Politecnico di Torino

Department of Mechanical and Aerospace Engineering

Master Thesis

Study, integration and Risk Analysis of GNSS Augmentation Systems

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Supervisor:

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Abstract

The aim of this Master project thesis is to study the effects of the Augmentation systems integration into a specific UAS/RPAS category in terms of risk analysis and performances.
The first part focuses on the study of a Global Navigation Satellite System (*GNSS*) based on *GPS* and Augmentation systems, more precisely the Satellite Based Augmentation System (*SBAS*). The *SBAS* of interest for this project is the European Geostationary Navigation Overlay System (*EGNOS*) and, among all its offered services, the attention has been focused on LPV 200.
This section has been accomplished at Universitat Politecnica de Valencia, under the supervision of Prof. Israél Quintanilla.
The second part is on the study of drones normatives in force in Italy nowadays and how the system studied in the first section could be integrated in a RPAS both considering *ENAC* position and at system level. The latter one consists on the selection of a specific *EGNOS*-enabled receiver basing on its weight, power supply, voltage and other technical parameters.
The third and final part is on the implementation of a risk assessment of an RPAS equipped with *EGNOS* receiver using *LPV 200* procedures and integrated into controlled airspace. Risk assessment results are summarized in a final risk matrix and discussed.
These two sections have been accomplished at Politecnico di Torino, under the supervision of Prof. Paolo Maggiore and with the help of PhD student Federica Bonfante.
This thesis is a first exampe of study on issues related to RPAS safe positioning and navigation within controlled airspace even over highly populated areas. The ideal prosecution of this work will be a more comprehensive investigation on more complex scenarios based on the operative implementation of satellite-based augmented navigation systems.

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Introduction

In the last years, the utility of satellite systems has been increasing. Nowadays, navigation systems are used in all the fields of the common civil life, from terrestrial, to maritime and air navigation. More precisely, this kind of positioning and navigation systems is used for surveying and mapping, military, mobile communications and precise time reference. In the future the usage of Global Navigation Satellite System (or *GNSS*) is going to intensify and the technological process will allow to reach higher precision levels. In this project application related to aviation sector only will be investigated. The International Civil Aviation Organization (ICAO), recognizes the potentiality of these systems, if compared to traditional navigation aids, to provide improvements in air navigation and cost reductions for aviation operators.For this reason ICAO is encouraging the operative use of satellite-based navigation systems besides traditional ones. More precisely, on the long term, traditional navigation aids will be gradually decommissioned in favor of the new ones (ICAO Doc. 9849).GNSS will be firstly integrated on manned aircraft and then on the new systems entering the modern aviation scenario, the Unmanned Aircraft Systems or UAS; among them Remotely Piloted Aircraft Systems are object of study of modern aeronautics. Investigations on the implementation of GNSS systems on RPAS is one of the main focus of this work. This issue is part of a more general theme, that is that of integration of RPAS with manned aircraft into controlled airspaces. From this perspective, GNSS can be considered because it can support automation of some functions onboard RPAS like (precision) navigation and landing.

The current regulations in force are not complete and let the remote pilot be able to use drones only in unhabitated zones and with specific permissions given by Aviation Authorities like *ENAC* in Italy. This is due to the level of precision of current positioning systems that do not comply with regulatory formal requirements.

Navigation Satellite systems are constellations of satellites with global coverage providing signals from space, transmitting messages with encoded positioning and timing data. Some examples of these systems that are going to be studied deeply during this project are the USA's NAVSTAR Global Positioning System (*GPS*), or Russia's Global'naya Navigatsionnaya Sputnikovaya Sistema (*GLONASS*) and within 2020 the European *Galileo* that will be composed of a constellation of 30 satellites able to interoperate with *GPS* and *GLONASS* satellites. Despite this, the *GNSS* are not satisfactory to meet the requirements imposed by *ICAO*. To overcome this problem, the so called "Augmentation Systems" are considered: Aircraft Based Augmentation System (*ABAS*), Satellite Based Augmentation System (*SBAS*), Ground Based Augmentation System (*GBAS*). In this thesis, will be focused on *SBAS* operating on the European region. The requirements that are enhanced by an Augmentation System are four:

- **Accuracy**: difference between the measured and the real position, speed or time of the receiver.
- **Continuity**: system's capacity to provide confidence thresholds as well as alarms in the event that anomalies occur in the positioning data
- **Integrity**: navigation system's ability to function without any interruption
- **Availability**: percentage of time during wich the signal fulfils the accuracy, integrity and continuty criteria.

In the following paragraphs it will be explained how an Augmentation System can help to meet these requirements, in particular the European Geostationary Navigation Overlay Service (*EGNOS*), that is Europe's regional *SBAS* used to improve the performance of *GPS* and *Galileo*. It has been deployed by European Union, European Space Agency (*ESA*) and *EUROCONTROL* to provide safety of life navigation services to aviation, maritime and land-based users over most of Europe.
A specific example of a service offered by *EGNOS* could be the *LPV 200* (Localizer Performance with Vertical Guidance for precision approach) that is equivalent to an *ILS CAT I* but with a lot of benefits in terms of performance and costs.

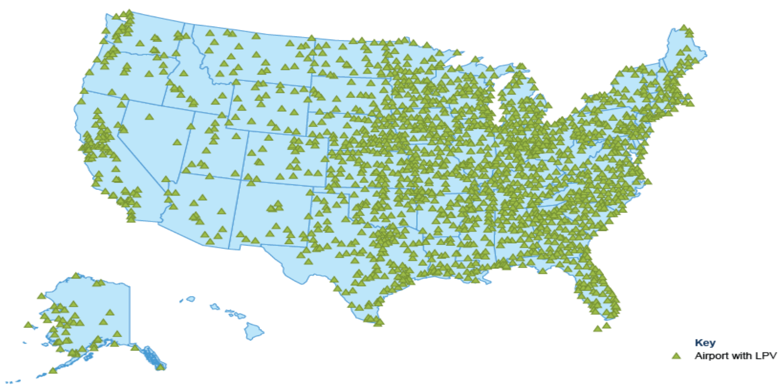


Figure 1: LPV 200 procedures implementation in USA

The United States of America have already the highest number of airports enabled for the highest precision instrument approach procedures *LPV 200*. In Europe, taking into account that the satellite constellation of *Galileo* is not fully operational, the implementation process is still ongoing. In fact only France, Germany and United Kingdom can count the most of their airports enabled to these approach operations. In the next years this technology will be available in most of the main europen airports.
In Italy, the first airsports where Galileo system is operative are those of Milan, Venice and Rome. Only in the last years, the airports of Florence, Bologna, Verona and Bergamo have reached a full operative condition.

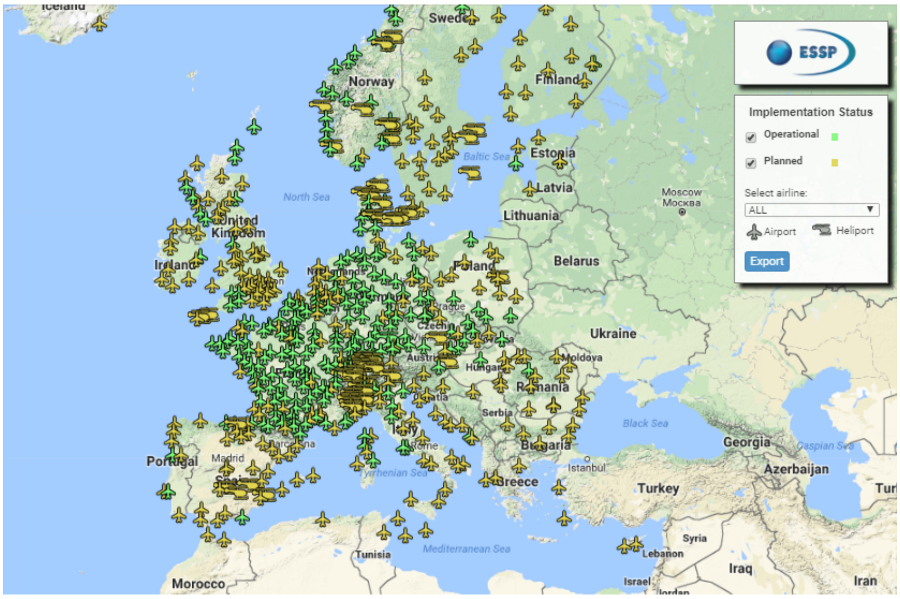


Figure 2: LPV 200 procedures implementation in Europe, [2]

Certainly, the fact that *LPV 200* is an instrument for approach procedures and it is able to provide very high precision data, indicates that *EGNOS* is able to offer other services during all the other flight phases. *EGNOS* system is a form of implementation of the 'Performance Based Navigation' (*PBN*) concept; in fact, where current navigation aids are based on the use of ground devices like RADARs, the *PBN* concept is based on performance parameters like the four ones before mentioned (availability, continuity, integrity, accuracy). A kind of navigation based on performances is the aRea Navigation *RNAV* that needs an accuracy performance level of 95% during the cruise phase and allows aircraft to know a precise route with horizontal and vertical precision.
EGNOS will be deeply described in this thesis; in addition, its receiver implementation on RPAS will be investigated from the perspective of operational risk related to the use of these augmented navigation systems into controlled airspaces.

Objectives

This project aims to study the integration of augmentation systems in drones in terms of performances and risk analysis. The results could be a basis for future works about fully automatic drones, that represents the future of transports, considering that nowadays it is catching on a lot of fields like agricultural, urban development, archeology, cartography, environment, surveillance, commerce and of course, military. For the most of non military applications it should be important to let drones fly above people with no risk of failures and possible injuries, so this is a study that wants to focus on the risk evaluation for drones using augmented navigation and positioning satellite systems.
To do this, the study started at the *Polythecnic University of Valencia* with the help of Prof. Israèl Quintanilla, and continued at *Polythechnic University of Turin* under the supervision of Prof. Paolo Maggiore and with the collaboration of PHD student Federica Bonfante.
During the first part of this project *EGNOS* messages protocol and content has been studied, as well as how *SBAS* systems operate in order to analyze results and to verify if they met ICAO requirements. To verify the requirements performances it has been fundamental the use of the software *PEGASUS*, implemented by *EUROCONTROL*. For the second part, ICAO documentation related to *EGNOS*-enabled receivers and RPAS has been considered to define possible scenarios for the risk analysis obect of the third part of this thesis.Finally, a risk analysis has been performed to implement the risk matrix related to the operation and the possible failures of an *EGNOS* based navigation system integrated into a RPAS.
The idea is that during a drone mission, it should be evalued the risk assessment in real time (because it depends on factors that always change during a mission, like the weather conditions) and the result of the risk analysis would be a value that, if it stands below a threshold value defined *a-priori*, then the drone must terminate its mission and land in a safe way, like a parachute if it has to happen instantaneously or with a defined route on the nearest unhabitated zone; if it stands above the threshold that represent the minimum level of security, then the drone can continue its mission.

Part I

NAVIGATION SYSTEMS

Chapter 1

Global Navigation Satellite System

A satellite navigation system (or *satnav*) is a system that uses satellites to provide autonomous geo-spatial positioning. It allows small electronic receivers to determine their location (longitude, latitude, and altitude/elevation) with high precision. The precision level depends on the type of encoding messages, which is different from civil to military. The system can be used to provide position, navigation or tracking of every kind of object that equips an enabled receiver. The signals sent by the satellites to the receiver (position data and time) are highly accurate. This allows to plan aircraft routes in a very precise way thus really implementing concepts like 'free routes'. This will concretely give the possibility to decommission traditional navigation aids like those ground-based (like, for instance, *VOR* or *ILS*). This will bring to reduction of on board avionic equipment, reduction of aircraft weight and reduction of fuel-related costs. It must be specified that satellite navigation systems operate independently of any telephonic or internet system, nonetheless it is possible to interact and enhance these different technologies.
More specifically, a satellite navigation system with global coverage is called Global Navigation Satellite System (or *GNSS*). Generally, a constellation of 18-30 medium Earth orbit satellites spread between several orbital planes is needed to achieve a system global coverage.
A *GNSS* system uses an inertial reference system for the geo-spatial positioning. In Italy, ROMA 40 and ED50 reference systems were used until 2000, when ICAO recommeded the use of World Geodetic System 1984 (*WGS84*) as international standard, that is a conventional Terrain System based on a Earth mathematic ellipsoidal model (i.e. the present reference system).

In the last decades, the use of these satellites systems has been growing in aviation applications. A Global Navigation Satellite System is composed of three segments briefly described hereinafter:

- **Space Segment**
  It is made by the satellite constellation. Each *GNSS* has its own constellation of satellites, orbiting about 20000 km above the Earth. It is important to note that satellites must be always in Line of Sight (LOS) respect to the receiver so that the signal could be transmitted and the position calculated. To reach this availability the satellite constellation shall made up by approximately 30 satellites positioned in differents orbital planes, so the 3 unknown positioning factors (X, Y, Z coordinates) and time correction can be easily calculated.

- **Ground Segment**
  It is also called Control Segment. It is composed of a certain number of Ground Stations, whose main function is monitoring the satellites and their transmissions and controlling if they are always fully operative. In addition, it is possible to move and update satellites, or change/correct their parameters or information. All these functions of ground stations could be considered as Telemetry, Tracking and Command functions. All these ground stations must calculate position all the time and send data to some Master Stations that validate and correct those informations.

- **User Segment**
  It is made of any kind of receiver able to compute its position by receiving a satellite signal. Then, it calculates and solves navigation differencial equations, taking into account all the possible errors that can affect the user position. All the sources of error will be analysed afterwards.

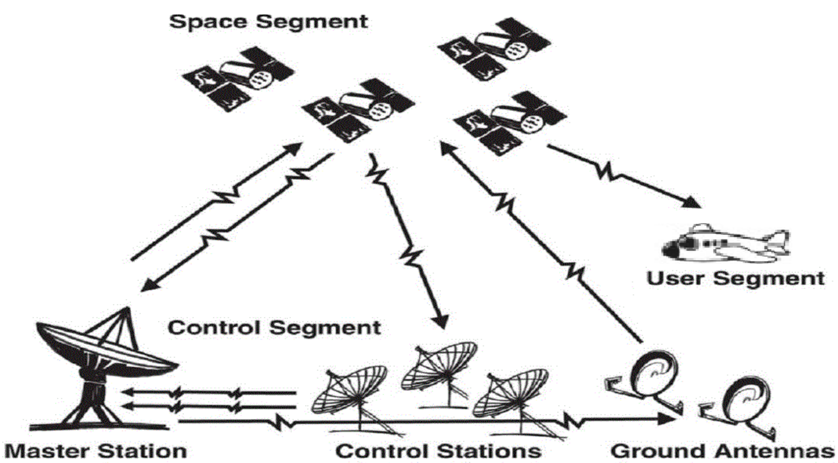


Figure 1.1: Architecture of a GNSS system

Nowadays, there are many Global Navigation Satellite Systems in the world, each one operating for a specific country. In the following paragraphs they will be descripted in detail.

- **GPS**
  The Global Positioning System is the U.S. *GNSS* which provides free positioning and timing services worldwide. Composed of 32 satellites, it was the first system and still the most used. Its satellites transmit right-hand circularly polarized signals to the Earth at two frequencies: the main *GPS* L1 at 1575.42 MHz that is modulated by two codes (Coarse/Adquisition C/A for civilian use and Precision/Secure P/Y for military or authorized civilian use) and the L2 signal at 1227.6 MHz that contains the precise code used for ionospheric corrections. In the year 2005 the modernization program started with the launch of other satellites that gave birth to a third new frequency for civilian and military use called L5 at 1176.45 MHz with the objective to reach better performances.
  The well known *Differential GPS* is an enhancement to primary *GPS* that uses a network of ground stations that improve the accuracy of the position calculation (an example is the Real Time Kinematics technique). The system performances is around 2 - 9 *[m]* precision for the only satellite signals and 0.5 - 2 *m* for the differential mode.

- **GLONASS**
  The Globalnaya Navigatsionnaya Sputnikovaya Sistema is the most expensive program of Russian Federal Space Agency. It is a space-based satellite navigation system operating in radionavigation-satellite service and is the second system operative with comparable precision to *GPS*. The russian satellite navigation system provides real time position and velocity determination for military and civilian users. It is composed of 25 satellites orbiting at about 20000 *km*. The orbit inclination makes it especially suited for usage at high latitudes. As the *GPS*, two services are available: the standard positioning service *SPS*, open and free of charge for worldwide users with two frequencies G1 at 1600 MHz and G2 at 1250 MHz and the precise positioning service *PPS* for military users at quite the same frequencies. At the beginning, the precision was worse than *GPS* until the last several improvements that rallowed the Russian system to reach the same performance as the *GPS*. Some modern receivers are able to use both American and Russian services together, providing greatly improved coverage in urban canyons or mountainous areas.

- **Beidou**

  The Beidou Navigation Satellite System is China's second generation system that will be capable of providing positioning, navigation and timing services to users on a continuous worldwide basis. It is composed of two separate constellations (one limited test system operational since 2000, and a full-scale global navigation system that will be operational in 2020). *Beidou-2* will consist of 35 satellites, 4 of which will be in GEO orbit and 30 in MEO, reaching the global coverage. At the moment it is operational with 15 satellites. The *Beidou-2* will be interoperable with all the other *GNSS* to reach better performances and will be open and free of charge for everyone and will offer more precise services to authorized users. Frequencies for *Beidou-2* are allocated in four bands: E1, E2, E5B and 36 and overlap with *Galileo*. The overlapping is as convenient from the point of view of the receiver design as inconvenient for problems of system interferences. Similarly to the others, it offers two services :civilian and military with different precision levels. The accuracy is of the same order of magnitude of the other *GNSS*.

- **NAVIC**

  The Navigation Indian Constellation (Indian Regional Navigational Satellite System or *IRNSS* until 2016) will be an indipendent and autonomous regional navigation system aiming a service area of about 1500 km around India, that is different from the other services with global coverage. *NAVIC* is planned to have 7 satellites complemented with the appropriate ground infrastructure as a minimum. Three of these satellites are geostationary and the other four are geosynchronous. It offers two kinds of services: the special positioning service SPS and the Precision Service PS. Both services will be carried on bands L5 at 1176.45 MHz and S 2492.08 MHz. The accuracy levels expected are about 20 m over the Indian Ocean Region and less than 10 m over India.

- **QZSS**

  The Quasi-Zenith Satellite System is a three-satellite regional time transfer system development and the satellite-based augmentation system for the global positioning system that would be receivable within Japan. It will provide highly precise and stable positioning services in the Asia-Oceania regions, mantaining compatibility with *GPS*. The main difference between *QZSS* and the other satellite systems is that the three satellites orbits are highly inclined, elliptical and geosynchronous. It is planned to launch other four satellites in GEO to reach a better coverage and precision. The accuracy will be of 0.01-1 m.

- **Galileo**

  It is the *GNSS* created by the European Union through the European Space Agency *ESA* to give Europe a satellite system that is independent from the American and Russian ones, but interoperable with them. *Galileo* is intended to provide horizontal and vertical position measurements of 0.01-1 m and better positioning services at higher latitudes. The system will consist of 30 satellites (24 in full service and 6 spares) in MEO orbit. As *Beidou*, it will have frequencies allocated in four bands: E5a, E5b, E6 and E1 and will offer a large quantity of services:

  Open Service OS that gives positioning accuracy to 1 m and targets the mass market like motor vehicle navigation and location-based mobile telephone services.

  Safety of Life Service SoL that is the most important service for the aviation because interoperates with the Open Service to give an integrity monitoring service aimed at users of Safety-of-Life applications in compliance with international standards.

  Commercial Service CS, encrypted, allows for development of applications for professional or commercial use owing to improved performance and data with greater added value than that obtained through the open service.

  Public Regulated Service PRS that is restricted to governments and authorised users, for sensitive applications which require a high level of service continuity. Encrypted too, this service is intended for security and strategic infrastructure.

  Search and Rescue Service SAR is a worldwide search and rescue service that will help to forward distress signals to a rescue coordination centre by detecting emergency signals transmitted by beacons and relaying messages to them.

  The *Galileo* performances are different for each service. For the Open Service the requirements are 4 and 8 m accuracy respectively for horizontal and vertical positioning. The minimum availability of the service is 99 %.

1.1 Augmentation Systems

As already said, the only *GNSS* is not satisfactory to meet the requirements imposed by *ICAO* during critical phases of an aircraft flight. To solve this problem, augmentation system are being implemented. These services are the way to improve the navigation attributes, known as **Accuracy**, **Integrity**, **Availability**,

Continuity.
The largest error in positioning systems is usually the unpredictable delay through the ionosphere. The spacecraft broadcast ionospheric model parameters, but imperfectly. Other sources of error are clock drift and ephemeris. To manage these errors, augmentation systems are divided in three categories:

- **Aircraft-based augmentation system**
  With the acronym *ABAS*, it indicates the augmentation obtained from other avionic sensors via separate principles than the *GNSS*. In aviation, the most widely used form of *ABAS* is Receiver Autonomous Integrity Monitoring (*RAIM*), which uses redundant signals to produce several *GPS* position fixes and compare them, and a statistical function determines whether or not a fault can be associated with any of the signals. Even more important is the ability to detect a failure and the time that pass until the user is aware of it (known as Time-to-Alert).

- **Ground-based augmentation system**
  It describes a system that supports augmentation through the use of terrestrial radio messages providing differential corrections and integrity monitoring. The navigation and precision service reaches very good levels only in station surrounding areas, (approximately 23 nautical miles radius), broadcasting its correction message via VHF radio data link from a ground-based transmitter. For this reason it is used in takeoff and approach phases, where there are stricter safety requirements about real-time accuracy and signals integrity, especially when the weather deteriorates to the extent that there is no visibility and *SBAS* could not more be used. In addiction, the shorter the distance between the ground station that calculates the correction and the inbound plane, the higher the accuracy is likely to be.
  The ground infrastructure for *GBAS* includes two or more *GNSS* receivers which collect pseudoranges and broadcasts differential corrections and integrity-related information for them based on its own surveyed position.

- **Satellite-based augmentation system**
  The *SBAS* is a system that supports wide-area or regional augmentation through the use of additional satellite-broadcast messages, so there is a primary satellite-based augmentation system for each continent. The *SBAS* system is composed of three main segments: space, ground and user. Its

concept is based on *GNSS* measurements by accurately-located reference station deployed across an entire continent. The navigation system's errors are then transferred to a computing centre, which calculates the corrections and the integrity messages, subsequently broadcasted over the continent using geostationary satellites as an augmentation or overlaying the original *GNSS* message. It will be studied more in deep, because it is the most used augmentation system in civil aviation.

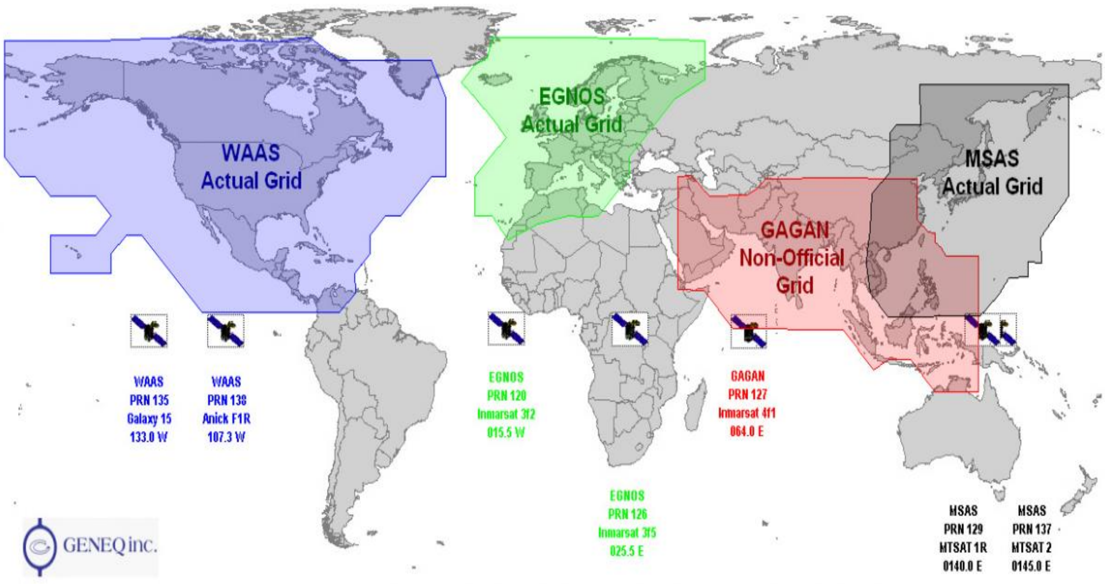


Figure 1.2: SBAS world coverage, [8]

Chapter 2

Satellite-based Augmentation System

SBAS are geosynchronous satellite systems that provide services for improving the above mentioned four requirements Accuracy, Integrity, Availability and Continuity of basic *GNSS* signals for a wide-area or regional augmentation. These augmentation services cover corrections of position errors, satellite clock and ionosphere signal delay.
The following table, which data are furnished by European Satellite Services Provider (ESSP), highlights the importance of *SBAS*.

	GNSS	GNSS + SBAS
Ionospheric propagation delay	2 m	0.3 m
Dilution of horizontal position	1.1 m	1.1 m
Satellite clock errors	1 m	0.5 m
Satellite orbital variations	1 m	0.5 m
Multipath	0.2 m	0.2 m
Tropospheric propagation delay	0.25 m	0.25 m
Receiver noise	0.5 m	0.5 m

Table 2.1: SBAS most influencing factors

As shown in figure 1.2, several countries have implemented their own satellite-based augmentation system. All of these systems comply with a common global standard and therefore they are all compatible (do not interfere with each other) and interoperable. An *SBAS* has a precise architecture:

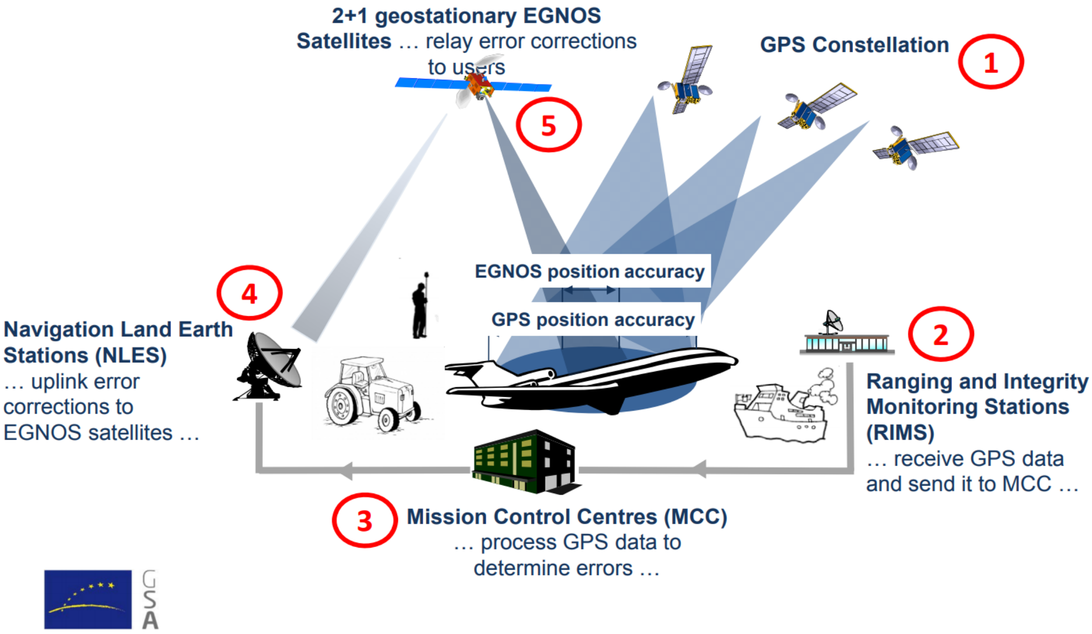


Figure 2.1: SBAS architecture, [10]

With reference to the scheme shown in figure 2.1, *SBAS* operating principle is the following one: the accurately-surveyed sensor stations (2) receive the data from the primary *GNSS* satellites (1) and send them to a Processing Facility Center (3) which computes integrity, corrections and GEO ranging data forming the *SBAS* Signal-in-Space *SIS*. Another group of stations send these new signals to *SBAS* GEO satellites that relay them to the user, now able to determine his position and time information using measurements both from the primary *GNSS* constellation and the GEO satellites and apply the correction data.
In general, it is said that an *SBAS* is divided in Space Segment, Ground Segment and User Segment.

- **Space Segment**
  It is composed of several GEO satellites that broadcast the navigation messages over the service area. Typically, *SBAS* satellites are multi-purpose (commercial communication) satellites that carry out an additional navigation payload capable to generate a GPS-like signal that retransmits to the users the navigation message generated on-ground.

- **Ground Segment**
  It generates and upliks the augmentation message that will be broadcasted by the GEO satellite and is in turn divided in subsystems: the Monitoring Station Network that collects data (through a network of *GNSS* receivers) from the satellites that are to be augmented; the Processing Facility Center

that processes the data provided by Monitoring Station Network to generate the messages to be broadcasted to the satellites; the GEO Satellite Control Center that generates signal with the message provided by the Processing Facility Center and up-links it to the GEO satellites; the Communication Layer interconnects all of these subsystems.

- **User Segment**
  It includes all the user equipment that makes use of the Signal-in-Space. It is not under control of *SBAS* service provider. In general, *SBAS* service operator provides different services aiming at different market sectors, namely Open Service and Safety of Life Service or Commercial Service. Depending on these services, a specific certified equipment (*SBAS* receivers) is needed.

