EGNOS-based navigation solution for RPAS in precision agriculture applications.

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1- Introduction

In the European Commission's 7th Framework Programme (FP7) project, FieldCopter, the added value of Remotely Piloted Aircraft Systems (RPAS) over satellite-based Remote sensing has been investigated. The principal benefits of RPAS are their flexible deployment at any time in the day and their ability to acquire imagery under cloudy conditions. To quantify the added value of RPAS-based remote sensing over satellite-based remote sensing, the project calculated the probability that usable satellite images would be unavailable because of cloud cover. The project then calculated the probability that RPAS-sourced images would be unavailable due to those weather conditions that limited RPAS flights and compared both results.

The increasing usage of precision agriculture machinery at farms has led to a growing need for crop status mapping throughout the season. Mapping spatial variation in crop status (biomass), crop health (chlorophyll and nutrients) and soil moisture content provides essential information for optimizing crop cultivation. Remote sensing is an adequate source of input information for Variable Rate Application (VRA) algorithms. Satellite services are reasonably mature: the number of earth observation satellites has increased significantly in recent years and their number is expected to increase from 125 in 2012 to 250 by 2017. A growing number of satellites now carry sensors that measure reflectance in different spectral bands and produce imagery with spatial resolutions in the range of 6.0 to 0.5 m. In addition, satellite service providers have improved the delivery time of their imagery, with most delivering within 1 to 3 days following image acquisition.

While many studies have shown the potential of satellite imagery to fill this need, prolonged cloud coverage in North-West Europe has prevented its reliable and timely acquisition and delivery. Clouds are an abundant feature, especially in mid-latitudes and the tropics, while cloud-free imagery in temperate regions is rare. Despite the increase in the number of satellite, better sensors, better quality images (by means of mosaicing and post-processing), cloud cover continue to pose a major problem for satellite service providers for 50 to 80% of the time, depending on the location. Over the past decade an increasing number of applications of RPAS in environmental monitoring and precision agriculture have appeared. RPAS provide an alternative source of remote sensing imagery and offer a very flexible method for providing farmers with near real time information on crop status.

The paper is organized as follows. In the next section an introduction on the use of RPAS for precision agriculture is presented. Next, in Section 3 a novel estimation algorithm based on EGNOS-transmitted integrity data is presented. In Section 4, an algorithm that improves heading estimation using a dual antenna GPS receiver and a magnetometer is presented. To validate these algorithms simulations using a GNSS RF emulator and MATLAB have been performed and their results are presented in Section 5. Finally, Section 6 is devoted to final conclusions.

2- RPAS for precision agriculture

In their latest Economic Report the American Association of Unmanned Vehicle Systems International' (AUVSI) analyzed the economic benefits that Remotely Piloted Aircraft Systems (RPAS) integration into in the National Airspace System (NAS) would yield in the United States (U.S.). In their report they conclude that "the commercial agriculture market is by far the largest segment, dwarfing all others". They expect that a positive decision from the FAA to accept RPAS in the American airspace will boost the use of this new technology. The report describes two main applications in agriculture for RPAS: i) Remote sensing and ii) Precision Application (1).

2.2 Remote sensing

In Remote sensing applications a variety of sensors are used to monitor growth rates and water needs, measure plant health status and locate disease outbreaks. The most popular sensor for agriculture applications are multispectral cameras that are sensitive to light reflectances in specific spectral bands. The crop reflectance varies with variables such as canopy structure, density and chemical composition. These cameras can be mounted on tractors, aerial vehicles and even satellites. In fact, the popularity of Remote sensing is mainly due to the satellite-mounted sensors that cover large areas at once. NASA's Landsat Multi Spectral Scanner was one of the first satellites that showed the potential for agriculture 40 years ago. Since then many applications have emerged around the use of remote sensing for agriculture. As stated previously, the largest drawback of Remote sensing based on satellites are cloud covers that obstruct satellite's view of Earth. Miniaturized and lightweight cameras in combination with RPAS are now a valid alternative to overcome this drawback and can provide near real-time crop status information to farmers.

2.3 Precision Application

Following the above, remote sensing provides farmers with more insight (both in terms of the number of sensed variables and in spatial extension) of their crops and how cultivation practices can be improved.

In the field of crop care – protection against weeds, fungus, insects etc. – spraying is a common cultivation practice. This practice is expensive and the excessive use of chemical agents in crops is unwanted from a food safety and environmental point of view. So, new cultivation practices arise where the right agent is used in the right dose on the right part of the field. This is often called Variable Rate Application (VRA). In most countries this refers mainly to tractors with sprayers and on-board controllers. In Japan this is currently a growing domain for RPAS. The Japanese government has already addressed safety and airspace regulatory issues allowing the use of unmanned aircraft for aerial spraying of pesticides. VRA allows farmers to selectively spray different parts of their fields and thus reducing the total amount of chemical agent sprayed saving money and reducing environmental impacts.

2.4 Regulatory issues

Aviation Authorities in many countries are looking into regulations for RPAS. Due to the lack of regulatory framework for RPAS, there are many questions pending such as airworthiness certification, operator licensing, aircraft classification and registration, traffic management, communication protocols and frequencies, security issues, legal responsibility, insurance etc. At present, the only applicable legal provision is article 8 of the 1944 Chicago Convention in pilotless aircraft (2). This only describes the conditions under which an unmanned aircraft can operate in the airspace but has no provisions for different uses or types of RPAS. In Europe, RPAS with a MTOW > 150 kg are regulated by Eurocontrol. All others, from 0 to 150 kg are the competency of national aviation authorities.

At the time of writing of this article, the situation across Europe is very diverse in terms of the nature of regulations and the route to get them in place. Despite efforts harmonization of proposed rules and regulations is not reached yet. This situation hampers commercial uptake of RPAS. In several countries, including the USA and Spain, commercial use of RPAS is prohibited at this moment.

Agricultural applications have a number of requirements towards regulations. First of all, regulations must be clear about flight altitude and range. At this moment all regulations seem to restrict operations to visual Line of Sight and 400 ft altitude. Adequate remote sensing applications in agriculture however require an altitude of 600 ft above the canopy and an extended range, i.e. 500 m. from pilot to RPAS. Spraying applications clearly require flying just above the crop. In the USA, where regulations are expected to open up the airspace for RPAS by 2015, the use of RPAS in spraying is expected to grow. In Japan, spraying is particularly important at this moment. The case of precision agriculture is one based on economic efficiency (3) and it is expected that this market will grow significantly, once the regulations are clear and phased in.

Air safety refers to two basic questions: Has the pilot full control over the RPAS? Is the RPAS a danger to other aircrafts? In this line, FieldCopter project looks into the use of EGNOS-enhanced GPS to increase the safety of the system. With EGNOS, the navigation solution improves so the RPA is better positioned and the pilot can heavier rely on this information to properly guide the aircraft. Besides the improved accuracy of GPS positioning and on-board autopilot performance, EGNOS also delivers an integrity message that can be used to assert GPS data and hence the positioning of the RPAS. For airspace safety and collision control, the RPAS estimated position of the RPAS can be used to accurately locate the RPAS both in horizontal and vertical place.

