Development of Loosely-Coupled FOG/DGPS and FOG/RTK Systems for ADAS and a Methodology to Assess their Real-Time Performances

Mikaël Kais (♣), Philippe Bonnifait (♦), David Bétaille (♠), François Peyret (♠)

(♣) INRIA, École des Mines de Paris

(♦) Heudiasyc UMR 6599, Université de Technologie de Compiègne

(♠) Laboratoire Central des Ponts et Chaussées

France

Abstract

This paper tackles the problem of precise car localization for Advance Driver Assistance System applications. Localization is performed by loosely coupling proprioceptive data with exteroceptive perceptions. Two localization systems were designed, one based on Differential GPS and the other on Real Time Kinematic GPS. In both cases, sensor latencies were precisely measured and taken into account to minimize their effects. Track experimentations were carried out with two vehicles at different speeds. A methodoly based on a comparison with a Post-Processed Kinematic GPS reference is presented to evaluate performances of the two systems.

I. INTRODUCTION

The French project ARCOS (*Action de Recherche pour une Conduite Sécurisée*) has gathered during 3 years 58 partners, from the research and from the industry, on the topic of safety-oriented Advanced Driver Assistance Systems (ADAS). Four global target functions were defined at the beginning of the project, among which two of them ("Incidents and accidents Warning" and "Lane Keeping") were using an on-board safety-oriented database and an absolute localization of the vehicle.

A high number of ADAS based upon these two major sources of information can be imagined, from standard navigation systems up to very challenging ones such as autonomous driving systems.

Within ARCOS have been targeted realistic systems, compatible with what could be expected from the development speed of the concerned technologies within 5-10 years from now. As far as positioning technology is concerned, the project has bet upon GNSS[1], which is surely the most promising one, bound to be significantly improved at this time horizon with the arrival of the second generation systems Galileo and Modernized GPS. At the moment, basic performances of GPS are incompatible with the needs of most ADAS in terms of availability and integrity, even if the accuracy (when available) may seem sufficient.

In order to demonstrate the ADAS that have been prototyped in ARCOS and to assess the today reachable performances in realistic conditions, 6 different localization prototype systems have been developed, targeting different functions, with an accuracy ranging from 10m to 30cm. The two most accurate were based upon hybridization between differential GPS (code-differential OmniSTAR, and phase-differential, also called real-time kinematic or RTK) and dead-reckoning sensors (fiber-optic gyrometer or FOG, and odometers). The hybridization pieces of software were designed to be, rather than innovative, as efficient as possible in particular for correcting the latency time of the GPS sensor or smoothing and complementing the GPS positions. Loose coupling has been used intentionally for keeping as much flexibility as possible in terms of the choice of sensors.

Much care has been taken to assess the performances in real environment. The prototypes were installed on test vehicles which were equipped with Post-Processed Kinematic (PPK) GPS systems providing off-line the reference trajectories. Synchronization of all the data allowed the evaluation of both longitudinal and lateral errors.

The paper is organized as follows. Next section depicts the state of the art and the different approach to hybrid GPS data with proprioceptive sensors. Then, two prototypes are described. A particular attention has been given to the management of the latency of the receivers and two approaches have been investigated. Finally, in section IV, a methodology is proposed to assess the performances of the prototypes in real conditions.

II. STATE OF THE ART

Fusion of proprioceptive and exteroceptive perceptions for localization

The localization process refers here to the estimation of position and orientation of a mobile versus time with respect to a reference frame. Two families of perception are usually fused to localize a mobile.

On one hand, **proprioceptive perception** provides time derivative information of position and orientation of the mobile, like linear speed, linear acceleration and angular speed. The proprioceptive measurements must be integrated to compute the relative position and heading of the mobile. This information comes mainly

[1] GNSS stands for Global Navigation Satellite Systems and means here any global positioning system based upon satellites (GPS, GLONASS, WAAS, EGNOS, etc.)

from sensors like encoders, gyrometers and accelerometers, able to run at high rate sampling frequency (typically 5Hz to 500Hz). The simple integration of travelled distance and heading (or heading speed) information refers to dead reckoning (DR). Systematic error like bias in gyrometers and accelerometers or change of the wheel radius for the encoder and random error e.g. sliding of the vehicle, lead the integration to diverge [3].

