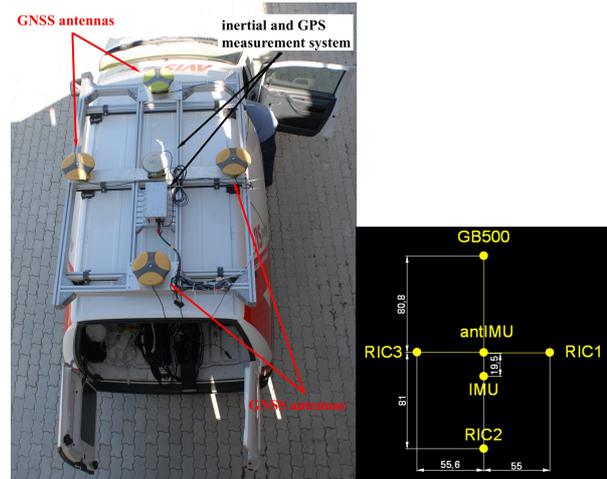

Figure 5 – MMV equipped for the tests and the instruments layout (measurements in cm)

The software supplied with the inertial platform, beside the configuration and post-processing functionalities, permits to display in real-time a number of the observed parameters, which is very useful for the operator during the survey. The motion parameters are estimated at a sampling rate of 100 Hz. The observation coming from the IMU and GPS sensors are elaborated through a Kalman filter using a loosely-coupled approach, the values of position and velocity are directly put in the adjustment process.

Positioning	Omnistar HP
Position accuracy	10 cm CEP
Velocity accuracy	0.07 Km/h RMS
Acceleration	
Bias	10 mm/s² 1σ
Linearity	0.01%
range	100 m/s²
Update rate	100 Hz
Roll/Pitch	0.03º 1σ
Heading	0.1º 1σ (dynamic)
Angular Rate	
Bias	0.01º/s 1σ
scale factor	0.1% 1σ
Range	100º/s
Track (at 50 Km/h)	0.08º RMS
Slip Angle(at 50 Km/h)	0.15º RMS

Table 1 - Main technical specs of the RT3040 platform

The extended Kalman filter (EKF) is composed from a 21-elements state vector (for the RT3040 model): 3 position errors (N-E-H), 3 velocity errors (N-E-H), 3 angles (heading, pitch

and roll errors), 3 gyro biases and 3 scale factors (for X, Y and Z directions), 3 accelerometer biases, and 3 GPS antenna position errors.

Considering the characteristics of the test vehicle, it would be more appropriate referring to it as a POS (Position and Orientation System) rather than a MMV, because the van only mounts GNSS and GPS/INS systems, but no cameras at the present time.

The test have been performed on the same road stretch of the previous experiences. In this case only one base GNSS station has been placed, locating it approximatively at the middle of the path. The instrument was a Topcon Legacy-E GGD with a Dome Margolin D choke-ring antenna.

The observation of the four GNSS receivers have been post-processed with OTF algorithms, in single base mode and using broadcast ephemerides, given the limited baseline length.

A filtering for time synchronization, code, RMS etc. has been applied in a similar way to that described in par. no. 2. In this case only one fixed station was present. Anyway, has been possible to control the obtained positions by verifying the invariance of the mutual distances between antennas, which are known *a priori* and constant in time.

In a first instance, a comparison has been made between the lowest-RMS solution among the four GNSS receivers and the one given by the inertial system. Only the IMU solutions obtained in presence of Omnistar differential corrections have been taken into account for that comparison. A problem is represented by the fact that in areas with frequent obstructions (trees, buildings, ...) the RT3040 IMU system often loses the signal containing the Omnistar HP corrections, transmitted by the geostationary satellite EA-SAT.

Table 2 shows that only for one of the testing runs more than the 50% epochs are Omnistar-corrected (run a). Therefore, the comparison has been performed on that specific run.