3- EGNOS and its application to RPAS navigation Systems

Global Navigation Satellite Systems (GNSS) have been used successfully in many applications over the last two decades. However, in the last years some applications with higher accuracy and cost-effective requirements have appeared such as Precision Agriculture applications.
The usual accuracy of the GPS signals is presented in Table 1 as described in the User Guide for EGNOS (4). It can be appreciated that this accuracy is not enough for Precision Agriculture applications like RPAS-based remote sensing.

	GPS Specifications	Real expected performance
Horizontal Accuracy	< 17 meters (95%)	7.1 meters
Vertical Accuracy	< 37 meters (95%)	13.2 meters
Time Accuracy	< 40 ns (95%)	12 ns

Table 1: Errors in GPS constellation.

To overcome these limitations, numerous augmentation systems have been developed. EGNOS (European Geostationary Overlay Service) is a SBAS (Satellite Based Augmentation System) system designed to complement GPS (and Galileo when available) improving the service accuracy (both in position and time) and integrity.

The operation of EGNOS is based on the calculation of differential corrections and integrity data by the Central Processing Facilities using information gathered by a ground-based network of stations whose positions are well known. The calculated differential corrections and integrity data and finally are uplinked to the three EGNOS satellites and then broadcast so they can be used for all receivers on the coverage region. The use of EGNOS jointly with GPS can provide a horizontal accuracy better than 3 meters and a vertical accuracy better than 4 meters at 95 % of the time.

In FieldCopter project, EGNOS have been used for improving navigation and guidance. An EGNOS-enhanced navigation system has been developed for RPAS allowing the estimation of the position and attitude of the RPA with higher accuracy than stand-alone GPS. In order to fulfill the stated requirements of accuracy, low cost and reliability, the GNSS data is combined with inertial measurements provided by a low cost IMU (based on MEMS technology) using probabilistic estimation techniques (such as Extended Kalman Filter and information or particle filters) (see Figure 1) that take advantage of the best properties of each type of sensors: inertial sensors high rate and small relative errors and GNSS bounded errors. This information is used by the autopilot to maintain the stability of the aerial vehicle and to navigate following a desired waypoint path, and also to correctly geo-referencing and ortho-rectifying of the images taken from the multispectral cameras (i.e., identification of the real-world geographic location of an each pixel of the image and geometric correction such that the scale of the whole image is uniform).

EGNOS are not only used to improve the accuracy, but it also provides integrity information that is used to improve the robustness and safety of the system in case of GNSS degradation. This information is integrated in a novel way where the probabilistic estimation algorithm adapts with respect to the integrity information coming from the EGNOS system. Integrity data is used to calculate the horizontal and vertical protection levels which give a measurement about the deviation of the estimated position with respect to the real one. Afterwards, this information is used to establish a configuration profile for the estimation filter depending on the alert limits and protection levels. Moreover, the established configuration profile adapts, on real-time, the estimation filter parameters to different situations.

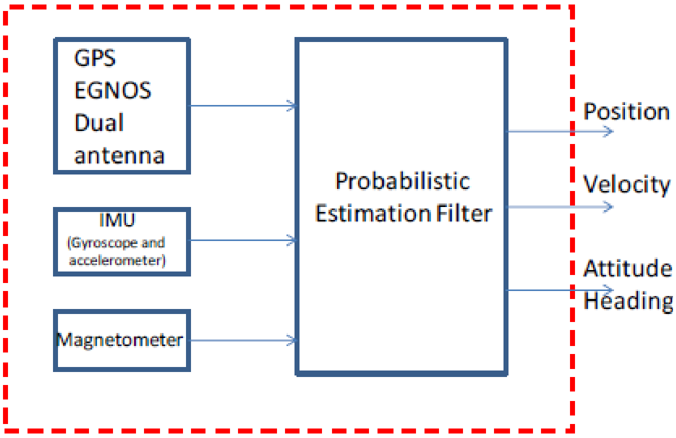

Figure 1: Sensor fusion approach.

Finally, in FieldCopter project, the benefits of fusing the data provided by a magnetometer and a dual-antenna GPS receiver for heading estimation has been explored. Dual-antenna GPS receivers can estimate the aircraft heading with an accuracy of less than 0.5º. This system is much more reliable than a stand-alone magnetometer and corrects the typical sensitivity issues caused by electromagnetic sources like the RPA engine through a continuous and automatic calibration of the magnetometer using the data provided by the dual-antenna GPS receiver.

3.1 Navigation Scheme

A loosely-coupled navigation system has been adopted to fuse the data provided by the different sensors. INS/GPS loosely-coupled integration is done in two steps by means of two cascaded independent Kalman filters as shown in Figure 2:

- GPS raw observations are first processed by the GPS Kalman filter to derive GPS velocity and position estimations.
- INS raw measurements (i.e., accelerations and angular rates) given by inertial sensors are processed using the INS mechanization equations to derive INS attitude, velocity and position. The INS Kalman filter output are the corrected attitude, velocity and position obtained from the INS attitude, velocity and position and the GPS velocity and position.

To correct the attitude, velocity and position estimations, the INS Kalman filter estimates the errors of the inertial sensors and then these estimations are used to compensate for these errors. To do this, the Kalman filter uses two models:

- The first one relates the inertial sensor errors with the differences between the estimations of the positions and velocities given by the INS and GPS systems.
- The second one models the dynamics of the inertial sensor errors.

When GPS data is available, the INS Kalman filter estimates the INS sensor and navigation errors using both the differences between INS and GPS position and velocity and the system model. When GPS data is unavailable, INS sensor and navigation errors will be predicted based uniquely on the system model.

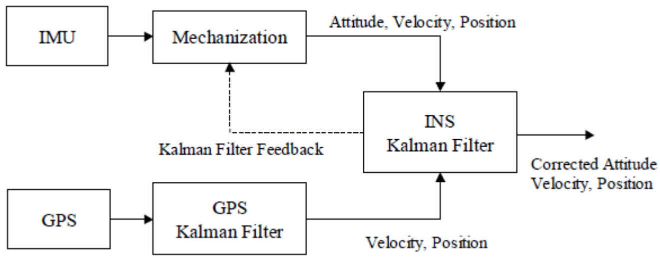

Figure 2: Typical loosely-coupled scheme.

Figure 3 shows the INS/GPS loosely-coupled integration scheme that has been followed in this work.

