An EGNOS Based Navigation System for Highly Reliable Aircraft Automatic Landing

Ettore De Lellis, *CIRA (Centro Italiano Ricerca Aerospaziale)*
Federico Corraro, *CIRA (Centro Italiano Ricerca Aerospaziale)*
Umberto Ciniglio, *CIRA (Centro Italiano Ricerca Aerospaziale)*
Pasquale Canzolino, *CIRA (Centro Italiano Ricerca Aerospaziale)*
Luca Garbarino, *CIRA (Centro Italiano Ricerca Aerospaziale)*
Salvatore Gaglione, *Università Parthenope*
Vincenzo Nastro, *Università Parthenope*

BIOGRAPHY

Ettore De Lellis – Senior research engineer at Italian Aerospace Research Centre (CIRA), Flight Systems Dept., since 2002. His research and development activities are in the field of autonomous guidance algorithms. He received his cum laude master degree in Electronic Engineering from University of Pisa, in 2001.
e.delellis@cira.it

Federico Corraro – Flight Systems Dept. scientific coordinator at Italian Aerospace Research Centre (CIRA), involved in guidance, navigation and control innovative systems development since 1994. He graduated cum laude with master degree in Electronics Engineering in 1992. He was on contract professor of Control System Technologies, at the Department of Automation Engineering of University of Naples “Federico II” (from 2001 to 2004).

Luca Garbarino – Research engineer at Italian Aerospace Research Centre (CIRA), Flight Systems Dept., since 2001. His research and development activities are in the field of embedded systems and avionic architectures. He received his degree in Computer Science from University of Genoa in 2001.

Umberto Ciniglio – ATM Dept. scientific coordinator at Italian Aerospace Research Centre (CIRA). He graduated cum laude with master degree in Electronics Engineering in 1992.

Pasquale Canzolino – Research Engineer at Italian Aerospace Research Centre (CIRA), Flight Systems Dept., since 1994. His research and development activities are in the field of Avionic Systems. He received his cum laude master degree in Electronic Engineering from University of Naples “Federico II” in 1992.

Salvatore Gaglione - graduated with honours in Navigation Sciences at Naples "Parthenope" University. In February 2006 had a PhD in Geodetic and Topographical Science, cycle XVIII, with a thesis entitled: The GBAS - Ground-Based Augmentation System. Since March 2008 he has been Assistant Professor in Navigation at the Department of Applied Sciences of Naples "Parthenope" University.

Vincenzo Nastro
Full Professor in Air Navigation and Air Traffic Control
Department for Technologies
University of Naples 'Parthenope

1. INTRODUCTION

Highly precise navigation is the core technology required for many applications, such as automated aerial refuelling (AAR), sea-based joint precision approach and landing systems (JPALS), station-keeping, unmanned aerial vehicles (UAV) swarming and formation flight and unmanned ground vehicles (UGV) convoys. Advances in the above mentioned technology are possible considering the future GNSS framework, given that adequate characterization of new GNSS devices are performed and that new algorithms are developed that fully exploits the functionalities made available by the future GNSS systems. In this paper both aspects are considered, with specific reference to the use of GPS/EGNOS for reliable fixed wing aircraft automatic landing applications.

For what concern experimental characterization of the satellite based navigation system GPS/EGNOS, the main aim of the activity was to describe the broadcasted messages to enhance the navigation accuracy and integrity of the core GNSS-1 elements GPS and GLONASS, and to exploit how the data can be used to compute and analyze the performance in terms of Required Navigation Performance (RNP) parameters. The paper describes the algorithm implemented to process the broadcasted EGNOS SIS in order to obtain a position solution and integrity information compliant with RTCA DO229C. Moreover, the paper presents test procedures and experimental results that may be used as a design guideline for monitoring manufacturing compliance and, in certain cases, for obtaining formal DO229C certification of equipment design and manufacture.

On the other hand, concerning the development of new algorithms for Guidance, Navigation & Control of fixed wing vehicles, that are already compatible with the future GNSS framework, it was initially considered a suite of navigation sensors with accuracy similar to the one obtainable by EGNOS. In order to overcome the effects due to an insufficient accuracy, the satellite measures can be in fact integrated with different sensor sources allowing a high precision navigation and an improvement of the integrity and reliability of navigation solutions. By means of an appropriate sensor suite, described in the next, and of a sensor fusion algorithm we obtained a high precision level in navigation measurements that, for instance, allows a high autonomous precision approach and landing. A very simple but effective sensor fusion algorithm based on the use of complementary filtering technique has been implemented. Moreover, some critical autonomous functionality, such as Autolanding, will utilize the GPS integrity signal in its decision-making logic for evaluating the key-decisions regarding the possible execution of an altitude recovery manoeuvre and, in case, also considering a degraded mode by changing the desired performances at touch down, with the aim to be still compatible with the current navigation system precision. In this way the integrity information provided by EGNOS is efficiently used for achieving a higher safety level during autonomous flight operations.

The selected on-board software architecture is actually fully compliant to the use of EGNOS based GPS units, without requiring any upgrade and the proposed sensor fusion algorithms have been already developed being basically compatible with integrity information coming from the future GNSS sensors. Anyway, in the presented first phase of flight experiments, we used a coarse DGPS unit, because EGNOS is still in the testing phase. The next steps are to perform autonomous GN&C flight experiment with EGNOS constellation with a runway completely not instrumented.

In the first part of the paper, concerning EGNOS system characterization, is presented an overview of EGNOS (chapter 2), are described the processing of the SBAS Signal-In-Space correction and integrity data and the related algorithm to estimate the integrity supplied by the system (chapter 3), the classes of equipment at which the test requirement are referred and the equipment performance and test procedure focusing on processing requirements and the validation performance assessment logic to assess the performance achievable with EGNOS (chapter 4). In its second part, describing the development of GNC algorithms already compatible with the future GNSS framework, the paper deals with the autolanding algorithms (chapter 6), the sensor fusion algorithms to achieve the desired navigation precision and the methodologies developed in order to safely manage the possible presence of sensor failures (chapter 5), the preliminary results of the real time validation with hardware in the loop simulation (chapter 7) and, finally, the algorithm performances achieved during the first experimental flights by using the CIRA experimental flying platform (chapter 8).