10Hz sampling test							
Run	Total epochs	Omnistar corrected	%	sps	%	none	%
a	4.097	2.254	55	1.794	44	49	1
b	3.987	625	16	3.272	82	90	2
c	3.902	692	18	2.961	76	250	6
d	4.651	274	6	4.299	92	78	2

20Hz sampling test							
Run	Total epochs	Omnistar corrected	%	sps	%	none	%
e	7.515	56	1	7.309	97	150	2
f	8.060	148	2	7.790	97	122	2
g	7.829	1.834	23	5.835	75	160	2
h	14.210	6.050	43	7.898	56	262	2

Table 2 –Omnistar correction rate in the four test runs

A recent paper by Hans Visser (2006) underlines the fact that on dynamic Omnistar positioning, an average time of about 24 minutes of continuous contact with the EA-SAT satellite is necessary to obtain a SEP (Spherical Error Probability) of 30 centimeters. If during the run the visibility of EA-SAT is interrupted, then *"... The 30 minute timer is reset EVERY TIME YOU HAVE A BREAK IN THE SIGNAL like a BRIDGE, TREE, BUILDING, etc. You can use it on aircraft and on*

airfields" (from the FAQs of the web site www.OXTS.info). The last words state that the IMU RT3040 system is not the most appropriate for terrestrial surveys in areas with frequent natural or artificial obstacles.

Figure 6a – Particular of the first part of the survey with good and converging solutions
(Green: GNSS points; Magenta: IMU points)

Figure 6b – Particular of a road stretch with no Omnistar correction and evident drift effect (the IMU solution in magenta colour falls out of the road)

Figure 6c – Particular of a road stretch with no Omnistar correction and evident drift effect (the IMU solution in magenta colour falls out of the road)

Such behaviour is confirmed by our experimental results. In fact, in the first road stretch, where the system has just been initialized, the differences IMU vs. GNSS are less than 0.5 meters in the three coordinates (see figure 6a and diagram in figure 8). But since the moment when the obstacles along the road (trees and buildings) start to become relevant and obstruct the EA-SAT visibility, then the differences start to get bigger, clearly showing the IMU drift effect: the inertial system is only

assisted by the undifferenced code positioning having some meters accuracy (see figures 6b – 6c).

On a total of about 400 epochs (at 10 Hz) in the whole run, for a 55% only has been possible to obtain data usable for a significant comparison. Many epochs has been deleted for lack of Omnistar HP corrections (45%), and a smaller number because the GNSS position RMS was too large (RMS > 0.2 m).

Figure 7a – Survey results with GNSS receivers: only seldom gaps have occurred

Figure 7b – Survey results with RT-3040 platform: more gaps are evident

The analysis of the spatial orientation of the vehicle has concerned in particular the heading computation, which only involves the planimetric coordinates, always more accurate than the height in any satellite positioning.

The heading has been estimated for each epoch from the N and E UTM-WGS84 coordinates of the fore and aft GNSS antennas on the vehicle, using the known expression:

$$\theta_{12} = arctg \frac{E_2 - E_1}{N_2 - N_1}$$

The clockwise angle θ is counted from North. The convergence of the meridian has been then added to θ to compute the heading.

The distance between the fore and aft antennas is quite short (1.62 meters). Therefore, it is necessary that the coordinates are accurate to get a good estimate of the heading. For this reason, only the epochs on which the coordinates satisfy the condition RMS < 0.05 m for both receivers have been taken into account. Such strong (but necessary) condition has determined the exclusion of about another 50% of the epochs, but has permitted to get reasonably accurate results for the heading.

On a total of 881 epochs resulting after filtering as described above, the absolute values of the heading differences between IMU and GNSS are less than 1 degree for the 87% of the cases.