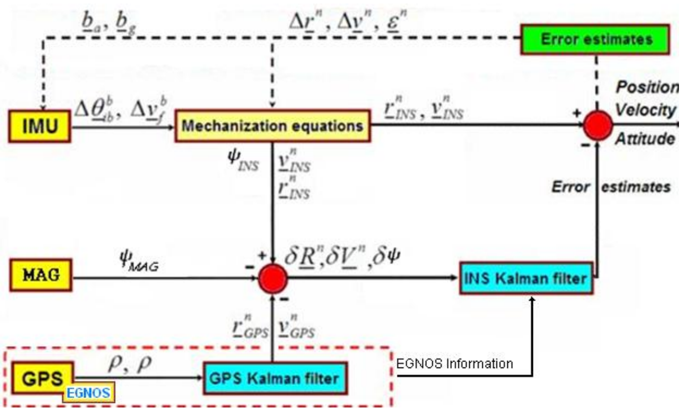

Figure 3: Integration Scheme

3.2 EGNOS SoL to improve the Navigation System

The SoL (Safety of Life) service is based on the integrity data provided by the EGNOS messages. The main purpose of the EGNOS SoL service is to support critical civil aviation operations as LPV (Localizer Performance with Vertical guidance) approaches. However, the SoL service is also intended to support applications in a wide range of other domains such as maritime, railway and ground transportation.

Available commercial navigation systems can already use EGNOS signals. However, these systems do not exploit all the functionalities that EGNOS offers to the users. Generally these systems only use EGNOS to improve the accuracy of GPS measurements by means of the differential corrections broadcasted in the satellite messages. However, EGNOS also provides integrity data that can be used to improve:

- Guidance: providing information about GPS data integrity to improve security.
- Navigation/estimation: improving the performance of the navigation filter using the integrity data in the sensor fusion process.

The use of the EGNOS integrity data for these purposes has been exploited in this project.

3.2 Guidance: improving the safety of the navigation system

Autopilots logic is generally designed as a state machine where transitions between states depend on several system variables. Usually when a device failure occurs, the RPA goes to a degraded-performance or emergency state. For example, it is a common practice that if the radiolink is lost, then the autopilot commands the aircraft to go to a predetermined waypoint (what is commonly known as return-to-home). However, what happens when a GPS signal outage is experienced? In this case the RPA usually enters an emergency state where the rotorcraft hovers and tries to land using other sensors such as an altimeter (in the case of fixed-wing aircrafts the engines are stopped and a parachute is launched). With EGNOS it is possible to anticipate to the situation of a complete loss of GPS signal using the integrity information included in EGNOS messages and take some countermeasures. EGNOS-capable receivers can use the integrity data included in EGNOS messages to calculate the so called protection limits which are related to the reliability level of the GNSS measurements. With this information four possible situations that could be mapped in different RPAS navigation states have been defined:

1- GPS signals are reliable and therefore the EGNOS-capable GPS receiver provides an estimated position with a good accuracy.
2- EGNOS signals are not being received from the EGNOS satellites so the corrections are not being applied to improve GPS positioning and there is not an integrity service for calculating the protection levels. In this case, only the GPS data can be used for position estimation purposes.
3- GPS signals are not reliable enough. This is detected when the protection levels are higher than user-fixed alarm limits that are set depending on the application. In this case it is not recommended to take GPS measurements into account by the INS Kalman filter.
4- GPS receiver is not able to calculate a position solution.

Figure 4 shows the state machine that has been proposed for the navigation module of the autopilot and the transitions between the different states. As can be appreciated, EGNOS integrity information is used for transitions between different states.

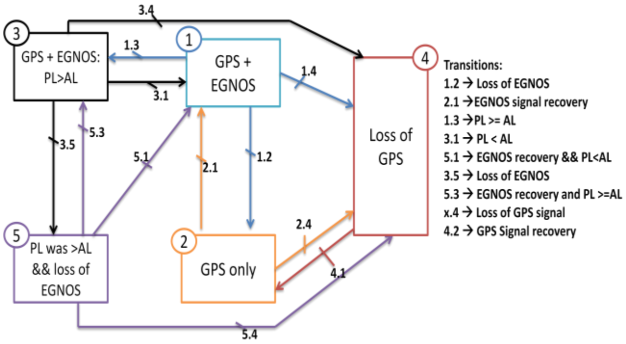

Figure 4: States Machine Using EGNOS.

The main concept here is to use EGNOS integrity information to detect degradation in GPS signal and anticipate to a possible loss of a GPS position solution. For this purpose, new states have been defined based on the values of the protection levels and the stated alarm levels. When the protection levels are higher than the alarm limits, then GPS signals cannot be considered to be reliable and the autopilot may decide to try to land the aircraft before further GPS signal degradation or even complete GPS signal outage is experienced.

3.3 Navigation/estimation: improving the estimation filter of the navigation system

The performance of a Kalman filter relies on the values of the sensor and system covariance matrices that model the sensor errors and the system noise dynamics respectively. An initial tuning process has to be performed to find those values that lead to an optimal operation of the filter. The behavior of the filter depends on these sensor and system covariance matrices (denoted as R and Q respectively) as follows (5) :

- The system noise or state covariance matrix Q provides the statistical description of the model of the dynamics of the estimation errors. A large value in Q indicates that the uncertainty about the error dynamics is high and results in noisy estimations. In this case, the GPS estimations will correct those of the INS. In other words, a large value in Q will cause the INS to closely follow the GPS position estimations. This, in turn, will lead to an inaccurate navigation solution, if the GPS estimations are noisy.
- The measurement noise covariance matrix R models the sensor noise. Large values for R imply inaccurate and noisy measurements and Kalman filtering will give less importance to

these measurements with respect to the system model. On the contrary, small values imply accurate measurements and Kalman filtering will give more importance to these measurements with respect to the system model.

In the navigation system proposed in FieldCopter project, the protection levels have been used for weighting the values of the sensor and system covariance matrices in order to take into account the reliability of GNSS measurements. This can help the Kalman filter to change the covariance matrices in real time (and hence changing the behavior of the filter) depending on the quality and accuracy of GNSS data. For the estimation algorithms to use this new procedure, it is necessary to perform the initial tuning of Q and R matrices in the usual way. These matrices can be written as:

$$Q = \begin{bmatrix} diag(q_a) & 0_{3x3} \\ 0_{3x3} & diag(q_g) \end{bmatrix}$$

$$R = \begin{pmatrix} \sigma_\varphi^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_\lambda^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_h^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_{V_N}^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_{V_E}^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_{V_D}^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \sigma_\psi^2 \end{pmatrix}$$

The adaptive changing of these matrices using the protection levels calculated from EGNOS integrity data can be done multiplying the static covariance values (i.e., the main diagonal of covariance matrices) by a weighted quotient between the protection levels and the user alarm levels as expressed below.