PART I - EGNOS SYSTEM CHARACTERIZATION

2. EGNOS OVERVIEW

EGNOS is the first European initiative in the satellite navigation field. EGNOS was mentioned for the first time in 1994, in a communication from the European Commission. This was followed by the December 19, 1994, resolution by the Council of European Union to define the terms of the European Commission, European Space Agency, and EUROCONTROL.

The EGNOS program is an integral part of the European satellite radio-navigation policy. It is currently under the control of GALILEO Joint Undertaking (JU). The aim of EGNOS, like the other SBAS services, is to provide complementary information to the GPS and GLONASS signals to improve the RNP (Required Navigation Performance) parameters.

According to the integrated strategic vision for the provision of European GNSS, new services can be conceived as a result of combining GALILEO Satellite-Only Services (GSOSs) [1-2]. The latter provides ranging service, wide area differential corrections, and integrity. The combination of EGNOS services with the GALILEO Service of Life (SoL) is of special interest. The combined services will provide independent and complementary integrity information on the GALILEO and GPS constellations that may support, for instance, precision approach type operations in the aviation domain.

The overall system architecture is divided into three segments (Figure 1) [3]:

- Space segment;
- Ground segment;
- User segment;

The space segment consists of three Geostationary Earth Orbit (GEO) satellites that provide triple coverage over Europe, the Mediterranean, and Africa. EGNOS currently foresees the use of two INMARSAT-3 satellites and the ARTEMIS (Advanced Relay Technology Mission) satellite (positioned 21.5°E and PRN code is 124), as shown in Figure 1. The INMARSAT satellites are, respectively, AOR-E 3F2 (positioned 15.5°W and PRN code is 120) and IOR-W 3F5 (positioned 25°E and PRN 126). The IOR 3F1 INMARSAT satellite (positioned 64°E and PRN code is 131) has been used during EGNOS System Test Bed (ESTB).

The next generation of INMARSAT-4 satellites will be located in the existing INMARSAT orbit location. The navigation payload is bent-pipe transponder enabling the messages uploaded to the satellites to be broadcast to users using a GPS-like signal.

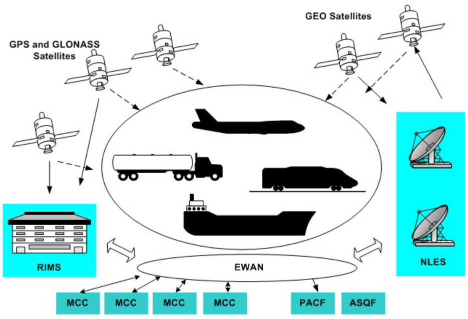

Figure 1: EGNOS overall system architecture

The ground segment includes the following elements:

- Four Mission Control Centres (MCC) that include Central Control Facility (CCF) and Central Processing Facility (CPF);
- Thirty-four ranging and Integrity Monitoring Stations (RIMS);
- Six Navigation Land Earth Stations (NLES);
- The Application Specific Qualification Facility (ASQF);
- The Performance Assessment and system Checkout Facility (PACF);
- The EGNOS Wide Area communication Network (EWAN)

These elements are distributed over the European territory and surrounding continents as shown in Figure 2.

The RIMS measure satellite pseudoranges (code and phase) from GPS/GLONASS and SBAS GEO satellites signals. The raw measurements are transmitted to the CPF, which determines the wide area differential corrections and ensures the integrity of the EGNOS system for users.

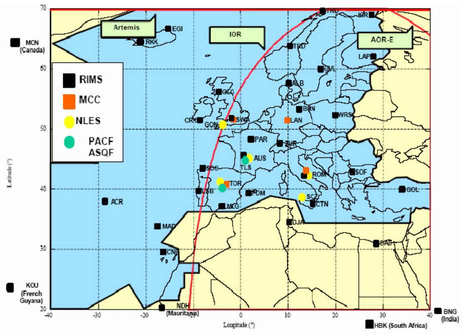

Figure 2: EGNOS Ground Segment Architecture

The RIMS can have two or three channels feeding the CPF called channel A/B and channel A/B/C respectively. Each channel is separated from the other (and developed by different main contractors) and transmits data to the EWAN. Channel A is used to transmit raw data for the computation of the differential corrections; Channel B is linked with CPF check chain for comparison and integrity monitoring purposes. Channel C is used for dedicated integrity function (satellite failure detection, or SFD). The RIMS continuously check the GPS and GLONASS signal to detect failures onboard the satellite, which imply errors in the measured satellite signal correlation function. In case an error is detected, the RIMS raise flag and send it to the CPF, to generate the Don't use flag for user.

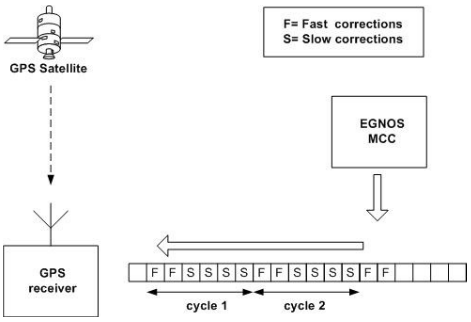

Figure 3: EGNOS message composition

The RIMS can also be remotely controlled by the CCF that is included in MCC. System architecture foresees four MCCs, located in Torrejon, (Spain), Gatwick, (United Kingdom), Langen, (Germany), and Ciampino, (Italy); only one of these MCCs is active and operational, whereas the remaining are hot spares to be activated if a problem occurs.

The EGNOS user segment is composed of a GPS and/or GLONASS receiver and EGNOS receiver. The two receivers are usually embedded in the same user terminal. The receiver can process the message that is scheduled in a 6-second duty cycle time. The EGNOS message includes more slowly changing errors, such as long-term satellite clock drift, long term orbital error correction, and ionosphere delay corrections and fast correction (rapidly changing errors, such as satellite clock errors) in the same frame, as showed in the Figure 3.