2.1 Theoretical constructs

The true position of a ground station (or a generic user) is calculated by considering the pseudorange and all the corrections that have to be added. A pseudorange is a *pseudo* distance between a satellite and a navigation satellite receiver. To determine its position, four satellites are needed (three for position in the space and one for time evaluation). Typically, three satellites would be enough to evaluate a receiver position, but that would be true only if the receiver had incorporated a Caesium atomic clock. So, the evaluation of the pseudorange (R)of a generic ground station (A) referring to a generic satellite (j), known the geometrical distance (ρ) between the station and the satellite is:

$$PR_A^j(t_0) = \rho_A^j(t_0) + \Delta\rho_A^j(t_0) - c\delta^j(t_0) + c\delta_A(t_0) \tag{2.1}$$

with $\Delta\rho$ the orbital radial error and ionospheric/thropospheric delay, δ the time/clock error and c the speed of light. To correct the pseudorange for the generic satellite (j) at a reference time t_0 :

$$PRC^j(t_0) = -PR_A^j(t_0) + \rho_A^j(t_0) = -\Delta\rho_A^j(t_0) + c\delta^j(t_0) - c\delta_A(t_0) \tag{2.2}$$

The correction of distance variations in a certain range of time RRC is calculated as follows:

$$PRC^j(t) = PRC^j(t_0) + RRC^j(t_0)(t - t_0) \tag{2.3}$$

Considering the same process for another station (B):

$$PR_B^j(t_0) = \rho_B^j(t_0) + \Delta\rho_B^j(t_0) - c\delta^j(t_0) + c\delta_B(t_0) \tag{2.4}$$

that with the pseudorange correction becomes:

$$PR_B^j(t)_{corr} = PR_B^j(t) + PRC^j(t) = \rho_B^j(t) + (\Delta\rho_B^j(t) - \Delta\rho_A^j(t)) + (c\delta_B(t) - c\delta_A(t)) \tag{2.5}$$

As shown, the satellites errors $c\delta^j(t_0)$ disappear. The first parenthesis represents the orbital radial error and ionospheric/thropospheric delay. The second term in parenthesis can be written as:

$$\Delta\delta_{AB}(t) = \delta_B(t) - \delta_A(t) \tag{2.6}$$

This term represents the combined error of both stations (receivers).

2.2 Service areas of SBAS

It has been said that *SBAS* supports wide-area or regional *GNSS* augmentation. The figure 1.2 represents the globe areas with several countries that implemented their own satellite-based augmentation system; the content of figure 1.2 is hereinafter described in detail.

- **Wide Area Augmentation System**
  It is the air navigation aid developed by the Federal Aviation Administration (*FAA*) to augment *GPS* performances. Started in 1992, it enables aircraft to rely on *GPS* for all phases of flight, including the critical ones like approach to an airport. Its ground segment is composed of 38 Wide-area Reference Stations distributed in the USA (included Alaska and Hawaii states), Puerto Rico, Mexico and Canada. The space segment consists of multiple communication satellites that increase the number of satellites available for a position fix. It is composed of three commercial satellites (during 2018 a fourth satellite is scheduled to be operative). The user segment is the *GPS* and *WAAS* receiver, which uses information broadcast from each *GPS* satellite to determine its location at the current time. There are two types of corretion message received (fast and slow). The fast correction data includes the corrected satellite position and clock data. The slow correction data is related to the ionospheric delay that, as it happens for ephemeris errors, they do not change frequently and once updated every two minutes they are considerated valid for up to six minutes.
  With the objective to offer Accuracy, Integrity, Continuity and Availability, *WAAS* meets the requirements of LNAV/VNAV (Lateral/Vertical Navigation), LP (Localizer Performance), LPV (Localizer Performance with Vertical Guidance) and LPV-200 (Localizer Performance with vertical Guidance for approach category CAT I).

- **Multi-Functional Satellite Augmentation System**
  The *MSAS* is the Japanese Satellite Based Augmentation System, owned and operated by the Japan Ministry of Land, Infrastructur and Transport and Japan Meteorological Agency. It started in 2007 and works processing *GPS* data collected by a network of reference stations to generate *SBAS* message, subsequently uploaded to the two GEO satellites. The ground segment is composed of four Ground Monitor Stations and two Monitor and Ranging Stations, whose purpose is primarily to correct orbit determination of the constellation satellites. The space segment consists of two GEO satellites,

used also for meteorological purposes. The user segment is the *GPS* and *SBAS*-enabled receiver, that uses information broadcasted from satellites to determine location and current time and receives *MSAS* correction from space segment.

- **GPS Aided Geo Augmented Navigation**
  It is the *SBAS* implemented in India in 2001 by the Airports Authority of India and Indian Space Research Organization. Through several development phases (technology demonstration, experimental phase, etc.) in 2013 it is now fully operative The Space segment is composed by three GEO satellites. The ground segment consists of 15 Indian Reference Stations located all over the Indian area. The Indian Master Control Center has two sites located in Bangalore that process data and estimate the Integrity level. Another station, the Indian Land Uplink Station havs to uplink *SBAS* to the GEO satellites.

- **European Geostationary Navigation Overlay Service**
  EGNOS is the European *SBAS* that complements the existing satellite navigation services provided by the US Global Positioning System. *EGNOS* provides the first European *GNSS* services to users and constitutes together with *Galileo* the two major initiatives in Europe in terms of satellite navigation. It will be studied in deep in the next subsection.

2.2.1 EGNOS

The European Geostationary Navigation Overlay Service is a joint project of ESA, European Commission and EUROCONTROL, the European Organisation for the Safety of Air Navigation. After the successful completion of its development, ownership of *EGNOS* was transferred to the European Commission on 1 April 2009. *EGNOS* operations are now managed by the European Commission through a contract with an operator based in France, the European Satellite Services Provider. *EGNOS* offers all users high-performance navigation and positioning services, superior to that currently available in Europe. The three services available are the Open Service (OS), the Safety-of-Life Service (SoL) and the EGNOS Data Access Server (EDAS). For the *EGNOS* Open Service, the signal-in-space has been continuously available since October 2009.
Open Service provides unprecedented positioning precision by improving the accuracy of *GPS* with excellent signal quality throughout Europe. The continuos monitoring of the augmentation signal shows that *EGNOS* Open Service imple-

mentation improved *GPS* accuracy up to 1-2 m (vs. simple *GPS* accuracy equal to 17 m) and it provides a signal with an avilability for more than 99% of the time. Since March 2011, the *EGNOS* Safety-of-Life service has been declared available for use, after the Certification of ESSP as Air Navigation Service Provider. EDAS disseminates *EGNOS* data in real-time and is the single point of access for the data collected and generated by the *EGNOS* infrastructure. It allows users to "plug in" to *EGNOS* by providing access to satellite navigation data generated by ground stations distributed over Europe and North Africa. As the other *SBAS*, *EGNOS* is composed of three segments:

- **Space Segment**
  EGNOS is currently composed by 2 fully operative satellites and a third one still under tests. These GEO satellites have the objective to transmit the corrections to users in theEuropean area. Each of these satellites is identified by one PRN (Pseudo Random Noise). In detail: PRN 120 is referred to Inmarsat-3 AOR-E (Atlantic Ocean Region East) satellite, and it is fully operative; PRN 123 is referred to Astra 5B satellite, in testing phase; PRN 126 is referred to Astra 4B (or Sirius 5, SES-5), fully operative.

- **Ground Segment**
  The *EGNOS* Ground Segment comprises a network of thirty-four Ranging Integrity Monitoring Stations (RIMS), four Mission Control Centres (MCC), six Navigation Land Earth Stations (NLES), and the EGNOS Wide Area Network (EWAN) which provides the communication network for all the components of the ground segment. Two additional facilities are also deployed as part of the ground segment to support system operations and service provision, namely the Performance Assessment and Checkout Facility (PACF) and the Application Specific Qualification Facility (ASQF), which are operated by the EGNOS Server Provider.

  – **Ranging Integrity Monitoring Stations:** thirty-four RIMS stations located in Europe, Canada and South Africa (see figure 2.2) are charged of receiving and monitoring signals received from *GNSS* constellations (*GPS*, *GLONASS* and *Galileo* when will be fully operational) and send them to the MCC. There are two types of RIMS: RIMS A that receive signal data and correct them and RIMS B, that prove those corrections.

  – **Mission Control Centres:** the four MCC located in Madrid, London, Rome and Frankfurt receive all the RIMS correction data and elaborate them. MMC has two main modules: the Central Processing Facility (CPF) which processes the corrections and estimation errors in the received messages (elaborate clock corrections for each *GPS* satellite, ephemeris correction and elaborate a model for ionospheric induced delay over Europe); the Central Control Facility (CCF) that handles system and stores the created data. In addiction, CPF provides the CCF with RIMS status information as derived from the CPF computations and with a subset of the elaborated data (residual errors, ephemeris). These stations are operative 24/7 in order to ensure permanent service monitoring and control.

– **Navigation Land Earth Stations:** the six NLES receive the navigation message from all the CPFs for the upload of the data stream to the GEO satellites. For each of the GEO satellites two dedicated NLES are deployed. As the GEO satellites do not have atomic clock on board (as *GPS* satellites), the *EGNOS* augmentation messages are combined with the PRN codes and with additional signals to form a preliminary *EGNOS* signal synchronized with the L1 frequency before the up-link. The six NLES send navigation messages to GEO satellites.

– **Support elements:** They are located in Madrid and Tolouse. PACF provide support to *EGNOS* management in such areas like performances analysis, troubleshooting, operational procedures as well as upgrade specification and validation, support to maintenance. ASQF provides civil aviation and aeronautical certification authorities with the tools to qualify validate and certify the different *EGNOS* applications.

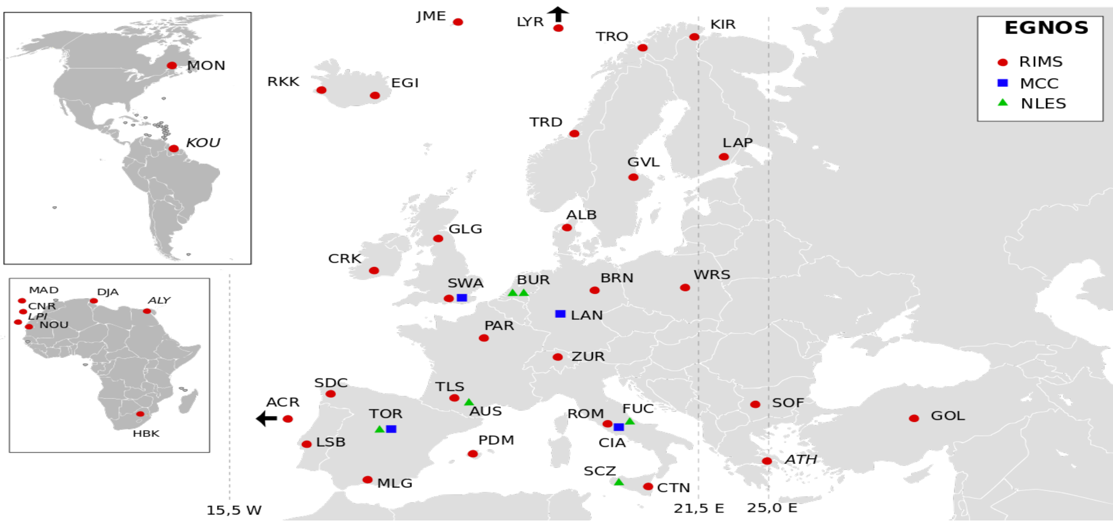


Figure 2.2: EGNOS stations

- **User Segment** As the other *SBAS*, the user segment includes *EGNOS* receivers that enable their users to accurately compute their position with integrity. An *EGNOS* receiver has the same size as a *GPS* receiver and uses the same type of antenna. It processes the individual satellite range measurements and combines them to compute an estimation of the user position. The estimation of the satellite-to-user range is based on the measurement of the propagation time of the signal and a number of errors already described before (satellite clock, signal distortions, ionospheric and tropospheric delay, etc.). Another service available for an *EGNOS* user is the Data Access Service. It disseminates *EGNOS* data in real time without relying on the signals from the three *EGNOS* satellites. EDAS is the single point of access for the data collected and generated by the european augmentation system.

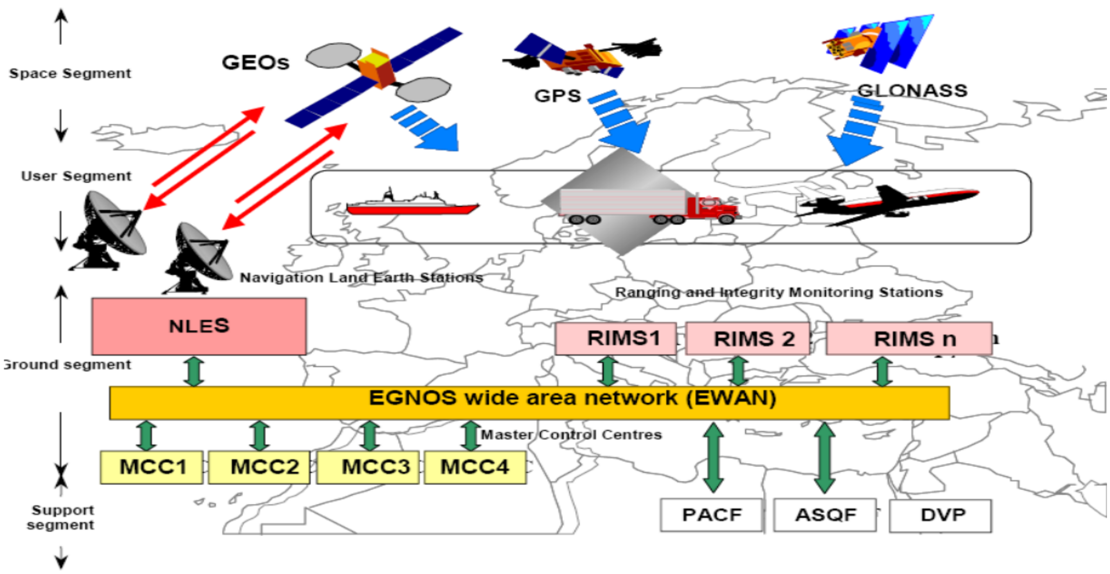


Figure 2.3: EGNOS architecture

Chapter 3

Performance Based Navigation

The continuous growth of aviation increases demands on airspace capacity therefore emphasizing the need for optimum utilization of available airspace. Improved operational efficiency derived from the application of aRea Navigation (*RNAV*) techniques has resulted in development of *PBN* procedures in various regions worldwide and for all phases of flight. These applications could potentially be expanded to provide guidance for ground movement operations. *RNAV* systems evolved in a manner similar to conventional ground-based routes and procedures. Systems like VOR, DME, ILS were developed, evaluated and certified on the basis of the performance of available equipment and specifications for requirements were based on available capabilities. In some cases, it was necessary to identify individual models of equipment that could be operated within the concerned airspace. Such prescriptive requirements resulted in delays in the indroduction of new *RNAV* system capabilities. To avoid these difficulties, an alternative method for defining equipage requirements by specifying the performance requirements has been introduced; the Performance Based Navigation *PBN*.

The *PBN* concept specifies that aircraft RNAV system performance requirements are defined in terms of **Accuracy**, **Integrity**, **Availability**, **Continuity** and **Functionality**, which are needed for the proposed operations in the context of an airspace concept. *PBN* represents a shift from sensor-based to performance-based navigation. Performance requirements are identified in navigation specifications, which also influences the choice of navigation sensors and equipment that may be used to meet the performance requirements. These specifications define the performance of *RNAV* or *RNP* systems and all the functional requirements. In the following paragraphs, specifications reated to RNAV and RNP systems are described more in detail hereinafter.

3.0.1 aRea NAVigation

With the acronym *RNAV*, aRea Navigation represents a kind of Instrument Flight Rules (IFR) navigation that allows an aircraft to choose any route within a network of navigation beacons. Area Navigation does not include the requirement for on-board navigation performance monitoring and alerting. An *RNAV* specification is designated as *RNAV X* where the expression *X* refers to the lateral navigation accuracy in nautical miles, which is expected to be achieved at least 95% of the flight time by the population of aircraft operating within the airspace, route or procedure.

3.0.2 Required Navigation Performance

The key difference between *RNP* and *RNAV* is the requirement for on-board performance monitoring and alerting. *RNP* systems provide improvements on the integrity of operation allowing, *inter alia*, possibly closer route spacing, and it can provide enough integrity to allow only the *RNP* systems to be used for navigating in a specific airspace. These systems may therefore offer significant safety, operational and efficiency benefits.
As the same of *RNAV*, *RNP* defines the accuracy requirement as the 95% Total System Error (TSE) for lateral and vertical navigation (*RNP* 'X' format). This allow an aircraft to fly a specific path between two 3D-defined points in space.

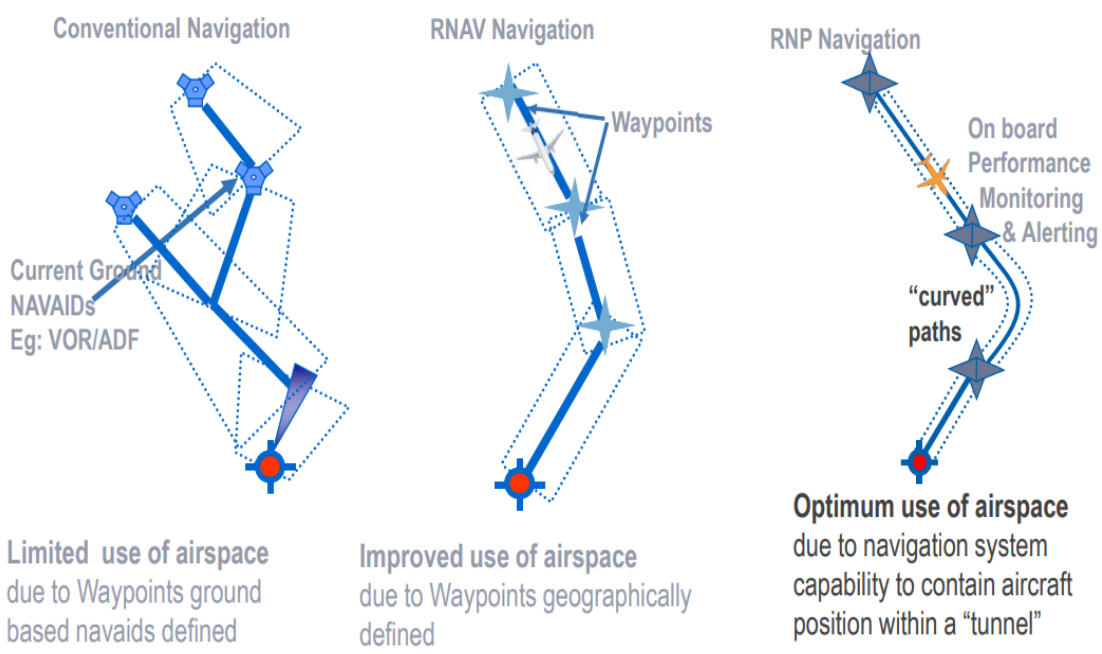


Figure 3.1: conventional versus RNAV and RNP in procedure design, [22]

Many *RNAV* systems, while offering very high accuracy and showing many of the functions provided by *RNP* systems, are not able to provide assurance of their performance. Recognizing this, and in order to avoid operators to incur unnecessary expense, where the airspace requirements does not necessitate the use of an *RNP* systems, many new well as existing navigation requirements will continue to specify *RNAV* rather than *RNP* systems. It means that both operations will co-exists for many years, taking in account that it is expected a gradual transition to *RNP* applications as the proportion of aircraft equipped with *RNP* systems increases and cost of transition reduces.

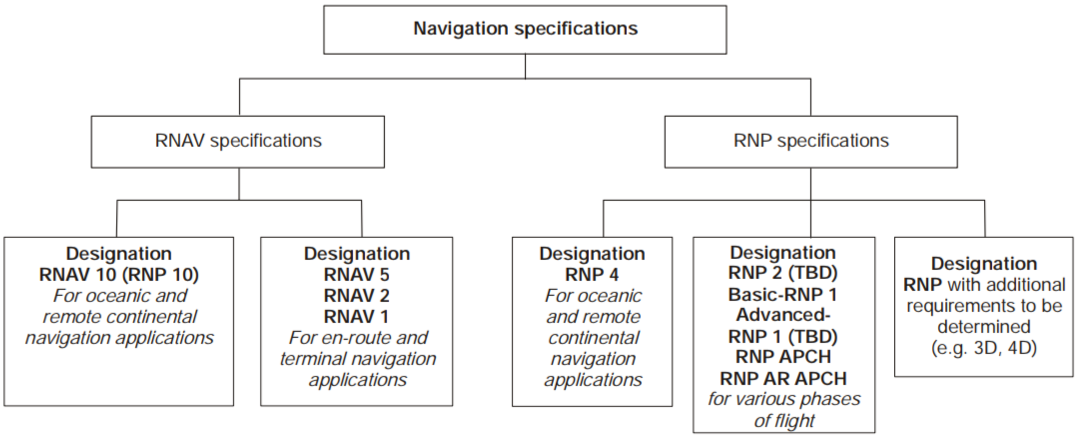


Figure 3.2: RNP and RNAV categories

With the 36th ICAO session, the assembly has urged all States to implement *RNAV* and *RNP* air traffic services (ATS) routes and approach procedures in accordance with the ICAO *PBN* concept laid down in the Performance-Based Navigation Manual (ICAO document 9613). In addiction, it required the implementation of approach procedures with vertical guidance *APV* for all instrument runway ends, either as the primary approach or as a back-up for precision approaches by 2016. Today, the navigation specifications are detailed as is shown in figure 3.2 and it can be noted that for each flight phase, different specifications are imposed. The approach phases (the most critical ones) have the highest level of performances. By the way, all *PBN* procedures have a number of benefits for all the flight phases like:

- Safety: Lateral and vertical track-keeping is much more accurate and reliable due to the new 3-D guided arrival, approach and departure procedures that can not be performed by conventional aids. *PBN* also reduces the flight crew's exposure to operational errors.

- Capacity: Reduction of delays, congestion or choke points at airports and crowded airspaces because of new parallel offset routes, that create additional ingress/egress, with cost reduction in terms of fuel and time.
- Efficiency: the high levels of reliability, repeatability and predictability of operations lead to increased air traffic throughput and smoother traffic flow.
- Access: obstacle clearance and environmental constraints can be bypassed applying optimmized *PBN* tracks.

3.1 PBN & GNSS union

Is important to point out the relation between *PBN* and *GNSS* in the contribution for the Required Performance Navigation. *GNSS* implementation has changed the definition of airspace by changing the way of positioning and navigation calculation. Meanwhile, *PBN* is one of the best way to take advantage of these changes. *GNSS* can be used for all *PBN* operations and flight phases, from the on-route which has benefits especially over oceans where there is no ground support, to end phases. About the latter one, it has to be said that Accuracy required corresponds to *RNAV 1* or *RNAV 2* using both *GNSS* (100% availability) and *DME* (high coverage area needed). In particular for the approach *GBAS* and/or *SBAS* are used. As a result, it is possible to state the indispensability of *GNSS* for *PBN* implementation.
In the next future, considering the technological process and improvements in this area, *RNP* for low routes useful for helicopters and *A-RNP* (Advanced) for navigation accuracy in all phases with the result of routes optimization will be implemented.

Chapter 4

Localizer Performance with Vertical guidance - LPV 200

As already mentioned in the previous sections, *EGNOS* provides *GNSS* augmentation. It augments *GPS* using the L1 (1575.42 MHz) Coarse/Acquisition (C/A) civilian signal function by providing correction data and integrity information to improve positioning, navigation and timing service all over the Europe.
EGNOS Safety of Life (SoL) service has been officially declared available on the 2nd March 2011. The SoL is an open and free accessible service, and is applied to various safety-critical fields, especially for the aviation. In fact, the main objective of *EGNOS* SoL service is to support aviation flight operations down to Localizer Performance with Vertical guidance (*LPV*) minima in approach procedures to aerodromes and helipads. This new procedure is thus compliant with *APV-I* signal-in-space performance requirements, as specified in ICAO annex 10.
LPV 200 provides 3-D approach procedures (Type A and B), corresponding to ILS CAT I. The number 200 refers to the Decision Height measured in feet ($\approx 61m$). In particular, the Decision Height is a specified alitude at which a Missed Approach must be initiated if the required visual reference to continue the approach has not been established, as mentioned in ICAO Annex 6.
LPV 200 EGNOS performances allow taking full advantage of the Performance Based Navigation advanced procedures as *RNP* approach down to *LPV 200* minima, curved steep and segmented approaches, improving Air Traffic Management (ATM) flexibility. Being an *SBAS* service, *LPV 200* works exactly as the previously mentioned Satellite Based Augmentation Systems, in order to provide better performance in terms of Accuracy, Integrity, Availability and Continuity, which have to meet ICAO requirements to be considered a validated system.

4.1 Benefits

It has been defined that *LPV 200* procedures are equivalent to ILS CAT I. Nevertheless, there are several reasons why in the next future *LPV 200* should replace all existing radionavigation aids:

- Reduced risks associated with landing in bad weather conditions.
- Increased accessibility to airports.
- Reduced delays, diversions and cancellations (cutting costs).
- Increased airspace capacity and reduction of both Air Traffic Control (ATC) and pilot workload.
- Improved efficiency of operations, lowering consumption, CO2 emissions and decreasing aviation's environmental impact.
- Reduced Installation and mainteinance costs.

In terms of operational benefits, with *LPV 200* there is no need to be aligned to the conventional runways or to have a clear area (terrain and generic obstacles does not affect the satellite system). *LPV 200* can be used without the need of a ground infrastructure, that means the possible use not only near airports or controlled airspaces. Of course, the user can trust about the safety levels because of not only horizontal precision but also vertical. In terms of economical impact, the user must have an *EGNOS* enabled receiver, whose installation on a generic aircraft or RPAS certainly will be possible and easy, with lower costs.
The implementation of *LPV 200* based operations could directly result in an important improvement on the existing Air Navigation capabilities and infrastructure, and therefore contribute to the socio-economic growth. Indirectly, *LPV 200* service level implementation will also bring public benefits generated by a reduction in pollution or by improved levels of safety.

4.2 Implementation

LPV 200 procedures have been implemented initially in the USA between years 2009 and 2013 by *WAAS*, reaching the total area coverage for approach operations in all airports. In Europe the process started in 2015 with first *LPV 200* implementation at Charles de Gaulle airport (Paris, France) and it is still ongoing. At this moment, only France and Germany have implemented *LPV 200* almost in all airports. The other European Union States have planned the system validation in the next 2 years. Sintetically, *LPV 200* consideration is increasing in the last years, thanks to its advantages and operational/economical benefits. This trend inevitably affects aircrafts, mobility, airports and all the areas regarding training and evaluation of pilots and flight operators.

Figure 4.1: LPV 200 Planned implementation in Europe, [2]

While *LPV 200* is being implemented all over Europe, other important objectives are going to be achieved, like the *EGNOS* coverage up to the 72° latitude degree before the end of 2018 and the Approach Performance with Vertical guidance all over the twenty-eight States of European Union (EU-28) with the addiction of other four new RIMS stations. These future evolutions of *EGNOS* services are represented in the following figure.

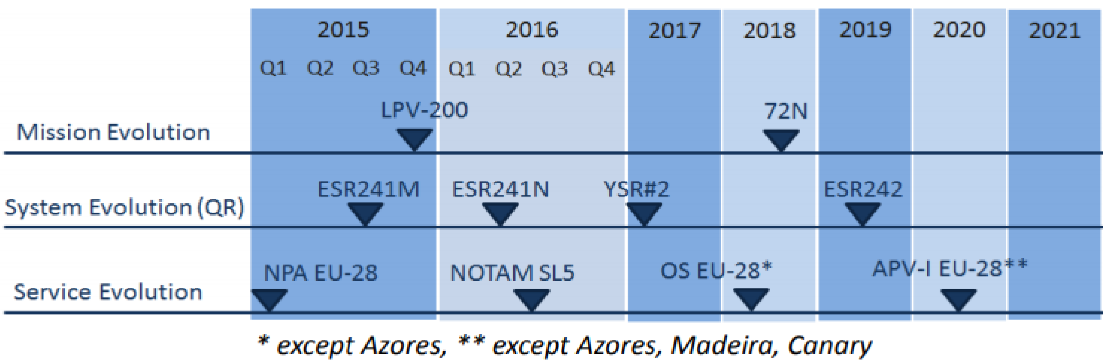


Figure 4.2: EGNOS services evolution plan, [26]

Considering the interoperability between *WAAS*, *EGNOS* and all the above mentioned *SBAS*, only one compatible (and enabled) receiver is needed on board.

Airbus company is integrating *EGNOS* in airplanes (e.g. A-350 Xwb) to ease implementation process. Theorically, *EGNOS* receivers could be implemented also onboard UAS/RPAS, but studies about new and updated regulations shall be performenced in the next future.

4.3 Requirements

Requirements have been expressed only for civil aviation operations, but *EGNOS* Safety of Life service could be used in other fields. By the way, the concept of Safety of Life is intended as a positioning augmentation signal service intended for all the domains where degradation in the navigation performance with a bad time to alert (or even without it) could led to dangerous conditions for people. In order to be able to provide the SoL service, *EGNOS* has been designed so that the Signal in Space is compliant to the Standard And Recommended Practices of ICAO (SARPs) for Satellite Based Augmentation System. The requirements that must have be met are defined in ICAO annex 10, which include Non-Precision Approach (NPA) and Approach with Vertical Guidance (APV-I) SoL service levels declared in 2011 and an addictional one regarding Localizer Performance with Vertical guidance (LPV) declared in 2015.