$$R_{new} = R * R_{Egnos}$$
$$Q_{new} = Q * Q_{Egnos}$$

$$R_{Egnos} = \begin{pmatrix} \frac{HPL}{HUL}*rxy & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{HPL}{HUL}*rxy & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{VPL}{VUL}*rz & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{HPL}{HUL}*rxyv & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{HPL}{HUL}*rxyv & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{VPL}{VUL}*rzv & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$Q_{Egnos} = \begin{pmatrix} \frac{HUL}{HPL}*qh & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{HUL}{HPL}*qh & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{VUL}{VPL}*qa & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

The values in the updating matrices are:

- HUL is the Horizontal User Level, a constant imposed by the user.
- HPL is the Horizontal Protection Level.
- VUL is the Vertical User Level, a constant imposed by the user.
- VPL is the Vertical Protection Level.
- rxy, rz, rxyv, rzv, qh and qa are parameters set by the user that allows further weighting of the integrity parameters. These must fulfill with the following conditions:

$$\forall \tau_i > 0 \quad rxy, rz, rxyv, rzv = \begin{cases} \frac{1}{\tau_1} if \ \frac{HPL}{HUL} \leq 1 \\ \tau_2 \ if \ \frac{HPL}{HUL} > 1 \end{cases}$$

$$\forall \tau_i > 0 \quad qh, qa = \begin{cases} \frac{1}{\tau_3} if \ \frac{HPL}{HUL} > 1 \\ \tau_4 \ if \ \frac{HPL}{HUL} \leq 1 \end{cases}$$

The final behavior of the navigation filter will be as follows:

- If GPS and EGNOS signals are available and good accuracy is being experienced (i.e., protection levels are lower than the xUL field), then the weights of the elements of the matrix R are smaller and the elements of the matrix Q become bigger. This way the Kalman filter gives more importance to the measurement model than to the system model.
- If GPS and EGNOS signals are available and the accuracy that is being experienced is not good (i.e., protection levels are higher than the xUL field), then the weights of the elements of the matrix R are bigger and the elements of the matrix Q become smaller. In this case the Kalman filter gives more importance to the system model than to the new measurements.
- If the no EGNOS signals are being received, then the matrix R and the matrix Q would remain constants and equal to the initial static matrices set during the tuning process.

Figure 5 summarizes the behavior of Kalman filter with respect to these matrices.

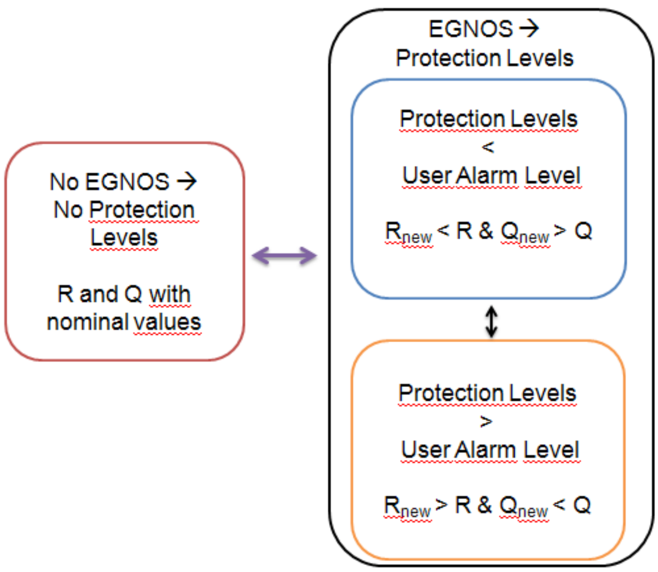

Figure 5: Behaviour of the EKF matrices.

4 Improving navigation accuracy using a dual-antenna GPS receiver for heading estimation

Due to the integrative nature of the navigation solution in low cost inertial sensors the measurement error grows unbounded with time as noise and the dynamic biases are integrated. In the RPA navigation, it is very important to have additional sensors for correcting the measurements in general and particularly the heading estimations calculated from the gyroscopes measurements. RPAS usually make used of magnetometers for heading estimations. Other sensors that can be used for heading estimation are dual-antenna GNSS receivers. Table 2 summarizes the main advantages and disadvantages of these two sensors.

	Dual-antenna GPS	Magnetometers
Main Advantage	High accuracy	Heading solution at high rate and always available
Main Disadvantage	Solution is not always available	Calibration is needed due to distortions in the magnetic field

Table 2: Sensors comparison.

When analyzing Table 2, it is possible to notice that both systems can complement each other and used jointly to provide a more better heading solution (high rate more accurate and highly available estimations). A new method that expands the navigation system presented in the last section fusing the heading solutions of a dual-antenna GNSS receiver and a magnetometer has been developed. The new navigation system is shown in Figure 6. This new navigation filter will increase both the heading estimation accuracy and the heading estimation availability as will be explained below.

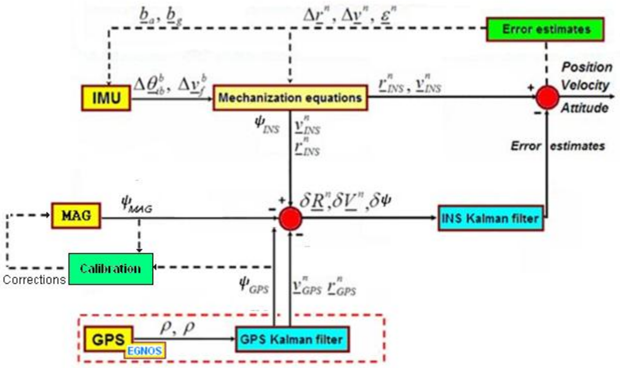

Figure 6: Navigation Scheme

With this new approach, the INS Kalman filter has two measurements of the heading error:

- The difference between the heading calculated by the INS and the calculated by the magnetometers.
- The difference between the heading calculated by the INS and the calculated by the dual-antenna GNSS receiver.

As the dual-antenna GNSS receiver provides higher accuracy, the values of the sensor covariance matrix corresponding to the magnetometer will be higher than those corresponding to the dual-antenna GNSS receiver. This way, the Kalman filter will give more importance to the heading error that was calculated using the dual-antenna sensor than to those calculated using the magnetometer. This will help to increase the accuracy of heading estimation.

As shown in Table 2, the heading solution provided by dual-antenna GNSS receiver has relatively high frequent periods of unavailability. Magnetometers heading solution is always available but distortions in the magnetic field causes this estimation to deviate from the real value. To have a highly available high accurate heading estimation, in this project the heading solution provided by the GPS is used to calibrate the magnetometers periodically. With these recalibrations, it is possible to remove errors of different sources during RPA flight when the environmental conditions are changing (e.g. distortions in the magnetic field that are different that those that were calculated in the initial point where the magnetometer was calibrated on ground). By removing these errors it is possible to improve the heading calculation of the magnetometer and dispose of a very accurate solution at any time.

With these two new improvements (using of two heading errors measurements in the Kalman filter and in-flight recalibration method), a high accuracy solution is available most of the operation time. With respect to the safety, the most important fact is not that the accuracy will be higher, but that the availability of these high accuracy estimations will be higher.