3. EGNOS SIS CHARACTERIZATION, CORRECTION AND INTEGRITY DATA PROCESSING

A given EGNOS GEO SATELLITE broadcasts either coarse integrity data or both such data and wide area corrections.

The coarse integrity data includes use/don't-use information on all satellites in view of the applicable region, including the GEOs. Correction data include estimates of the error after application of the corrections. The parameter, σ^2_{UDRE}, is the variance of a normal distribution associated with the user differential range error for a satellite after application of fast corrections and long term corrections, excluding atmospheric effects.

The parameter, σ^2_{GIVE}, is the variance of a normal distribution associated with the residual ionospheric vertical error at an Ionospheric Grid Point (IGP).

3.1 Data Rate

The baseline data rate is 250 bits per second. The data is always rate 1/2 convolutional encoded with a Forward Error Correction (FEC) code. Therefore, the symbol rate that the GPS receiver must process is 500 symbols per second (sps). The convolutional coding is constraint length 7 as standard for Viterbi decoding, with a convolutional encoder logic arrangement as illustrated in Figure 4. The G1 symbol is selected on the output as the first half of a 4 millisecond data bit period. If soft decision decoding is used, the bit error rate (BER) performance gain of this combination of coding and decoding is 5dB over uncoded operation. The algorithms for the implementation of this decoding are described in [4].

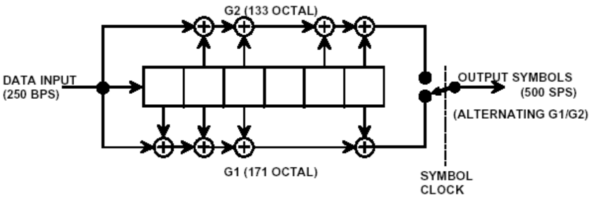

Figure 4: Convolutional encoding

3.2 Error corrections

There are two types of correction data: fast and long-term. The fast corrections are intended to correct for rapidly changing errors such as GNSS clock errors, while the long term corrections are for slower changing errors due to the atmospheric and long term satellite clock and ephemeris errors. The fast corrections are common to all users and will be broadcasted as follows. For the slower corrections, the users are provided with ephemeris and clock error estimates for each satellite in view. Although long term satellite clock errors are common to all regions, they are slow-varying and Issue of Data (IOD) dependent. Therefore, they are best accommodated as part of the slower corrections. Separately, users are provided with a wide-area ionospheric delay model and sufficient real-time data to evaluate the ionospheric delays for each satellite using that model ([5]).

The fast correction data for each satellite supported is accompanied by a Fast Correction Issue of Data (IODF) to prevent erroneous application of σ^2_{UDRE}.

The long term satellite correction data for each satellite supported is accompanied by Issue of Data (IOD) information to prevent erroneous application of correction data. The EGNOS issue of long term satellite correction data is identical to the GPS IOD

Ephemeris defined in [28] for the GPS satellites, and identical to a similar term for the GLONASS satellites when defined. Various other EGNOS issues of data defined below are also applied to prevent erroneous use of the PRN and Ionospheric Grid Point (IGP) masks.

3.3 Block Format and Message Types

The sequence of the data words is shown in the figure 5 describing the message formats while the number of bits per data word is given in the tables describing message contents.

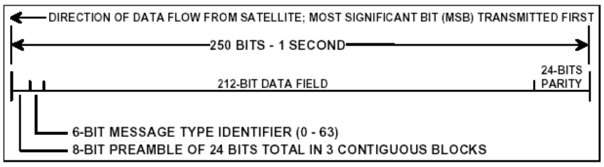

Figure 5: Data block format

Unless otherwise stated, data are represented in unsigned binary format. In order to associate data in different message types (describer in Table 1), a number of issue of data (IOD) parameters are used. These parameters include:

- IODk (GPS IOD Clock - IODCk, GPS IOD Ephemeris - IODEk, GLONASS Data - IODGk): Indicates GPS clock and ephemeris issue of data or GLONASS clock and ephemeris issue of data, where k = satellite
- IOD PRN Mask (IODP): Identifies the current PRN mask
- IOD Fast Correctionsj (IODFj): Identifies the current fast corrections, where j = fast corrections Message Type (Types 2 - 5)
- IOD Ionospheric Grid Point Mask (IODI): Identifies the current Ionospheric Grid Point mask
- IOD Service Message (IODS): Identifies the current Service Message(s) Type 27

Table 1 : Message Types

Type	
0	Don’t use for safety applications (ESTB)
1	PRN Mask assignments, set up to 51 of 210 bits
2 to 5	Fast corrections
6	Integrity information
7	Fast correction degradation factor
8	Reserved for future messages
9	GEO navigation message (X,Y,Z, time, etc.)
10	Degradation Parameters
11	Reserved for future messages
12	EGNOS Network Time/UTC offset parameters
13 to 16	Reserved for future messages
17	GEO satellite almanacs
18	Ionospheric grid point masks
19 to 23	Reserved for future messages
24	Mixed fast corrections/long term satellite error corrections
25	Long term satellite error corrections
26	Ionospheric delay corrections
27	EGNOS service message
28	Clock-Ephemeris Covariance Matrix message
29 to 61	Reserved for future message
62	Internal Test message
63	Null message

The relationship among the messages is shown in Figure 6. The IOD's (including GPS IODC and IODE and GLONASS equivalent term when defined) are specific to each satellite, and are updated separately.