This is why, on the other hand, proprioceptive perception is generally hybridized with **exteroceptive perception**, which provides position and orientation with respect to a reference frame. This information is generally extracted by matching sensory landmarks with a spatio-temporal model of the position of these landmarks. The nature of landmarks can be various: satellites, like in the GPS system, reflective poles, when a laserscanner is used [8] [11], or even the urban environment in the case of vision [6] [7]. Problem inherent with this kind of sensor is the limited sampling frequency (1Hz to 30Hz) and their availability (e.g. GPS satellite outage).

In order to get the best estimate from the proprioceptive and exteroceptive perceptions, hybridization is performed. It is generally based on a state estimator, like the well known Extended Kalman Filter (EKF) to compute the best estimate.

When the hybridization is realized between the position solutions coming from different sensors, it is called **loose coupling**. When it is performed at a deeper level, for instance at the level of the pseudo-range GPS measurement, it is called **tight coupling**. Tight coupling is generally performing better and allows position improvement even when measurements are not numerous enough to compute a position, for instance when the GPS can lock less than 4 satellites [9]. In the frame of this work, we definitely investigate only loosely coupled hybridization. We also relied on the kinematic constraint that the vehicle is rolling in the road surface without sliding. The FOG gyrometers that we used were medium-class ones, displaying a bias of the order of a few degrees per hour.

Evaluation of localization systems

The evaluation of localization systems is a difficult task, and many research teams do not have appropriate tools to evaluate properly their systems, particularly in the context of accurate positioning for safety applications [13] [5] [4].

For instance, [12], who illustrates what MEMS (Micro-Electro Mechanical Systems) and stand-alone GPS are capable of in terms of continuity and precision of positioning, shows results on graphics that superimpose the trajectory delivered by the described DR-GPS system upon a digital map whose accuracy is (in the better case) similar as that of the system itself. For accurate positioning, digital maps may not provide an adequate reference [13]. Other authors will make the comparison between MEMS-based system and a more sophisticated IMU. For example, [2] computes the error of its prototype with respect to the Honeywell HG 1700 output, which is considered to be a reference accurate enough to assess the MEMS system. But in our case, the specifications of the gyrometers that were implemented (see the next section) are not that different from those of an IMU like the HG 1700, so, it is absolutely mandatory to use a more accurate reference trajectory.

Kinematic GPS, more reliably in post-processing than in real time, can provide a reference trajectory of the vehicle, with an accuracy of one order of magnitude better than that of typical safety-oriented ADAS this article deals with.

Another drawback of most tests results available in the literature concerns the calculation of the error itself. When a reference trajectory exists, this one is usually not time-tagged (in this case, we call it “path”). This means that a given navigation solution provided at time *t* by the system in test can only be compared to the reference by computing a lateral deviation by projecting the point on the reference path. A kinematic GPS path is very accurately time-tagged (in the GPS time reference system), deserving that way the name “trajectory”, and allows the computation of both lateral and longitudinal (or axial) errors.

III. DEVELOPMENT OF LOCALIZATION SYSTEMS

Fusion methodologies

The usual way to fuse proprioceptive and exteroceptive data relies on state observation. A loosely coupled filter (as discussed in this paper) leads to a state representation having a non-linear evolution model and a linear observation equation:

$$\begin{cases} x_{k+1} = f(x_k, u_k, \gamma_k) + \alpha_k \\ y_k = C \cdot x_k + \beta_k \end{cases}$$

Where x_k describes the mobile pose, u_k the proprioceptive data, y_k the GPS data, α_k the model noise, β_k the observation noise and γ_k the input noise. A common approach to solve this problem is to consider the level of noise affecting the sensor. Under the assumption of zero-mean and white disturbances, Kalman filtering and more generally Recursive Bayesian Estimation is the classical tool. Since the evolution model is non-linear and since the proprioceptive data appear in the evolution model, Extended Kalman filtering can be used within the framework of noisy inputs [1].

In addition to the spatial error affecting sensor data, latency time, i.e. the time difference between the measurement by the sensor and its availability for the controller, has to be considered. This latency time has two origins: the time to perform the measurement computation (for a GPS, the time to perform the navigation computation) and the time to transfer the information to the controller in charge of the fusion.