	Accuracy		Integrity				Continuity	Availability
Typical operation	Horizontal Accuracy 95%	Vertical Accuracy 95%	Integrity	Time-To-Alert (TTA)	Horizontal Alert Limit (HAL)	Vertical Alert Limit (VAL)		
En-route (oceanic/ continental low density)	3.7 km (2.0 NM)	N/A	$1 - 1x10^{-7}/h$	5 min	7.4 km (4 NM)	N/A	$1 - 1x10^{-4}/h$ to $1 - 1x10^{-8}/h$	0.99 to 0.99999
En-route (continental)					3.7 km (2 NM)	N/A		
En-route, Terminal	0.74 km (0.4 NM)	N/A	$1 - 1x10^{-7}/h$	15 s	1.85 km (1 NM)	N/A	$1 - 1x10^{-4}/h$ to $1 - 1x10^{-8}/h$	0.99 to 0.99999
Initial approach, Intermediate approach, Non-precision approach (NPA), Departure	220 m (720 ft)	N/A	$1 - 1x10^{-7}/h$	10 s	556 m (0.3 NM)	N/A	$1 - 1x10^{-4}/h$ to $1 - 1x10^{-8}/h$	0.99 to 0.99999
Approach operations with vertical guidance (APV-I)	16.0 m (52 ft)	20 m (66 ft)	$1 - 2x10^{-7}$ in any approach	10 s	40 m (130 ft)	50 m (164 ft)	$1 - 8x10^{-6}$ per 15 s	0.99 to 0.99999
Category I precision approach	16.0 m (52 ft)	6.0 m to 4.0 m (20 ft to 13 ft)	$1 - 2x10^{-7}$ in any approach	6 s	40 m (130 ft)	35.0 m to 10.0 m (115 ft to 33ft)	$1 - 8x10^{-6}$ per 15 s	0.99 to 0.99999

Figure 4.3: SoL service performance requirements (ICAO), [60]

4.3.1 Accuracy

It is defined by ICAO SARPs as the *GNSS* position error, that means the difference between the estimated position and the actual position. For an estimated position at a specific location, the probability should be at least 95% that the position error is within the accuracy requirement.
The position error is calculated as the Horizontal Navigation System Error (HNSE) and the Vertical Navigation System Error (VNSE). ICAO accuracy requirements declares that Vertical Accuracy must be at least within $6-4m$ and the Horizontal Accuracy within $16m$ at 95%. In case of *APV-I* procedure, the ICAO requirement imposes a vertical accuracy within $20m$ and the same horizontal accuracy.

	Definition	Value	APV-I requirement
Horizontal	Corresponds to a 95% confidence bound of the 2-dimensional position error[17] in the horizontal local plane for the Worst User Location[18]	3m	16m
Vertical	Corresponds to a 95% confidence bound of the 1-dimensional unsigned position error in the local vertical axis for the Worst User Location	4m	6m to 4m

Figure 4.4: LPV 200 Accuracy requirements, [60]

4.3.2 Integrity

Defined by ICAO SARPs, integrity is intended as a measure of trust which can be placed in the correctness of the information supplied by the total system. Integrity includes the availability of a system to provide timely and valid warnings (or alerts) when the system must not be used for intended operations (or phase of flight). Integrity service has to protect the user from both Failure of *GPS* satellites (detecting and excluding faulty satellites through the measurement of signals with the reference stations network) and the transmission of wrong differential corrections (may depend on undetected ground segment failures or reference data corrupted by noise). *EGNOS* makes use of Stanford Diagrams to evaluate integrity. Some concepts might be introduced for a better comprehension of this performance.

- **Integrity risk:** the probability that the position error (PE) is larger than the alert limit (AL) defiined for the intended operation and the user is not warned within the time to alert (TTA).

- **Integrity Event:** it occurs when the HNSE (or VNSE) is greater or equal to the corresponding horizontal (or vertical) protection level (HPL or VPL) for the intended operation and the receiver does not provide an alert within the TTA.

- **Alert Limit :** the error tolerance not to be exceeded without issuing an alert. Each operation has a defined HAL or VAL (LPV 200 limits are the most demanding for SoL service).
- **Protection Levels :** with the acronyms HPL and VPL the dimension of a cylinder are intended, which center represents the true position. The cylinder is intended as the region which is assured to contain the indicated horizontal and vertical position (4.6).
- **Time To Alert :** the maximum allowable time elapsed from when a failure occurs to the moment in which the user equipment reports it.
- **Out of Tolerance :** this condition occurs when the error exceeds the protection level (HPE>HPL or VPE>VPL in absolute value).

An example of Stanford Diagram is shown in the following figure.

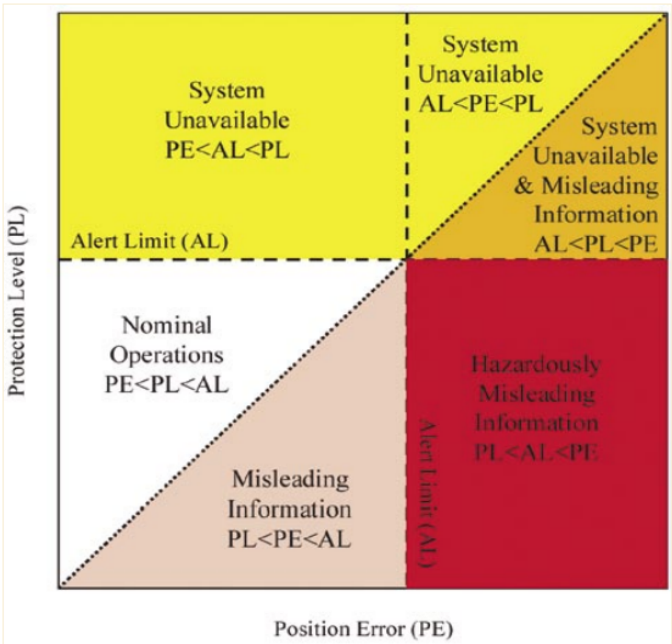


Figure 4.5: Stanford Diagram example, [31]

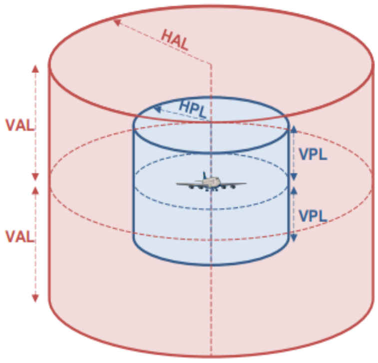


Figure 4.6: HPL & VPL scheme, [60]

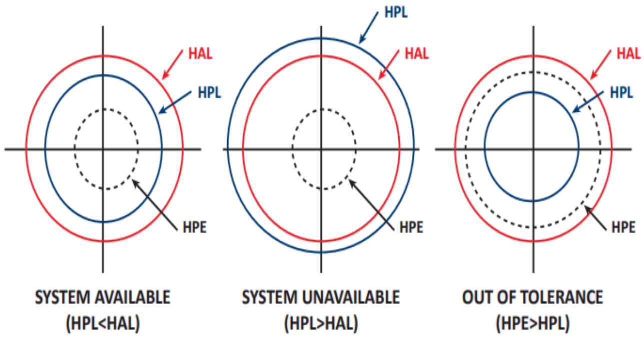


Figure 4.7: Integrity possible conditions, [60]

4.3.3 Continuity

Defined by ICAO SARPs, the continuity of service of a system is the capability of the system to perform its function without unscheduled interruptions during the intended operations. It relates to the capability of the navigation system to provide a navigation output with the specified accuracy and integrity during the approach, assuming that it was available at the start of the operation. The minimum continuity risk performance is less than 10^{-4} per 15 s. Some EU-28 regions do not meet this requirement (the continuity risk performance is $\approx 10^{-3}$ per 15 s. Considering that the *LPV 200* requirement is defined as $1 - 8 \times 10^{-6}$ per 15 s, this performance does not meet it. ICAO defines values such as 10^{-4} per 15 s sufficient to start the *EGNOS* use in civil aviation. Obviously, ICAO SARPs provide interpretative material stating that when the continuity performance is not achieved, *LPV* approaches are still allowable. Analysis regarding the failure modes are very important for this requirement.

4.3.4 Availability

Defined by ICAO SARPs, the availability of *GNSS* is characterised by the proportion of time during which reliable navigation information is presented to the crew, autopilot, or other system managing the flight of the aircraft. It is represented in percentage of time in which the Protection level is below the Alert limit. The main influence on this requirement is the number of visible satellites. The ICAO requirement imposes the minimum availability of 99 %.

Chapter 5

Data study and analysis

This chapter is intended to demonstrate the relevance of *LPV 200* procedures. In a theoretical way, to declare a *PBN* procedure validated, it requires a series of steps declared by ICAO. In particular, studies of monthly reports, field trials simulations and flight tests must have be done. Nevertheless, validation is not the objective of this thesis. The importance will be given to studies of monthly reports and field trials simulations to evaluate the attitude of the four performances of *PBN*: Accuracy, Integrity, Continuity and Availability. The study and analysis have been performed referring to the RIMS station of Rome (RIMS code ROMA).

5.1 Monthly Reports studies

EGNOS Service Provider (ESP) provides publicly available monthly reports, that show the *EGNOS* services performances during a given month and contains global results, including maps and tables of each performance parameter at different locations in Europe using the two GEO satellites (combined) PRN 120 and PRN 123. For this section, the study has covered six months, from August 2017 to January 2018. Monthly Performance reports can be found at *EGNOS* User Support website.

5.1.1 Accuracy

As explained in the previous chapter, Accuracy error value corresponds to the 95% of errors calculated during the day, and its requirements for *LPV 200* procedure are $4m$ for VNSE and $16m$ for HNSE. The monthly accuracy results in terms of navigation system errors are listed in the following table.

Table 5.1: LPV 200 accuracy errors per month

	Aug 17	Sep 17	Oct 17	Nov 17	Dic 17	Jan 18
HNSE 95% (m)	0.7	0.6	0.6	0.6	0.6	0.7
VNSE 95% (m)	1.1	1.2	1.1	1	1	1.1

It is easy to see that accuracy performance values satisfy the ICAO required maximum error.

5.1.2 Integrity

In order to evaluate monthly the Integrity, some other concept might be introduced. As defined in each monthly report:

- **EGNOS LPV-200 Integrity Event :** it is defined as an event that occurs when the Navigation System Error (HNSE or VNSE) is greater or equal to the corresponding Protection Level (HPL or VPL).
- **Safety Index :**is defined as the relation between Navigation System Error (HNSE or VNSE) versus Protection Level (HPL or VPL) for each second (assuming PA algorithms to compute xNSE and xPL). In case of ratio xPE/xPL is greater than 1, it indicates that a Misleading Information situation has occurred.

EGNOS monthly reports provide some histograms representing all the Safety Index (SI) values during the given month. In the following table, the worst values per month are considered.

Table 5.2: LPV 200 horizontal and vertical Safety Index per month

	Aug 17	Sep 17	Oct 17	Nov 17	Dic 17	Jan 18
HSI	0.28	0.24	0.23	0.25	0.29	0.23
VSI	0.3	0.29	0.31	0.33	0.31	0.33

Even the Integrity performances values meet the requirements by standing always below the value 1. As a result, each of the monthly reports analyzed declares that "No integrity event was detected".

5.1.3 Continuity

To obtain the monthly Continuity performance results, it might be studied in ranges of $15s$ as already mentioned in the previous chapter. The continuity Risk value is the number of failures based on the evaluation time. This value represents the performance obtained under fault-tree conditions with all satellites in view and with both GEO operative satellites. The monthly results are represented in the following table.

Table 5.3: LPV 200 Continuity Risk per month

	Aug 17	Sep 17	Oct 17	Nov 17	Dic 17	Jan 18
Continuity Risk (lower than)	$1 \cdot 10^{-5}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-5}$

ICAO requirements establish that Continuity risk value must be below $1 - 8 \cdot 10^{-6}$, so it is clear that this performance is not meeting the requirements requested for *LPV 200*. Nonetheless, these results are considered acceptable only if air navigation authorities define measures to mitigate the risk of an operational nature (Annex 10, Volume 1 of Chicago Convention, Attachment D, 3.4.3.4).

5.1.4 Availability

As already defined, the Availability performance is defined as the percentage of time in which the user can make use of the given service, in this case *LPV 200*. The percentage values correspond to the expected minimum performance measured by a fault-tree receiver using all visible satellites during a given month, and using the two GEO operative satellites (combined). Two ways to evaluate the Availability performance are used: the first one considers the time percentage of Signal in Space (SIS) availability; the latter one represents the time percentage in which the signal meets ICAO requirements for a given service *LPV 200* in terms of Horizontal and Vertical Protection Levels. The following tables contain the monthly results of both analysis.

Table 5.4: EGNOS Signal in space availability per month

	Aug 17	Sep 17	Oct 17	Nov 17	Dic 17	Jan 18
PRN 120 (%)	99.97	99.74	99.88	99.90	99.97	99.89
PRN 123 (%)	99.99	99.99	99.99	99.99	99.99	99.99
PRN 120 or 123 (%)	100	100	100	100	100	100
PRN 120 & 123 (%)	99.97	99.74	99.88	99.90	99.97	99.89

Table 5.5: LPV 200 Availability per month

	Aug 17	Sep 17	Oct 17	Nov 17	Dic 17	Jan 18
Availability (%)	>99.9	>99.9	>99.9	>99.9	>99.9	>99.9

The Availability results are almost the same all over the Europe, so *EGNOS* widely meets the ICAO requirement.

5.2 Field trials

The second step to validate *PBN* procedures is the field trial. In order to obtain satisfactory results, the trials have the duration of at least five consecutive days, continuing to use the same reference station, in this case RIMS station of Rome (ROMA). In this instance, to obtain the results, simulations have been done with the toolset PEGASUS, implemented by EUROCONTROL, whose characteristics and use will be described in the next chapter.

5.3 Flight tests

The last step for *PBN* procedure validation is the flight test. It is quite clear that to get to this point, satisfactory results must have been obtained from the previous steps. It is an interesting study that confirms if the given procedure can be started or not, but it is not the objective of this thesis.

Chapter 6

Software PEGASUS

In this chapter the simulation process in order to obtain the results of field trials simulations, evaluate and compare them with ICAO SARPs will be explained. The software used for this step is PEGASUS.
As defined in the factsheet of EUROCONTROL, PEGASUS is a toolset which allows analysis of *GNSS* data collected from different *SBAS* and *GBAS* systems implementing the algorithms issued in the Minimum Operational Performance Standards (MOPS) documents. It is designed to evaluate performances of Signals in Space (SIS) and navigation augmentation systems' performances. It is able to evaluate the *GNSS* augmentation attributes (Accuracy, Integrity, Continuity, Availability), to compute position simulations, trajectory errors and *GBAS* Ground Stations processing algorithms.
It is important to underline the importance of this toolset as the core component of the *EGNOS* Data Collection Network, which provides *SBAS APV-I* and *LPV 200* approach independent performance monitoring and support to the European Commission.
PEGASUS file formats used will be described hereinafter, before deepening the explanation of PEGASUS ananlysis processes and algorithms.

6.0.1 RINEX files

In the satellite navigation systems field a wide range of data formats and transmission protocols exists. Some examples could be the Radio Technical Commission for Maritime Services (RTCM), Network Transport of RTCM via Internet Protocol (NTRIP), or Radio Technical Commission for Aeronautics (RTCA) and each of these protocols has a precise use and is applied in a determined field with determined characteristics. For the analysis described in this thesis, the RINEX format has been applied.

RINEX is the acronym of Receiver Independent Exchange Format, developed by University of Berne in 1989. It was created with the purpose to be easily exchanged between different types of *GPS* receivers. With the passing of the years and technological improvements, the latest version allows to receive data from all satellite systems (e.g. *GLONASS* or all GEO satellites of *SBAS*). The International GNSS Service (IGS) is responsible of format updates, and furnish detailed technical information on RINEX format. The latest RINEX version format consists of three ASCII file types: **Observation** data File, **Navigation** data File (*GPS* and *GLONASS*) and **Meteorological** data File.
Each file type is divided in two main parts: an header section and a data section. The header section contains basic information (this is a common part for all file types). The data section contains all the information needed. A given RINEX file has a specific nomenclature, expressed in the following image of RINEX v.3.02 released by IGS.

```
ssssdddf.yyt

|   |  | | |
|   |  | | +--   t:  file type:
|   |  | |           O: Observation file
|   |  | |           N: GPS navigation message file
|   |  | |           M: Meteorological data file
|   |  | |           G: GLONASS navigation message file
|   |  | |           L: Galileo navigation message file
|   |  | |           P: Mixed GNSS navigation message file
|   |  | |           H: SBAS Payload navigation message file
|   |  | |           B: SBAS broadcast data file
|   |  | |                        (separate documentation)
|   |  | |           C: Clock file (separate documentation)
|   |  | |           S: Summary file (used e.g., by IGS, not a standard!)
|   |  | +---   yy:  two-digit year
|   |  +-----    f:  file sequence number/character within day.
|   |                daily file: f = 0 (zero)
|   |                hourly files:
|   |                a =  1st hour: 00h-01h; b =  2nd hour: 01h-02h;
|   |                            . . .        x = 24th hour: 23h-24h
|   +-------  ddd:  day of the year of first record
+----------- ssss:  4-character station name designator
```

Figure 6.1: Recommended RINEX filenames scheme, [30]

So, an example could be "ROMA030A.18O" which represent the Observation file of the 1st hour of the 30th day of year 2018 (30 January), related to the station of Rome. In the following paragraphs, the three types of RINEX format are studied deeply.

Observation Files

As explained before, is composed of an header section which gives information about RINEX format version, navigation system used, reference station and date,

receiver antenna and its manufacturer company and the time range of observation. Not only the nomenclature explained before exists, but is also used another nomenclature for 15-minutes high-rate tracking data, that is the format used in this case. Basically the nomenclature is the same, with the addiction of two numbers representing the starting minute within the hour. An example could be "ROMA030A15.18O" which represents the same as before but the observation is referred only to the 2nd quarter of the first hour (from 00:15 to 00:29).
As explained in the same IGS factsheet as before, the data section of RINEX Observation Files contains:

- **Time :** the time of the measurement is the receiver time of the received signals. It is identical for the phase and range measurements and it is identical for all satellites observed at that epoch. The actual time can be indicated in the Start Time header record.

- **Pseudo-range :** is the distance between the receiver antenna and the satellite antenna including receiver and satellite clock offsets (or atmospheric delays, etc.), and it is indicated in meters m.

- **Phase :** The phase is the carrier-phase measured in whole cycles. The phase changes in the same sense as the range (negative doppler). The phase observations between epochs must be connected including the integer number of cycles.

- **Doppler :** the sign of Doppler shift is considered positive for approaching satellites and is an additional observable data.

Navigation Files

Each *SBAS* has is own Navigation Files, despite having the same structure code and information. Navigation Files Header section contains information about RINEX format version, date, ionospheric and almanac parameters, reference time. The data section contains satellite clock errors, ephemeris (tables containing orbital data), antenna references, transmission time of message, satellite health.

Meteorological Files

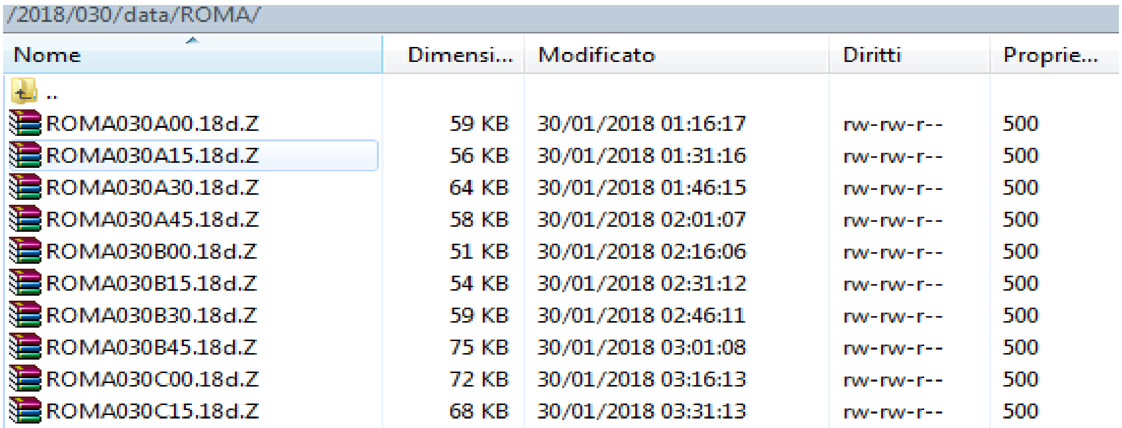
Meteorological Files contain the basic information like reference station, date, RINEX format version and the type of observed parameter (Pressure, Dry temperature, relative humidity, etc.). The data section contains epochs in *GPS* time and the type of observation data.

6.1 EGNOS Data Access Service

Among all the *EGNOS* offered services, the one used for this section is the *EGNOS* Data Access Service (EDAS), which offers access to *EGNOS* data through the Internet. EDAS, in turn, provides a series of services (e.g. Data Filtering Service, SISNeT Service, etc.). To obtain the files of interest, EDAS FTP Service has been used. It allows EDAS users to get *EGNOS* historical data using a standard File Transfer Protocol (FTP). Obviously, this service is available only for registered users. Once registered, the user might download the WinSCP open source freeware SFTP, SCP and FTP client for Windows OS, which allows in an easier way to find and download files, in this case, regarding the *EGNOS* historical data.

6.2 Hatanaka and TEQC

The historical data files of EDAS are encoded and compressed. Yuki Hatanaka (Geographical Survey Institute, Japan) developed a compression scheme to reduce the observation files size, and the extension type file is no more ".O" but ".d". Files are compressed again with WinRAR to further reduce its dimensions.



/2018/030/data/ROMA/

Nome	Dimensi...	Modificato	Diritti	Proprie...
..				
ROMA030A00.18d.Z	59 KB	30/01/2018 01:16:17	rw-rw-r--	500
ROMA030A15.18d.Z	56 KB	30/01/2018 01:31:16	rw-rw-r--	500
ROMA030A30.18d.Z	64 KB	30/01/2018 01:46:15	rw-rw-r--	500
ROMA030A45.18d.Z	58 KB	30/01/2018 02:01:07	rw-rw-r--	500
ROMA030B00.18d.Z	51 KB	30/01/2018 02:16:06	rw-rw-r--	500
ROMA030B15.18d.Z	54 KB	30/01/2018 02:31:12	rw-rw-r--	500
ROMA030B30.18d.Z	59 KB	30/01/2018 02:46:11	rw-rw-r--	500
ROMA030B45.18d.Z	75 KB	30/01/2018 03:01:08	rw-rw-r--	500
ROMA030C00.18d.Z	72 KB	30/01/2018 03:16:13	rw-rw-r--	500
ROMA030C15.18d.Z	68 KB	30/01/2018 03:31:13	rw-rw-r--	500

Figure 6.2: Example of EDAS FTP interface

As showed in the figure 6.2, EDAS disposes files every 15 minutes. It results as 96 observation files (hatanaka compressed) per day. To solve this inconvenience, two steps have to be done in order to obtain a single Observation file per day.

Hatanaka

The first step is to restore EDAS files from CompactRINEX (or Hatanaka-compressed format) to the RINEX format. In order to do that, it has been necessary to download a compression/restoration software called RNXCMP. This soft-

ware contains two executable files called "*cmp2rnx.exe*" which restores files from Hatanaka-compressed to the standard RINEX format and "*rnx2cmp.exe*" which acts backwards.
In a practical way, by the command prompt window (Windows OS), having the RNXCMP files and the compressed files in the same folder, is possible to convert them as illustrated in the following image:

```
Microsoft Windows [Versione 6.1.7601]
Copyright (c) 2009 Microsoft Corporation. Tutti i diritti riservati.

C:\Users\unknown>cd C:\Users\unknown\Desktop\FILE_STP\ROMA_30\teqc_crx2rnx

C:\Users\unknown\Desktop\FILE_STP\ROMA_30\teqc_crx2rnx>crx2rnx ROMA030A00.18D

C:\Users\unknown\Desktop\FILE_STP\ROMA_30\teqc_crx2rnx>crx2rnx ROMA030A15.18D

C:\Users\unknown\Desktop\FILE_STP\ROMA_30\teqc_crx2rnx>crx2rnx ROMA030A30.18D

C:\Users\unknown\Desktop\FILE_STP\ROMA_30\teqc_crx2rnx>crx2rnx ROMA030A45.18D

C:\Users\unknown\Desktop\FILE_STP\ROMA_30\teqc_crx2rnx>crx2rnx ROMA030B00.18D

C:\Users\unknown\Desktop\FILE_STP\ROMA_30\teqc_crx2rnx>crx2rnx ROMA030B15.18D

C:\Users\unknown\Desktop\FILE_STP\ROMA_30\teqc_crx2rnx>crx2rnx ROMA030B30.18D

C:\Users\unknown\Desktop\FILE_STP\ROMA_30\teqc_crx2rnx>crx2rnx ROMA030B45.18D

C:\Users\unknown\Desktop\FILE_STP\ROMA_30\teqc_crx2rnx>crx2rnx ROMA030C00.18D

C:\Users\unknown\Desktop\FILE_STP\ROMA_30\teqc_crx2rnx>crx2rnx ROMA030C15.18D
```

Figure 6.3: Conversion example from Hatanaka-compressed to RINEX

TEQC

At this moment, all 96 files per day are in RINEX format. The problem of the conspicuous number of observation files still remains. Fortunately it has been solved with the software Translation, Editing and Quality Checkiing (TEQC), created by UNAVCO, a non-profit university-governed consortium, funded by National Science Foundation and NASA. Among all the possible uses of this software, it has been used for the concatenation of the 96 observation files per day, in order to unify them in a single observation file.

```
C:\Users\unknown\Desktop\FILE_STP\ROMA_30\teqc_crx2rnx>teqc ROMA030A00.18O ROMA0
30A15.18O ROMA030A30.18O ROMA030A45.18O ROMA030B00.18O ROMA030B15.18O ROMA030B30
.18O ROMA030B45.18O ROMA030C00.18O ROMA030C15.18O ROMA030C30.18O ROMA030C45.18O
ROMA030D00.18O ROMA030D15.18O ROMA030D30.18O ROMA030D45.18O ROMA030E00.18O ROMA0
30E15.18O ROMA030E30.18O ROMA030E45.18O ROMA030F00.18O ROMA030F15.18O ROMA030F30
.18O ROMA030F45.18O ROMA030G00.18O ROMA030G15.18O ROMA030G30.18O ROMA030G45.18O
ROMA030H00.18O ROMA030H15.18O ROMA030H30.18O ROMA030H45.18O ROMA030I00.18O ROMA0
30I15.18O ROMA030I30.18O ROMA030I45.18O ROMA030J00.18O ROMA030J15.18O ROMA030J30
.18O ROMA030J45.18O ROMA030K00.18O ROMA030K15.18O ROMA030K30.18O ROMA030K45.18O
ROMA030L00.18O ROMA030L15.18O ROMA030L30.18O ROMA030L45.18O ROMA030M00.18O ROMA0
30M15.18O ROMA030M30.18O ROMA030M45.18O ROMA030N00.18O ROMA030N15.18O ROMA030N30
.18O ROMA030N45.18O ROMA030O00.18O ROMA030O15.18O ROMA030O30.18O ROMA030O45.18O
ROMA030P00.18O ROMA030P15.18O ROMA030P30.18O ROMA030P45.18O ROMA030Q00.18O ROMA0
30Q15.18O ROMA030Q30.18O ROMA030Q45.18O ROMA030R00.18O ROMA030R15.18O ROMA030R30
.18O ROMA030R45.18O ROMA030S00.18O ROMA030S15.18O ROMA030S30.18O ROMA030S45.18O
ROMA030T00.18O ROMA030T15.18O ROMA030T30.18O ROMA030T45.18O ROMA030U00.18O ROMA0
30U15.18O ROMA030U30.18O ROMA030U45.18O ROMA030V00.18O ROMA030V15.18O ROMA030V30
.18O ROMA030V45.18O ROMA030W00.18O ROMA030W15.18O ROMA030W30.18O ROMA030W45.18O
ROMA030X00.18O ROMA030X15.18O ROMA030X30.18O ROMA030X45.18O > ROMA0300.18O
! Notice ! splicing RINEX files
! Notice ! splicing RINEX files
! Notice ! splicing RINEX files
! Notice ! splicing RINEX files
! Notice ! splicing RINEX files
! Notice ! splicing RINEX files
! Notice ! splicing RINEX files
! Notice ! splicing RINEX files
```

Figure 6.4: Example of TEQC concatenation

The previous image represents an example of executing TEQC, considered the day 030, giving as input a single file called *ROMA0300.18O*, according to figure 6.1 the zero after three numbers (ddd) represents the daily file.

At the end of this conversion step, the files in possession are: Observation single file obtained after Hatanaka decompression and TEQC concatenation (e.g. "ROOMA0300.18O"); the navigation file downloadable by EDAS, in common with all the reference station and generally located at the bottom of station list (e.g. "brdc0300.18N"); the *SBAS* broadcast, in common with all the reference stations and generally located at the bottom of station list (e.g. "brdc0300.18B"). In order to have a correct work, the previous three files must have the same name.

6.3 Convertor

The first thing to do with PEGASUS software is to convert the previous three files (Observation, Navigation and *SBAS* broadcast) in a single file to be used in the second analysis tool. Its function is to converto the above mentioned files in ASCII format. The input file is the Observation file and the tool searches all the files with the same name (navigation and *SBAS* broadcast). It must be executed as much times as the number of analysis days (5 for this project, from day 029 to 033). The interface allows user to set the type of receiver, corrections, and leap seconds (generally pre-defined in the header section of observation file). During the process, the message section shows the number of *GPS*, *SBAS* and/or *GBAS* message and the relevant message types; the PRN section shows the number of received *SBAS* and *GPS* ranges according to the broadcasting PRN.

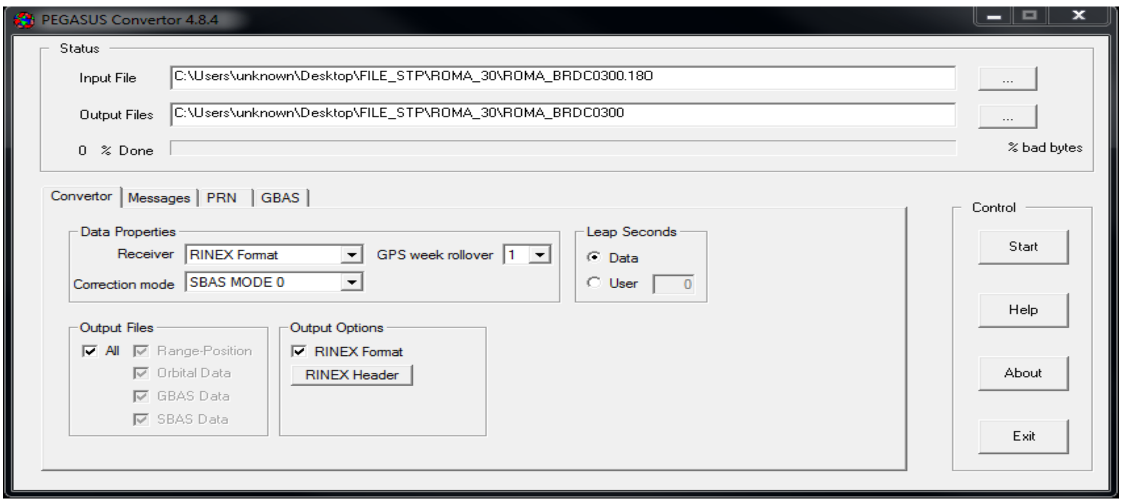


Figure 6.5: PEGASUS Convertor tool interface

6.4 GNSS Solution

After having completed the convertor process, some files in output will be available. The files with extension ".rng" (besides, the output file of Convertor tool) have to be input to start the GNSS solution. For a correct process, as an advanced option, it is necessary to ignore Almanac files. In the configuration section the user can choose the parameters of the solution and the reference station (in this case, ROMA). Info and Warning and Error sections show possible errors; Graphical info displays in real time the evaluation of protaction level and position errors (HPL & HPE, VPL & VPE) and compares the results with the procedures requirements (NPA, APV-I, APV-II, CAT-I, CAT-II/III); Data counter section shows the number of evaluated of *GPS*, *SBAS* and/or *GBAS* evaluated messages.