Although the magnetometer will be recalibrated in-flight, in order to reduce the initial errors it is a good practice to calibrate the magnetometer at ground before the flight. With initial calibration the most of the errors due to hard-iron perturbation can be removed. However, some errors affect the heading solution of the magnetometer due to:

- Soft-iron perturbations.
- Little changes in the value of the hard-iron perturbations due to changes in the location of the RPA with respect to the initial calibration location or due to displacements of any of the components of the RPA with respect of the magnetometers.
- Other no modeled errors.

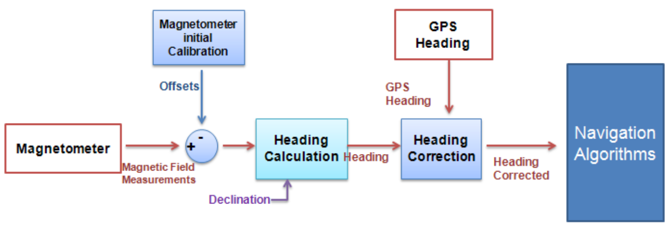

Figure 7: Magnetometer heading calculation scheme.

To improve the initial calibration, dual-antenna GPS receiver will be also used during the initial calibration of the magnetometer. It is important to note that in the initial calibration and the in-flight calibrations the corrections are applied in different ways. In the first case the errors are removed directly from the measurements of the magnetic field while in the second case corrections are applied directly to the heading solution. A scheme of the complete system is shown in Figure 7.

The pseudo-code of the magnetometer re-calibration algorithm is presented in Figure 8. During the initialization, all the parameters are set to zero. When a heading measurement is received from the dual-antenna GNSS receiver, the error of the magnetometer heading solution with respect to that of the dual-antenna GNSS receiver (i.e. $Heading_{GPS}$-$Heading_{MAG}$) are store into a dynamic lookup table and corrects the heading of the magnetometers through linearization techniques. When new heading measurement is received from the dual-antenna GNSS receiver the values from the lookup table are used.

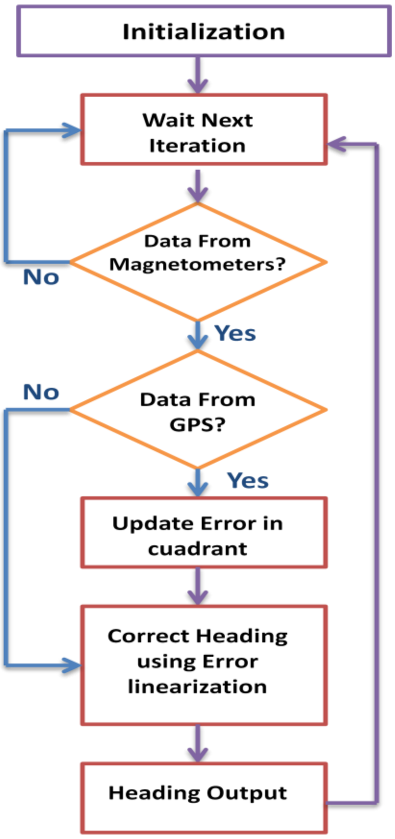

Figure 8: Heading correction algorithm.

5 Simulations.

5.1 Simulation Framework.

In remote sensing applications using RPAs, one of the main objectives is to be able to know with a high level of accuracy where an image was taken. Hence, the GNSS sensor is the most important part of the navigation system. With the goal of demonstrating that the performance of the proposed improves the performance of the existing ones the following devices have been used:

- GNSS Constellation Simulator: Spirent GSS8000.
- GNSS receiver: Septentrio PolaRx3EG PRO.

The GNSS simulator provides an effective and efficient means of testing GNSS receivers and other systems that make use of them. This simulator provides control over the signals generated by GNSS constellations and over the global test environment, so that testing can be conducted in controlled laboratory conditions. The simulator generates the same RF signals transmitted by GNSS satellites, thus GNSS receivers process the simulated signals exactly the same way as signals from actual satellites (6). Standard capabilities enabled through the software of this system (SimGEN) include simulation of atmospheric effects, multipath reflections, terrain obscuration, antenna reception gain and phase patterns, differential corrections, trajectory generation for land, air, sea and space vehicles and error generation. Figure 9 shows the Spirent GSS8000 GNSS emulator.

Figure 9: Spirent GSS8000

The Septentrio PolaRx3eG PRO receiver (7) is a high-accuracy dual-frequency multi-constellation GNSS receiver for precise positioning and navigation applications. It provides access to Galileo and modernized GPS signals and offers the opportunity to track the new signals as they become available. This receiver is shown in Figure 10.

Figure 10: Septentrio GNSS receiver.

Figure 11 shows the simulation User Interface of SimGEN software where the different parameters can be introduced and visualized.

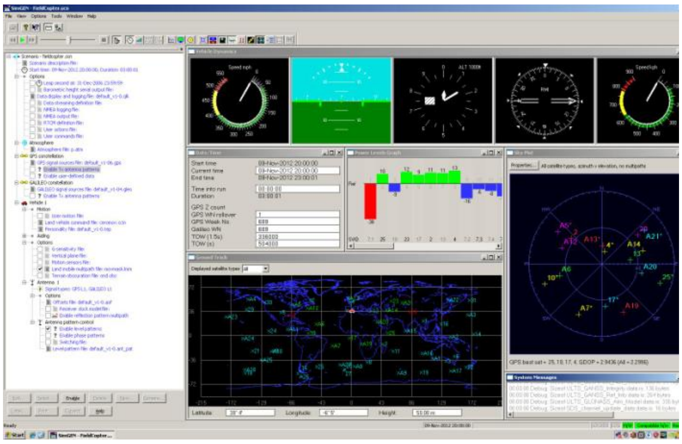

Figure 11: SimGEN GUI.

The tropospheric delay and terrestial ionospheric models used for this simulation are the STANAG and Klobuchar models respectively. For modeling the multipath of an agricultural scenario where the RPA could perform its mission, a suburban scenario with an Open Sky mask has been used. Figure 12 shows the masks for the receiver in three dimensions.

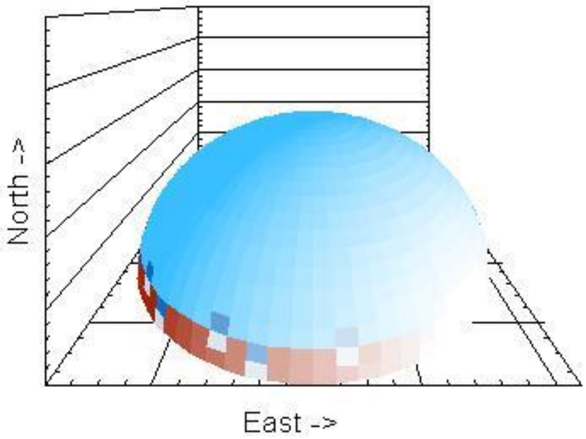

Figure 12: Open sky multipath mask 3D

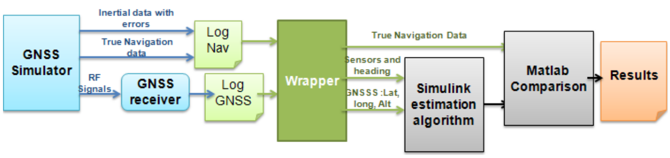

Figure 13: Framework for testing.