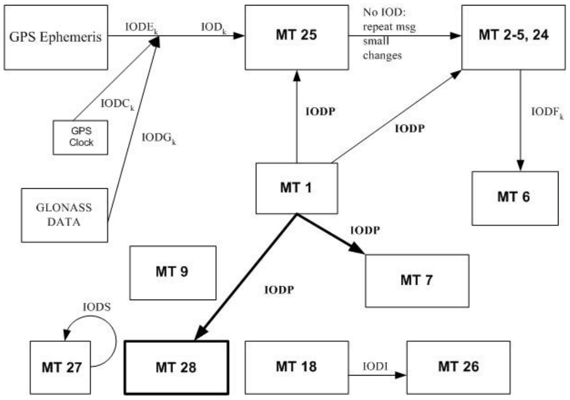

Figure 6: Interrelationships of messages

3.4 Integrity Data Processing

The accuracy of a navigation system is defined in term of Total System Error TSE which is referenced to a required flight path defined for each phase of flight. To follow the required path, the aircraft navigation system estimates the aircraft’s position and generates commands (either to a cockpit display or to the autopilot). Errors in the estimation of the aircraft’s position is referred to as Navigation System Error NSE which is the difference between the aircraft’s true position and its displayed position (Figure 7). The difference between the required flight path and the displayed position of the aircraft is called Flight Technical Error FTE and contains aircraft dynamics, turbulence effects, man-machine-interface problems, etc. The vector sum of the NSE and the FTE is the Total System Error. Since the actual Navigation System Error can not be observed without a high-precision reference system (the NSE is the difference between the actual position of an aircraft and its computed position), an approach has to be found with which an upper bound can be found for this error.

- **Horizontal Protection Level**: The Horizontal Protection Level (HPL) is the radius of a circle in the horizontal plane (the plane tangent to the WGS-84 ellipsoid), with its centre being at the true position, which describes the region which is assured to contain the indicated horizontal position. It is the horizontal region for which the missed alert requirement can be met. It is based upon the error estimates provided by EGNOS.
- **Vertical Protection Level:** The Vertical Protection Level (VPL) is half the length of a segment on the vertical axis (perpendicular to the horizontal plane of WGS-84 ellipsoid), with its center being at the true position, which describes the region which is assured to contain the indicated vertical position. It defines the vertical region for which the missed alert requirement can be met. It is based upon the error estimates provided by EGNOS.

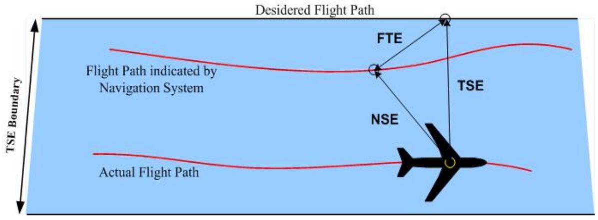

Figure 7: Navigation System Error; Flight Technical Error and Total System Error

The computed protection levels [5] must be compared to the required Alert Limits (AL) for the particular phase of flight.
If the protection level is smaller than the required alert limit, then the phase of flight can be performed. However, if the protection level is greater than or equal to the required alert limit, then the integrity of the position solution can not be guaranteed in the context of the requirements for that particular flight phase.

$$XPL < XAL \text{ integrity can be assured} \quad (1)$$
$$XPL \geq XAL \text{ integrity can not be assured} \quad (2)$$

With XPL we have denoted the Horizontal or Vertical Protection Level and with XAL we indicate the Horizontal or Vertical Alert Limit. The corresponding situation in the Horizontal plane is depicted in Figure 8.

It should be noted that the main significance using this approach is not the computation of the protection levels and their comparison with the corresponding alert limit.

The major interest should be considered to be on the assurance that the computed protection levels represent an upper bound on the NSE with a certain confidence. "Misleading Information" results only, if the NSE is greater than the alert limit and the protection level does not indicate this fact (for a more complete and detailed description of the "overbounding concept" and problems resulting of it, refer to [7]).

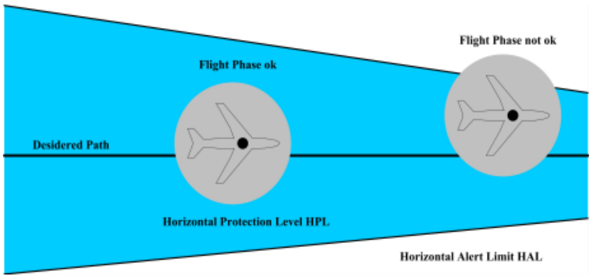

Figure 8: Horizontal Protection Levels and Horizontal Alert Limits

As defined, an *Integrity event* is an epoch where the Position Error (PE) exceeds a maximum allowable limit, called the Alert Limit (AL) while no alert is generated within an allowable time period, called the Time to Alert (TTA).

The impact of the TTA value is neglected in the context of the First Glance Algorithm.
Thus, every situation where the position error exceeds the protection level is reported. Hence the worst case scenario is considered and the analysis stays on the conservative side.

- *Misleading Information (MI)*: Misleading Information (MI) event is considered every epoch where PE > PL which can be regarded as a system anomaly.
- *Hazardous Misleading Information (HMI)*: Hazardous Misleading Information (HMI) event is considered every epoch where PE > AL and AL > PL which can be regarded as a system anomaly that is hazardous for a specific user. (note that AL can differ for different users/operations).
- *Near Misleading Information (Near MI)*: Near MI event is considered every epoch where PE/PL>0.75.
- *Integrity pass criteria*: If one or more MI or HMI is present in a data set, the first glance test will be failed and an investigation into the causes should be performed.

For integrity only the total number of integrity events is given.

- From all valid samples all the Misleading Information (MI) events are determined based on samples with XPE>XPL. Horizontal and vertical events are counted separately and the total is determined by counting all events for which HPE>HPL *OR* VPE>VPL.
- For each operation the same is done but now the Hazardous MI (HMI) are counted according to XPE>XAL>XPL.

4. TEST EQUIPMENT AND EGNOS PERFORMANCE ASSESSMENT LOGIC

The qualification activities for EGNOS Service of Life are under control and validation also by dynamic test. This is the main difference with ESTB phase when the SIS validation were established mainly by static session of measures. [7]
For this reason and in order to define all the requirements of an EGNOS/GPS receiver, able to be used in a dynamic test, in this section we introduce the configuration used as airborne equipment during the European research made in this area.
The analysis methodology is composed of the following steps:

1. Estimation of expected performances by pure simulation
2. Pre-flight estimation of expected performances by extrapolation from static real data
3. On-board real flight data collection
4. On ground real data collection during the real flight
5. Computation and analysis of real flight results and performances.