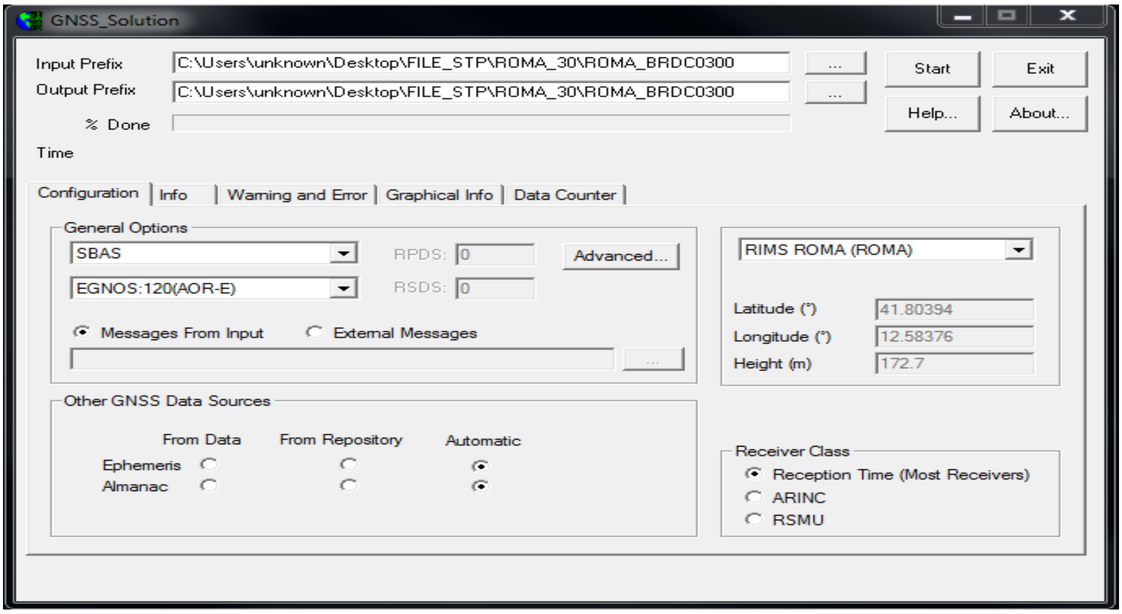


Figure 6.6: PEGASUS GNSS Solution tool interface

6.5 XPL Estimation

The Protection Level Estimation is necessary to deliver an estimation of *SBAS* performances compared to the ICAO Requirements. It uses real Signal in Space data but is not tied to real receiver raw measurements like GNSS Solution. It is necessary to be able to obtain in particular Availability and Continuity output results. The input file needed is the one created by GNSS Solution with extension ".smt". The configuration section allows the user to set the reference station, time range and which satellites use. As the other tools, Info and Warnings and Errors sections show possible errors.

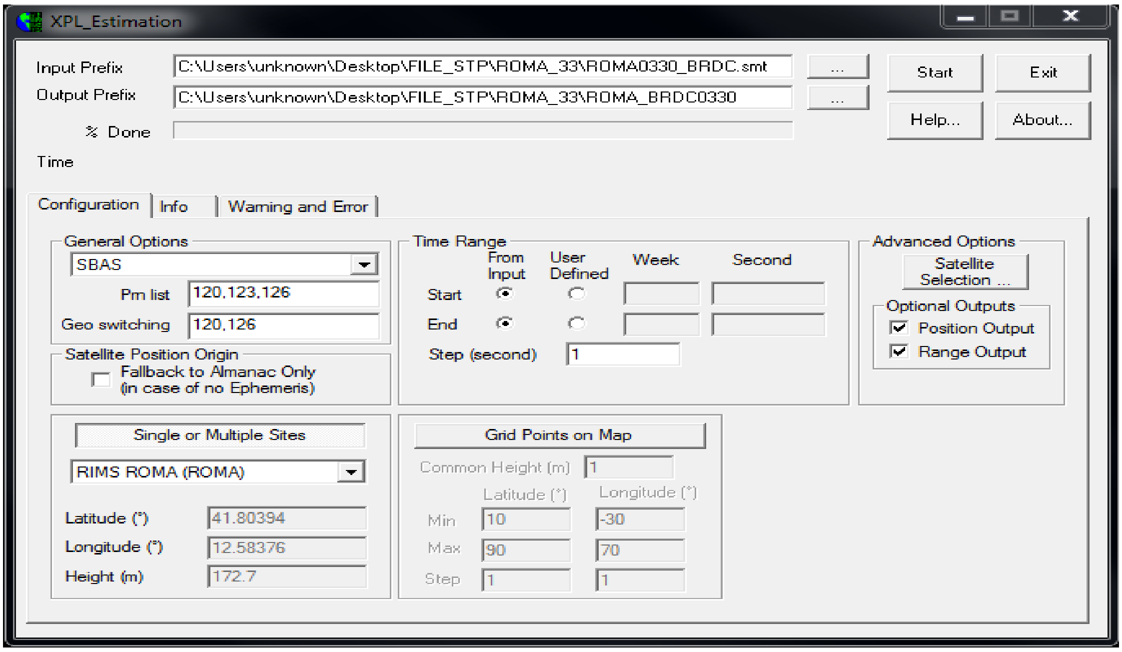


Figure 6.7: PEGASUS XPL Estimation tool interface

6.6 M-File Runner

The Pegasus analysis ends with the M-File Runner tool. Its function is to read all the solutions obtained with GNSS Solution and XPL Estimation tools and to give output files as graphics and tables, that will be used to evaluate *LPV 200* performances in the next chapter. M-File Runner offers a list of possible postprocessing options and for the present analysis, the four of them of interest are:

- Analyze SBAS: gives graphics about fast and slow corrections, Ionospheric delays and signal availability.
- Analyze Position: gives information about Protection Levels, Position Errors and consequently, Stanford Plots (needed to evaluate Integrity).
- SBAS Accuracy: gives ".xml" files with information on Horizontal and Vertical Navigation System Errors (HNSE & VNSE) for each procedure.
- SBAS Integrity: gives ".xml" files with information on Horizontal and Vertical System Index (HSI & VSI).
- SBAS Continuity: gives tables of continuity events referring to the considered reference station for APV-I and LPV 200 procedures.

- SBAS Availability: gives tables of APV-I and LPV 200 Availability percentage.

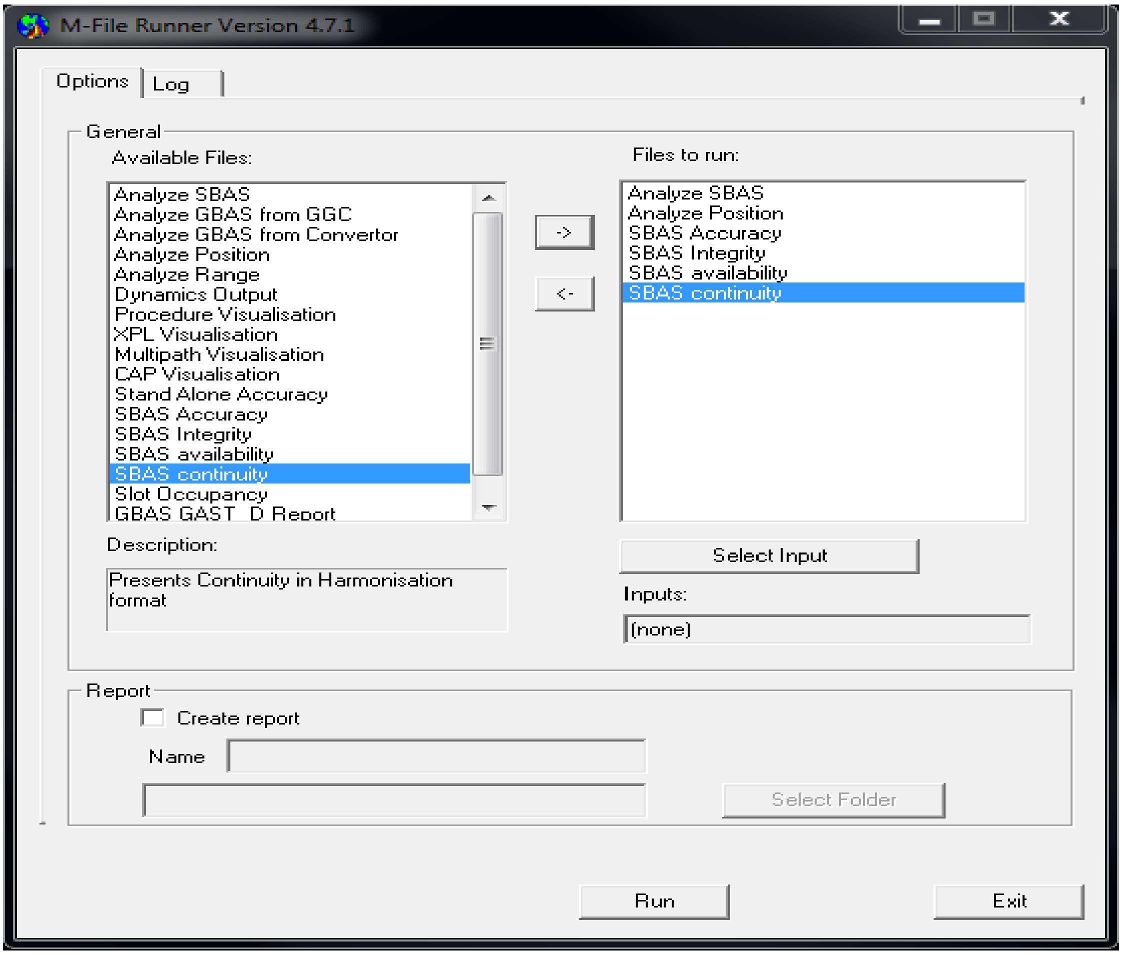


Figure 6.8: PEGASUS M-File Runner tool interface

Chapter 7

Results

This chapter shows the results of *LPV 200* Accuracy, Integrity, Continuity and Availability performances for the five days (from 029 to 033) obtained in the previous chapter and discusses them in order to understand the possible *LPV 200*. For each of the following sections there will be shown the given performance results for each day.

7.1 Accuracy

In this section the Accuracy results for the five days are shown, in terms of Navigation System Error mean and Root mean square.

- **29 January (029)**


```
<name>HNSE</name>
<service>LPV200</service>
<samples>78991</samples>
<mean>0.906125</mean>
<rms>0.944835</rms>
- <histogram>
```

```
<name>VNSE</name>
<service>LPV200</service>
<samples>78991</samples>
<mean>0.469417</mean>
<rms>0.601041</rms>
- <histogram>
```


Figure 7.1: LPV 200 Accuracy results, day 029

- **30 January (030)**


```
<name>HNSE</name>
<service>LPV200</service>
<samples>76160</samples>
<mean>0.868001</mean>
<rms>0.910452</rms>
- <histogram>
```

```
<name>VNSE</name>
<service>LPV200</service>
<samples>76160</samples>
<mean>0.500673</mean>
<rms>0.633934</rms>
- <histogram>
```


Figure 7.2: LPV 200 Accuracy results, day 030

- **31 January (031)**

<name>HNSE</name>
<service>LPV200</service>
<samples>75044</samples>
<mean>0.911715</mean>
<rms>0.95568</rms>
- <histogram>

<name>VNSE</name>
<service>LPV200</service>
<samples>75044</samples>
<mean>0.465275</mean>
<rms>0.588465</rms>
- <histogram>

Figure 7.3: LPV 200 Accuracy results, day 031

- **1 February (032)**

<name>HNSE</name>
<service>LPV200</service>
<samples>78991</samples>
<mean>0.844599</mean>
<rms>0.884235</rms>
- <histogram>

<name>VNSE</name>
<service>LPV200</service>
<samples>78991</samples>
<mean>0.612935</mean>
<rms>0.750705</rms>
- <histogram>

Figure 7.4: LPV 200 Accuracy results, day 032

- **2 February (033)**

<name>HNSE</name>
<service>LPV200</service>
<samples>79026</samples>
<mean>0.86564</mean>
<rms>0.90571</rms>
- <histogram>

<name>VNSE</name>
<service>LPV200</service>
<samples>79026</samples>
<mean>0.5912</mean>
<rms>0.7152</rms>
- <histogram>

Figure 7.5: LPV 200 Accuracy results, day 033

Reminding the *EGNOS* Safety of Life service performance requirements for *LPV 200* procedure, (Horizontal accuracy below 16m and Vertical Accuracy below 6 to 4m), it canbe said that *LPV 200* Accuracy results largely meet the given requirements.

7.2 Integrity

In this section the Integrity results for the five days are shown, in terms of Horizontal and Vertical Protection Level, Position Error and Alert Limit (HPL, VPL, HPE, VPE, HAL, VAL). All these values are shown in the Stanford diagrams, which indicates the possible system conditions.