Figure 13 shows the block diagram of the process that has been used during the simulations. This process is as follows:

1. Spirent simulator simulates the trajectory of the RPA and generates the RF signals that feed the Septentrio GNSS receiver. Simultaneously, the true data of the vehicle (position, velocity, attitude, etc) and the simulated noisy inertial data are logged.
2. Septentrio GNSS receiver processes the RF signal, and logs the data selected by the user using the software provided by Septentrio (including position, velocity and protection levels).
3. Logged data is converted to an appropriate format so they can be used for simulations and comparisons in Matlab.
4. Logged data is feeded to the estimation algorithm that is implemented in Simulink. This gives the navigation solution for comparing it with the true data.
5. The true data (data without errors) is compared with the one provided by the estimation algorithm in both configurations: GPS and GPS+EGNOS. Some scripts of Matlab finally depict the results and perform the statistics calculations.

5.2 Simulation results of the new algorithm.

To check if the new algorithm improves the accuracy of the navigation solution, a flight of 600 seconds was simulated with the close route presented in Figure 14.

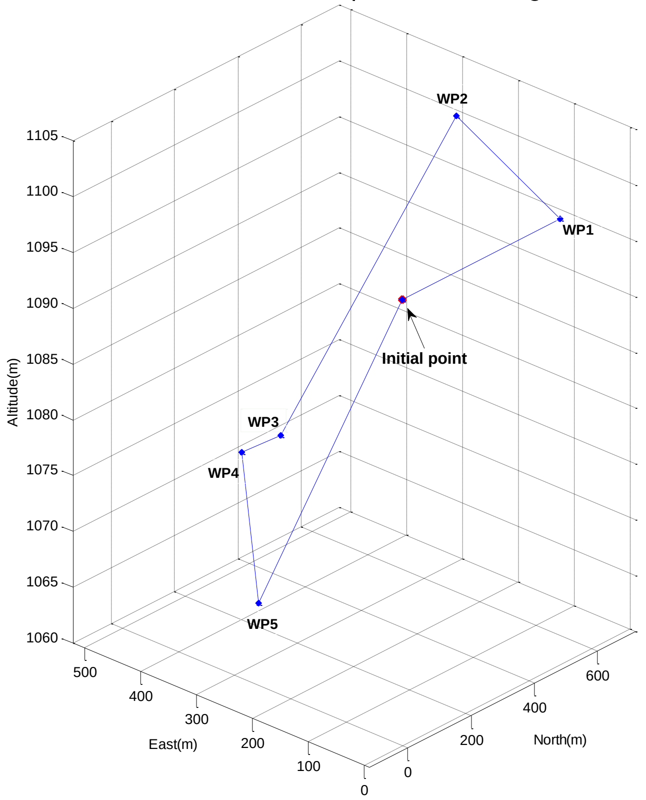

Figure 14: Route of Waypoints.

In order to study the performance of the proposed navigation filters in different situations, the simulation time has been divided in sections. Each section has different errors properties for the GPS data. Table 3 shows the slot of time corresponding to each section and the variance of the error introduced in the horizontal and vertical plane for the position and velocity measurements. As can be appreciated from Table 3, the error that has been introduced in the slot 300-400 is intentionally very high to simulate a degraded GPS output. This can also be seen in the Figure 15 where the real altitude versus the GPS estimated altitude is plotted.

Slot of Time (s)	Horizontal Position variance (m)	Vertical Position variance (m)	Horizontal Velocity variance (m/s)	Vertical Velocity variance (m/s)
0 - 100	10	20	0.5	3
100 - 200	10	30	0.5	3.5
200 - 300	20	40	1	4
300 - 400	30	50	1.4	3.5
400 - 500	20	35	0.5	3
500 - 600	10	25	0.5	3

Table 3: Simulation errors in GPS

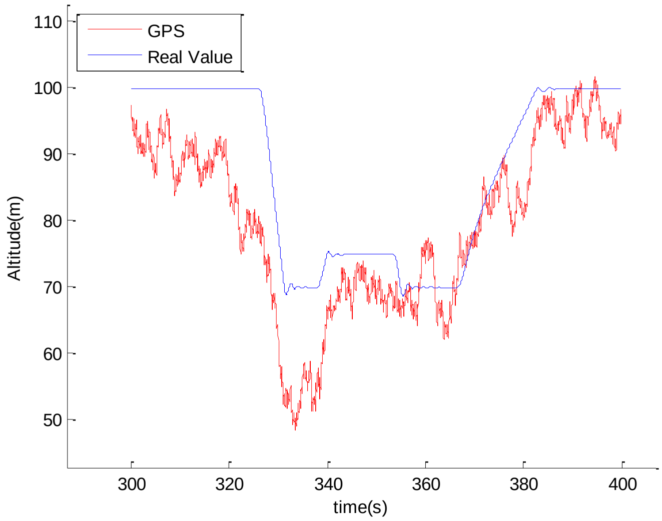

Figure 15: Real Value versus GPS in the fourth section.

As can be deduced from Figure 15, the navigation system cannot accurately estimate the position using the position estimation of the GNSS receiver when these are too noisy. In these cases, the calculated protection limits will be high and the proposed navigation system will adapt the covariance matrices for adapting improving the solution. In the slots where the protections limits are higher the values of the sensor covariance matrix increases and vice versa. To compare the performance of the new algorithm that uses EGNOS integrity data with respect to the traditional one different figures have been plotted with the real value of the variables, the GPS sensor outputs and the results of the filter with and without using the protection levels (i.e. new filter and old filter respectively). Tables showing the mean value of the error committed with the different approaches are also presented.

Figure 16 and Figure 17 show the real and estimated horizontal component of the positions and velocities. In this case, the results of both navigation systems are similar; however, the adaptative changing of the matrices according to the calculated Protection Levels slightly improves the accuracy of the new navigation filter with respect to the traditional one.