Actually, GPS data have latency time of typically 20ms to 200ms depending on the way the receiver computes its solution (for instance synchronised or extrapolated mode for RTK receivers) and the output baud rate. This induces a spatial distance error of the order of 0.4m to 4m when driving at 20m/s.

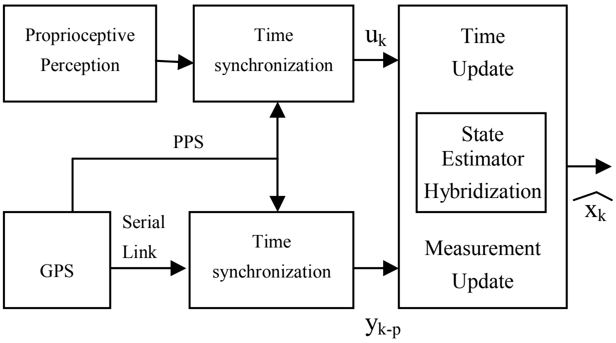

Fig. 1: Overall fusion architecture

Estimation of the latency time is the first important step. For a GPS receiver, it consists in the time between the rising edge of the Pulse Per Second (PPS) signal from the receiver and the reception of the position message. For the proprioceptive perception, the measurement time can generally be considered as negligible for a road vehicle. If the hardware architecture is distributed (on a CAN bus for example), the transmission time of the information to the controller is predominant.

In order to cope with the latency time, it exists roughly three strategies: buffered proprioceptive data, synchronised estimation/prediction mechanism and extrapolated GPS observation. The first two strategies have been studied in this work.

The buffered proprioceptive data approach has been developed for the fusion of the RTK receiver. Each sensor data is precisely time-stamped in a unique timebase then processed by a filter (see Fig. 1). This filter computes the best estimate state of the vehicle given the last available measurements from proprioceptive and exteroceptive perceptions.

Time prediction of the position is computed by integrating proprioceptive perception (time update). When a GPS fixed position is received, it is fused with the Kalman filter (measurement update) to compute the best estimate. To mitigate the effect of latency, the GPS fixed position is not fused with the most recent state of the vehicle but with the state corresponding to the PPS time (hence the measurement time). In the case where the PPS time is not exactly synchronized with the proprioceptive perceptions time, interpolation of the state is performed with the assumption of constant linear and angular vehicle speed. Afterwards, the buffered proprioceptive data and the evolution model are used to estimate the current value of the pose.

The synchronised estimation/prediction mechanism has a different philosophy. First, the GPS latency time has to be bounded. This bound defines the minimum sampling period, which has to be compatible with the dynamics of the system. If it is, the filter implements an estimation/prediction mechanism time-triggered on the PPS signal. At time k, the GPS data corresponding to k-1 are collected. It is used to estimate $\hat{x}_{k-1|k-1}$. Then, a prediction of the state $\hat{x}_{k|k-1}$ is computed using the proprioceptive sensors. This prediction is the output of the filter. One can notice that there are several interests in using a multi-sensor filter. First, the fusion improves the precision. Secondly, it allows performing some prediction by integrating proprioceptive perception and so solves the latency problem of the GPS receiver. Another natural benefit of this approach is that, when no GPS fixed position is available (outage of GPS satellites), the filter continues to integrate the proprioceptive data to compute estimates of the state. In this case, obviously the imprecision of the estimates increases.

DGPS OmniSTAR prototype

This prototype uses the ABS sensors of the two rear wheels and a fiber optic gyro KVH e-core 2000. The differential GPS receiver (a Trimble AgGPS132) is used at 5 Hz on a RS232 link. The PPS signal trigs the computation. As the Satellite Base Augmentation Systems (SBAS) like WAAS seem to be very well adapted to car localization, Omnistar corrections available on Europe have been used (EGNOS service was yet operational). In this system, a geostationary satellite broadcasts pseudo-range corrections of several base stations. Thanks to this information, the receiver builds the corrections of a Virtual Reference Station (VRS) near to its position.

The development methodology of this localization system relies on rapid prototyping. First tests have been carried out in order to log the data of the sensors during characteristic scenarios with an experimental car (Fig. 2) Afterwards, several algorithms have been tested with Matlab. Considering vehicle dynamic, it turned out that a 5Hz sampling frequency is enough to compute dead-reckoned pose estimation (ABS and gyro).

