A Study on Robust Navigation by Means of GNSS, Network LTE and INS Integration

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Abstract

This paper summarizes the results of the exploratory research work performed by Airbus Defence and Space (ADS) in the context of the EMPHASIS project (EMPowering Heterogenuous Aviation through cellular SIgnalS), which aimed at developing innovative technologies to increase safety, reliability, and interoperability of General Aviation/Rotorcrafts (GA/R) operations. ADS contribution focused on the development and implementation of signal processing and navigation algorithms for real-time network-based radio aircraft positioning and tracking – specifically, real-time joint wireless-network and GNSS based positioning approaches aided by Inertial Navigation Systems (INS). This activity was an opportunity for ADS to upgrade its company-own end-to-end navigation simulator tool "PIPE", in order to be able to process wireless positioning signals and perform hybrid GNSS-network LTE navigation. Results obtained from simulations of integrated GNSS, network LTE and INS navigation in representative urban scenarios are presented. It is shown that positioning accuracy below 5m can be obtained in difficult scenarios with poor satellite visibility if GNSS is integrated with LTE and INS.

Keywords

Hybrid GNSS, LTE, INS, GA/R, sensor fusion, robust navigation, positioning, PNT, filterbank, RAIM.

1. Introduction

The project EMPHASIS (EMPowering Heterogenuous Aviation through cellular SIgnalS) was funded by the SESAR Joint Undertaking (SJU) and run over two years (throughout 2018 and 2019) within a consortium of 4 companies and institutions led by Honeywell and including Evektor, Tampere University of Technology and Airbus Defence and Space (ADS). The key objective of the project was to develop innovative technology to increase safety and reliability of General Aviation/Rotorcrafts (GA/R) operations, and their interoperability with both commercial aviation and emerging drones operations. These aspects are foreseen as critical to secure and improve airspace access for GA/R users in future airspace environment and increase the safety of their operations. This objective was addressed by exploring affordable CNS capabilities tailored for GA/R users, focusing in particular on the use of telecommunication infrastructure and mobile networks for data-link and positioning, low power ADS-B concept, obstacle/terrain hazards detection, and possible alternative certification approaches. Results of the different work packages and general information on project and consortium can be found in [1-3].

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ADS work focused on the development of network based navigation techniques and their integration with GNSS to maximize navigation performance for GA/R applications, in particular in terms of availability and integrity in challenging (urban and sub-urban) scenarios. Assessment of GNSS-only positioning accuracy and availability for flying vehicles in a multi-GNSS scenario was performed in ADS through simulations and measurement results from an urban mobile campaign, confirming the weaknesses of GNSS-only navigation. Following, ADS activities proceeded with: an analysis and discussion of wireless communication channel models and algorithms for generating radio channel simulations; a review of viable strategies of INS/GNSS fusion, to aid GNSS navigation in sub-urban and urban environments; an assessment of the existing network based positioning algorithms; and a study on viable methods to monitor the integrity, quantify the integrity risk and maximize the robustness of navigation. GNSS weaknesses in urban and sub-urban environments, even when using precise multi-GSNS multi-frequency carrier-phase based techniques (PPP, PPP-RTK), are well known in the scientific community [4,5]. Similarly, positioning in the 4G and 5G era is topic of an extensive literature (see e.g. [6-11]), which has been extensively reviewed in the frame of EMPHASIS project. An overview of the INS system and of the different INS/GNSS coupling strategies is provided in [12], whereas robust filtering techniques and integrity monitoring methods, of paramount importance for navigation in aviation and overall for Safety of Life (SoL) applications, are presented for instance in [13,14].

In the framework of this project, ADS had the opportunity to upgrade its in-house developed simulation tool “PIPE”, dedicated to GNSS navigation, to be able to generate 4G signals, process them and integrate the ranging information into INS and 4G-aided PVT. After upgrading of the simulator software, analyses were run in simulated challenging navigation scenarios, e.g. with occurrence of anomalies and presence of external attacks (spoofing), to assess the navigation and the integrity monitoring performance of the chosen robust GNSS+INS+4G navigation algorithm.