- **29 January (029)**

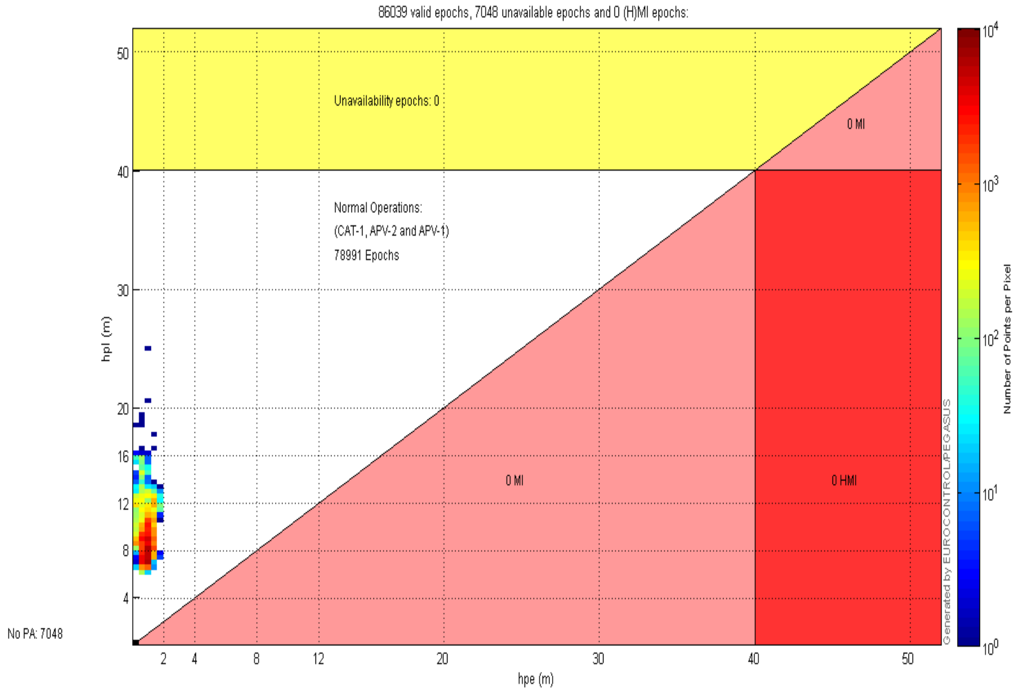


Figure 7.6: LPV 200 Horizontal Integrity Stanford diagram, day 029

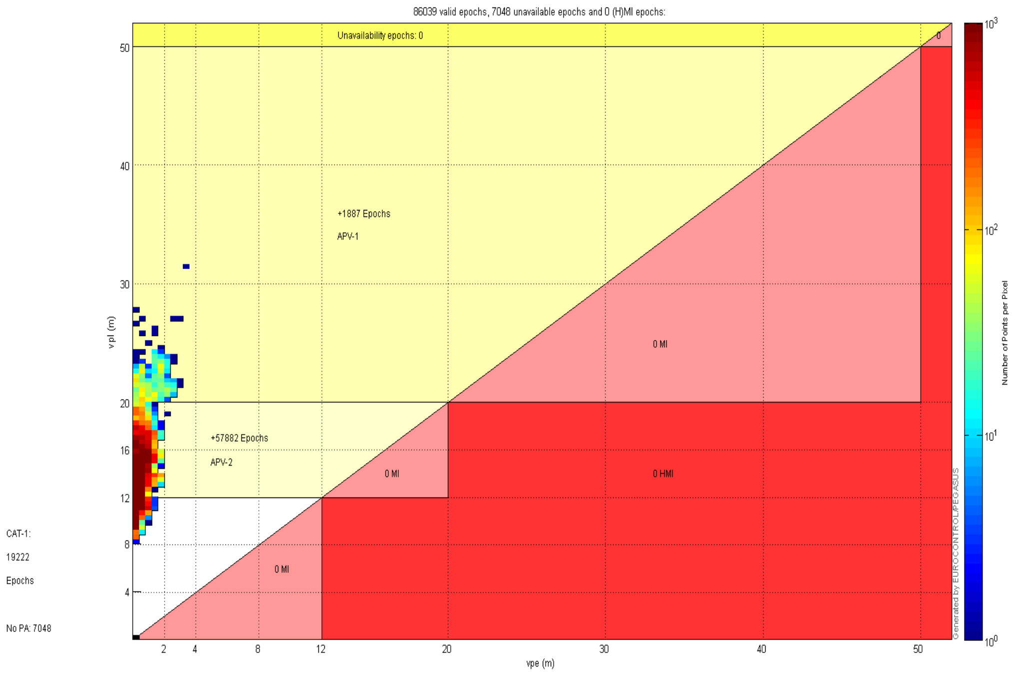


Figure 7.7: LPV 200 Vertical Integrity Stanford diagram, day 029

- **30 January (030)**

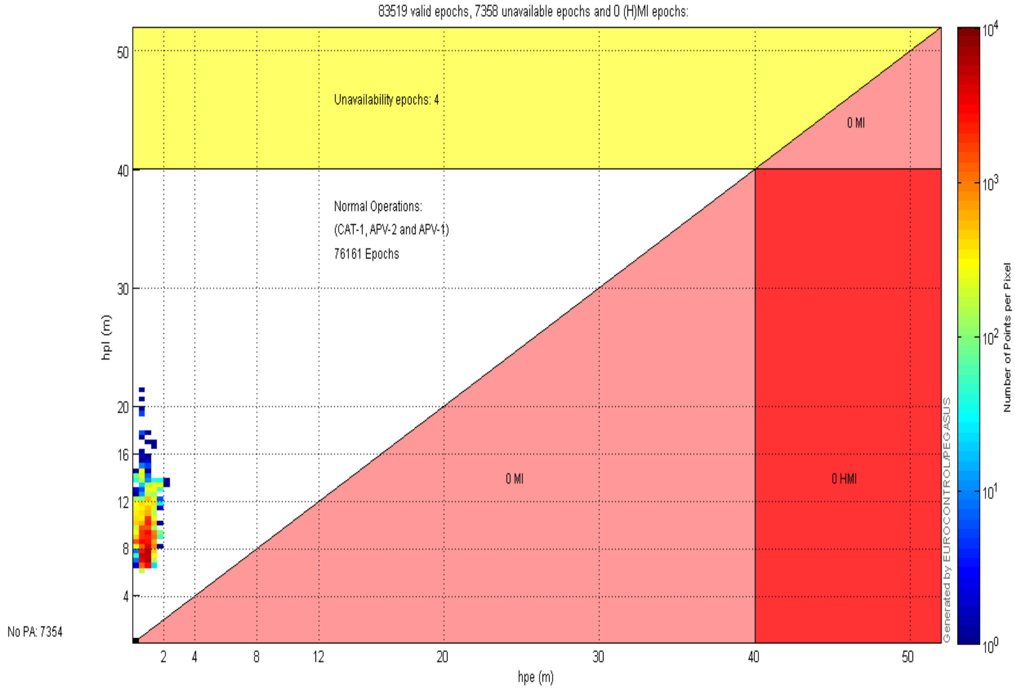


Figure 7.8: LPV 200 Horizontal Integrity Stanford diagram, day 030

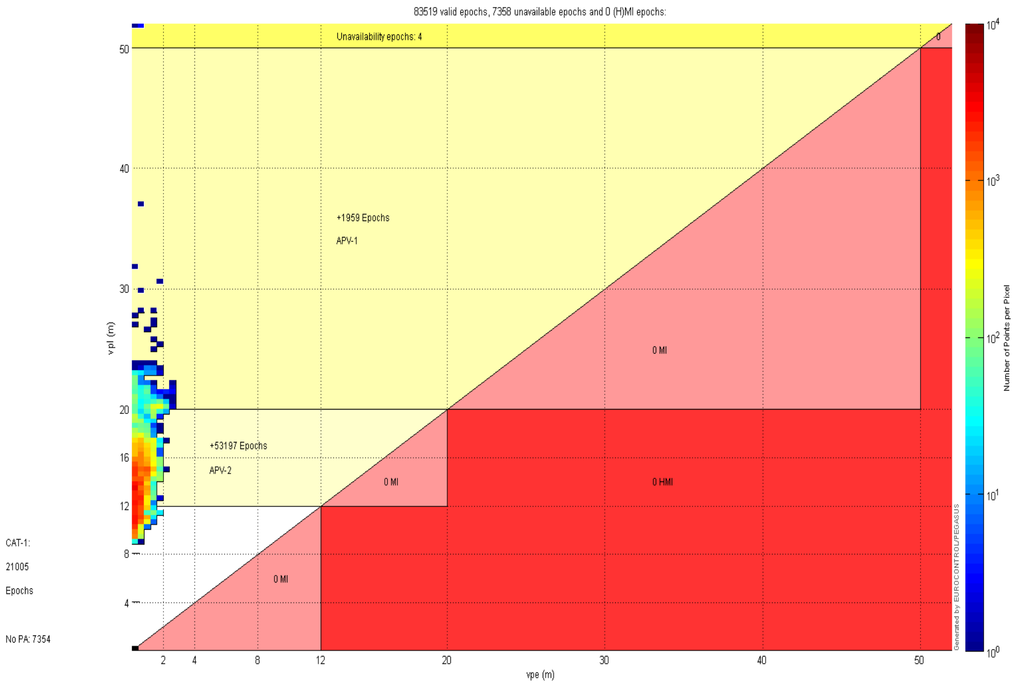


Figure 7.9: LPV 200 Vertical Integrity Stanford diagram, day 030

- **31 January (031)**

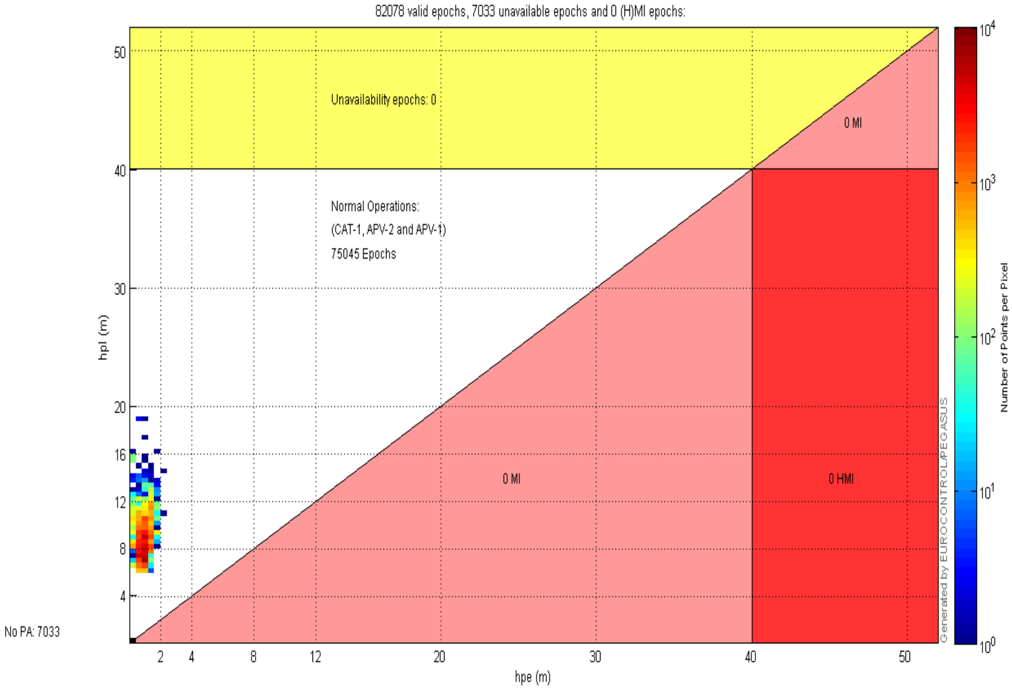


Figure 7.10: LPV 200 Horizontal Integrity Stanford diagram, day 031

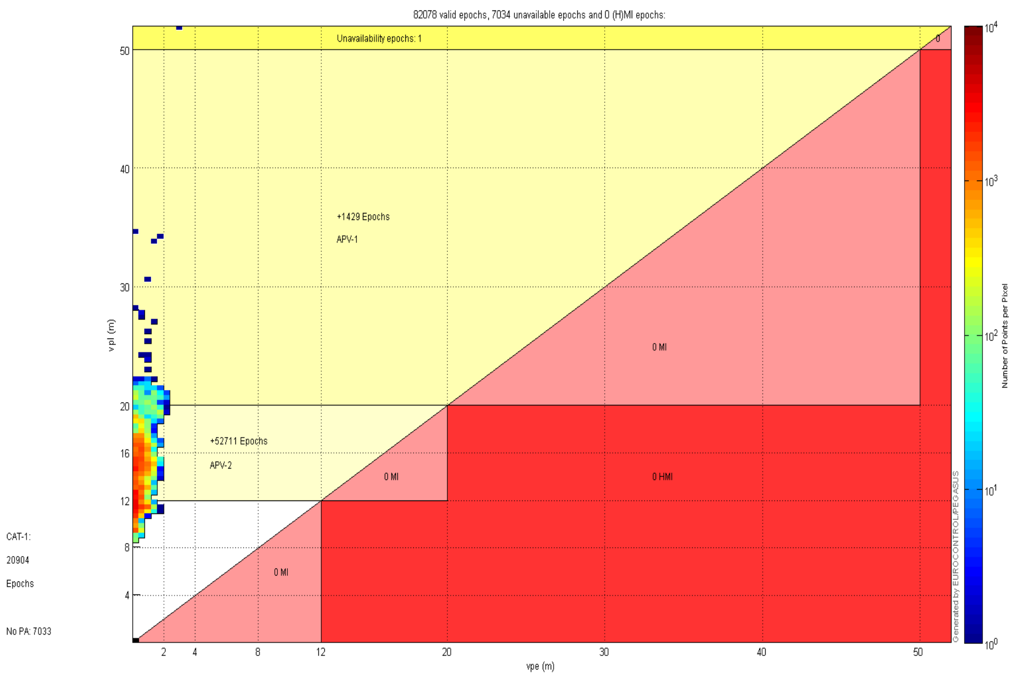


Figure 7.11: LPV 200 Vertical Integrity Stanford diagram, day 031

- **1 February (032)**

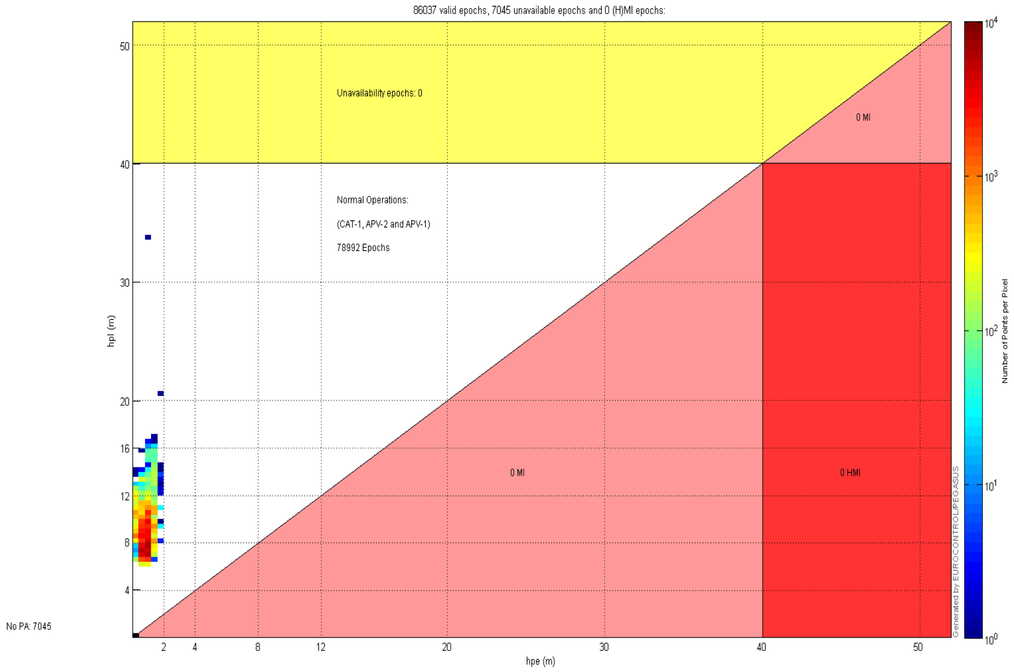


Figure 7.12: LPV 200 Horizontal Integrity Stanford diagram, day 032

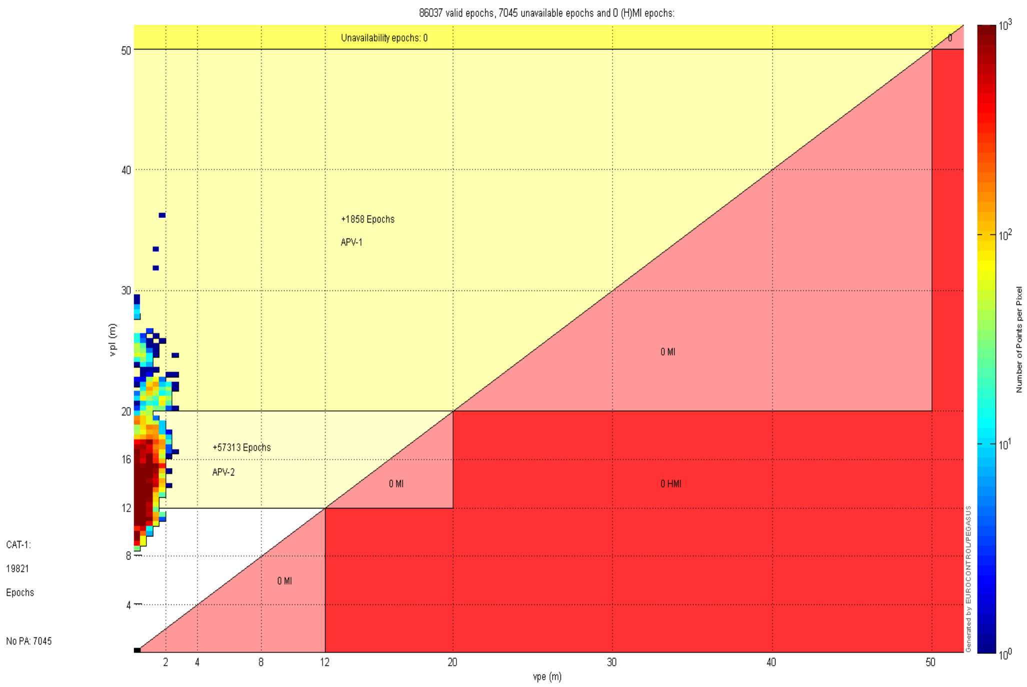


Figure 7.13: LPV 200 Vertical Integrity Stanford diagram, day 032

- **2 February (033)**

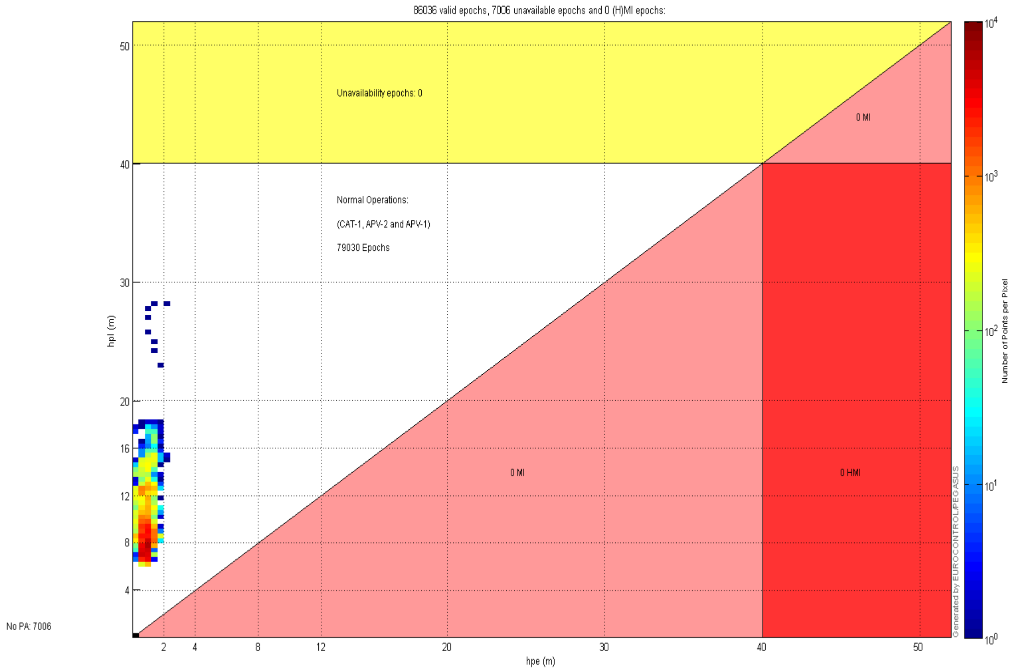


Figure 7.14: LPV 200 Horizontal Integrity Stanford diagram, day 033

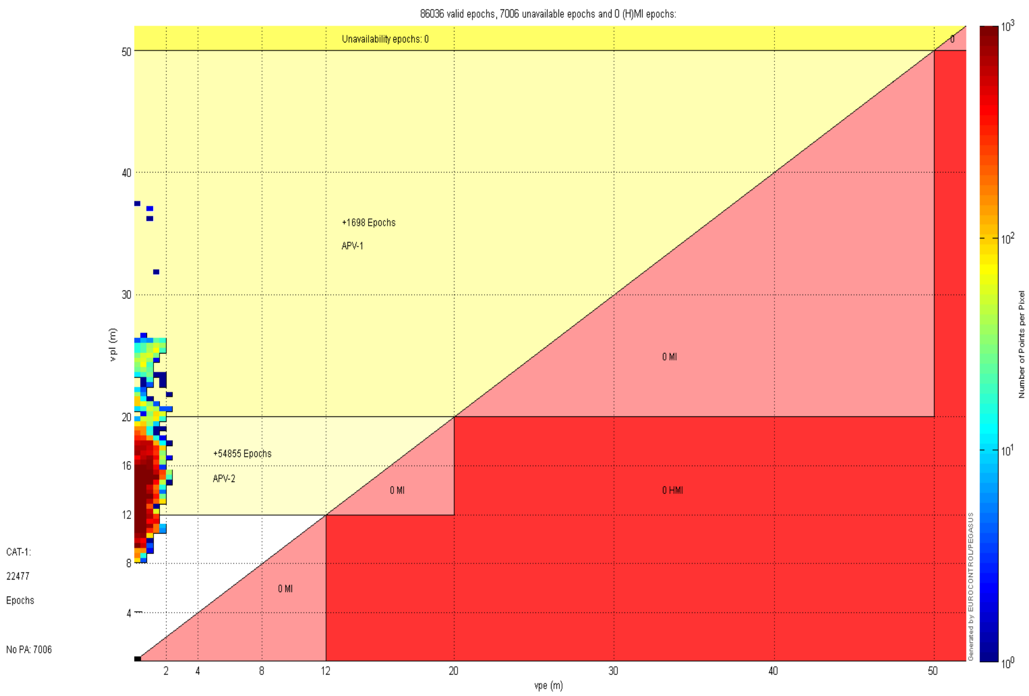


Figure 7.15: LPV 200 Vertical Integrity Stanford diagram, day 033

It can be noted that no integrity events occur during the considered 5 days. In the Horizontal Integrity Stanford Diagrams is observable a good compliance to ICAO requirements and all evaluated epochs result in nominal operations. The Vertical Integrity Stanford Diagrams show a little bit worse trend among the analyzed days; some evaluated epochs do not meet the *LPV 200* Vertical Alert Limit (VAL). Despite that, Horizontal and Vertical System Index results (Appendix B) are always below 1, so *EGNOS* Integrity requirement is largely met.

7.3 Continuity

In this section the Continuity results for the five days are shown, in terms of *LPV 200* Continuity Events, which occur if the system is available at the start of a given mission and in at least one of the following 15s the system becomes non-available. Those values are necessary to evaluate the Continuity risk. In addiction, the number of *LPV 200* Continuity Events are evaluated considering the PRN switching (the worst single PRN events are taken in account, in order to be conservative).

- **29 January (029)**

Site	Lat (°)	Lon (°)	Events for LPV-200
ROMA	41.8	12.58	36

Figure 7.16: LPV 200 Continuity events results, day 029

- **30 January (030)**

Site	Lat (°)	Lon (°)	Events for LPV-200
ROMA	41.8	12.58	1

Figure 7.17: LPV 200 Continuity events results, day 030

- **31 January (031)**

Site	Lat (°)	Lon (°)	Events for LPV-200
ROMA	41.8	12.58	0

Figure 7.18: LPV 200 Continuity events results, day 031

- **1 February (032)**

Site	Lat (°)	Lon (°)	Events for LPV-200
ROMA	41.8	12.58	0

Figure 7.19: LPV 200 Continuity events results, day 032

- **2 February (033)**

Site	Lat (°)	Lon (°)	Events for LPV-200
ROMA	41.8	12.58	1

Figure 7.20: LPV 200 Continuity events results, day 033

The Continuity results obtained with PEGASUS analysis reflect the Continuity monthly values. In other words, Continuity performance does not meet the *EGNOS* Safety of Life service performance requirements but, despite of this, the Continuity levels are sufficient to determine *LPV 200* procedure to be started, considering Air Navigation authorities to define measures to mitigate the possible risk (as defined in Annex 10, Volume 1 of Chicago Convention, Attachment D, 3.4.3.4).

7.4 Availability

In this section the Availability results for the five days are shown, in terms of *LPV 200* procedure percentage of time. The last two column represent the values of Horizontal and Vertical Protection Levels, that must stay below the value defined in the *EGNOS* Safety of Life service performance requirements.

- **29 January (029)**

Site	Lat (°)	Lon (°)	LPV-200 (%)	HPL (99%)	VPL (99%)
ROMA	41.8	12.58	99.17	17.6	20.8

Figure 7.21: LPV 200 Availability results, day 029

- **30 January (030)**

Site	Lat (°)	Lon (°)	LPV-200 (%)	HPL (99%)	VPL (99%)
ROMA	41.8	12.58	99.43	13	20

Figure 7.22: LPV 200 Availability results, day 030

- **31 January (031)**

Site	Lat (°)	Lon (°)	LPV-200 (%)	HPL (99%)	VPL (99%)
ROMA	41.8	12.58	99.8	12.8	19.2

Figure 7.23: LPV 200 Availability results, day 031

- **1 February (032)**

Site	Lat (°)	Lon (°)	LPV-200 (%)	HPL (99%)	VPL (99%)
ROMA	41.8	12.58	99.83	12.8	20.4

Figure 7.24: LPV 200 Availability results, day 032

- **2 February (033)**

Site	Lat (°)	Lon (°)	LPV-200 (%)	HPL (99%)	VPL (99%)
ROMA	41.8	12.58	99.85	14.2	19.6

Figure 7.25: LPV 200 Availability results, day 033

It is clear that *LPV 200* Availability results excellently meet the requirements ($99 - 99.999\%$). Identically to Continuity results, Availability has been evaluated considering PRN switching (the worst single PRN events are taken in account, in order to be conservative).

Finally, it is possible to assert that through field trials analysis, good results have been obtained, in terms of meeting the *EGNOS* SoL service performance requirements, even tough better results can be achieved. Of course, it strictly depends on the technology improvements (it has to be underlined that these results are not considering the *GALILEO GNSS* constellation because it is not fully operative at the moment. As a matter of fact, the goodness of such those results, shows the potential impact that *GNSS* and its Augmentation System will have in the next future in terms of operative and economic benefits.

Part II

SYSTEM INTEGRATION AND REGULATIONS

Chapter 8

Unmanned Aerial Systems

This part of the Thesis aims to introduce the Unmanned Aerial Systems in terms of their technical features and applicable regulations at International and National level (focusing on Italian rules) and to show possible *EGNOS* enabled receivers that can be integrated on a determined Unmanned Air Vehicle category. The issues related to the integration of the receiver will be examined and discussed with regards to risk assessment.

ICAO defines an Unmanned Aerial System (UAS) as an aircraft and its associated elements which are operated with no pilot on board, that means UAS include the vehicle itself and a ground segment (it could be a station or even a single pilot).

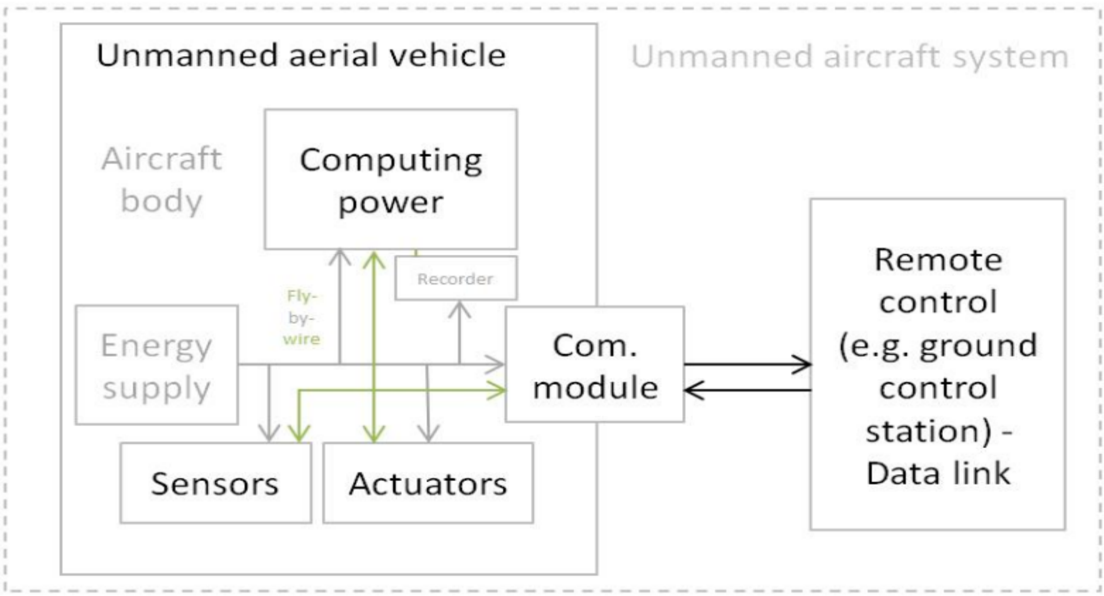


Figure 8.1: Unmanned Aerial System scheme, [32]

An Unmanned Aerial System, as shown in Figure 8.1, is composed of three main elements: an autonomous or remote controlled Aerial Vehicle, a Ground Control Station and a Command and Control Link to control the vehicle and to receive telemetry data from the aircraft. The problem of an unique definition of unmanned aircraft is related to the wide variety of its applications. As intended by *ICAO* in the Chicago Convention of 1944 (doc 7300), any aircraft intended to be flown without a pilot on board is referred by *ICAO* Assembly as a pilotless aircraft.
The term "pilotless" nowadays has been replaced by "unmanned". Nonetheless, the term Unmanned Aircraft includes a lot of different types of aircraft (e.g. meteorological balloons) which clearly are not a matter of interest for this thesis. With the term Unmanned Aircraft also remotely piloted aircraft are meant. As remotely piloting it can be intended a licensed operator (one or even more) or a ground station. These types of unmanned aircraft are defined as Remotely Piloted Aircraft Systems (RPAS). As RPAS are a subcategory of UAS, one soon realizes that its components scheme can be attributed as the same of 8.1. It is underlined the need of all RPAS components to be approved as a system considering all the interdependencies. In a more detailed way:

- the Remote Pilot Station is the component containing all the equipment used to control the RPA. It can be stationary or mobile and, as already said, it could be more than one as long as only one should be in control of the RPA at a given moment of the mission.

- the communication command and control system is the connection between RPS and RPA to allow flight management. The link can be in direct radio line of sight (RLOS) or beyond the direct radio line of sight (BRLOS):

  - RLOS is the condition in which the transmitter and receiver can be able to communicate directly or through a ground network.
  - BRLOS is the condition in which the transmitter and receiver and possible ground network needed for RLOS are not sufficient to have a link but the including a satellite system. It shows an appreciable communication delay.

- the RPA, once the pilot is no longer situated inside the given aircraft, can change its architecture in a lot of new ways. It can result in higher performances in terms of endurance, flight levels, etc. Some of its part could be no longer considered as permanent features (e.g. landing gear and wheels), taking into account that some of RPA do not have the need of safe operation or

re-usage. Despite that, some components are still needed (ICAO doc 10019), such as Navigation Equipment, ATC communications and surveillance equipment (e.g. ADS-B, SSR or CPDLC), launch and recovery equipment, flight control computer, flight management system and autopilot, system health monitoring equipment, flight termination system. The latter one has the scope to minimize the severity of a possible failure to person, properties or other aerial systems. Of course, the main subsystems must be present.
The body is the first way to divide RPAS in two main functional categories: Tailless Quad-copters (or more) and Tailed mono/bi copters. Depending on the RPA size, a different Power Supply system is needed. Sensors and actuators and on board Computer let the RPA complete.

8.1 RPAS applications

As a main difference compared to manned aircraft, RPAS were originally invented and used for 3D missions (Dull, Dirty, Dangerous), which means that kind of missions that can be monotonous or hazardous for the pilot itself. With unmanned aircraft, these problem were solved. In the last decades, air navigation authorities and military forces are understanding the widespread potential of UAS, thanks also to the technological progress. Improvements and upgrades are being pursued not only in military field, but also (and especially) in the civil commercial one. As time goes by, RPAS civil applications are increasing day by day, that suggests the incredible utility of these vehicles. Nowadays RPAS are used for a wide range of things such:

- Security surveillance
- Emergency response including Search And Rescue (SAR)
- Facilitation of communications and broadcast, small package and bulk cargo transport
- Visual, spectral and thermal examination of structures
- Photography and sartography survey
- Agricultural fertilizer and chemical applications
- Aircraft external maintenance inspections
- Atmospheric research

and much more (considering also military and recreational purposes). Some parallel researches and studies exist on future Drones applications, such as package delivery or Flying taxi. Such kind of applications clearly require high precision accuracy. This allows the interpretation of the future developments and evolution of RPAS applications.
With reference to RPAS, issues related to their categorization, current operational issues and applicable rules and regulations shall be considered and discussed.

8.2 Operational safety issues

Safety assessment for RPAS operations is quite difficult due to the variety of RPAS technical fetures and applications. The most challenging aspect of RPAS operations in case of failure of an equipment or loss of a subsystem function is the fact that there is not a humna pilot onboard to manage the problem. Depending on a the failure, it is not certain that the remote pilot has the possibility to control the RPA; this means that the potential consequence of a given failure are difficult to predict. Some examples are a mid-air collision with another RPA or manned aircraft; the risk of loss of control of the RPA; the risk of intentional misuse of RPA; the type of RPA itself (military, commercial, civil).
The possible causes for those failure are multiple: from an unintentional collision, deliberate attack (terroristic use), meteorological problems or even the human error (caused by distraction or anything can reduce the attention). To avoid, or almost mitigate, the possible RPAS lack of safety, not only components that allow physical flight have to be installed, but also systems with the objective to meet operational requirements. A practical example could be the ability to provide communication and surveillance information to Air Traffic Control (ATC), as Automatic Dependent Surveillance - Broadcast (ADS-B) does.
In the same way, complex operations like Instrumented Flight Rules (IFR) will be allowed when RPAS will have been equipped with Detection and Avoid (DAA) devices. This technology allows to detect and avoid potential collisions, configting aircraft and other terrain obstacles and is able to determine the necessary maneuver and to safely return to the original route. Of course, the pilot must be able to obtain those information in order to enable the appropriate decision/action. Nowadays, for most of the States regulatory requirements, prohibition is a good way to provide safety for certain uses or RPA classes, because Regulations are not definitely completed and well defined.
Despite of the safety management systems ,that analyze the safety level of equipped

systems, for manned aircraft the Human error has always been the most frequent cause. As known, aviation safety passed through tecnical factors, human factors anad arrived to organizational factors to explain possible causes of aircraft accidents. The same applies for RPAS. The more trained is the remote pilot the better he will mange the RPAS operation. A remote pilot must be able to override or modify automated functions (for example, if the RPAS is equipped with *EGNOS* enabled receiver in order to obtain high positioning precision and the communication needed to obtain the positioning message fails), except where possible actions cannot be executed safely. Also the definition of areas of operation and its limitations help to mitigate risks for people on the ground, but at the moment it results difficult to enforce these types of recommendations. Being aware of the future operations or future new technologies that will be installed on an RPAS, it goes without saying that safety management principles are the more important aspect for an RPAS operator, and should have to be improved in tandem with all the future purposes. Safety management principles have to be proportionate to the type and complessity of a given operation. In this way, RPAS operators will contribute to the ability of a State to manage the fully integration of RPAS and manned aircraft.

Chapter 9

Regulations in force

Rules, regulations and technical standards for Unmanned vehicles systems are always changing and are a bit difficult to define due to the wide range of drones type and categories. Nowadays, ICAO and EASA in Europe (but also FAA for the USA), are working hardly on it and frequently the Assemblies ,through workshops or meetings, are gathering to obtain a set of global norms and regulations as much as is possible. In this chapter, norms and regulations structure will be described, explaining them at international and national level, focusing on the case of Italy and all the institution concerned.

9.1 UAS categories

Drones vary greatly in size, type and performances. As an example, their dimensions can go from an insect size to a manned aircraft and, depending on type and performances, some of them can reach speed over 1000 km/h and cover considerable distances and flight for long time. The communication modes are various and even a smartphone or a tablet can be used to guide unmanned aircraft. According to the concept defined in A-NPA 2015-10, the Unmanned Aerial Systems operations are classified in three macro categories: Open, Specific and Certified.

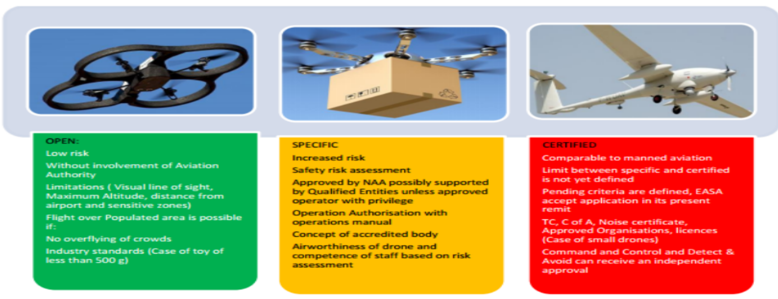


Figure 9.1: RPAS categories scheme, [38]

Categories are useful for airworthiness certification, air traffic management, operations and pilot licensing. RPA share many attributes of manned aircraft but also have unique features to be taken into account in defining categorization schemes (e.g. damage potential, on-board automation levels). Once defined, categories simplify the articulation of system design criteria, standards, and limitations. The following subsections explain the European Aviation Safety Agency (EASA) definition of RPAS Operation Categories in the document A-NPA 2015.10.

- **Open Category**
  The open category refers to small-unmanned aircraft operation, where the risk to third parties on the ground and other space users is low and mitigated through operational limitations and product requirements. Operations of this drones category do not require a specific authorization by the National Aviation Authority (aviation authority of a given State) to fly, but the considered drone has to stay within a determined operational area and to comply specific requirements. For the open category, the regulatory system is minimal and it focuses on the operational area limits and on the drones components requirements for the manufacturers.
  Even though this category includes also very small aircraft, some of them can be able to fly high enough to cause severe damages if a failure (e.g. engine shutdown) to people on the ground and also severe risk to manned aviation if it flies near ATZ.
  An open subcategory is the Harmless category, which includes those very small unmanned aircraft (e.g. toys) which can not cause serious injuries due to the limited thrust power and weight. Regulations for open category include a series of Proposals regarding the possibility to mitigate risk by imposing a safe distance with third persons and to separate two (or more) airspace users. At the moment, the latter proposal imposes the flight in Visual Line of Sight (VLOS) and below150 m.

- **Specific Category**
  The specific category is referred to all the unmanned aircraft operations outside the open category limits. This requires specific mitigation of higher risk to third parties on the ground and other airspace users due to the exceeding safety barriers of open category. Specific category includes bigger unmanned aircraft sizes and missions above populated areas. The Detect And Avoid (DAA) function is strictly required.
  To reduce and mitigate the risk until reaching an acceptable level, a Specific Operation Risk Assessment (SORA) has to be performed by the operator,

which has to take in consideration all the possible elements that could mitigate the mission risk. To perform a SORA some key factors of risk assessment must be considered, such as area of operation, RPAS design, mission type, pilot competencies and environment. Operators must provide to the National Aviation Authority all the information required for a first applicability check of the operation category, a SORA and a manual containing personnel qualification certifications, description of the mission, maintenance conditions of RPAS. As Operational Assessment (OA) is intended the way to define limitation of a given operation of a given drone with particular equipment. Additional local limitations like no-fly zones defined by the competent State authority.

- **Certified Category**
  The certified category includes all operations with an higher risk level, similar to a manned aviation operation. These operations are expected to be complex and characterized by a risk level comparable to that of manned aircraft. At the moment this category is purely teoretical.
  The operator must be provided of a Remote Operator Certificate (ROC), granted by official training organizations. A ROC holder with an high level of experience can authorize his own Operational Assessment and can have the privilege to authorize other operations. Of course, a Remote Operator Certificate holder must ensure that all the equipment related to the type of operation complies with limitations and conditions imposed, and provide Type Certificate (TC) or Restricted Type Certificate (RTC). Those certificates, granted by NAA, represent the appropriateness of systems to obtain the airworthiness approval. A Certified operation category needs the approval of all the single parts and equipment involved by the manufacturer, independently from the aircraft approval itself. That allows the interpretation of NAA responsibilities in certified category as the same of manned aircraft operations.

Nowadays, the current regulations refer not to categories of operation but to weight classes. This helps to have a clear idea on which Aviation Authority is responsible for a RPA category rather than others defining, in a more distinct way, RPA categories. Despite this, the European Aviation Safety Agency (EASA) is trying to introduce a new regulatory framework to have a clearer idea of unmanned aircraft categorization. The Proposal document (Opinion No 01/2018) has been published in December 2017, but the official recognition will be probably in 2019. The current unmanned aircraft categories are better explained in the following image:

Type of drone	Current and potential future uses	Current regulation
Small (<20/25 kg) Price: €140-28 000	Leisure and commercial use (e.g. surveillance, inspection, photography)	Falls under Member State regulations
Light (20/25-150 kg) Price: €55 000-420 000	Used in geospatial surveying and wide-area surveillance. Potential to inspect pipelines and power cables, spray crops, search and rescue, control borders and monitor forest fires	Falls under Member State regulations
Large (>150 kg) Price: €670 000 and above	Used by the military and defence forces. Potential to carry cargo and passengers	Civil drones with an operating mass of more than 150 kg fall under Regulation 216/2008/EC and EASA competency, unless operated by a state agency

Data source: European Parliament study on 'Privacy and Data Protection implications of the civil use of drones', 2015, p. 12.

Figure 9.2: Drones types basing on weight classes, [36]

As shown in figure 9.2, in Europe, Regulations and responsible Authorities for civil drones aviation are split: for drones category with Maximum Take Off Weight (MTOW) below 150 kg, the institution in charge is different for each country; for drones category with MTOW greater than 150kg, the only one Authority in charge is EASA. It is clear that despite of this division, defined as an arbitrary cut off point by European Commission, the risk of RPAS operations and categorizations should not depend only on the mass. The result of the European Parliament briefing in October 2015 is the urgent need of develop safety rules at European Union level, and most ministers accorded to the consideration of EASA as the best Authority able to develop technical and safety standards, licenses and certificates. This need comes due to the problem of different rules from one State to another, even if the categorizations and operational and altitude limits do not vary (e.g. in Spain the distance limit is over VLOS with special permits; other countries impose the limit as 500m). This would result as an easier passage of RPA from a national airspace to another without regulations inconsistencies and a general homogenization of operators rules and ground personnel training process, to assure a determined level of experience and ability to remotely pilot an RPA, which means in an increasing of Safety.
At the global level, the Authority in charge to recommend a single set of technical, safety and operational requirements for Unmanned aircraft (or at least to harmonize the many existing sets of Rules) is Joint Authorities for Rulemaking on Unmanned Systems (JARUS), in which 52 countries are contributing.
The following sections are explaining which are the rules in force at this day at International and national level, focusing on the Italian environment.

9.2 Regulations in force in Europe

The reference document that establishes all the regulations in force in Europe is the *REGULATION (EC) No 216/2008* and contains a wide series of articles concerned to Airworthiness, pilots, air operations, possible missions in which are involved more than one national airspace (in and out European Union), certificates, qualified entities and all possible politic or bureaucratic issues. As already said, this set of regulations is the same used for manned aircrafts, since the risk management level of unmanned aircraft with MTOW greater than 150 kg is effectively considered as high as manned aircraft one. The document, in a synthetic way, declares regulations as:

- the the need of Aircraft (and all its subsystems, components, etc.) to be certified, registered and provided by authorized and certified manufacturers
- to obtain the clearance of airworthiness it must be provided: Product (and all its components) integrity and to assure safety conditions for all operational envelope of the aircraft; Aircraft must be free from excessive aeroelastic and vibrational phenomena; the propulsion system integrity must be demonstrated and maintained for the whole operational life, and the same demonstration must be done for structure and loads.
- the aircraft configuration must not have design features that experience has shown to be hazardous and equipped systems must be able to provide alerts and advice for any type of event to pilots or crew, in a reasonable time. To minimize hazards, design precautions must be taken.
- Restrictions applicable to the issue of permits to fly in particular operations concern the purpose of the flight, the airspace used, the qualification of flight crew.
- As essential requirements for environmental protection, the product (and all its components) shall comply the environmental protection requirements contained in Amendament 8 (Volume I) and Amendament 5 (Volume II) of Annex 16 of Chicago Convention.

It is perceived that the previous document treats , indeed, unmanned aircraft as a manned one. It has to be taken into account that RPA with MTOW greater than 150 kg are only used by military forces, which means that to comply with air traffic management regulations is mandatory. In addiction, the European Military Aviation Requirements (EMARs) are military adaptation of the proven EASA airworthiness rules.