Fig. 2: The UTC-STRADA vehicle

A coherence test has been introduced, at the measurement update stage, to eliminate incoherent GPS fixed position due to multipath for example.

The prototype implements a real-time version of the synchronised estimation/prediction mechanism that eliminates the GPS latency. It is a 5Hz, C++, WIN32 and multi-thread application running with a "time critical" level of priority.

RTK Prototype

The INRIA LARA vehicle (Fig. 3) is a Twingo car from the Renault car maker. Proprioceptive sensors sampled at a frequency of 20Hz consist of the pulse from the output of the gear box for the linear speed estimation and a FOG KVH e-core 2000 gyrometer for the angular speed estimation. Exteroceptive perception comes from an Ashtech/Thales ZExtrem RTK receiver set to 1Hz update and linked by GSM to the reference station located at the INRIA Rocquencourt campus (8km baseline). The state of the Kalman filter comprises the position of the reference point of the car in 2D as well as the heading angle.

Proprioceptive and exteroceptive perceptions are timestamped by a low level controller, a MPC555 of the power PC family. The data are sent through a CAN bus to a personal computer running the RtMaps software platform [10]. RtMaps is a C++ object-oriented prototyping platform for automotive application. Outputs of the system are the position, orientation of the vehicle and related imprecision. This information can be displayed on a map with a decimeter accuracy recovered from a Geographic Information System (GIS) server.

Fig. 3: The INRIA-LARA vehicle

IV. Dynamic Assessment of the Prototypes

As stated previously, the true trajectory is considered to be given by a kinematic GPS survey of the vehicle in test. At this stage of the paper, we can underline the interest of PPK instead of RTK GPS. Actually, PPK enables the recovery of the trajectory that is necessarily lost during real-time initialisation and re-initialisation. Particularly, post-processing of raw data could enable solutions to be computed immediately after outages of satellites, leaving only blanks during these outages. RTK would have given such solutions (i.e. would have fixed on the fly the ambiguities) only after a minimum of let say 20s.

Back to the analysis of the performance of the system in test. Figures 4 and 5 illustrate the difference between the comparison of paths and the comparison of trajectories. The axial deviation is obviously dependent on the carefulness when engineering the DR + GPS filter.

- The first way to process the data consists in comparing the paths. The computed vectors are HG, where H are the orthogonal projections of the system solutions noted: G (Fig. 4). The lateral deviation that is derived is particularly relevant to appreciate how much the location may diverge during GPS outages. In a 3-dimentional scheme, the vertical deviation could be derived similarly. In the frame of the experiment reported in this paper, the vertical dimension is unused.

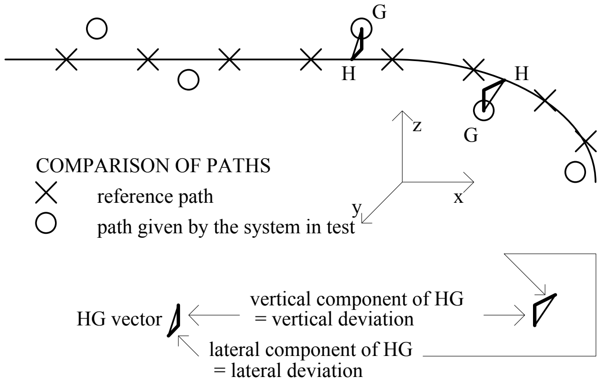

Fig. 4: Comparison of paths

- The second way to process the data consists in comparing trajectories. The computed vectors are SG, where S are reference positions synchronised with the system solutions noted: G (Fig. 5). Such a comparison is also called "point to point". It is particularly relevant to evaluate the lag between the system solutions and the reference positions when the system solutions are available (a lag that is due to the latency time and the vehicle speed).

Point to point deviations mean comparison of reference data and system in test data at the same time. To do so, both data are time tagged with UTC time, by means of logging on the acquisition PC the output of the system in test and the PPS signal provided by a GPS receiver on-board (either that included in the DR-GPS system in test or that used for kinematic GPS post-processing).