The paper is organized as follows: in section 2 the integrated navigation solutions proposed by ADS are discussed. First the network-based navigation concepts and methods studied and implemented by ADS are described, next INS and integrated GNSS/INS navigation are discussed and finally hybrid GNSS, INS and network LTE navigation algorithms and software implementation are described. In section 3 the simulations set-up and results are discussed. Conclusions are given in section 4.

2. Integrated Navigation Solutions

2.1. Network-based Navigation

After reviewing different existing network-based positioning techniques, the Time Difference of Arrival TDoA was the preferred choice for software implementation, since it is the most promising in terms of achievable positioning accuracy. Such technique, which was the downlink positioning procedure foreseen in the LTE specification Release 9 [15], uses the difference in the arrival times of downlink radio signals from multiple base stations (BS) to compute the user position. The LTE technology included new positioning methods in later specification releases, of which still the most promising methods, in terms of expected horizontal accuracy, are those based on ranging measurements, e.g. Assisted GNSS (A-GNSS) and TDoA. Only A-GNSS has so far been successful, as all the other methods require additional infrastructure or mobile device modifications, which have limited their deployment. However, ranging-based localization is foreseen to be a fundamental functionality for future high positioning accuracy applications in 5G. Determining the achievable localization accuracy in LTE can provide an indication (or better a lower bound) for the performance of future 5G networks’ localization services.

The PRS signals PSD and CCF were modeled and simulated in a Matlab software implementation, and lower bounds on the range accuracy obtainable were obtained by means of Cramer-Rao bound approximation. Figure 1 shows PSD and CCF results obtained for PRSs simulated on Matlab software, Figure 2 shows the Cramer-Rao bound for two different bandwidths (~1 and 10 MHz).

However, these results can be representative of the actual ranging performance of LTE signals only in ideal conditions of Line of Sight (LoS) signal reception, with no errors coming from the propagation in the medium others than space losses. In urban environments, although the TDoA method is still the most accurate cellular-based location method in LTE, its position accuracy is mainly limited due to dense multipath. Experimental field measurements in [6] already show the effects of harsh environment on the positioning. There are two main and complementary strategies for multipath mitigation: based on the position calculation, and based on time-delay estimation (TDE).

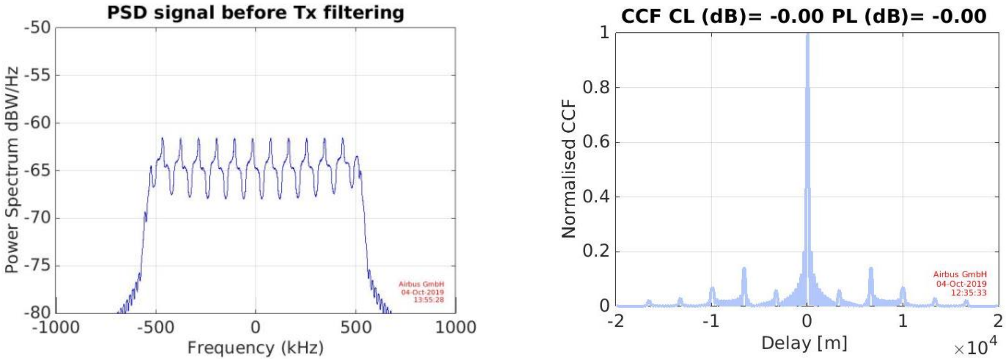

Figure 1 - PSD (left) and CCF (right) of a LTE PRS signal of ~1MHz bandwidth (Matlab simulation).

These methods are presented in detail in [7,8].

Multipath is the major source of ranging bias in urban environments, due to the blockage of the LoS signal. Figure 3 shows the expected range accuracy of 4G PRS signals as estimated in [7], for different multipath models and tracking methods, and for different signal bandwidth. Only at the largest bandwidths the range accuracy is better than 10m. An equivalent multipath error model was introduced in ADS scenario simulator within the company own software PIPE (discussed in next section).