9.3 Regulations in force in Italy

The Italian Authority in charge for civil aviation regulations is the *Ente Nazionale Aviazione Civile* (ENAC). The reference document containing the regulations in force at this day is the *Remotely Piloted Aerial Vehicles Regulation-Issue 2 (revision of 24 March 2017).* As already explained, NAAs regulate RPA civil operations for unmanned aircraft which MTOW is below 150 kg, and at operational level corresponds to Open and Specific categories.
Whatever the RPA category is taken into account, RPAS operations shall comply with all the applicable sections of the Regulation itself, and operations are allowed for specialized operations and R&D activities. The RPAS operations can be in VLOS, EVLOS or BVLOS.

- **VLOS operations**
  VLOS operations are intended missions in which the remote pilot mantains the direct visual contact with the RPA. These operations are allowed only in daylight, with maximum horizontal distance of 500m and vertical distance of 150m. To reach higher distances, operator needs to submit a risk assessment. VLOS operations are prohibited in areas within 5 km to Aerodrome Traffic Zone (ATZ) and restricted (or prohibited) areas.

- **EVLOS Operations**
  Enhanced VLOS Operations are carried out according to VLOS horizontal and vertical limit (or beyond if authorized), but the remote pilot has alternative means to maintain visual contact with the RPA and is able to avoid collisions. More than one remote ground pilot stations can be used to maintain visual contact of RPA, but for each ground pilot station the limitations and conditions required for VLOS operations are established.

- **BVLOS Operations**
  BVLOS represents all operations carried out Beyond VLOS, and in general, beyond horizontal and vertical VLOS limits. This type of operations require systems able to detect and avoid collisions (authorized by ENAC). BVLOS operations also require airspace segregation, based on the kind of operations and on the risk assessment performed by the operator.

RPAS (MTOW $< 25\,kg$) regulations

The above mentioned reference document contains some general provisions for this specific RPAS class, declaring a list of needs independently to the intended operation category. Some of them specify the need of RPAS to be: supplied with a flight manual; identified by a plate installed on it which gives information about the system and the operator; equipped with appropriate systems depending on the operation; to be piloted by an operator with certified competences; equipped with lights in order to be recognized easily. Operations for RPAS (MTOW $< 25\,kg$) are divided in Non-critical and critical operations. A section for RPAS (MTOW $< 0.3\,kg$) is also defined by ENAC.

- **Non-critical Operations**
  They are VLOS operations in which the RPAS will not fly over congested areas (even in case of failure), high density population areas and critical infrastructures. In case of non-critical operations, the RPAS operator shall provide ENAC with declaration of compliance to the regulation in force, and define limitations and conditions for the intended flights on the official ENAC website. In addition, the operator is responsible for operation risk assessments and has to assure the validity of non critical conditions. Tests, maintenance programme, and all documentations regarding risk assessments and safety management procedures must be provided on the official ENAC website and shall keep documentations updated.

- **Critical Operations** Critical operations, substantially, are meant as operations where the RPAS can overcome the above mentioned non-critical limits (e.g. to overfly in congested areas, etc.). Before starting a critical operation, the operator shall obtain the ENAC authorization. In addition, the given operation can be started only if the safety level is adequate. The safety level depends on RPAS design, pilot, flight management procedures, environment. As the same of non-critical operations, RPAS performances must be appropriate to the demanded safety level for the given operation. In addition, it is compulsory the installation of a flight termination system (it has to be an independent system), with a predetermined minimum operational altitude to guarantee its proper operation.
  It is strictly forbidden to overfly on persons during events or entertainments but, if the operation is in VLOS comply EUROCAE ED-12 (a standard for on board software requirements certification) and the RPA is able to maintain its operation even if the data link is lost, in that cases it would be permitted as long as the acceptable safety level is demonstrated.
  In general, to obtain the ENAC authorization, the operator shall be in possession of manual of operations and propedeutic experimental activities (needed to know the operational limits of RPA) are done (over unpopulated areas and

by pilots holding certifications). ENAC reserves the right to conduct eventual inspections during those activities.

- **RPAS (MTOW $< 2\,kg$)** All operations that involve this RPA class are considered non-critical independently from the operative scenario, as long as the design criteria of the RPA result in harmless features. Operations like overfly on persons during events is still strictly forbidden and, as the same of the previous two categories, the pilot must hold certifications and flight manual. As a subcategory, RPA with MTOW$< 0.3kg$ are considered non-critical, but the operator must provide ENAC declaration of compliance and all the documentations needed as already described for Non-critical operations.

RPAS (MTOW$> 25\,kg$ & $< 150\,kg$) regulations

Some general provisions are declared for all RPA included in this category. An RPA with MTOW $> 25kg$ must be registered by ENAC in RPAS register and some marks have to be shown on the ground pilot station and on the RPA itself. RPAS of the above mentioned class need a Permit to Fly certificate (valid for three years), which is generally needed for experimental activities (e.g. R&D) or specialized operations. The Permit to Fly certificate specifies operations limitations, depending also on the overflown areas. As already declared in the previous subsections, the RPAS owner shall provide to ENAC all documents declaring the type of missions, safety level, certifications. It is also needed the Restricted Type Certification in case of series RPA production by manufacturers.
As the same of the previous classes, Operator must: have ENAC authorization and shall submit it; have operational organization adequate to the intended activities; be in possession of all the certifications required for specialized operations.
A maintenance programme must be established by the operator, which shall be provided also of replacement parts and safety occurrences. Maintenance can be provided by the RPA manufacturer.

9.4 UAS integration into non-segregated airspace

The possibility to fly aircraft without the pilot onboard goes back to the years of the Second World War and in 1944 ICAO officially acknowledged the existence of UAS too in the Chicago Convention. As said, such aerial vehicles have been used almost exclusively for military purposes. The development of RPAS started in the 1950s. Drones have been used by armed forces for decades. Recent conflicts and

peace-keeping operations around the world have demonstrated their operational capacities and led to a quasi-exponential increase of military applications. Drones have become a crucial pillar for military activities.This situation continued until 2013 when, during the European Summit on the Future Defence Policy hold on the 19th December 2013. During the Summit a formal commitment was made to enhance the European UAS/RPAS military capability. The debate was focused both on technical issues and on regulatory and research activities. In the same context efforts to integrate UAS/RPAS into the European civil aviation system startng from 2016. As said, both ICAO and local Member State Code of Navigation (this the case of Italy) allowed the operation of RPAS only. Years from 2005 until have been demonstrating to be the most fertile period to make RPAS tecnology feasible and economically viable and competitive. Reaserch and development and combination of lighter and more resistant materials together with software, data processing and miniaturisation tecniques at ever lower cost made RPAS technology entering civil aviation market like a sort of spin-off industry.
As explained in ICAO Cir 328, the safe integration of Unmanned Aircraft Systems into non-segregated airspace will be difficult and a long-term project. Nonetheless, Unmanned aircraft integration can be reached in the medium-term as long as the aircraft will be managed by a remotely-located pilot, which is a critical element to reach adequate levels of safety. Of course is implicit that an integrated UAS must address technical specifications, command and control, detect and avoid and other functionalities, in order to reach the key factor to be able to act and respond as a manned aircraft does. Unfortunately, ICAO itself defines this as an accomodation and not an effective integration. Despite that, the principle to integrate RPAS at this day is the safety risk assessment. JARUS developed this methodology, called SORA (Specific Operations Risk Assessment) already mentioned in previous paragraphs, and it is approved by EASA and EUROCONTROL. Also ICAO declares the concept of the operator to provide a Safety Management System (SMS), as the same way for manned aircraft (Annex 19).

9.4.1 Safety Management System

Safety Management System is a systematic approach to safety management, including the necessary organizational structures, accountabilities, policies and procedures. It is an explicit and systematic process for risk management and manages, determines and schedule the adequate performances to achieve the defined safety requirements for a given operation. SMS requires a deep integration into organization, culture and way of work of people involved in the considered operation.

The ICAO SMS framework consists of four components: Safety Policy, Safety Risk Management, Safety Assurance and Safety promotion.

- **Safety Policy :** is the statement of the organization's fundamental approach to achieve acceptable or tolerable safety. It defines the value of safety in the overall business and performance framework of the organization. Substantially, it is a written document that describes the generic principles upon SMS is built and operate.
- **Safety Risk Management :** is the identification, analysis and mitigation of those hazards, as well as the subsequent risks that threaten the viability of an organization. Operational hazards related to flight actvity shall be identified and propely mitigated so to reach and maintain an acceptable safety level. This is the most dynamic part of the SMS because of the continuous searching with proactive and reactive methods for new risks and hazards. The process, explained in ICAO Doc 9859 explains that for each hazard identified, a risk assessment in terms of severity and then of probability must be done. Following these elements, risks can be considered acceptable or not; in this case residual risk can be estimated; finally proper recovery actions/recommendations can be implemented as final solution.
- **Safety Assurance :** contains all planned and systematic actions necessary to afford adequate confidence that a product (or service, system, etc.) achieves acceptable safety or tolerable risk level. Assurance activities are strictly necessary if aviation service provider want to meet ICAO SARPs requirements.
- **Safety Promotion :** it contains all the processes and procedures to ensure that personnel are trained to perform safety management duties. As a supporting role to achieve safety acceptable levels, it sets the predispositions for individual or team behaviour during an operation to be sure that the right thing at the right time in emergency situations will be done. Safety Promotion includes also the way to report every single potential hazard identified during operations (it is compulsory but also wants to be an automatic and routine process).

9.4.2 UAS Traffic Management

Indicated with the acronym UTM, it represents a traffic management system for Unmanned Aerial Systems, studied and developed by NASA. UTM represents

a way to amplify the drones technologies in civilian applications and to enable important UAS at lower altitudes that do not have to interfere with National Airspace System operations. UTM has a series of benefits, e.g. ease delivery of small packages or analysis of congestion in cities, route planning, conflict avoidance, wildfire mapping, environment monitoring (agriculture, disasters, weather) or even the capability to select a landing zone if RPAs failures have occurred.
Of course UTM functions can support also strategic and tactical operations. As the technical aspect, it does not require high UAS systems to communicate.

Chapter 10

EGNOS-enabled receivers

After the *EGNOS* study and *LPV 200* performance analysis and after having described the most important issues related to RPAS and and their integration into controlled airspaces, the next step explained in this chapter will be the hypothesis to install an *EGNOS* receiver on a given RPA class and to analyze the integration in terms of technical and risk assessment implications.

As described in *EGNOS* Safety of Life Service Definition Document (SDD), since *SBAS* standards had initially to meet stringent navigation performance requirements, the correspondent receiver standards had also to be developed in respect of civil aviation community requirements. These standards are called *SBAS* Minimum Operational Performance Standards (MOPS) published by the Radio Technical Commission for Aeronautics (RTCA). Nowadays, *EGNOS* receivers are able to provide horizontal and vertical precision to user and a wide range of features are also included (e.g. evaluation of derived position's integrity). MOPS identifies four different classes of user receivers, depending on the intended operation.

Operational Class	Phases of Flight
Class 1	Oceanic and domestic en route, terminal, approach (LNAV), and departure operation
Class 2	Oceanic and domestic en route, terminal, approach (LNAV, LNAV/VNAV), and departure operation
Class 3	Oceanic and domestic en route, terminal, approach (LNAV, LNAV/VNAV, LP, LPV), and departure operation
Class 4	Equipment that supports only the final approach segment operation

Figure 10.1: EGNOS receiver classes, [60]

The minimum performance level is accomplished by receivers of Class I (for NPA service level), or receivers of Class III (for APV-I and LPV 200 service levels). Subsequently, depending on the intended operation, ASA provides technical requirements and indications on the Acceptable Means of Compliance suitable for the equipment qualfication referred to as European Technical Standard Order (ETSO). In order to complete the installation, assuming that up to this point everithing is compliant to AMCs, the last step is to obtain an operational approval from the National Supervisory Authority (unless the given aircraft has an airworthiness approval AMC 20-28, in this case is not needed an approval for LPV 200).
An *EGNOS* receiver is essentially like a *GPS* receiver with the addition of special software that compute the *EGNOS* corrections to the *GPS* signals. Despite of that, both are very similar, also in terms of dimensions and weight. The design technologies of *EGNOS*-enabled receivers are for chipsets, hybrid components or auxiliary cards and vary in terms of integration difficulties and costs.
By the way, European Space Agency (ESA) is the authority in charge to keep updated the list of official *EGNOS* receiver manufacturers and their products.

10.1 Rockwell Collins GPS-4000S

An example of *EGNOS* enabled receivers manufacturers is the Rockwell Collins and an example of receiver can be the GPS-4000S model. It provides *GPS*-based navigation and approaches (if aircraft equips also Flight Management System). In addition, it equips a *SBAS* sensor, able to take advantage of *WAAS*, *EGNOS* and *MSAS* systems. It provides also *LPV* precisions.
Receivers like this, are able to use up to 10 *GPS* satellites and two GEO satellites (*SBAS*), even if four satellites are mathematically sufficient. However, the system's RAIM is able to detect and isolate erroneous satellites improving navigation accuracy, so there is no need to run a pre-flight prediction of RAIM availability, that means a benefit for pilots. In terms of physical characteristics, it is composed of two modular concept units (MCU) per ARINC 600, dimensions of $200 \times 61.7 \times 368.8$ $[mm]$, with a weight of $2.9\,kg$ approximately.
It is also similar to GPS-4000A model and equally provides simple and intuitive operations, by being fully integrated with Rockwell Collins Flight Management Systems (e.g. Pro Line 4 or 21).

Figure 10.2: Rockwell Collins GPS-4000S, [43]

Considering that some *EGNOS* receivers are heavier Rockwell Collins GPS-4000S, it would be difficult to think to install it on a RPA with MTOW $< 25kg$, due to thrust problems and difficult flight conditions. So, at this day, an installation on RPA with MTOW $> 25\,kg$ could be done with no problems, even with display data transmission to the ground pilot station in order to be able to fly in EVLOS or BVLOS maintaining an adequate safety level and without asking for permissions to NAAs (which sometimes take long time). Basing on the hypothesis to be able to let an RPA with MTOW $> 25\,kg$ fly with an *EGNOS*-enabled receiver on board and that *LPV 200* performances meet the *EGNOS* SoL service requirements, it will be possible to do the last step of this thesis, explained in detail in the next part.

Part III

RISK MANAGEMENT

Chapter 11

Risk analysis

This last part will introduce the fundamental concepts of safety, risk and how to evaluate them and why. The main document that contains all those concepts and definitions is the ICAO doc 9859. After a panoramic view of this argument, some results of Risk assessment methods, obtained thanks to Federica Bonfante (PhD student of Polytechnic University of Turin), will be showed and commented.

11.1 Safety concept

Safety is defined as "*the state in which the possibility of harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and safety risk management.*"
It is impossible to eliminate hazards and concatenated risk, because the human actions (and consequently all the systems built by humans) can not be completely free from errors. This means that the only possible thing to do is to set an acceptable safety level as a compromise between protection and production.
During the history of progress, safety concept has been involved in different areas: the technical era (first half of XX century) where the most of the failures were related due to the unadapted technologies; the human factors era (last decades of XX century) where there were not much failures related to technologies but for human errors (lack of focus, no strict rules or investigation authorities were already created). Effectively, it seemed that the human error mitigation through new regulations, investigation processes and of course the technological progress were sufficient to guarantee an appropriate safety level for transportation. The problem was that the human factors concept focuses on the single person without considering the environment and that is what gave birth to a third era: the organizational era (present day). Now safety is analyzed through a systemic prospective and sub-

stantially consists in a continuous data collection and analysis using proactive and reactive methodologies to monitor safety risk.

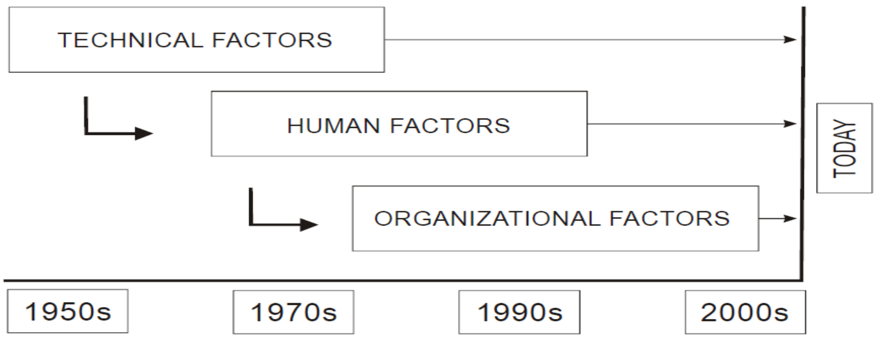


Figure 11.1: Safety concept evolution, [52]

It must be intended that, as in any organization, safety risk and production are strictly linked. In other words, for a product/service provider (and also for the State), the acceptable correlation between Production and Protection is called "Safety Space", that means a virtual zone in which the given organization balances the desired production maintaining the required safety protection through safety risk controls. It is intended that an allocation of excessive resources to reach an high protection or risk control, may implicate a condition in which the product/service results unprofitable and inconvenient in economic terms. On the other hand, excessive allocation of resources for production may lead to the creation of a lot of products/services that do not have the acceptable or required safety performance, that means the possibility to cause accidents.
Both situations are inconvenient and, as explained before, the Safety Space represents a good equilibrium between these issues.

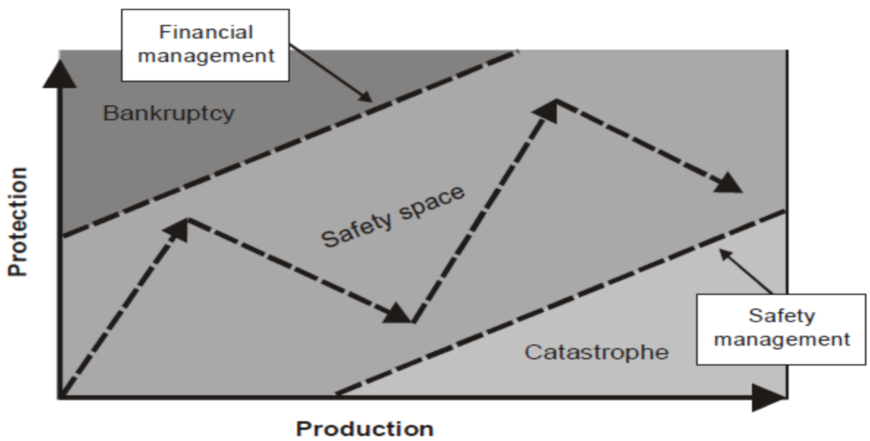


Figure 11.2: Safety space concept (James Reason), [52]

However, not only the safety performance of a given service is involved in the safety management. It has to be considered the system within the environment, and environment have to be studied considering humans in it and how humans interface with systems and environment itself. The SHELL model helps to understand this concept of multi-correlation.
SHELL Model contains:

- *Software (S) :* procedures, training, support, etc.
- *Hardware (H) :* machines and equipment
- *Environment (E) :* the working environment in which the rest of the L, H, S system must function
- *Liveware (L) :* humans in the workplace

It will be shown in the following figure that Liveware is positioned to the center, because humans are not standardized as software, hardware and procedures to obtain given products. Humans are the core of safety management and integration issues. The human interface with software (S) means all the problems linked to checklists, standard operating procedures (SOPs), manuals and computer software, or even symbologies. The human interface with environment refers to physical and psychological considerations, such as ambient light, temperature, vibrations or even illness, fatigue, different biological rhythms and sleep patterns. The human interface with hardware tends to automatically adapt potential mismatches; this could lead to latent failures that will be studied further. The SHELL Model structure also considers an important aspect: the human-human interface, which refers to the work environment in terms of relationship among persons, how well a group works, communication problems or organizational problems.

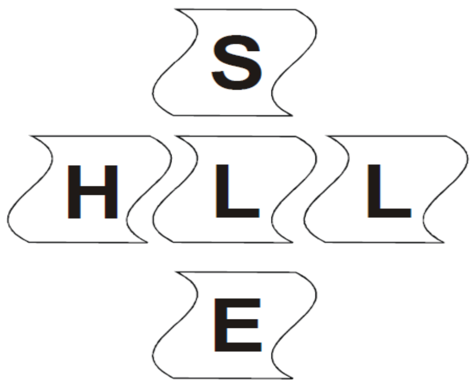


Figure 11.3: SHELL Model scheme, [52]

11.2 Swiss-Cheese model

A simple method that takes into account all the environment if a failure occurs is the Swiss-cheese model (developed by Prof. James Reason). As a Swiss cheese has some breaches, the same is for multiple system defences. Breaches can be triggered by a number of enabling factors, such as equipment or operational failures. This model can be very useful to find and eliminate possible single-point failures which, at this day, are rare in such systems.
Breaches in safety defences can be a delayed consequence, apparently dormant, of decisions made at high levels of the system and could be potential hazardous in particular circumstances. An intended failure at the operational level, with these dormant problems, can breach the system's defences. This model, indeed, helps to evaluate these situations as a combination of latent and active failures.

- **Active failure**
  is an action (or even a inaction), including errors or violations which have an immediate effect and are generally associated with front-line personnel (pilots, aircraft engineers, air traffic controllers, etc) and can be harmful. For both the State and the product/service provider it is important to understand that humans will commit errors independently to how improved is the system technology. Considering that errors can be identified as slips and lapses (failures in the execution of an intended action) and mistakes (failures in the plan of action, impossible to avoid even if the plan execution was correct), the real goal to reduce active failures or errors, then, is to set and maintain defences to reduce the consequences.

- **Latent condition**
  is intended as a not-harmful condition that exists long before that a potential active failure occurs. Its consequence can even remain dormant after the given failure for a not determined time. Even if it is not harmful, the latent condition can be evident once the system fails (defences have been breached). The probable causes can be a problem in procedural design, conflicts or bad decisions in organizational phases.

It is interesting that the Reason model has been described as a model based in percolation theory that, in simple terms, describes the behaviour of the failure probability distribution for connected clusters. An intuitive scheme, used also in the ICAO DOC 9859 helps to intend how failures go through all the "slices of Swiss cheese" and its possible causes.

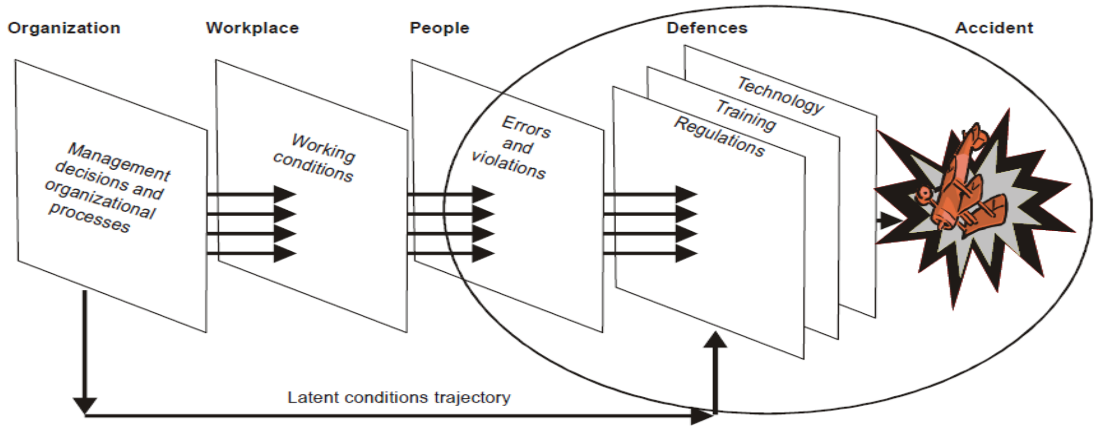


Figure 11.4: Swiss-Cheese Model, [52]

Chapter 12

Risk Management

At this point, the concepts of safety and failure are known. It is also comprehended that when a failure occurs, not only the intended failure shall be studied in order to eliminate (or mitigate) it for future operations but all the structure around it, from the organization and decision plans, to the human working conditions, the environment etc. and are explained by some type of models.
Despite this, that is not enough to understand the safety risk management process that is what will be studied in this chapter.

12.1 Safety data collection and analysis

The data-based decision making is one of the most important facets of State Safety Programme (SSP) and Safety Management System (SMS) development and implementation. It is a database containing information about accidents, incidents, events, errors, hazards, non-conformance, wrong actions.
An important aspect of Safety database is the quality of data contained in such database. The failure to account limitations of those data for safety risk management could lead to imperfect analysis results with bad consequences in terms of faulty decisions. So is important that data shall assure its validity, completeness, consistency, accessibility, timeliness, security and accuracy.
ICAO Annex 13 establish that safety database systems should be standardized in order to facilitate exchange and to be easily intended. At this day, only the European Coordination Center for Accident and Incident Reporting Systems (ECCAIRS) software operates on taxonomy. ECCAIRS also applies the SHELL model.
Data management not only regard its collection, but also its analysis and exchange.
For every occurrence, data analysis process is divided in three steps: the analysis of the occurrence itself, the analysis of its symptoms and the analysis of its causes.

Data analysis is mostly used to decide what additional facts are needed or study latent factors entity, to measure safety trends or performance.

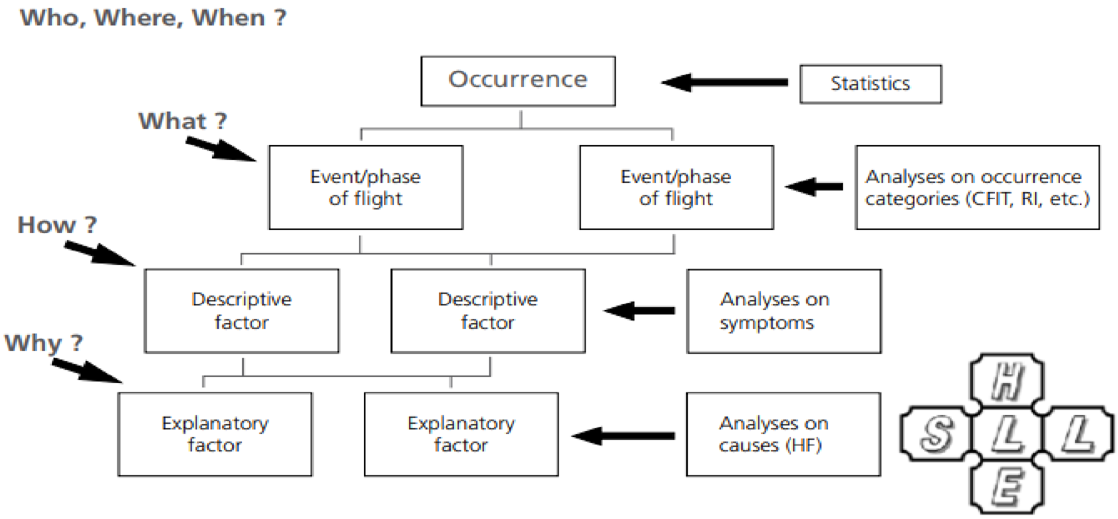


Figure 12.1: Safety Data analysis process, [52]

The safety data analysis is not easy. In fact, most of the time is an iterative process and may be quantitative or qualitative. Of course exist many methods for the analysis:

- Statistical : used to intend the significance of an intended safety trend. Data quality must be considered to avoid erroneous conclusions.
- Trend : used to predict future events. Trends may be indicative of emerging hazards.
- Normative comparison : used in case of insufficient data quantity.
- Simulation and testing : used to let hazards become evident. Laboratory testing is used to validate safety implications of existing (or new) type operations.
- Cost-benefit : used to evaluate the cost of implementing new measures to let safety risk acceptable and compare it to expected benefits over time.

The last part regards the data exchange. Most states are not comfortable with this concept, due to the sensitivity of the information, which could be misused. At the moment no agreements or safety data exchange programme exist to protect information. By the way, ECCAIRS software is able to remove sensitive information from data. The possibility to exchange safety data results among States, could be useful to homogenize safety levels at a global (or almost international) level.

12.2 Safety risk management

Safety Risk Management (SRM) is the second step of Safety Management System (SMS), defined as the identification, analysis and elimination (or at least mitigation to an acceptable level) of those hazards, as well as the subsequent risks, that threaten the viability of an organization. Its objective is to ensure that the risk associated to hazards to flight operations are systematically and formally identified, assessed, and managed within acceptable safety levels.
As already intended, it is impossible to eliminate risks in the aviation field, both for economic/logistic issues and for conceptual impossibility. In other words, it is preferred that an intended risk occur with some residual risk of harming people (or properties, environment) but in an acceptable way, accepted by the responsible authority. It has been said also that Safety Risk Management is the core of SMS, and the most dynamic part. The process follows a detailed and strictly mandatory series of steps to achieve the ability to mitigate a given hazard or to do other analysis about new consequential action to reach the intended safety level. This eventual work should be done in the third step of SMS, the Safety Assurance.