4.1 On-board Equipment.

Regarding the avionics installed on a test - aircraft, during the experimental flight trials, the platform installed in the aircraft is to be easily and quickly mountable in order to minimize the time the aircraft had to be out of its regular service..
The diagram in Figure 9 shows a Stand Alone avionics installed on-board the aircraft and the flow diagram of the on-board real data collection process.

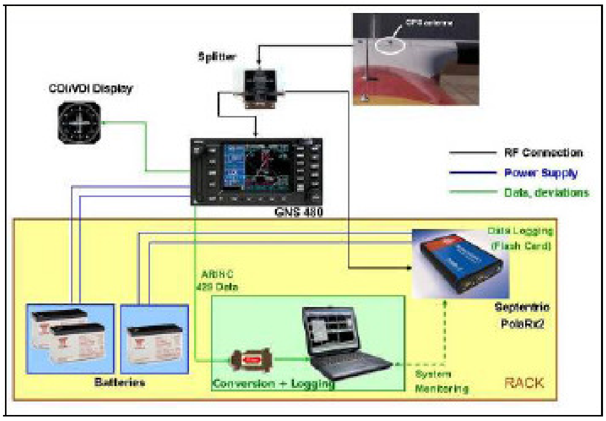

Figure 9: Stand alone avionics

4.2 Ground Equipment

The main objective of installing equipment on ground is to log GNSS data before, during and after the flight, for using them in post processing to compute the trajectography and obtain the AFP (*Aircraft Flight Path*).
As part of this primary objective, these stations allows staff on ground to monitor the EGNOS SIS and user performances in real time and, in case of a detection of an anomaly, inform the onboard team via radio.
To accomplish this goal, and in order to have redundancy, two logging stations are to be installed on ground inside airfield, one located at a geo referenced point in the airport
Each station used satellite receiver able to collect GNSS raw data.

EUROCONTROL for the analysis of static and dynamic GNSS data. PEGASUS is composed of several modules for conversion, analysis and representation of data (Mfile Runner module).

PEGASUS tool was also used to generate what is known as the Desired Flight Path (Dynamics module), the path in the air that the pilot would fly in an ideal hypothetic situation.

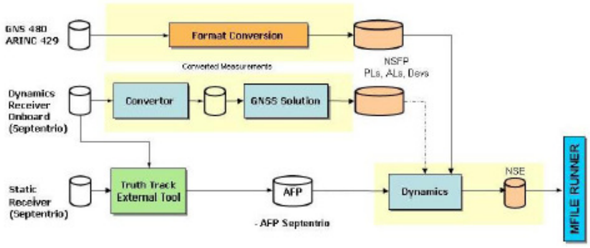

Figure 10: PEGASUS Software Architecture

The system architecture used for the flight trial is described in the next (§8).

PART II – GNC ALGORITHMS FOR GNNS BASED NAVIGATION

5. SENSOR FUSION ALGORITHMS

As already mentioned in the introduction, in order to overcome the effects due to an insufficient accuracy, the satellite measures can be integrated with different sensor sources allowing a high precision navigation and an improvement of the integrity and reliability of navigation solutions. The sensor suite used to these end is currently composed by: two GPS units, a laser altimeter, an AHRS (Attitude Heading Reference System) and an ADS (Air Data System). More in details, the two GPS units have different configurations: one is configured in coarse DGPS mode while the other in the carrier phase high precision mode (RTK). Both GPS receive a differential correction from a GPS base station located near the runway, but are capable of receiving the EGNOS system correction. This solution has been selected in order to use the data from the coarse DGPS in the navigation and control algorithms, while using the data from the RTK GPS, as the meter comparison of the vehicle position and velocity estimation.

A very simple but effective sensor fusion algorithm based on the use of complementary filtering technique has been implemented. This algorithm contributes to integrate position and speed measures coming from GPS with accelerations, attitude and orientation coming from an AHRS (Attitude and Heading Reference Systems). So this filter aims to determine in the best way the aircraft position and speed by using both the raw measures from the inertial sensors and the measures supplied by the GPS. The general concept of the complementary filter is the integration of acceleration measures supplied by the AHRS, in order to obtain position and speed less affected by noise and with a larger band respect to GPS measures. However, even if the AHRS measures are little noisy, they are affected from remarkable bias errors, so speed and position calculated only by integration of the accelerations can quickly diverge from the real values. In order to limit the effects due to the bias, therefore, it can be thought to integrate the accelerations and to process them through a high-pass filter, obtaining the medium-high frequency component of the considered signals. The low frequency components can be obtained by a filtering stage of the GPS measures through a low-pass filter. The final estimate of position and speed is equal to the sum of two components above mentioned.

The resulting architecture of the complementary filter we developed is, therefore, the one shown in the follow schematic representation .

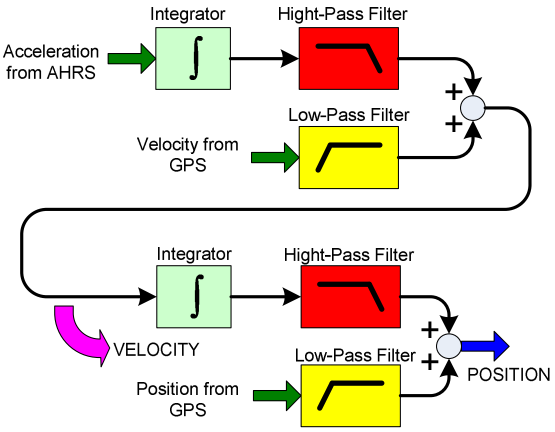

Figure 11– Conceptual representation of the complementary filter

It is important to emphasize that, in both velocity and position measures estimation, the high-pass filter applied to AHRS measures and the low-pass filter applied to GPS measures must be "complementary", in the sense that the sum of the transfer functions of the two filters must be equal to one. The specific cut-off frequencies utilized in the filters shown in Figure 11 have to be chosen to reach the following two contrasting aims: minimizing the noise power due to the GPS and avoiding the error arising from the integration of the AHRS accelerometers bias.