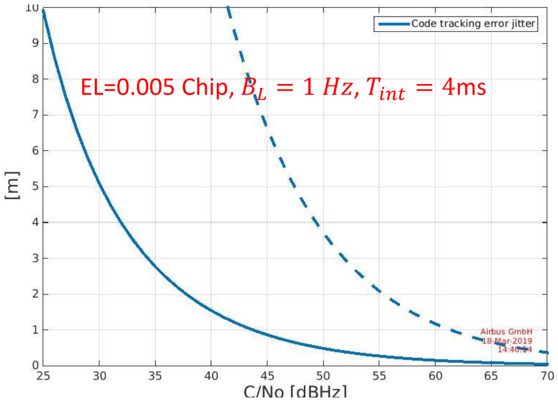

Figure 2 - Cramer-Rao bound for LTE PRS signals, with 1 MHz (dashed line) and 10 MHz bandwidth.

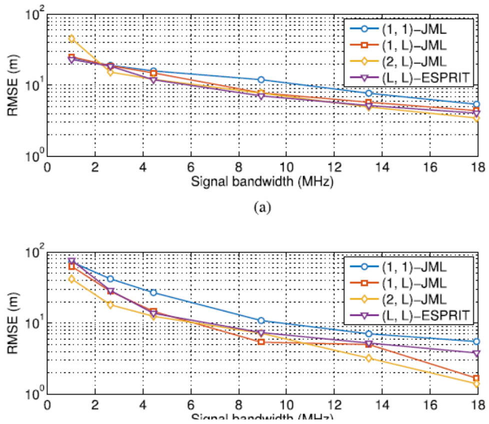

Figure 3 - Expected range accuracy of 4G PRS signals as estimated in [7], for different multipath models (top, EPA channel model, bottom, ETU) and tracking methods (in different colors), and for different signal bandwidth

2.2. Inertial Navigation

INS/GNSS fusion can provide aid to GNSS navigation in sub-urban and urban environments, where satellite visibility is obstructed and multipath/NLOS errors are prevalent. INS/GNSS fusion is particularly helpful in enhancing the integrity of the navigation solution, as the INS provides redundancy of measurements in all navigation scenarios, it cannot be spoofed (differently from GNSS), complementing GNSS in most aspects (especially in bridging outages). Among the different INS/GNSS fusion implementation strategies, the tight-coupling scheme was deemed the most suitable for a reasonably low-cost solution for commercial drones. Main reasons are that it allows to use GNSS observations to aid positioning also when less than 4 satellites are visible, it allows the implementation of filter-bank integrity monitoring techniques, which guarantee integrity in case of Slow Growing Errors (SGEs), and it is a solution commercially available, at reasonably low costs. INS limitation lies in the fact that it can only bridge GNSS outages for a limited amount of time. INS only positioning accuracy in fact diverges rapidly with time, and when using low-cost IMU the positioning error in absence of GNSS observations, or in presence of only few of them, can grow over 1m in few tens of seconds. As a result, an external aiding – for instance, from the cellular network – will be necessary, at least in some specific areas of operation.

2.3. Robust positioning and integrity monitoring

Among the Integrity Monitoring (IM) algorithms reviewed during the EMPHASIS activities, an eRAIM approach [13] and a filterbank approach [14], based on adaptive filtering, were chosen for software implementation. The second is relatively heavy computationally, but is also the most robust against anomalies affecting the system. PPP/PPP-RTK techniques (carrier phase based positioning) were also reviewed within the scope of the project, as they represent absolute precise positioning techniques that do not require extra infrastructure (close-by reference stations/network). The advantage of PPP/PPP-RTK is a sensibly increased accuracy (in GNSS-available areas), better than 10cm horizontal and 20cm vertical, however the same limitations (availability of positioning) of any GNSS-based positioning technique are still present in challenging environments with limited GNSS satellites visibility.