Computations made are the following:

- Linear interpolation of the solutions given by the system in test at the same epochs as the PPK solutions (this is needed because a priori the tested prototypes are driven by their own clock, that is of course different from that of the receiver used for GPS raw data logging on-board);
- At this stage, the asynchronous issue is solved: we have 2-dimentional co-ordinates of both reference (x_{PPK}, y_{PPK}) and prototype (x_s, y_s) at the same epochs ;
- Computation of the deviations $e_x = (x_s - x_{PPK})$ and $e_y = (y_s - y_{PPK})$ in Lambert 93 co-ordinates (Lambert 93 is used in France for direct plane projection of GPS geographical co-ordinates in the national reference system RGF-93);
- Computation of the deviations $e_a = (a_s - a_{PPK})$ and $e_l = (l_s - l_{PPK})$ where « a » denotes the axial projection

and « l » denotes the lateral projection. The movement of the vehicle is mainly carried by the axis « a » (the vehicle lateral slipping and vertical heave are neglected) and the left hand orthogonal axis corresponds to the axis « l » ; e_a and e_l deviations are computed from e_x and e_y and the heading. The heading is computed from the PPK reference trajectory;

- Computation of min, max, standard deviation and mean value of the axial and lateral deviations.

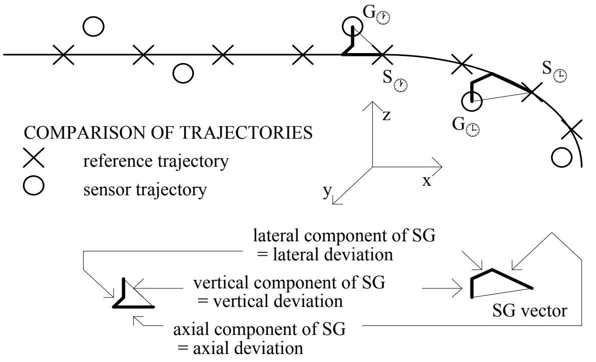

Fig. 5: Comparison of trajectories

Note: the axial, lateral (left hand) and vertical unit vectors compose what is usually called the RPY frame (for Roll, Pitch and Yaw) or "Frenet" frame.

V. RESULTS

The data sets that we chose to report in this paper correspond to 2 tests performed at 2 different average speeds: 10m/s and 20m/s. The test track on which we performed the experiments is located near Versailles, and it is used by LCPC amongst other public and private users, civil or military. Its length is approximately 3.5km. Fig. 6 shows a plane projection of the track in Lambert 93 plane co-ordinates.

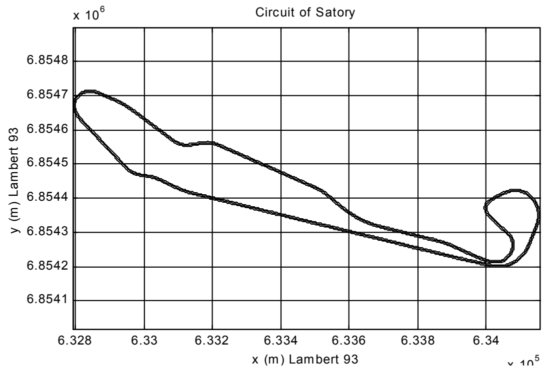

Fig. 6: Plane projection of the test track

GPS raw data were logged on-board and at a local base station with a pair of THALES L1/L2 6500 receivers and NAP 2 lightweight antennas.

Results of the hybridization based on Omnistar DGPS

Table 1 presents the statistics on the deviations, both lateral and axial, at the 2 speeds, for the raw DGPS system and for hybridized system. Deviations are in m and speeds in m/s.

		min	max	**std**	**mean**	speed
axial dev.	**DGPS**	-3.81	-0.01	**0.49**	**-0.79**	10m/s
		-3.33	0.31	**1.25**	**-0.89**	20m/s
axial dev.	**hybrid system**	-1.02	0.49	**0.26**	**-0.21**	10m/s
		-1.51	1.48	**0.41**	**-0.21**	20m/s
lateral dev.	**DGPS**	-2.26	5.33	**0.62**	**-0.53**	10m/s
		-3.55	1.70	**0.89**	**0.35**	20 m/s
lateral dev.	**hybrid system**	-2.02	3.52	**0.69**	**-0.08**	10m/s
		-4.59	2.17	**0.84**	**0.31**	20m/s

Table 1: Performances of the DGPS prototype

It can be seen from this table that the improvement of the hybridization is particularly significant upon the axial deviation, denoting the importance of the prediction function of the filter, this phenomena being amplified by the speed, as expected. Fig. 7 shows time series of the deviations for the 20m/s test and illustrates the smoothing and latency correction of the filter on the axial deviation.