The following table 3 contains the more relevant results of the test, and a diagram (figure 9) shows the differences. Most values are concentrated around the zero value (see also the table 3).
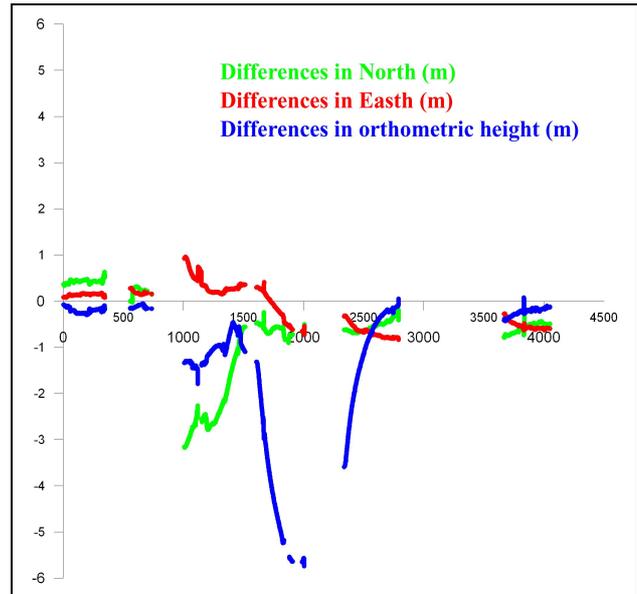

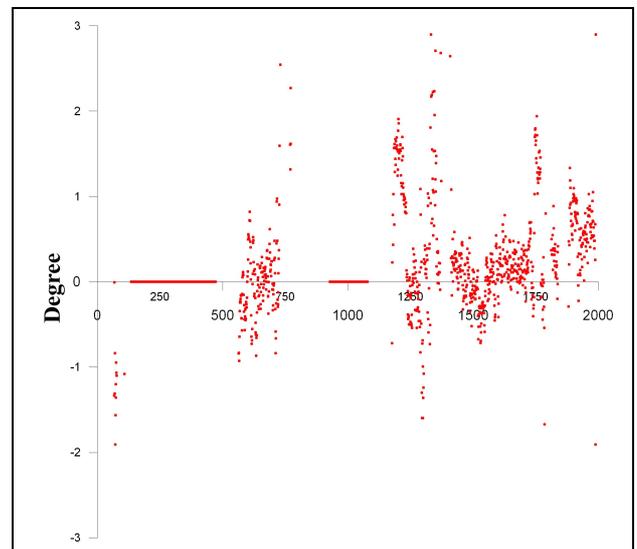Figure 8 Graphs of position differences IMU vs GNSS

Figure 9 Heading differences between IMU and GNSS

HEADING DIFFERENCES BETWEEN IMU AND GNSS (DEGREES)	
Min	-1,91
Max	2,89
Mean	0,26
RMS	0,67

Table 3

4.CONCLUSIONS

The increasing diffusion of MMS and the relevant research carried out on such systems, encouraged in Italy by the law which imposes to the agencies owning or managing roads to build up a Road Cadastre, make the use of such surveying vehicles convenient and reliable for a number of applications.

Our tests show that MMV can also be very useful for road design. A kinematic survey can supply the trajectory and the velocity values on a long run with a relevant accuracy. If the sampling rate is less than one second (values up to 20 Hz are possible) the kinematic data are also quite dense, so that a driver behaviour can be accurately described for long road stretches. Such information permits to perform statistical analyses on a data base comprising many tests for different driving styles, understanding their response to the road geometry in a more complete way than data from fixed roadside stations, which only give a punctual survey.

The first phase of our research, consisting in the post-processing of kinematic data, has shown that some positions, even if flagged as fixed, are characterized by outliers unacceptable if compared with the usual accuracies. A possible solution to this problem is to place more fixed (base) stations along the survey path: redundancy makes a control possible, and a more accurate and reliable survey is obtained. Simple routines can perform data analysis, which volume increases proportionally to the number of fixed stations.

The necessity of a continuous satellite visibility is a limit to the proficiency of MMV surveys. For this reason, also a IMU system assisted by GPS has been tested. It has been possible to compare the road survey obtained by the IMU-GPS integrated system with the other surveys derived from the only post-processing of GNSS observations. The differences are reasonably small for the epoch on which the IMU-GPS platform has received the Omnistar HP corrections, while are greater for the uncorrected epochs.

The short distance between the fore and aft antennas mounted on the test vehicle has partially compromised the heading analysis. Anyway, the research has shown that affordable heading values can be obtained even with GPS only, if the data are adequately processed and filtered.

It is our intention to deepen the knowledge of the IMU system behaviour analysing the instrument drift in the case when it is not assisted by GPS, and to repeat some of the tests using other types of IMU-GPS devices.

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