3. Simulations

In the frame of EMPHASIS project, the company-own simulation tool (PIPE) was upgraded to be able to simulate 4G signal generation and signal reception, and to perform PVT in GNSS+INS+4G integrated mode. In this way, it could be employed to assess the integrated GNSS+4G systems performance (and GNSS+INS+4G) in a reference environment. The PIPE software has a modular structure, in which different modules can work independently and provide output which would serve as input to the next module. PIPE is able to generate realistic trajectories, generate GNSS observations, generate GNSS, IMU and other sensors observations, and simulate antenna and receiver – acquisition, tracking and PVT.

A simulation illustrating the positioning performance of GNSS+INS+4G has been set up and run. The simulation consisted in three different scenarios, characterized by same simulated trajectory, at the same time of the day, but different sky visibility conditions and different positioning systems used:

1. Reference scenario of GNSS+INS navigation in a favorable environment with no GNSS signals blockage
2. Scenario of GNSS+INS navigation with obstructed sky visibility (only two satellites visible)
3. Scenario of GNSS+INS+4G navigation again with obstructed sky visibility (only two satellites visible), but three BSs always in LoS.

In the simulation, a vehicle is travelling at low speed (<50km/h) over a circuit of about 3km length in sub-urban area. It is a 6 minutes' drive around the block next to ADS headquarters in Ottobrunn. Figure 4 shows the location for the simulated scenario, with the simulated position of the BSs, and the reference 4G BS network considered. Navigation results for the run are given in Table 1 – positioning accuracy was better than 5m in all directions (NEU).

Table 1 – Positioning performance in the simulated scenario

KPI	Galileo (8 SVs) + INS	Galileo (2 SVs) + INS	Gal. (2 SVs) + INS + 4G (3 BS)
STD North [m]	0.11	1574	0.88
STD East [m]	0.13	1790	1.07
STD Up [m]	0.22	515	1.14
Bias North [m]	0.38	1418	0.38
Bias East [m]	-0.36	-1605	4.50
Bias Up [m]	-0.08	494	-1.47
RMSE North [m]	0.40	2119	0.96
RMSE East [m]	0.38	2405	4.62
RMSE Up [m]	0.24	714	1.86

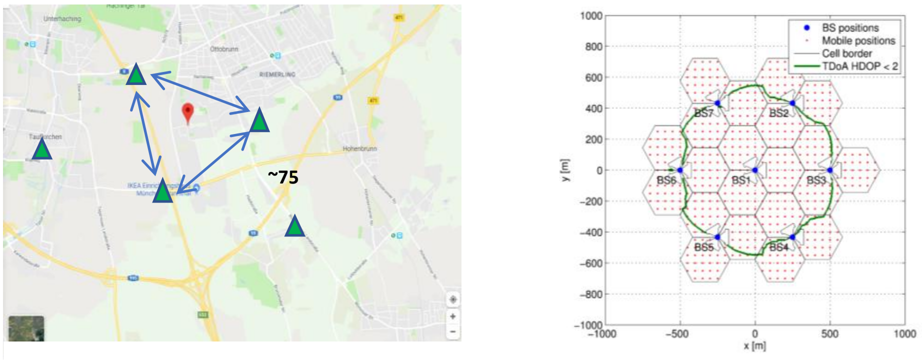

Figure 4 - Location for the simulation scenario (top) and reference 4G BS network (bottom, from [6]).