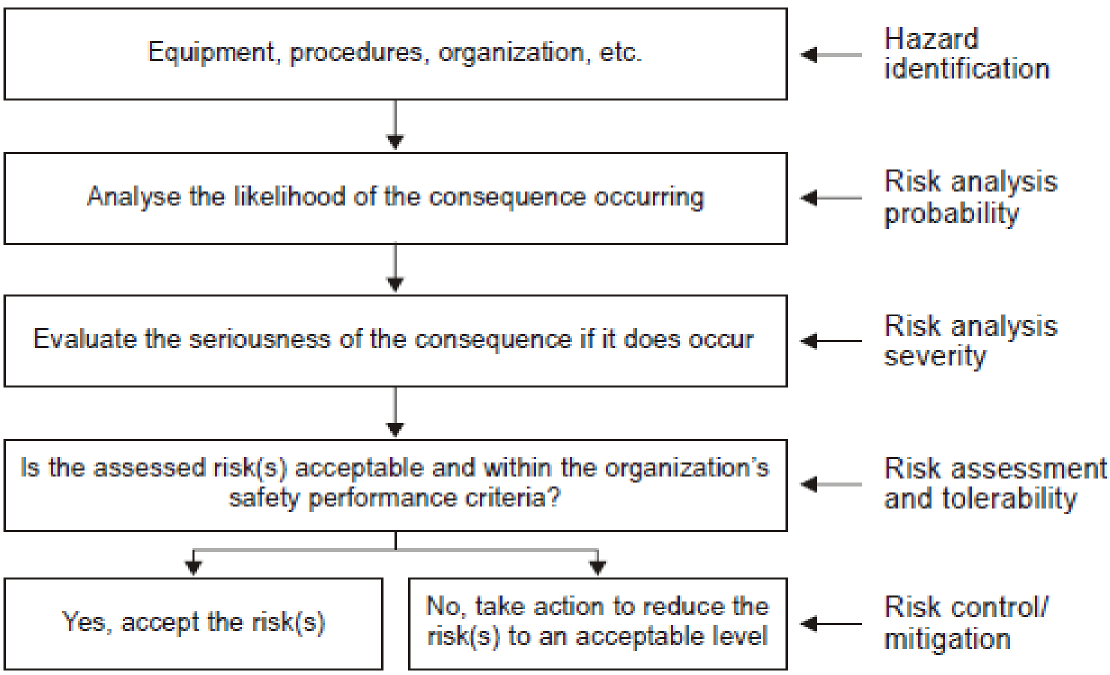


Figure 12.2: Safety Risk Management process, [52]

12.3 Hazard Identification

Hazard identification is a prerequisite to the Safety Risk Management process. It is important to do not confuse the definition of risk with the hazard one. In fact, with the term Hazard is intended the condition (or an object) with the potential to cause death, injuries to personnel, damage the equipment or structures, loss of material, or reduction of the ability to perform a prescribed function. For the purpose of aviation safety risk management, the term hazard should be focused on the conditions which could cause or contribute the unsafe operation of an aircraft or aviation safety-related equipment, products or service (ICAO DOC 9859).
Hazard are an inevitable part of aviation activities, and can exist at all levels in the organization. They can be found through investigation reports, inspections and audits especially for indirect hazards.
Hazards are divided in categories, that objectively facilitate prioritization of risk mitigation actions depending of the severity categorization. A scheme of hazard categorization, provided by EUROCAE ED-78 A is as it follows:

Hazard Class	**1 (most severe)**	**2**	**3**	**4**	**5(least severe)**
Effect on Operations	Normally with hull loss. Total loss of flight control, mid-air collision, flight into terrain or high speed surface movement collision.	Large reduction in safety margins or aircraft functional capabilities.	Significant reduction in safety margins or aircraft functional capabilities.	Slight reduction in safety margins or aircraft functional capabilities.	No effect on operational capabilities or safety.
Effect on Occupants	Multiple fatalities.	Serious or fatal injury to a small number of passengers or cabin crew.	Physical distress, possibly including injuries.	Physical discomfort.	Inconvenience.
Effect on Air crew	Fatalities or incapacitation.	Physical distress or excessive workload impairs ability to perform tasks.	Physical discomfort, possibly including injuries or significant increase in workload.	Slight increase in workload.	No effect on flight crew.
Effect on Air Traffic Service	Total loss of separation.	Large reduction in separation or a total loss of air traffic control for a significant time.	Significant reduction in separation or significant reduction in air traffic control capability.	Slight reduction in separation or slight reduction in air traffic control capability. Significant increase in air traffic controller workload.	Slight increase in air traffic controller workload.

Figure 12.3: Safety Risk Management process, [52]

Another influential parameter of hazards is the frequency of occurrence. Both hazard severity and frequency of occurrence parameters allow to assess its associated risk to aircraft operations and human life. This represents a good hazard identification approach that ensures its assessment for the risk management process, giving inputs for the subsequent steps, already known as Risk assessment and Risk mitigation. To identify such hazards, three main methodologies exist at this day:

- **Reactive**
  Hazard identification process is done taking into account the analysis and investigation of past events. Incidents/accidents represent eventual system lacks and this can contribute to determine if the hazard contributed to the active failure or to the latent fault.

- **Proactive**
  Hazard identification process is done involving analysis of existing or real-time situations. This, in fact, is the main job of safety protection function with revisions, reports and associated analysis and assessment processes.

- **Predictive**
  Hazard identification process is done using collected data in order to predict possible events, analyzing system processes, environment, liveware with the aim of identify potential future hazards and dispose mitigating actions.

Despite of this, hazard identification process includes the understanding if it affects aviation safety or occupational safety, health and environment (OSHE). If the intended hazard has consequences only in the OSHE "segment" (also called workplace hazard), it shall be analyzed by separate organizations in accordance to separate requirements.

12.4 Risk Assessment

Once hazards have been determined, the next step would be the analysis to assess that such hazard occur in terms of probability and severity. Risk assessment is the second phase of Safety Risk Management, and consists in engineering and operational judgements and/or analysis methods in order to establish if the achieved risk level is acceptable or not. In this way, it is possible to determine the magnitude of an intended risk and, consequently, establish actions or measures to let the risk level stay within acceptable levels. Some concept must be introduced to better comprehend this phase: Safety risk probability and Safety Risk severity. In addiction it has to be clear that the safety risk, as intended by ICAO (doc 9859), is defined as the projected likelihood and severity of the consequence or outcome from an existing hazard or situation, not to confuse with the previously mentioned safety concept.

12.4.1 Safety Risk probability

Safety Risk probability is defined as the likelihood or frequency that a safety consequence or outcome might occur, and it is the first process that takes place to control safety risk. A mental scheme is recommended to determine such probability, as a sort of questions that point out, for example, if the given event is an isolated one or an history or some databases exists, how much the equipment in question is in use, what other equipment may be subjected to the same event. These questions affect as much as any other consideration the possibility to assess the likelihood that an hazard may exist, considering all possible scenarios. A practical way to quantify the probability of an event occurrence, is to use a table with five categories, that represent the likelihood from improbable to frequent and giving a numeric value. It is important that the categorization is not fixed; it depends on the complexity of an intended scenario with a particular event (e.g. the maximum scale of probability is of 15 values, that means 15 different likelihood levels). An example of probability categorization follows.

Table 12.1: Safety risk probability table

Likelihood	Meaning	Value
Frequent	Likely to occur many times	5
Occasional	Likely to occur sometimes	4
Remote	Unlikely to occur, but possible	3
Improbable	Very unlikely to occur	2
Extremely improbable	Almost inconceivable that the event will occur	1

Each likelihood category also includes numerical values, and go from 1 event per hour (frequent) to 10^{-9} per hour (extremely improbable). In some cases, for failures of hardware components, the quantity of data available is sufficient to directly estimate the numerical probability of occurrence.

12.4.2 Safety Risk severity

The next step is the categorization of severity of an intended hazard, which means how serious its potential consequences can be. ICAO defines Safety risk severity as the extent of harm that might reasonably occur as a consequence or outcome of a given hazard. The main bases on which severity categorization is evaluated are the consequences in terms of fatalities/injuries (that means the quantity of lives lost) and damages (that means consequences to aircraft, equipment, properties, etc.). As the safety risk probability, severity is categorized in five levels comprehending from the lowest type of unsafe condition to the highest (catastrophic). An example of severity categorization follows.

Table 12.2: Safety risk severity table

Severity	Meaning	Value
Catastrophic	- Equipment destroyed - Multiple deaths	A
Hazardous	- A large reduction in safety margins, physical distress or a workload such that the operators cannot be relied upon to perform their task accurately or completely - Serious injury - Major equipment damage	B
Major	- A significant reduction in safety margins, a reduction in the ability of the operators to cope with adverse operating conditions as a result of an increase workload as a result of conditions impairing their efficiency - Serious incident - Injury to persons	C
Minor	- Nuisance - Operating limitations - Use of emergency procedures - Minor incident	D
Negligible	-Few consequences	E

12.5 Safety risk matrix and tolerability

Once safety risk likelihood and severity have been categorized, it is possible to continue the risk assessment by crossing both variables in order to obtain a safety risk matrix. The result is a table with alphanumeric values.
This process of risk assessment is needed to evaluate the Safety risk tolerability. In fact, once created the safety risk assessment matrix, is possible to identify another type of categorization: for example if an intended event is not hazardous (e.g. Neglegible, value E) and in addition is not so frequent (e.g. extremely improbable, value 1) the result in the risk matrix will be "1E" and will correspond to an acceptable tolerability.
There are many definitions of risk assessment in aviation industry (EUROCONTROL, FAA, etc.). This can imply different ways to create safety risk assessment matrices, but it is clear that the basis concepts remain the same. Depending on the magnitude of an intended safety risk, three tolerability levels exist. For each one, different strategies or actions can be applied to mitigate or reduce the risk in order to stay within tolerable limits. The fourth part of risk assessment, known as

Risk mitigation has exactly this objective. The tolerability levels are:

- **Acceptable**
  An acceptable level of safety means that there is no need of mitigating actions to be taken. Of course it may exist the possibility to reduce the given risk even more but, to do that, an analysis of costs and organizational impact should be done.

- **Undesirable**
  An undesiderable (or also called tolerable) level of safety means that even though a given event occurs with some uncritical consequences, human life is not in danger. This condition needs mitigating actions in order to lower as much as possible the risk level.

- **Unacceptable** An unacceptable level of safety means, as is perceived, that operational conditions must be ceased until some actions that reduce the risk are applied.

In the following figure, for example, tolerability levels are represented with three colours, in particular red(unacceptable), yellow (tolerable), green(acceptable).

Risk probability		Risk severity				
		Catastrophic A	Hazardous B	Major C	Minor D	Negligible E
Frequent	5	5A	5B	5C	5D	5E
Occasional	4	4A	4B	4C	4D	4E
Remote	3	3A	3B	3C	3D	3E
Improbable	2	2A	2B	2C	2D	2E
Extremely improbable	1	1A	1B	1C	1D	1E

Figure 12.4: Safety Risk assessment matrix, [52]

As previously mentioned, for each tolerability level, some mitigating measures have to be taken. In case of acceptable risk level, the only actions that could be done refer to the additional reduction of risk level but it shall not affect economic and organizational factors; in case of tolerable risk level, the recommended action can be to schedule performance of a safety assessment to bring down the risk index to the low range if viable; in case of unacceptable risk level, first of all the operation must be terminated and, in addiction, enhanced preventive controls must be inserted to mitigate the risk.

Chapter 13

Risk analysis methods

According to ICAO doc 9859, there are many ways to analyze risk assessment. Concentrating on the operational risk evaluation, which mean mismanagement and/or technical risks, two main types exist: Top-down and Bottom-up approaches. The top-down approach analyzes risks by taking into account all the possible internal operational failures. It relies on historical data and is not so complicated because does not need a lot of data. The concept top-down means that for a given single failure (top event), the analysis goes through all the single components or processes and considers its associated risk. The analysis proceeds deeper and deeper reaching the core (down) that contains all the possible events that can trigger the top event. An example of top-down analysis is the Fault Tree Analysis (FTA).
The bottom-up approach works in the opposite way of top-down. It starts analyzing and identifying all the components/operations of a given system and consider each possible failure (bottom). Once known all the potential failures the analysis goes higher and study all the possible causes and consequences of each failures, evaluating their severity (up). An example of bottom-up analysis is the Failure Mode and Effect and Criticality Analysis (FMECA).

13.1 Fault tree analysis

Fault tree analysis, as well as being defined a top-down analysis, is a deductive failure analysis. It is based on Boolean logic ports which allow user to create a sort of "tree" which connect a certain number of lower-level events connected in a determined way with the top event, that is the one to be effectively analized. It is mostly used in safety and reliability engineering. Is obvious that depending on the severity of a given event, the complication and extension of the tree analysis can

change. FTA helps to identify lacks in the project phase, which FMEA is not able to do. An important aspect of Fault Tree Analysis is that is able to consider also human factors: it is used in fact for investigations after an accident.
Boolean logic is used because any system's failure is subjected to more subsystems (or sub-parts) failures and a series of symbols help to represent the relationship between all these sub-part failures.

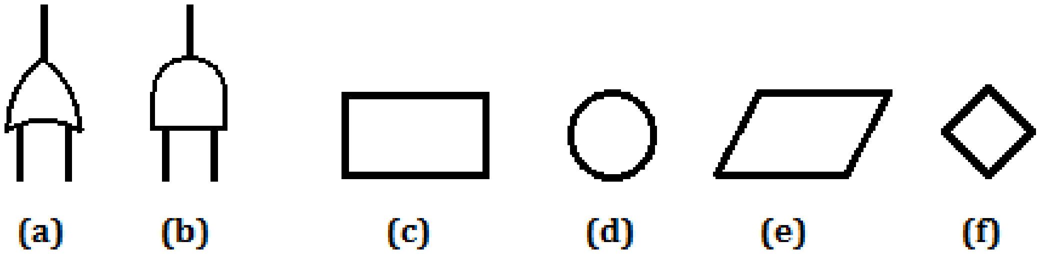


Figure 13.1: Boolean symbols in Fault Tree Analysis

In Fault Tree Analysis, each boolean symbol has its specific meaning: **(a)** is the OR gate, which means that failure can occur if at least one of input fails; **(b)** is the AND gate, which means that failure occur if both input fail; **(c)** represents another event to analyze further; **(d)** represents an elementar (single) event; **(e)** represents the top event (at the root of FTA); **(f)** represents an important event that shall be studied in a separated FTA. By joining all the previous symbols, what is obtained is the Fault Tree Analysis properly.

13.2 Failure Mode Effect and Criticality Analysis

The Failure Mode Effect and Criticality Analysis is an extended version of the Failure Mode and Effects Analysis (FMEA). FMECA, as well as being defined as a bottom-up analysis, is an inductive failure analysis. The fact that also the Criticality analysis is present means that the user is able to chart the probability of failure modes against its severity. A valuable aspect of FMECA is the possibility to be applied also to single system components (e.g. a single resistor of the electronic module of a given system). FMECA is more difficult than FTA because of the big quantity of data and considerations needed but gives also better results and benefits in terms of estimation of likelihood. By the way it may be applied also in very early phases of product development, allowing to ensure good safety levels of the product itself.

FMECA method consists of a table containing all the possible failure modes. For each of them, possible causes, effects, probability SOD (Severity, Occurrence, Detection), Criticality level and possible mitigating actions are provided in respect of a well determined procedure dictated by military standard MIL-STD-1629A. It mainly used to identify critical parts of the systems and help to apply mitigating actions to events that may affect the system integrity and, above all, human lives.

It is interesting to consider FMECA and FTA analysis as complementary safety risk evaluation methods. In fact, FMECA (or FMEA) allow to study single failures in a deep way; FTA, on the other hand, allows to identify and study combinations of more than one single event which lead to a specific (top event) failure.

Chapter 14

Results

The last step, after a global view of Safety Risk Management concepts is the analysis of Fault Tree Analysis and Failure Mode Effect and Criticality Analysis results. These analysis are available thanks mainly to Federica Bonfante (PhD student at Polytechnic University of Turin, which is the most important contributor to all the risk management part. Before showing all the images, some notes shall be considered for FTA and FMECA. Both safety risk methods have been applied to EGNOS receiver as a Satellite-based NAVaid, which obviously do not works alone but is supported (and also supports) the present Ground-based NAVaids.
FTA top event is in fact the "Navigation capability – En-route/Approach and landing phases of flight" and includes failures of ground NAVaids and Satellite NAVaids, both at the same relevance level. It helps to understand how the top event can be affected by a potential failure.
FMECA tables contain a list of EGNOS receiver possible faults, with the relevance in terms of SOD (Severity, Occurrence, Detection), and possible mitigating actions. Some columns refer to different things:

- Identification Number : it only identifies a given equipment failure with an alphanumeric code (EGNOS Satellite Based Navigation Sub-system + numeric value).
- Mission phase : it is a number that goes from 1 to 9 and each of them represents a specifi mission phase. A generic structure of mission phases follows the NASA scheme:

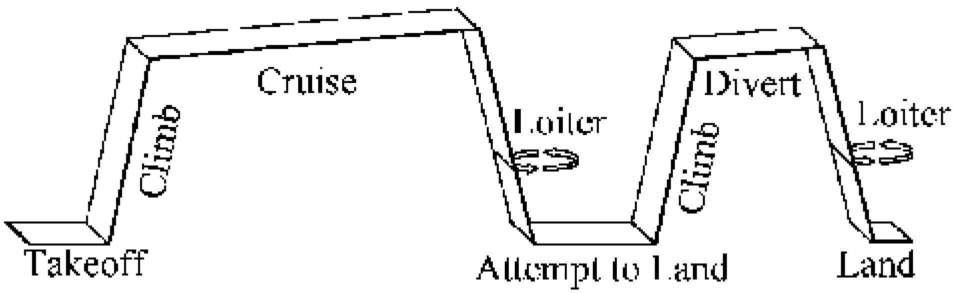


Figure 14.1: Mission phases scheme

So Takeoff is expressed with (1), Climb with (2), Cruise with (3), Loiter with (4), attempt to land with (5), Climb with (6), Divert with (7), Loiter with (8), Land with (9).

- Detection ranking : it follows a scale from 1 to 10, respectively from highly certain to absolutely uncertain and represents the capability to isolate the origin of a potential failure.

- Risk Priority Number (RPN) : it is the product of Severity, Occurrence and Detection (its value, potentially, can go from 1 to 1000 depending on the scales used). RPN represents the total criticality of the intended failure. The higher its value the more is the urge of mitigating actions.