The method above described applies in normal no-failure conditions. However, also in the case of GPS failure or GPS degraded mode it is necessary obtain estimation, even if not optimal, of vehicle navigation data. The strategy adopted in this situation is described in the next.

Considering an integrity level as defined in §3.4, when it occurs, depending from the particular flight phase, the satellite measures have to be substituted for the estimation of the vehicle velocity and position. The basic idea is to replace them with the ones provided by a sensor characterized by the same characteristics, even if with lower precisions: in this case ADS, with an appropriate offset adjustment, represents a good solution. When an integrity event, involving a Vertical Protection Level (VPL) greater than the applicable Vertical Alert Limit valid in the particular flight phase, occurs than the Pressure altitude (PALT) is used as vertical position measure, while for the vertical speed is used the PALT RATE measure. When instead an integrity event, involving an Horizontal Protection Level (HPL) greater than the applicable Horizontal Alert Limit valid in the particular flight phase, occurs than the ADS is not more be able to directly supply such measures. In this case, for estimating the velocity the horizontal plane the procedure described in the next is used. As long as GPS correctly works, it is continuously performed a wind estimation. When an horizontal integrity event occurs, this wind estimation is frozen and constant wind is considered, so from the TAS measure derived from ADS it is possible to approximately estimate the inertial speed. In this way it is possible approximately to estimate the inertial speed components in the horizontal plan. Such components are used in place of GPS velocity measures as inputs in the complementary filter whose outputs velocity and position estimatation.

Each time is used the ADS the cut-off frequencies of the complementary filter are opportunely set. For further details on the proposed sensor fusion algorithm see references [11] and [12].

6. AUTOLANDING ALGORITHMS

This chapter presents the automatic approach and landing algorithm for fixed wing UAVs developed by CIRA within the complete autonomous mid air flight and landing system worked out in the national founded project TECVOL (Technologies for the Autonomous Flight).

The proposed approach and landing system is designed to perform a fully adaptive autonomous landing starting from any point of the three dimensional space, based on the use of the DGPS/AHRS technology. The main novel feature of this algorithm is that it generates on line, with a desired updating rate or at a specified event, the nominal trajectory for the aircraft, based on the actual state of the vehicle and on the desired state at touch down point. Main features of the described algorithm are: on line trajectory re-planning in the landing phase, fully autonomy from pilot inputs, weakly instrumented landing runway, ability to land starting from any point in the space and autonomous management of failures and/or adverse atmospheric conditions, decision-making logic evaluation for key-decisions regarding possible execution of altitude recovery maneuver based on the GPS integrity signal and compatible with the functionalities made available by the future GNSS system. The algorithm is fully adaptive, in the sense that it can generate on line, with a desired updating rate or in case of a selected driven event, the nominal trajectory for the aircraft, based on the actual state of the vehicle and on the desired state at touch down point. The fully adaptive generation starts with the Flare phase and is active up to the touch down event. The algorithm is free path, in the sense that it is able to accomplish the alignment to the assigned runway starting from any initial state, in terms of position and velocity. The autonomous landing process is divided into four main phases, each corresponding to a specific state of the high level mission automation logic. These main phases are called Alignment, Approach, Flare and Pre-Touch Down (see Figure 12).

The Alignment phase is intended to move the vehicle from its generic initial state (in terms of position and velocity) to a specified state, in which the vehicle is near the runway and aligned with the centreline. The Approach phase has the aim of reduce the vehicle TAS and insert it into a fixed glide path, down to a specified height above the runway, always maintaining its alignment with the centreline. The Flare phase aims to reduce the vertical speed module and to increase the pitch angle of the vehicle. The Pre-Touch Down phase, finally, is intended to continue the flare manoeuvre with relaxed constrains related to the kinematical state, while providing the vehicle with the proper landing attitude.

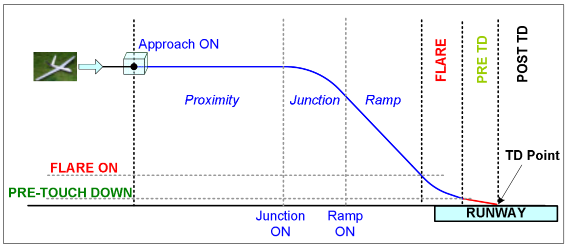

Figure 12: Automatic landing process conceptual breakdown

The development of the off-nominal algorithm has been preceded by a Failure Mode Effect Criticality Analysis (FMECA). By means of the FMECA, for each autolanding phase, it is defined the minimum set of sensors with their minimum performance modes that still assure a safely autolanding. When the sensor fusion algorithms, with their integrated FDIR functionalities, detect a failure considered critical for the safety of the vehicle the mission automation logic starts a missed approach phase.

Finally, a total performance index of the system is continuously monitored and, in case of lacking satisfaction of the correct range for the index, again a missed approach phase is executed. The total performance index concerns with the know error of the tracking control algorithm, with the estimated Navigation System Error (NSE) (see §3.4 for its definition) and with the geometric parameters and constrains of the particular runway. For further details on the proposed autolanding algorithm see references [9] and [10].

7. REAL TIME HARDWARE IN THE LOOP ALGORITHM VALIDATION

In the framework of the national founded project TECVOL (technologies for the autonomous flight) connected with the UAV CIRA program, with the aim of performing a real-time ground validation of the on board segment SW, a test rig that simulates the on board system and the on ground system has been done. Its functional architecture is in Figure 13.