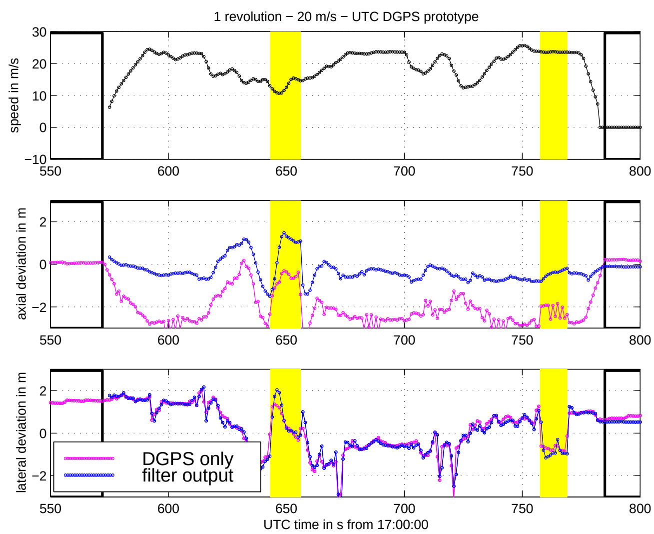

Fig. 7: Axial and lateral deviations, for hybrid system (–) and DGPS (–) outputs

DGPS outage corresponds to corrections aged 30s or more (is the current configuration of the receiver). In this case, the output solutions are autonomous and they are used by the filter. Two outage periods of approximately 15s happened during this test, highlighted in yellow in the deviations time series (Fig.7).

The bias can be explained by the OmniSTAR geodetic reference system that does not match exactly with the French one used for the PPK base station.

Results of the fusion based on RTK GPS

Table 2 presents the statistics on the deviations, similarly to Table 1.

		min	max	std	mean	Speed
axial dev.	**RTK**	-2.17	0.01	**0.80**	**-1.35**	10m/s
		-5.36	0.01	**1.94**	**-1.79**	20m/s
Axial dev.	**hybrid system**	-0.73	0.80	**0.21**	**0.00**	10m/s
		-1.78	0.76	**0.25**	**-0.01**	20m/s
lateral dev.	**RTK**	-1.49	0.56	**0.13**	**0.01**	10m/s
		-2.11	1.61	**0.36**	**0.02**	20m/s
lateral dev.	**hybrid system**	-0.26	0.43	**0.07**	**-0.01**	10m/s
		-1.20	1.66	**0.27**	**-0.03**	20m/s

Table 2: Performances of the RTK prototype

One can note from this table that the hybridized system outputs almost zero-mean errors with a standard deviation of 25cm or less, on both axial and lateral deviations, illustrating the excellent performances of RTK GPS. Both “float” and “fixed” ambiguities RTK solutions are input in the filter.

Figure 8 shows time series of the deviations for the 20m/s test and illustrates the smoothing and latency correction of the filter on the axial deviation, even more efficient than for DGPS prototype, since the latency time is here twice bigger (200ms vs. 100ms) because of the relatively low baud rate used (9600bit/s).

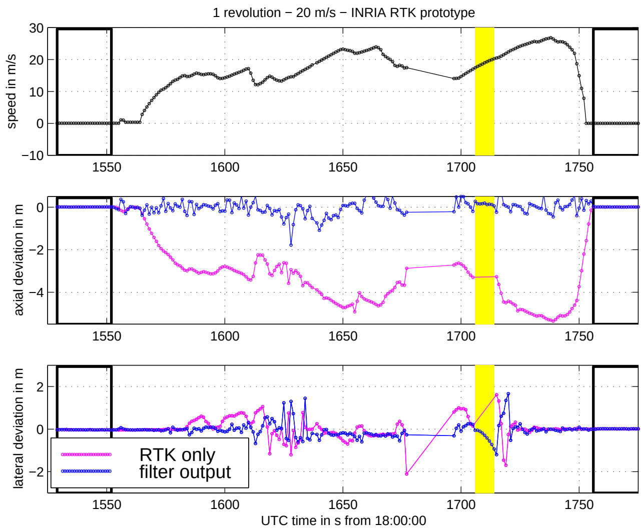

Fig. 8: Axial and lateral deviations, for hybrid system (−) and RTK GPS (−) outputs

One RTK outage period of 10s happened during this test, highlighted in yellow in the deviations time series. Note that, just before it, another mask affected both RTK and PPK processes. No result is given there.