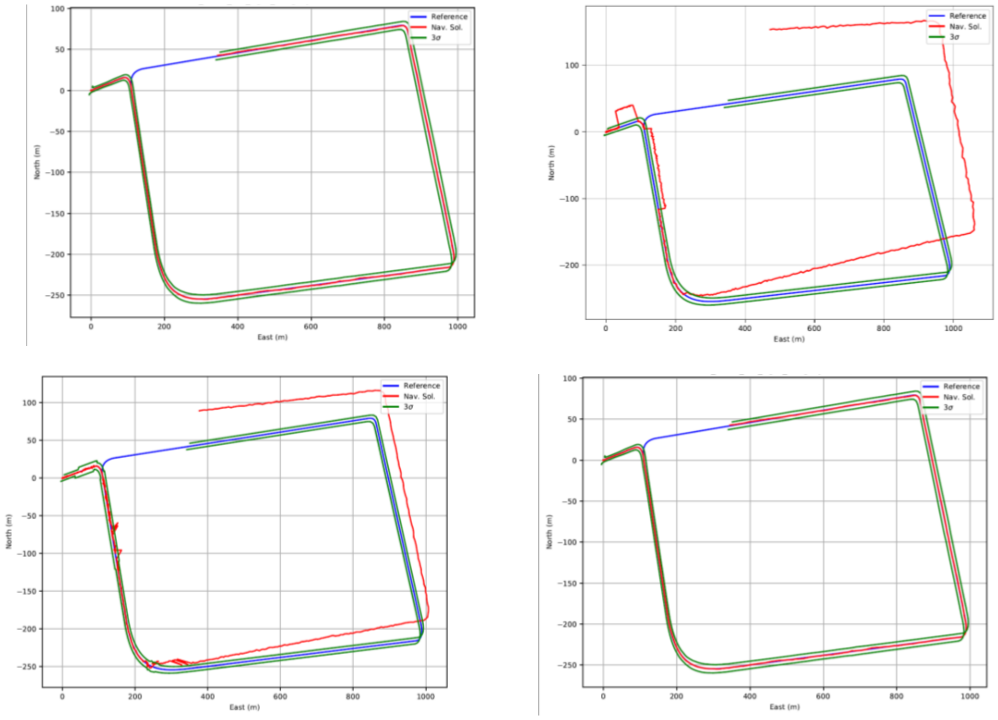

Figure 5 - Horizontal positioning results for outlier and spoofing simulation scenarios. Top left: nominal case (no anomalies/attacks injected); top right, outliers and spoofing attack injected, no integrity monitoring algorithm implemented; bottom left, outliers and spoofing attack injected, eRAIM algorithm implemented; bottom right, outliers and spoofing attack injected, filterbank algorithm implemented.

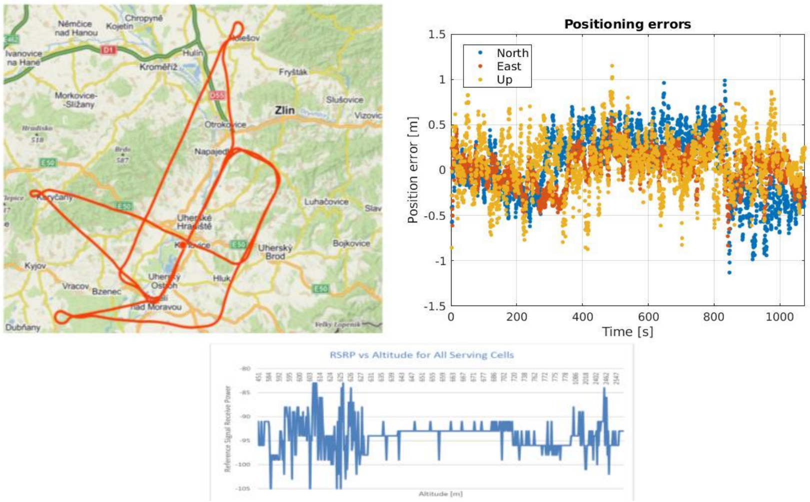

Figure 6 - Flight-demo trajectory (left), network signal RSRP recorded at different altitudes (middle-bottom) and positioning error results from the simulation run (right).