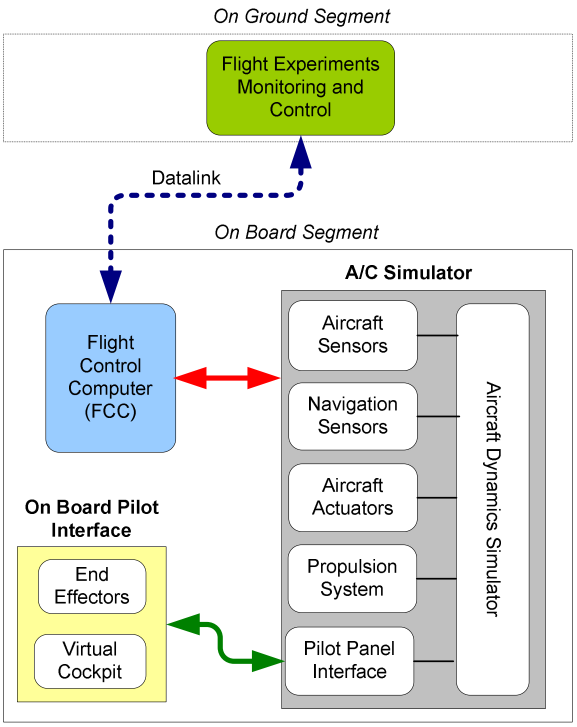

Figure 13 - On Ground Validation Test Rig

The FCC of the test rig is the same *Flight Control Computer* used for the on board segment. It is connected to the *A/C Simulator* that simulates entirely the aircraft and is composed of the following functional blocks:

- *Aircraft Dynamics Simulator* that simulates the dynamics of the vehicle.
- *Aircraft Sensors* that simulates the surface angular sensors, RPM sensors, WoW sensor.
- *Navigation Sensors* that simulates the GPS, AHRS, Altimeter sensors and ADS.
- *Aircraft Actuators* that simulates surfaces actuators, throttle actuators, flaps and pitch trim actuators.
- *Propulsion System.*

The *Pilot Panel Interface* block interfaces the simulated vehicle with the On Board Pilot Interface containing:

- *Virtual Cockpit*, MMI for the pilot;
- *End Effector*, that represents the Pilot Inceptors (Sidestich, Throttle, Pedals, Flap switch e Pitch Trim Switch)

The FCC communicates with the on ground segment, *Flight Experiment Monitoring and Control*, in order to:

- transmit flight data to allow a test engineer to supervise the test.
- receive setting data.

The *On Ground Validation Test Rig* allows the validation of the FCC SW and simulates the presence of an on-board safety pilot that interacts with the vehicle via the on-board pilot interface.

The performances of both the sensor fusion and autolanding algorithms above described have been tested by means of both simulated and real world flights.

With references to real time testing, the simulator values of the relevant variables have been assumed as real and compared with the values obtained from complementary filter and GPS. The values obtained from GPS are filtered through a first order low-pass filter, whose cut-off frequency has been chosen in order to reduce as much as possible the noise, but without attenuating the aircraft dynamic. Based on these requirements, the cut-off frequency used for GPS has been set to 1 Hz.

In order to emphasize the performance and the usefulness of the complementary filter, in the next figures are shown some comparisons among measures obtained by complimentary filter (red line), measures obtained by GPS (black line) and real value (blue line) of some inertial parameters of interest. The figures refers to an autonomous landing off-line simulation and are representatives of the several off-line simulations performed in the validation stage of the autonomous guidance algorithms and, as a consequence, of the complementary filter too.

In particular, Figure 14 shows the comparison among the above mentioned values with reference to the altitude measure during an autonomous landing, while Figure 15 shows this comparison regarding the vertical speed during the same manoeuvre.

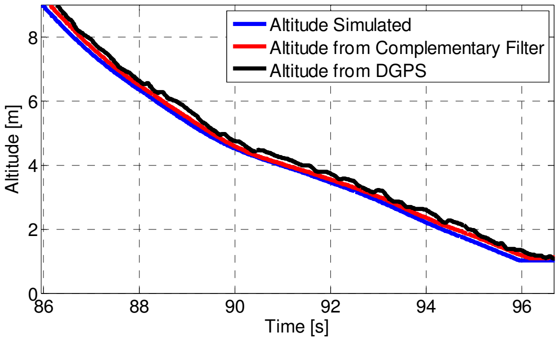

Figure 14 - Comparison among measures obtained by complimentary filter, GPS and real value of altitude during off-line simulated autonomous landing

Both figures show that using a complementary filter there are two advantages:

- complementary filter is able to attenuate the noise more than the first order low-pass filter;
- measures obtained from complementary filter have more accuracy than the ones obtained by filtering the GPS measures.

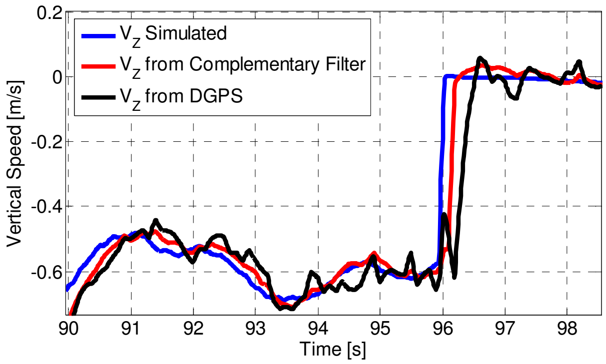

Figure 15 - Comparison among measures obtained by complimentary filter, GPS and real value of vertical speed during off-line simulated autonomous landing

From the autolanding algorithm point of view the two figures above show a nominal conditioning approach and landing without sensor failures or sensor degraded mode.

8. FLIGHT TESTING ALGORITHM VALIDATION

The functional on-board system architecture used to validate the control algorithms on-flight is shown in Figure 16.

The on-board *Flight Control Computer* runs the SW that implements the algorithms under test. It receives data from the *Aircraft Sensors* (surface angular sensors, RPM sensors, WoW sensors) and from the *Navigation Sensors* (GPS sensor, Inertial Sensor, Altimeter, ADS) and command the primary and secondary surface angular position (*Aircraft Actuators*) and the throttle (*Propulsion System*).

Moreover the FCC interfaces with the *Pilot Panel* to interact with on board pilot. The *Pilot Panel* allows to start/end the testing phase and shows several information about the FCC, diagnostic alarms and actuators states.