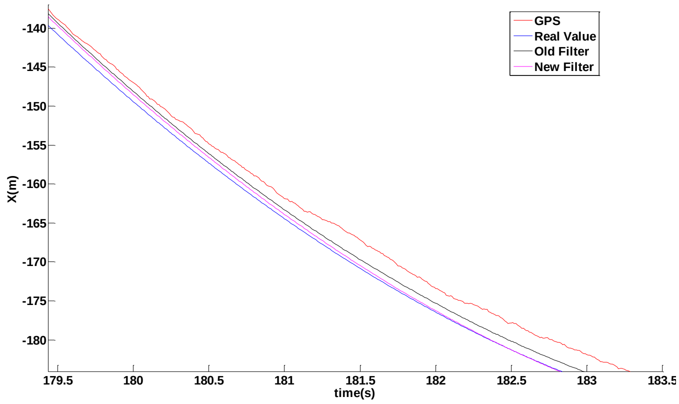

Figure 16: Horizontal Position

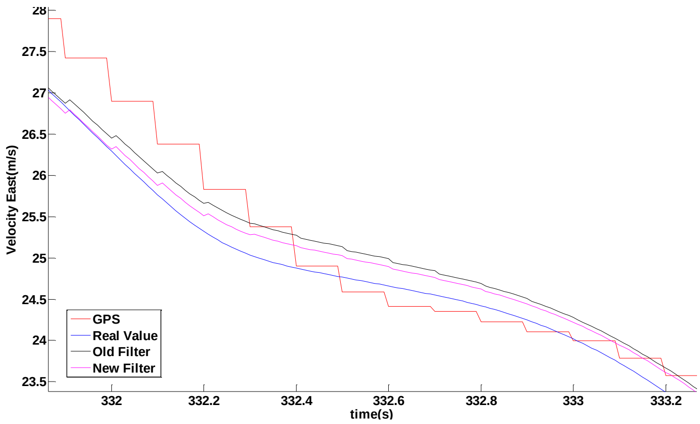

Figure 17: Horizontal Velocity

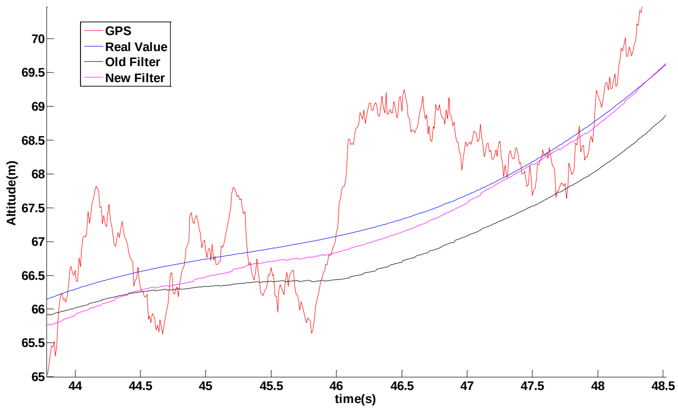

Figure 18: Altitude in the first section.

The improvement is more evident in the vertical component of the position and velocity estimations. GNSS data is less accurate in altitude so the navigation solution obtained is normally less accurate in the vertical plane than in the horizontal one. Figure 18 and Figure 19 show the vertical component of the position estimations of both navigation filters in two different sections of the route (first and fourth sections). In the first section the error is not too big so both navigation filters present a similar behaviour. However, in the fourth section the error of the GPS greatly increases. In this case the new filter modifies the weights of the covariance matrices so the Kalman filter gives more importance to the inertial sensors than to the GPS data. The performance of this new navigation filter is better than that of the traditional filter. This fact can also be seen also in the vertical velocity as shown in Figure 20.

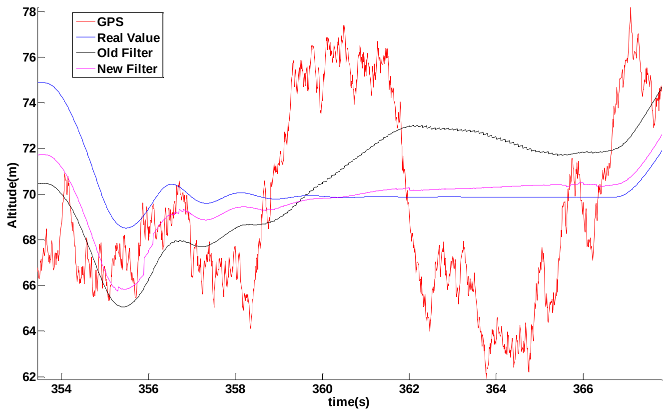

Figure 19: Altitude in the fourth section.

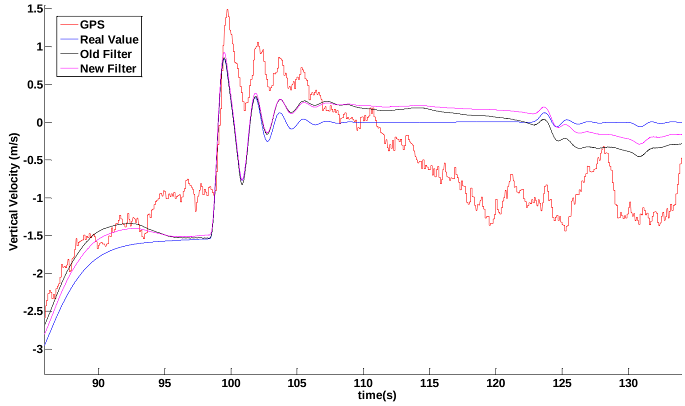

Figure 20: Vertical Velocity

	Mean Position Error					
	North Plane		East Plane		Vertical Plane	
Section	No PL	PL	No PL	PL	No PL	PL
1	2,584	1,972	1,898	1,494	2.777	1,977
2	1,462	1,077	1,715	1,383	5,495	3,588
3	2,423	1,855	3,626	2,771	7,457	4,798
4	4,032	3,658	4,238	3,916	8,510	4,156
5	1,996	1,106	1,965	1,484	2,445	1,844
6	1,670	1,576	2,599	2,129	2,775	1,924

Table 4: Mean position estimation error.

Table 4 summarizes the mean values of the errors for the different components of the position using both algorithms. With these results it is possible to conclude that EGNOS integrity data can be used to improve the safety of the navigation tasks in the navigation module of the autopilot and also for improving the navigation solution accuracy of the estimator allowing having a more accurate estimation of the vehicle state.

5.3 Simulation results of the heading sensors fusion

For comparing the performance of the new algorithm with respect to that obtained using a single heading sensor (magnetometers or a dual-antenna GPS), some simulations have been performed in Simulink. The steps that have been followed for the simulations are:

1- Simulate an RPA flying for recording the true values of the position, velocity and attitude and obtaining the data of ideal sensors (i.e., without noise).
2- Add noise to the ideal sensor measurements to model real sensor measurements (magnetometer, inertial sensors and GPS).
3- Modify the GPS log for simulating a period of unavailability of GPS heading solution.
4- Introduce hard-iron, soft-iron and sensor errors in the magnetometers simulated measurements in order to simulate a degraded situation.
5- Compute the solution of the navigation system using the simulated data when the magnetometer is the only heading sensor.
6- Compute the solution of the navigation system using the simulated data when the dual-antenna GNSS receiver is the only heading sensor.
7- Obtain the solution of the estimation process using the simulated sensor data with the new systems that combines the magnetometer and GNSS dual-antenna receiver.
8- Compare the obtained results.