VI. Conclusion and perspective

This article is an extract from experiments that were carried out at the end of the French research project ARCOS, dedicated to ADAS. It presents the results obtained by 2 of the 6 prototypes that have been developed during the project, the most accurate ones, relying upon EKF hybridization between differential GPS and dead-reckoning sensors.

It also stresses:

- The importance of a good correction of the GPS latency that can be obtained through the prediction function of a Kalman filter, thanks to a good time-tagging of the measurement data,

- The interest of establishing a reference trajectory with a post-processed kinematic GPS, to be able to synchronize all the data, to compare the positions “point to point” and to compute the axial deviation which is often left apart because of lack of suitable methodology.

As far as accuracy is concerned, the DGSP-based systems proved to be capable of roughly 1m accuracy, whereas the RTK-based one proved to be four times more accurate, with a mean error close to zero and a standard deviation of 25cm or less. Although this accuracy can be considered as sufficient for challenging ADAS such as lane-keeping systems, the associated integrity level is far from being acceptable. Only the combined used of Galileo + GPS in the hybridized localization systems, in association with advanced real-time integrity monitoring software, could guarantee a reliable use of positioning information for safety-oriented ADAS.

In this paper moreover, is not addressed the issue of the long-term accuracy in pure dead-reckoning mode during long lasting GPS outages. It is foreseen to write another paper on this important point.

VII. References

[1] Ph. Bonnifait, P. Bouron, P. Crubillé, D. Meizel. "Data Fusion of Four ABS Sensors and GPS for an Enhanced Localization of Car-like Vehicles", IEEE IROS, 2001.

[2] Alison K. Brown, Navsys Corp., “Test results of a GPS/inertial navigation system using a low cost MEMS IMU”, Proceedings of 11th Annual Int. Conf. on Integrated Navigation Systems, 2004.

[3] J. Borenstein, H.R. Everett and L. Feng, “Where am I ? – Systems and Methods for Mobile Robot Positioning”, internet ressource, March 1996.

[4] F. Chausse, V. Voisin, J. Laneurit, R. Chapuis, “Centimetric localization of a vehicle combining vision and low cost GPS”, MVA, 2002.

[5] Sio-Song Ieng and Dominique Gruyer, “Merging lateral cameras information with proprioceptive sensors in vehicle location gives centimetric precision”, ESV, 2003.

[6] M. Kais, S. Morin, A. De La Fortelle and C. Laugier, “Geometrical Model to Drive Vision Systems with Error Propagation”, ICARCV, 2004.

[7] M. Kais, S. Dauvillier, A. De La Fortelle, I. Masaki and C. Laugier, “Towards Outdoor Localization Using GIS, Vision System and Stochastic Error Propagation”, ICARA 2004.

[8] C. Pradalier, and S. Sekhavat, “Concurrent matching, localization and map building using invariant features”, IEEE IROS, 2002.

[9] B. M. Scherzinger, “Precise Robust Positioning with Inertial/GPS RTK”, ION, 2000.

[10] B. Steux, P. Coulombeau, and C. Laurgeau, “RtMaps: a Framework for Prototyping Automotive Multi-Sensor Applications”, IEEE IV, 2000.

[11] D. Wang, C. Low, B. He, and M. Pham, “Accurate Positioning for Real-Time Control Purpose: Integration of GPS, NAV200 and Encoder Data”, ICARCV, 2004.

[12] C. Wood and O. Mace, Neve Technologies Pty Limited, “Dead reckoning keeps GPS in line”, GPS World, May 2001.

[13] J. Wang and C. Wilson, “Integration Challenge Safety at the wheel, Improving KGPS/INS Performance and Reliability”, GPS World, May 2003.