The FCC communicates, via radio link, with *Flight Experiments Monitoring and Control Ground Station* through the couple of *Communication Systems* devices. The test engineer has a complete picture of the flight test state looking at the monitors of the ground segment. Moreover he can send setting data to the on-board system.

For what concerns real world in-flight testing, in all flights performed in order to validate the advanced guidance developed algorithms, as previously described, the behaviour of complementary filter fully confirmed results obtained in off-line simulations.

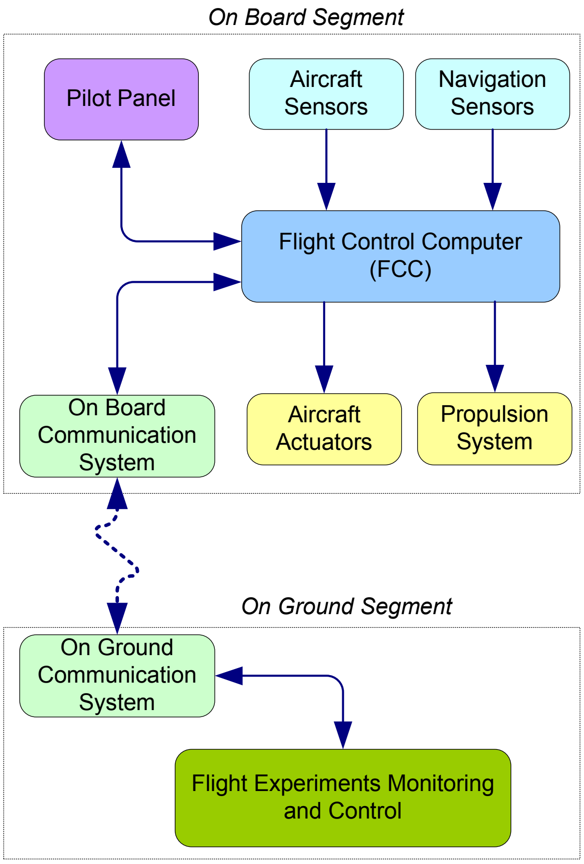

Figure 16 – On-Board System Architecture

Figure 17 shows a real world automatic landing that confirms the good performance of both sensor fusion and autolanding algorithms.

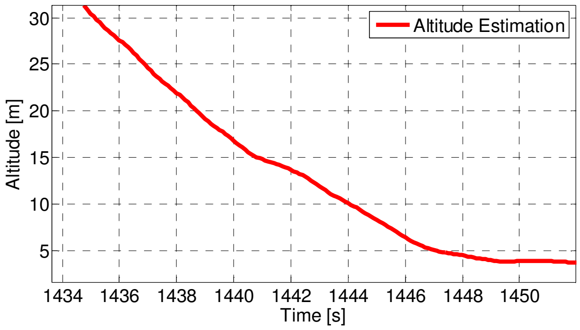

Figure 17 - Altitude estimation during real world autonomous landing manoeuvre

The complementary filter has a further feature: it is able to delete the frequency content due to a sudden GPS precision loss. This is shown in Figure 18 which refers to a GPS precision loss case experienced during real flights (as confirmed by increasing value of GPS error estimation).

Finally, Figure 19 shows a real world test with an approach and landing manoeuvre executed with a virtual touch down point objective placed at a height of 100 m above the runway and with a simulated vertical integrity event.

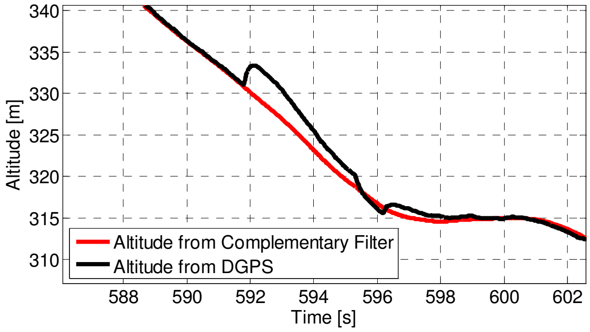

Figure 18 - Comparison among altitude measures obtained by complimentary filter and GPS during real flight in case of GPS precision loss

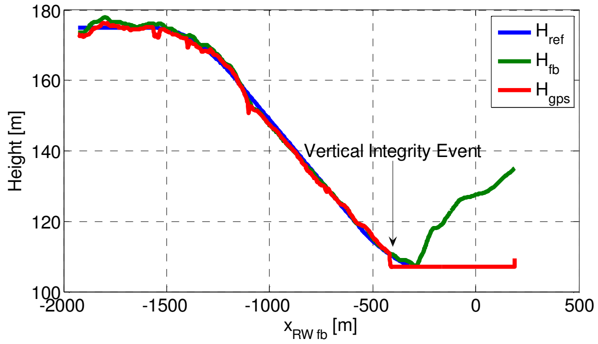

Figure 19 – Altitude recovery manoeuvre caused by a Vertical Integrity Event (VPL)

9. CONCLUSION

This paper presented some aspects concerning the possible advances in the highly precise navigation considering an adequate characterization of new GNSS devices and algorithms exploiting new functionalities made available by the future GNSS systems. In particular in the paper both aspects are considered, with specific reference to the use of GPS/EGNOS for reliable fixed wing aircraft automatic landing applications. For what concern experimental characterization of the satellite based navigation system GPS/EGNOS, the main aim of the activity was to describe the broadcasted messages to enhance the navigation accuracy and integrity of the core GNSS-1 elements GPS and GLONASS, and to exploit how the data can be used to compute and analyze the performance in terms of Required Navigation Performance (RNP) parameters. Moreover, in the paper is described the algorithm implemented to process the broadcasted EGNOS SIS in order to obtain a position solution and integrity information compliant with RTCA DO229C.

On the other hand, concerning the development of new algorithms for Guidance, Navigation & Control of fixed wing vehicles that are already compatible with the future GNSS framework, the paper described a sensor fusion algorithm and an autolanding algorithm. For both the presented algorithms are shown some experimental results related both the laboratory real time validation and the real world flight testing phase.

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