Figure 21 shows the heading results obtained from the different configurations. As can be appreciated the estimations of all the configurations are accurate for most of the flight.

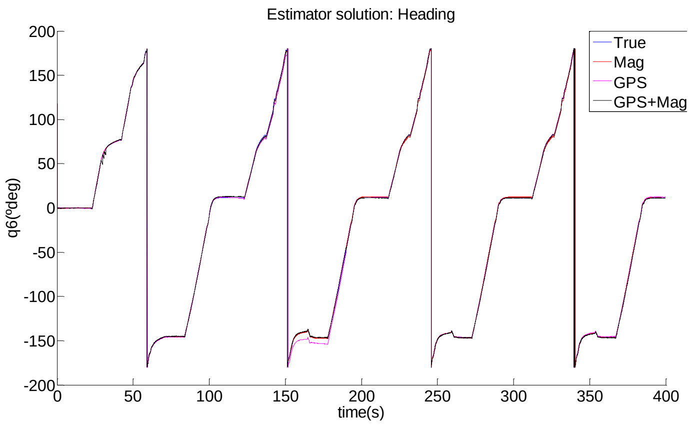

Figure 21: Heading results: complete route.

Figure 22 shows the part of the route where GPS heading solution is not available and the navigation solution degrades. The behaviors of the navigation filter in this situation depending on the different sensor configurations are the following:

- Only GPS (pink line): the estimator can only use the gyroscopes for calculating the orientation so the error increases with time.
- Only magnetometers (red line): in this part of the simulation, the error introduced to the

magnetic fields measurements was low so the solution provided by this scheme is good.

- GPS + Magnetometer (black line): if there is not solution from the GPS, the heading calculation is done by using the magnetometers and the corrections stored in lookup table that were calculated before the GPS heading solution lost. The solution is very accurate.

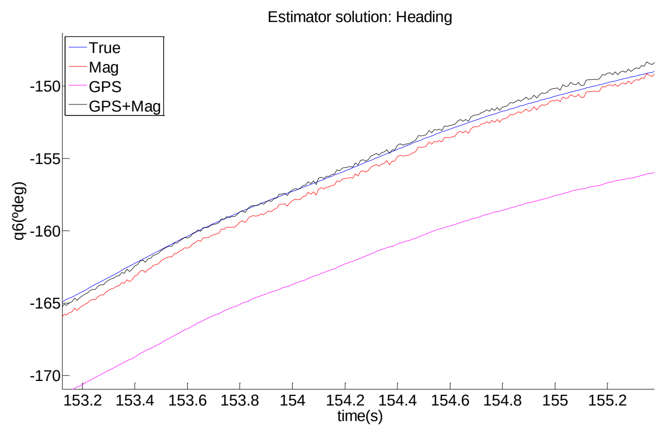

Figure 22: Heading results: GPS heading unavailability.

Once the GPS heading is recovered and all the sensors are working properly, the architectures that use the heading of the GPS sensor can perform corrections and their solutions are improved. This behaviour can be seen in Figure 23.

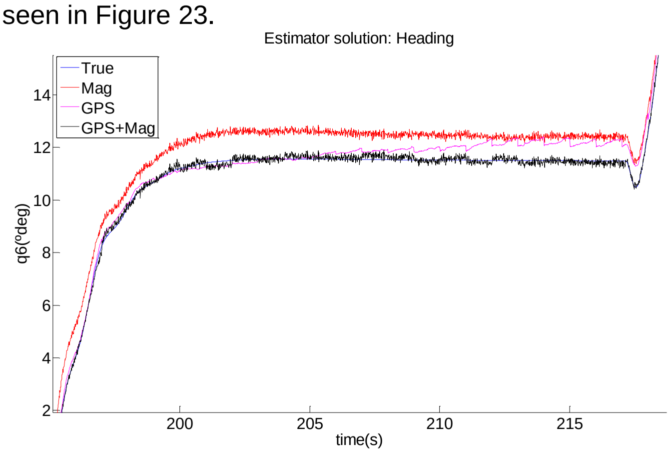

Figure 23: Heading Results: Normal situation.

To summarize, during the nominal operation (i.e. all the sensors works normally) the behavior of the system for the different schemes are:

- **Only GPS.** Results are very accurate, the heading corrections are done at the rate of the GPS heading sensor (5 Hz) and sometimes it is possible to find that the corrections are translated in big steps in the output of the estimator solution.
- **Only magnetometers.** The magnetometers have a little error due to the distortions of the magnetic field. These distortions are translated in 3 or 4 º of heading error.
- **GPS+Magnetometer.** This configuration offers the best solution of the different schemas. The corrections are done at the rate of the magnetometers, and therefore, there are not high steps in the computed solution. Using the GPS for calculating the errors of the magnetometers also allows having a very accurate solution at any time, even if the GPS is lost. In these cases, the solution is very accurate because the values for the corrections of the magnetometers do not usually change too quickly, so the calculated correction table remains valid.

Finally, it is possible to conclude that the new algorithm allows improving the performance of the current algorithms for the heading estimation, and more important, increases the percentage of flight time with an accurate heading estimation (even in situations with errors in the sensors), which at the same time, increases the safety of the system.

6 Conclusions.

In this work, new navigation architectures have been proposed to increase the RPAS safety of the system and the navigation solution accuracy.

On one side, protection levels calculated from EGNOS integrity data have been used to monitor GNSS signal quality in order to detect degradation conditions and act in consequence before higher errors or even a complete signal outage causes an emergency situation. This proposal improves the safety of the system. The integrity data is also used to improve the navigation solution accuracy providing information to the Kalman filter about the accuracy and reliability of GNSS signals.

On the other side, heading solution has been improved by fusing the solutions of a dual-antenna GNSS receiver and a magnetometer. This fusion increases the availability of high accurate heading estimations by recalibrating the magnetometer during the flight. This way, when GNSS dual-antenna heading solution is not available, high accurate heading estimation provided by the recalibrated magnetometer is still available. This solution improves both the safety and accuracy of the system.

References.

1. **AUVSI.** http://www.auvsi.org/econreport.
2. 1944 Chicago Convention, Article 8, p. 5., http://www.icao.int/publications/Documents/7300_Orig.pdf.
3. http://azstarnet.com/business/local/future-of-drones-farming-looks-to-flying-tractors/article_00cc2dea-22a6-5da1-8d6a-00223d5f5d71.html.
4. User Guide for EGNOS Application Developers Ed 1.1, 2009, http://ec.europa.eu/enterprise/policies/satnav/egnos/files/cnes-user-guide-egnos-2009_en.pdf.
5. *Integration of a GPS aided Strapdown Inertial Navigation System for Land Vehicles.* **Schumacher, Adrian.**
6. http://www.spirent.com.
7. http://www.septentrio.com