Additional simulations illustrating the positioning performance of GNSS+INS+4G in different integrity-challenging scenarios have been set up and run. The scenarios analysed simulated the occurrence of anomalies (outliers) and an external attack (spoofing). Figure 5 shows the positioning results for the following scenarios:

1. Reference scenario (top left of Figure 5): the reference scenario consisted in GNSS+INS+4G navigation in a partially sky-obstructed environment with visibility of 4-5 satellites, and 3 cellular network BSs.

2. Challenging scenario (other three sub-plots of Figure 5): in the challenging (faulty) scenario, single outliers are injected first, and later a spoofing attack is simulated, with a slowly growing error simultaneously in the observations from 3 satellites. The outliers are jump errors, the first of 50m size and the second of 20m. For the spoofing simulation, ramp errors starting with 5m size and reaching over hundred meters size are injected.

In the top two sub-plots of Figure 5, no integrity monitoring algorithm was implemented, whereas, in the bottom two, eRAIM was implemented on the left, and filterbank algorithm on the right. It can be seen that the eRAIM algorithm is able to detect and exclude the outliers (single satellite faults), but it is not able to cope with the anomaly affecting three channels at the same time. However, is able to exclude one of the three spoofed satellites. The filterbank algorithm is instead able to cope with both outliers' faults and spoofing attack. The ramp errors are detected almost instantaneously.

After input from the flight-demo results obtained by the project partner Evektor, an additional simulation was run in a new scenario reproducing the actual flight. **Figure 6** shows the trajectory flown by the Evektor aircraft during the flight-demo, the network signal RSRP registered as function of the altitude, and the results of the simulated hybrid GNSS-LTE-INS navigation based on the information on GNSS and LTE signals reception recorded during the flight. The positioning accuracy recorded is better than one meter during the whole run; in fact, as the flight was performed in very sky visibility conditions, the positioning performance is highly dominated by the GNSS performance (the aiding from LTE is almost negligible).

4. Conclusions

PVT availability obtainable with GNSS only is not sufficient for critical applications, e.g. SoL services run through GA/R operations, when flying below 500ft or in terminal areas with obstructed sky visibility. With three GNSSs available, in urban areas the maximum PVT availability reachable is estimated by ADS at about 94%. As a consequence, additional sensors, such as IMU for INS and/or other signals of opportunities (e.g. RF network-based schemes), are required to offer a reliable navigation service. Simulations have shown that INS/GNSS fusion can guarantee significant improvement in navigation performance with respect to GNSS only, with a contained cost. Consumer grade INS can guarantee an improvement of performance of both GNSS network-based standard positioning technique (SPS) and precise positioning techniques (e.g. PPP), in environments with degraded satellite visibility (e.g. urban and sub-urban). INS/GNSS fusion results particularly helpful in enhancing the integrity of the navigation solution, as the INS provides redundancy of measurements in all navigation scenarios, and it cannot be spoofed, complementing GNSS in most aspects (especially in bridging outages). After design and implementation of network signals (4G) processing methods, both Cramer-Rao bounds and PVT simulations have shown that 4G PRS signals, when considering an average-to-high bandwidth, deliver a range positioning accuracy comparable to GNSS or only slightly worse (range standard deviation of about 5m), in areas with densely distributed 4G network. Positioning accuracy for GNSS+INS+4G in a scenario with 2 satellites visible and 3 4G Base Stations considered was better than 5m in all directions (NEU), under the assumption of good visibility of network BSs and low multipath for network signals. Two Integrity Monitoring (IM) algorithms, an eRAIM and a filterbank approach, based on adaptive filtering, were also reviewed and implemented in the proposed navigation algorithm. Navigation simulations were run in different scenarios, in nominal and faulty conditions, to test the robustness of the navigation solution. Outlier faults and a spoofing attack were simulated. The outlier fault simulations showed that both eRAIM and filterbank algorithms were able to detect and exclude jump errors in the observations, while the spoofing attack simulation showed that the filterbank IM algorithm (based on adaptive filtering) is robust also against threats affecting multiple channels at the same time, and it is able to detect and exclude this type of anomaly within few seconds of its injection.

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