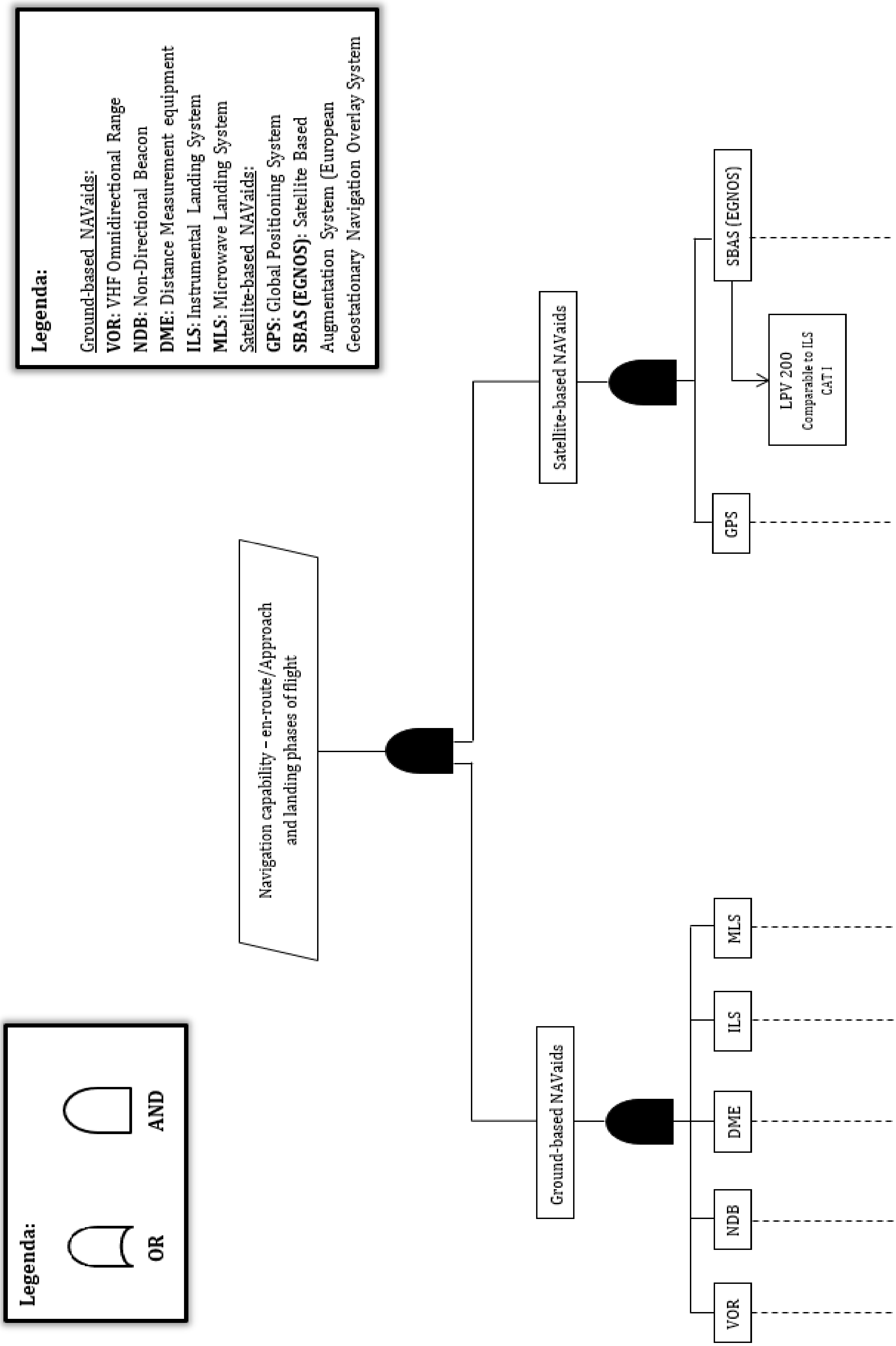


Figure 14.2: RPAS FTA pt.1

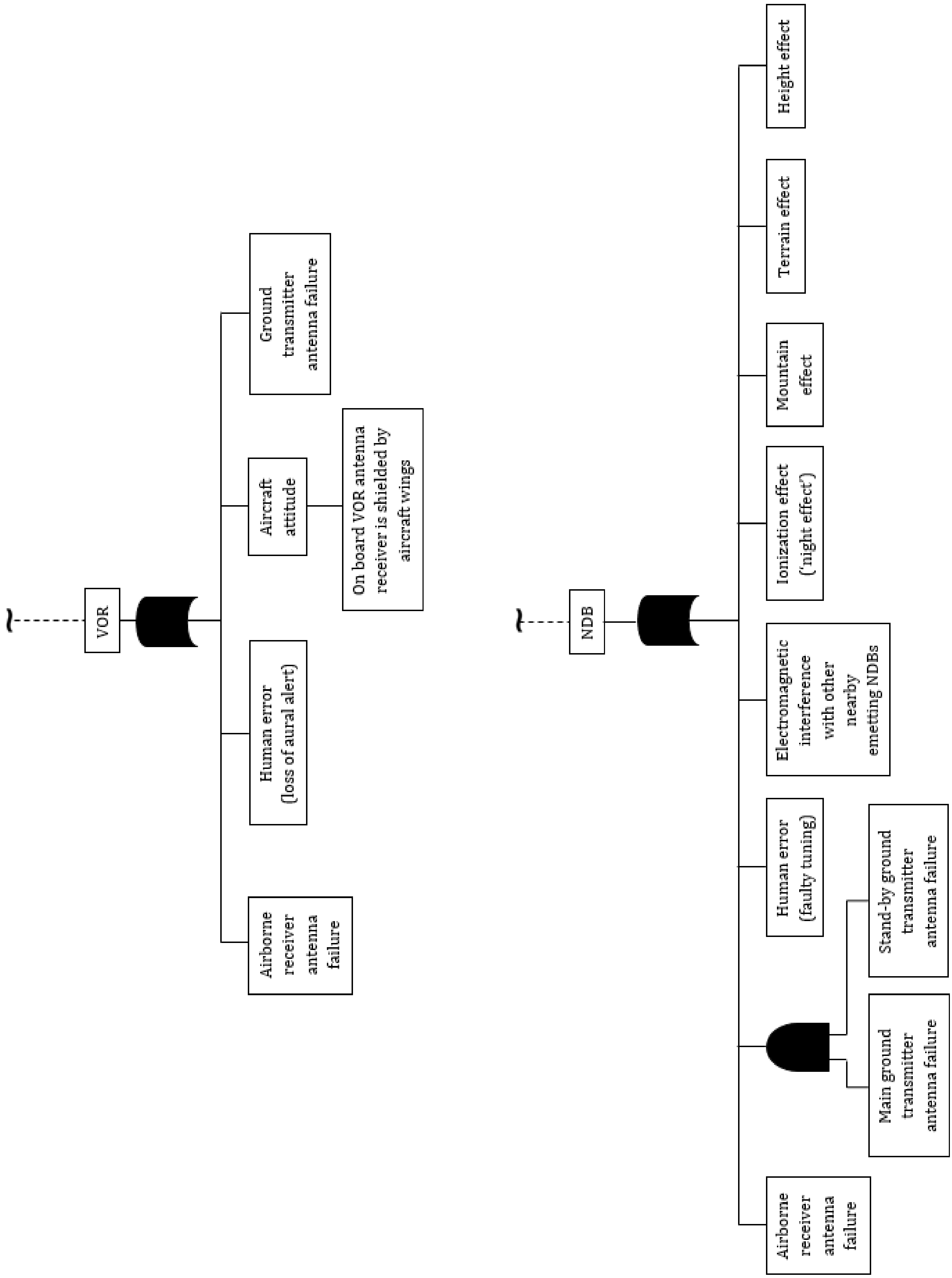


Figure 14.3: RPAS FTA pt.2

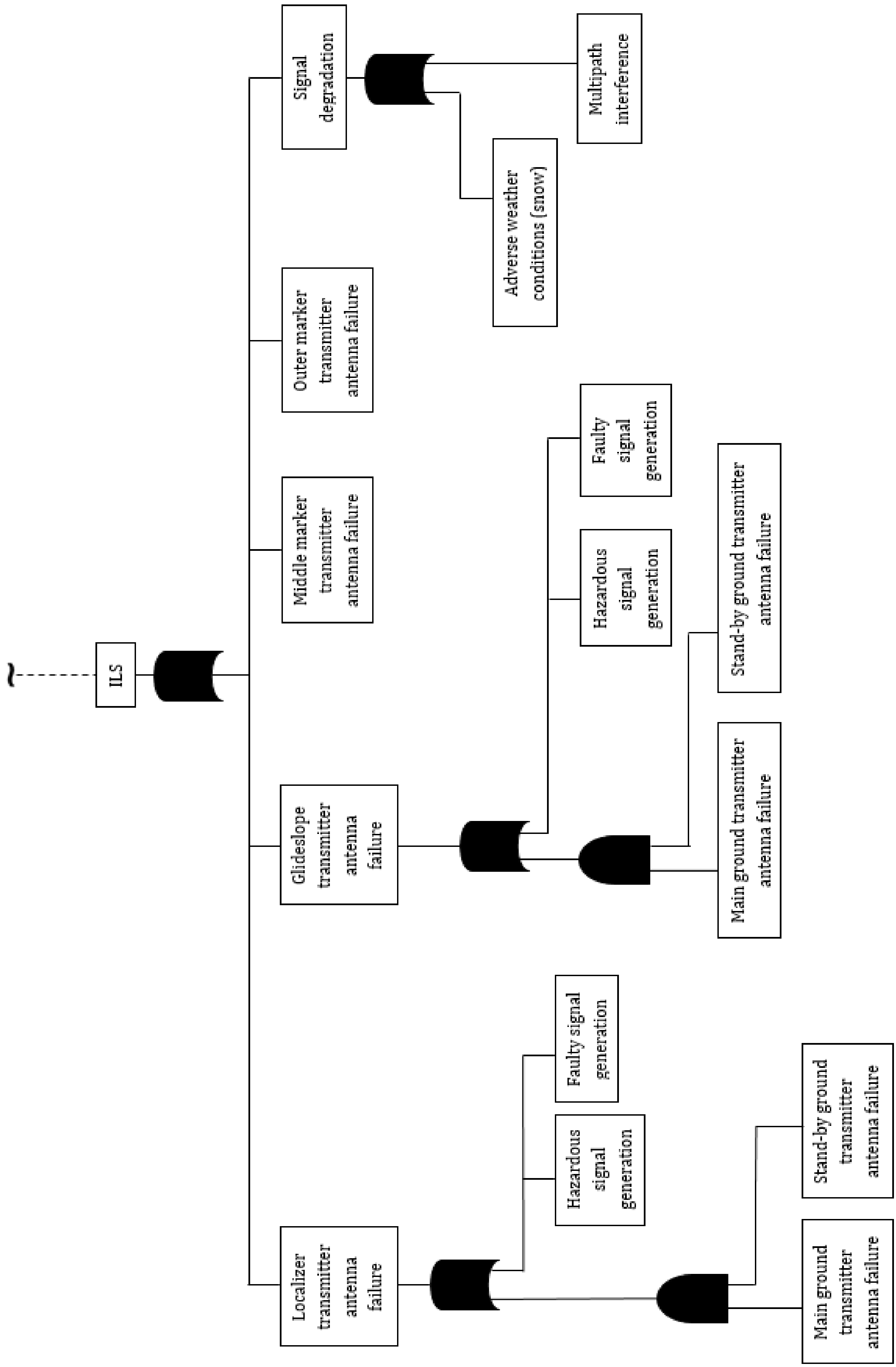


Figure 14.4: RPAS FTA pt.3

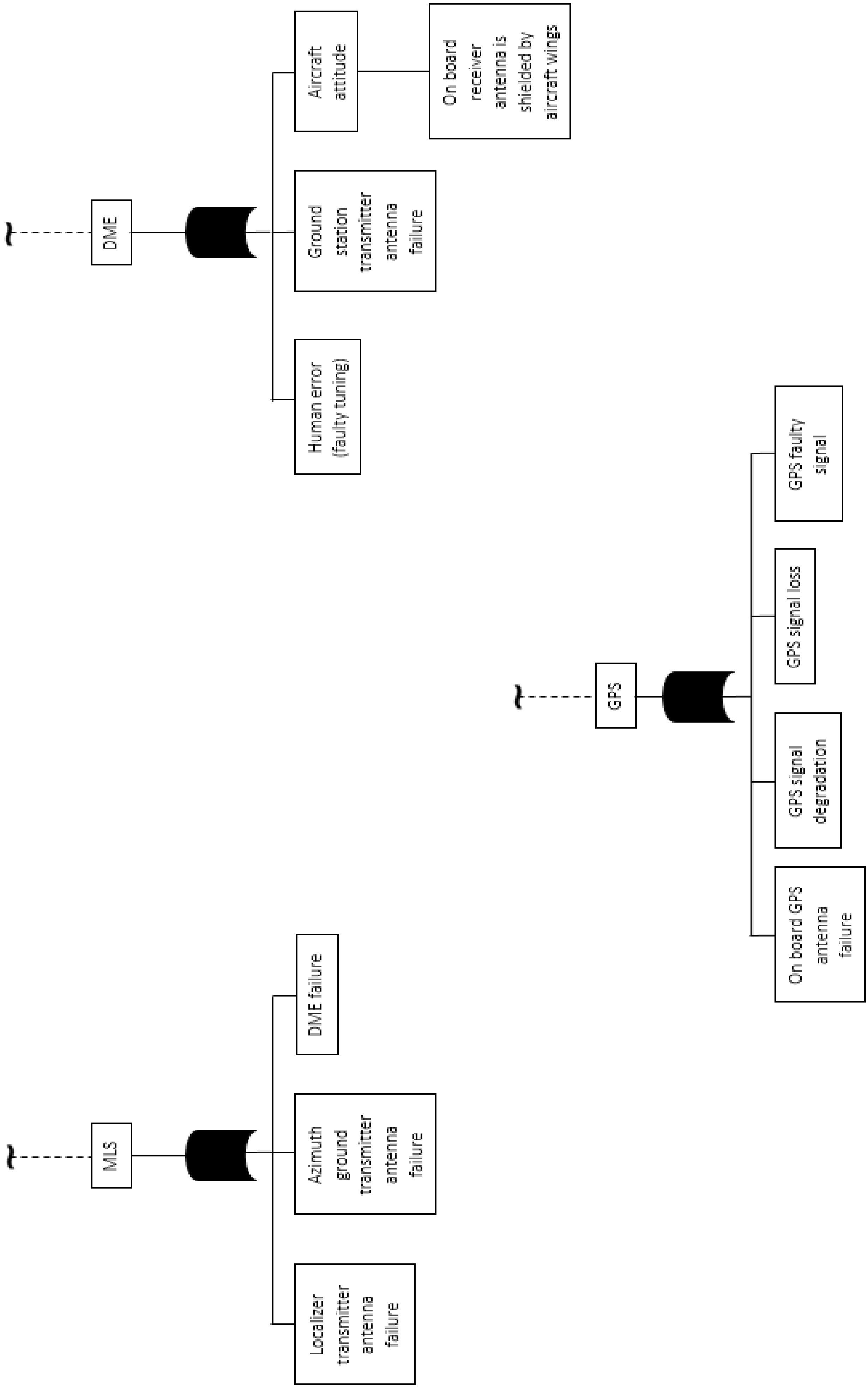


Figure 14.5: RPAS FTA pt.4

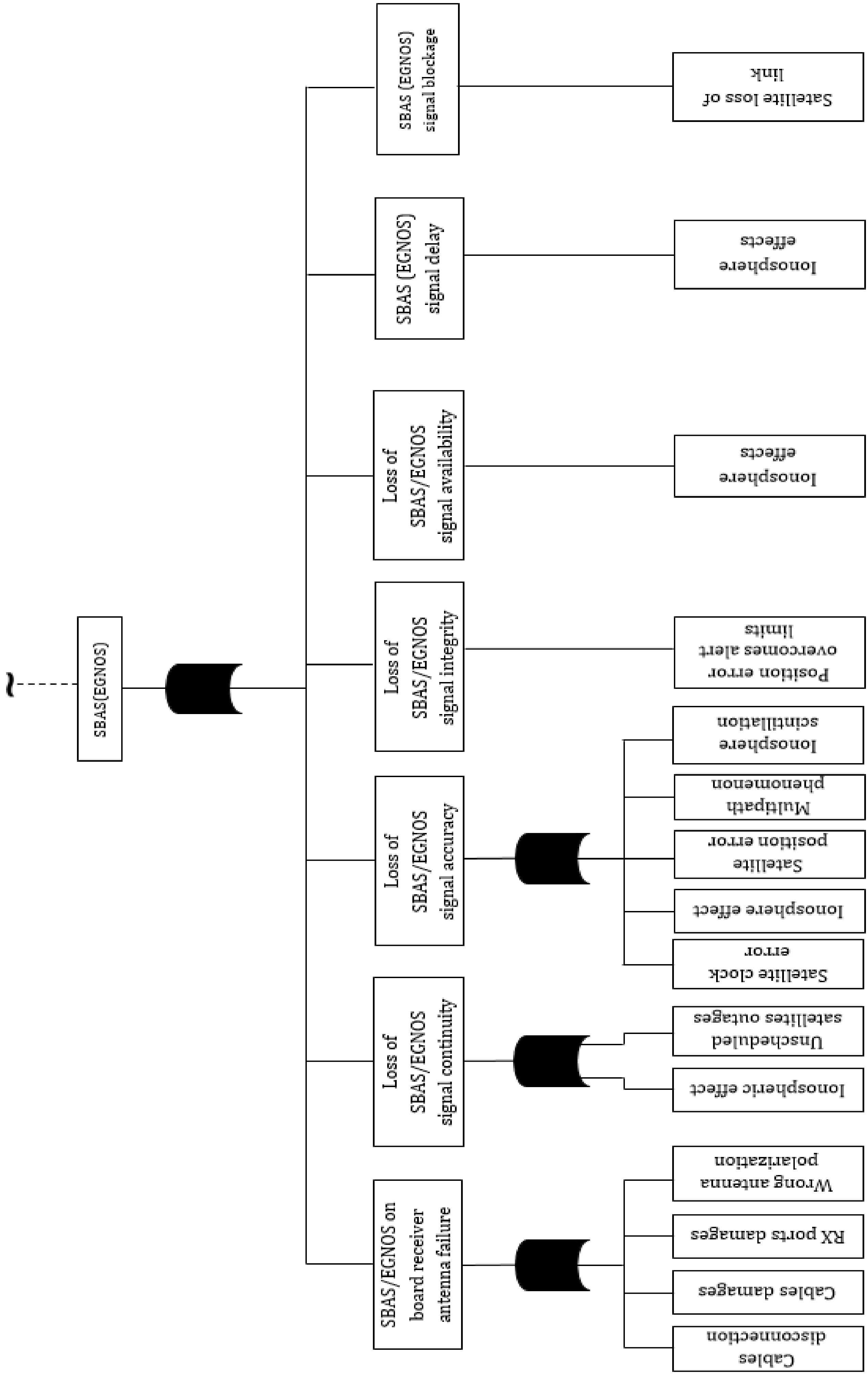


Figure 14.6: RPAS FTA pt.5

Remotely Piloted Aircraft Systems FMECA

System name: Aerial segment

Type of aerial segment: rotor wing aircraft		
EASA Weight class A1	< 250 g and < 80 J or < 900 g	25 kg < Weight < 150 kg
EASA Weight class A2	< 4 kg	
EASA Weight class A3	< 25 kg	

Subsystem: Flight Subsystem/Navigation Information Subsystem/EGNOS Satellite Based Navigation Subsystem

Equipment	Function	Identification number	Failure modes	Failure causes	Mission phase	Failure effects			Severity classification	Severity number (SN)	Occurrence probability	Probability number (PN)	Failure detection method/Observable symptoms	Detection ranking (DR)	Criticality number	RPN	Mitigation actions	Remarks
						Local effect	Next higher level	End effects										
EGNOS receiver	GEO Satellites signal reception	ESBNSS1	Lack of GPS/SBAS Functionality (GPS/SBAS receiver Failure)	Receiver cables disconnected or damaged/Damaged RX ports/Wrong antenna polarization settings	4, 5, 6, 7, 8, 9	EGNOS receiver loss of functionality	-	Loss of en-route, terminal, or non-precision approach navigation/Loss of precision approach navigation data/ Mission degradation	Marginal – Level III	2	C	3	Visual or audible warning devices	2	1	12	Operational procedure (Use traditional NAVaids/ approach aids)	-
EGNOS receiver	GEO Satellites signal reception	ESBNSS2	Loss of GPS/SBAS signal continuity	Environmental conditions (ionosphere effects)/Unscheduled satellite outages	4, 5, 6, 7, 8, 9	EGNOS receiver degradation or loss of functionality	-	Loss of en-route, terminal, or non-precision approach navigation/Loss of precision approach navigation data/Loss of mission	Critical – Level II	3	E	1	Visual or audible warning devices	1	3	3	Use of at least two GEOs satellites/ Operational procedure (Use traditional NAVaids/ approach aids)	-
EGNOS receiver	GEO Satellites signal reception	ESBNSS3	Loss of GPS/SBAS signal accuracy	Error on satellite clock/Satellites signals distortions/ Satellites position errors /Multiple reflections (among urban environment elements like buildings or vehicles) called multipath phenomenon/ Ionospheric scintillation due to solar electromagnetic activities/Tropospheric effects due to weather conditions (temperature, humidity)	4, 5, 6, 7, 8, 9	-	-	Loss of en-route, terminal, or non-precision approach navigation/Loss of precision approach navigation data/Mission degradation	Critical – Level II	3	D	2	Visual or audible warning devices	1	6	6	Operational procedure (Use traditional NAVaids/ approach aids)	-

Figure 14.7: RPAS FMECA Egnos receiver pt.1

EGNOS receiver	GEO Satellites signal	ESBNSS4	Loss of GPS/SBAS signal integrity	The error associated to the position is larger than the alert limits defined for the intended operation	4, 5, 6, 7, 8, 9	-	-	Loss of en-route, terminal, or non-precision approach navigation/Loss of precision approach navigation data/Loss of mission	Critical – Level II	3	E	1	Visual or audible warning devices	1	3	3	Operational procedure (Use traditional NAVaids/ approach aids)	-
EGNOS receiver	GEO Satellites signal reception	ESBNSS5	Loss of GPS/SBAS signal availability	Ionospheric effects	4, 5, 6, 7, 8, 9	-	-	Loss of en-route, terminal, or non-precision approach navigation/Loss of precision approach navigation data/Loss of mission	Critical – Level II	3	D	2	Visual or audible warning devices	1	6	6	Support from RAIM corrections (use of redundant GNSS measurement for fault detection and exclusion)/ Operational procedure (Use traditional NAVaids/ approach aids)	-
EGNOS receiver	GEO Satellites signal reception	ESBNSS6	GPS/SBAS signal delay	Ionosphere dispersion effect	4, 5, 6, 7, 8, 9	-	-	Loss of en-route, terminal, or non-precision approach navigation/Loss of precision approach navigation data/Mission degradation	Marginal – Level III	2	C	3	The receiver does not immediately use EGNOS to compute a navigation solution and therefore the position accuracy improvement is not available until a few minutes after the receiver is turned on// Visual or audible warning devices	1	6	6	Operational procedure (Use traditional NAVaids/ approach aids)	-
EGNOS receiver	GEO Satellites signal reception	ESBNSS7	GPS/SBAS signal blockage	Satellites link loss (due to the temporary position or satellite under the horizon, to the presence of buildings (in urban environments) or due to the orography of the navigation area	4, 5, 6, 7, 8, 9	-	-	Loss of en-route, terminal, or non-precision approach navigation/Loss of precision approach navigation data/Mission degradation/ Loss of mission	Critical – Level II	3	C	3	The navigation solution is still available but it shows a degraded accuracy since no clock ephemeris or ionospheric corrections will be available to the user receivers// Visual or audible warning devices	1	9	9	Operational procedure (Use traditional NAVaids/ approach aids)	-

Figure 14.8: RPAS FMECA Egnos receiver pt.2

	Safety risk Hazard probability	Safety risk severity	Safety risk assessment	Tolerability	Risk range description	Recommended action	Recovery action	Residual safety risk assessment	Tolerability	Risk range description
Lack of GPS/SBAS Functionality (GPS/SBAS receiver Failure)	Occasional (4)	Minor (2 or D)	4D	Acceptable based on risk mitigation	Moderate risk	Schedule performance of a safety assessment to bring down the risk index to the low range if viable.	Use traditional ground-base NAVAids	2D	Low risk	Acceptable as is. No further risk mitigation required.
Loss of GPS/SBAS signal continuity	Extremely improbable (1)	Minor (2 or D)	1D	Acceptable	Moderate risk	Schedule performance of a safety assessment to bring down the risk index to the low range if viable.	Use traditional ground-base NAVAids	2D	Low risk	Acceptable as is. No further risk mitigation required.
Loss of GPS/SBAS signal accuracy	Remote (3)	Minor (2 or D)	3D	Acceptable based on risk mitigation	Moderate risk	Schedule performance of a safety assessment to bring down the risk index to the low range if viable.	Use traditional ground-base NAVAids	2D	Low risk	Acceptable as is. No further risk mitigation required.
Loss of GPS/SBAS signal integrity	Extremely improbable (1)	Minor (2 or D)	1D	Acceptable	Low risk	Acceptable as is. No further risk mitigation required.	No further risk mitigation is required	2D	Low risk	Acceptable as is. No further risk mitigation required.
Loss of GPS/SBAS signal availability	Remote (3)	Minor (2 or D)	3D	Acceptable based on risk mitigation	Moderate risk	Schedule performance of a safety assessment to bring down the risk index to the low range if viable	Use traditional ground-base NAVAids	2D	Low risk	Acceptable as is. No further risk mitigation required.
GPS/SBAS signal delay	Frequent (5)	Minor (2 or D)	5D	Acceptable based on risk mitigation	Moderate risk	Schedule performance of a safety assessment to bring down the risk index to the low range if viable.	Use traditional ground-base NAVAids	2D	Low risk	Acceptable as is. No further risk mitigation required.

Figure 14.9: Risk matrix data

GPS signal jamming (NISS2a) GPS signal spoofing (NISS2b)	HIGH
GPS antenna receiver amplifier failure (NISS1)	MEDIUM
INS circuitry overload (NISS3a) INS calibration loss (NISS3b) INS disconnection from battery (NISS3c)	LOW
Lack of GPS/SBAS Functionality (GPS/SBAS receiver Failure) (ESBNSS1) **Loss of GPS/SBAS signal continuity (ESBNSS2)** **Loss of GPS/SBAS signal accuracy (ESBNSS3)** **Loss of GPS/SBAS signal integrity (ESBNSS4)** **Loss of GPS/SBAS signal availability (ESBNSS5)** **GPS/SBAS signal delay (ESBNSS6)** **GPS/SBAS signal blockage (ESBNSS7)**	**LOW**

Figure 14.10: Failure Criticality levels

LEVEL **5** - FREQUENT					
LEVEL **4** - OCCASIONAL					
LEVEL **3** - REMOTE			GPS/SBAS receiver Failure **(ESBNSS1)** GPS/SBAS signal delay **(EBNSS6)**		
LEVEL **2** - IMPROBABLE				Loss of GPS/SBAS signal accuracy **(ESBNSS3)** Loss of GPS/SBAS signal availability **(ESBNSS5)** GPS/SBAS signal blockage **(ESBNSS7)**	
LEVEL **1** - EXTREMELY IMPROBABLE				Loss of GPS/SBAS signal continuity (GPS/SBAS data invalid or unavailable) **(ESBNSS2)** Loss of GPS/SBAS signal integrity **(ESBNSS4)**	
	CATEGORY **E** - NEGLIGIBLE	CATEGORY **D** - MINOR	CATEGORY **C** - MARGINAL	CATEGORY **B** - CRITICAL	CATEGORY **A** - CATASTROPHIC

Figure 14.11: Safety Risk Assessment matrix results

Chapter 15

Conclusions

At the end of this thesis, some final considerations can be done. After the *EGNOS* services performances verification, which results have been very good and consistent with ICAO requirements and after norms and regulations analysis, it has been legitimate to hypothesize an *EGNOS* enabled receiver to be integrated on RPAS. The only missing step was the Risk Management due to the new equipment integration. After the last step analysis, Risk analysis results have been good too. In particular, after FTA and FMECA analysis, the obtained results mean that the Risk level of a potential *EGNOS* service that aims to obtain augmented performances (Accuracy, Integrity, Continuity and Availability) has been categorized at the acceptable level, which intends that there is no need to mitigating actions (except in cases to the need to obtain even lower risk levels). It must be taken in consideration that Risk analysis have been done considering *LPV 200* as a supporting service to already existing ground-based NAVaids because at this day, however, *GALILEO* satellite system is not fully operational and a full replace is still considered not applicable.
Despite of these considerations, the results obtained through this thesis suggest that however it will be possible to let RPA fly with high precision in flight areas not accessible at this day, for example in high populated zones. The idea is to let RPA fly through cities with an adequate level of safety with a subsystem capable to evaluate in real time the risk level and, if below its defined level (that could depend on the intended operation, zone, flight level, mass etc), a flight termination system can be connected to this, which can be automatically activated. In this way the RPA would be able to fly in safety, but if not, mitigating measures depending on the loss of *EGNOS* signal can be applied.
The impact of this idea is considerable. Taking into account that in the last decade the number of RPA has exponentially increased, an higher number of remote (and

certified) pilots will be needed. This means more job placements, but also more operational possibilities for the Unmanned aircraft world, such as better product delivery performances, or traffic monitoring, security control among determined areas (rural or not).
Certainly, this will influence also the regulations in force at this day. Authorities have already predicted how fast RPAS field for civil operations will change fastly and some measures and modifications are already proposed and going to become official in the next years.

Aknowledges

These five years have been the most intense of my entire life. Effectively, it has been full of difficult moments, but the good side of bad moments is that they have been able to make more important the beautiful ones I had. I look to these five years with happiness, because I had the possibility to learn, to travel, to meet new people (and some of them had become very important) and to live and enjoy life. All that I am today, the experiences I had and what I achieved until this day, all these things are not only a personal achievement, because it has been possible thanks to what is more important for me, that means the luckiness of having great people by my side, and some lines to say thanks are the least I can offer.

First of all I want to thank my parents, for what they have done since I was born. They have worked everyday, with sacrifice, to let me and my brother live a good and happy life and I really owe them everything I am and everything I have. If I am here writing my MSc thesis, it is mostly thanks to them. I also want to thank my brother for staying always by my side and trusting in me, despite everything.

I want to thank my friends, the best people I had the chance to meet, from my friends of Trapani, to the ones of Torino, all the beautiful people met in Valencia, because you made my life happier. Even more I want to thank Giulia, Sasi, Marzia and Federico. Thanks for being always my reference points, my comfort zones, my second family.

At last but not the least, I have to thank my Italian supervisor Prof. Paolo Maggiore for the help during the thesis project, to Federica Bonfante for the big and fundamental help and to Prof. Israèl Quintanilla to introducing me in this field. Without them, maybe this document would not exist.

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Appendix A

Acronyms

ABAS	Aircraft-Based Augmentation System
APV	Approach with Vertical Guidance
ASQF	Application Specific Qualification Facility
ATC	Air Traffic Control
ATM	Air Traffic Management
ATZ	Aerodrome Traffic Zone
BRLOS	Beyond Radio Line Of Sight
BVLOS	Beyond Visual Line of Sight
CS	Commercial Service
DAA	Detect And Avoid
DME	Distance Measuring equipment
EASA	European Aviation Safety Agency
ECCAIRS	European Coordination Center for Accident and Incident Reporting Systems
EDAS	EGNOS Data Access Server
EGNOS	European Geostationary Navigation Overlay System
ENAC	Ente Nazionale Aviazione Civile
ESA	European Space Agency

ESP EGNOS Service Provider

ESSP European Satellite Services Provider

EU European Union

EVLOS Enhanced Visual Line Of Sight

FAA Federal Aviation Administration

FMEA/FMECA Failure Mode and Effect (and Criticality) Analysis

FTA Fault Tree Analysis

FTP File Transfer Protocol

GAGAN GPS Aided Geo Augmented Navigation

GBAS Ground-Based Augmentation System

GEO Geostationary Earth Orbit

GLONASS Global'naya Navigatsionnaya Sputnikovaya Sistem

GNSS Global Navigation Satellite System

GPS Global Positioning System

GSO GeoSynchronous Orbit

HAL Horizontal Alert Limit

HNSE Horizontal Navigation System Error

HPE Horizontal Position Error

HPL Horizontal Protection Level

HSI Horizontal Safety Index

ICAO International Civil Aviation Organization

IFR Instrument Flight Rules

ILS Instrument Landing System

JARUS Joint Authorities for Rulemaking on Unmanned Systems

LNAV Lateral NAVigation

LOS Line Of Sight

LPV 200 Localizer Performance with Vertical guidance

MCC Mission Control Centers

MEO Medium Earth Orbit

MOPS Minimum Operational Performance Standards

MSAS MULTI-Functional Satellite Augmentation System

MTOW Maximum Take-Off Weight

NAA National Aviation Authority

NAVIC NAVigation Indian Constellation

NLES Navigation Land Earth Stations

NPA Non-Precision Approach

NTRIP Network Transport of RTCM via Internet Protocol

OS Open Service

OSHE Occupational Safety, Health and Environment

PACF Performance Assessment and Checkout Facility

PBN Performance Based Navigation

PRN PseudoRandom Noise

PRS Public Regulated Service

PS Precision Service

QZSS Quasi-Zenith Satellite System

RADAR RAdio Detection And Ranging

RAIM Receiver Autonomous Integrity Monitoring

RIMS Ranging Integrity Monitoring Stations

RINEX Receiver INdependent Exchange Format

RLOS Radio Line Of Sight

RNAV	aRea NAVigation
ROC	Remote Operator Certificate
RPAS	Remotely Piloted Aerial System
RPN	Risk Priority Number
RTC	Restricted Type Certificate
RTCA	Radio Technical Commission for Aeronautics
RTCM	Radio Technical Commission for Maritime Service
SAR	Search And Rescue
SARPs	Standard And Recommended Practices of ICAO
SBAS	Satellite-Based Augmentation System
SIS	Signal In Space
SMS	Safety Management System
SOD	Severity-Occurrence-Detection
SoL	Safety of Life
SORA	Specific Operation Risk Assessment
SPS	Special Positioning Service
SRM	Safety Risk Management
TC	Type Certificate
TEQC	Translation, Editing and Quality Checking
TTA	Time To Alert
UAS	Unmanned Aerial System
UTM	UAS Traffic Management
VAL	Vertical Alert Limit
VLOS	Visual Line Of Sight
VNAV	Vertical NAVigation

VNSE Vertical Navigation System Error

VOR VHF Omni-directional Range

VPE Vertical Position Error

VPL Vertical Protection Level

VSI Vertical Safety Index

WAAS Wide Area Augmentation System

WGS84 World Geodetic System 1984

Appendix B

Complementary results LPV 200

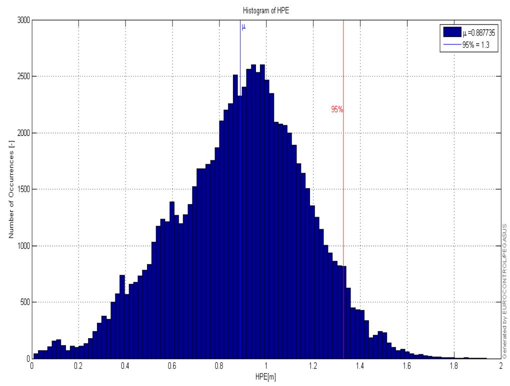

Figure B.1: HPE distribution (029)

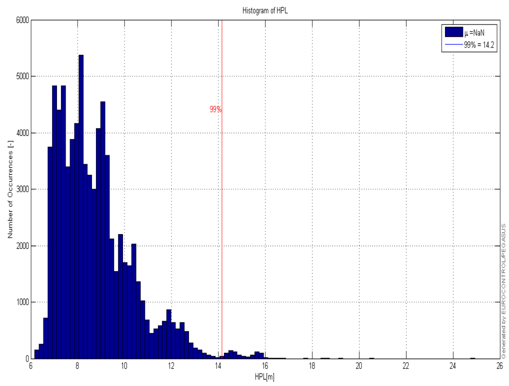

Figure B.2: HPL distribution (029)

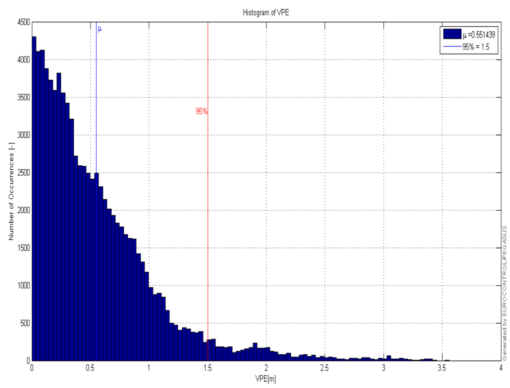

Figure B.3: VPE distribution (029)

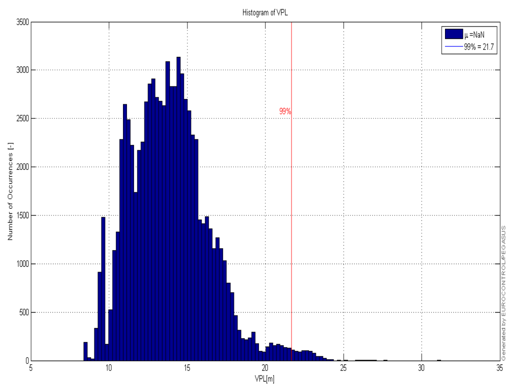

Figure B.4: VPL distribution (029)

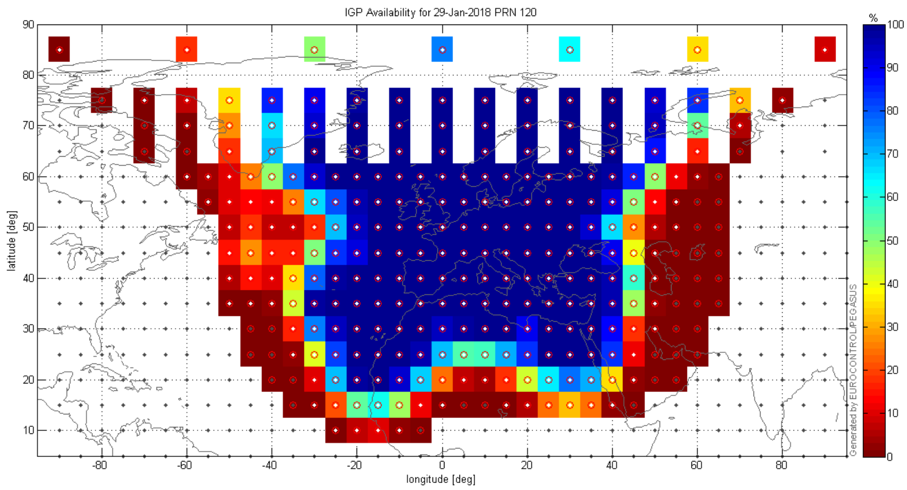

Figure B.5: Availability map PRN 120 (029)

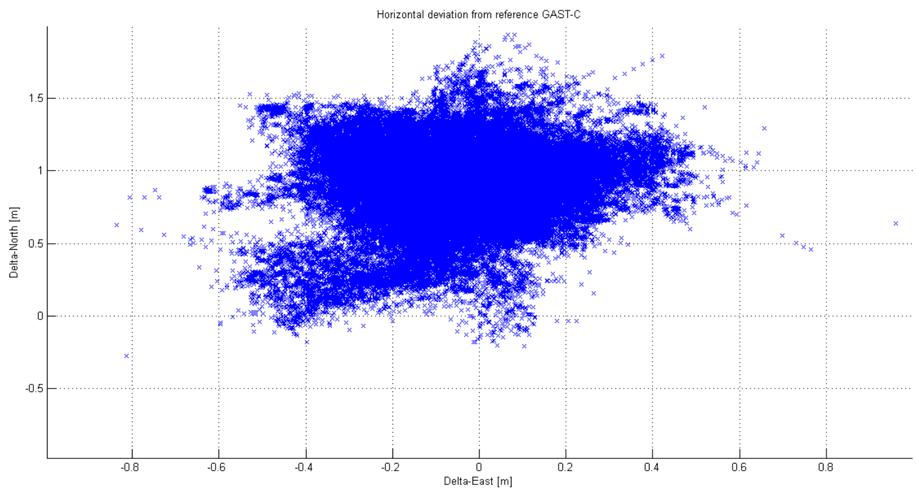

Figure B.6: North-East deviation statistics (029)

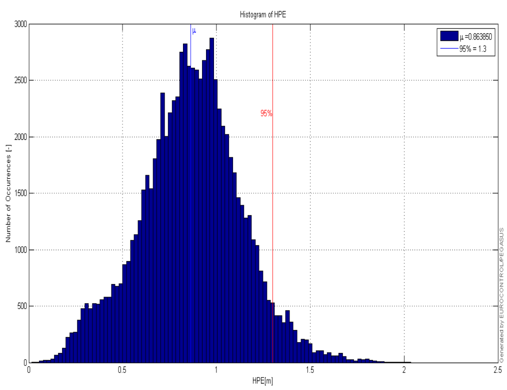

Figure B.7: HPE distribution (030)

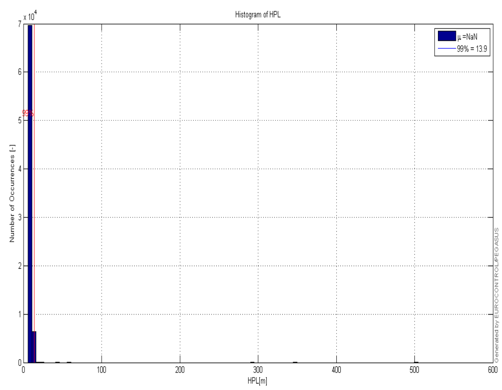

Figure B.8: HPL distribution (030)

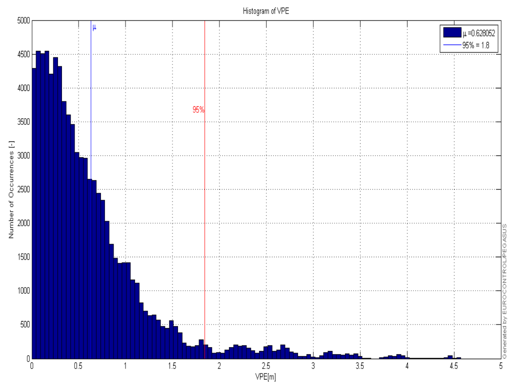

Figure B.9: VPE distribution (030)

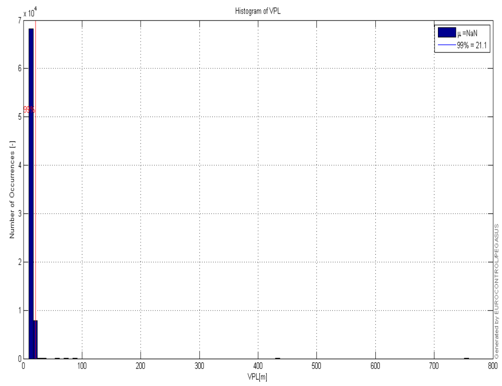

Figure B.10: VPL distribution (030)

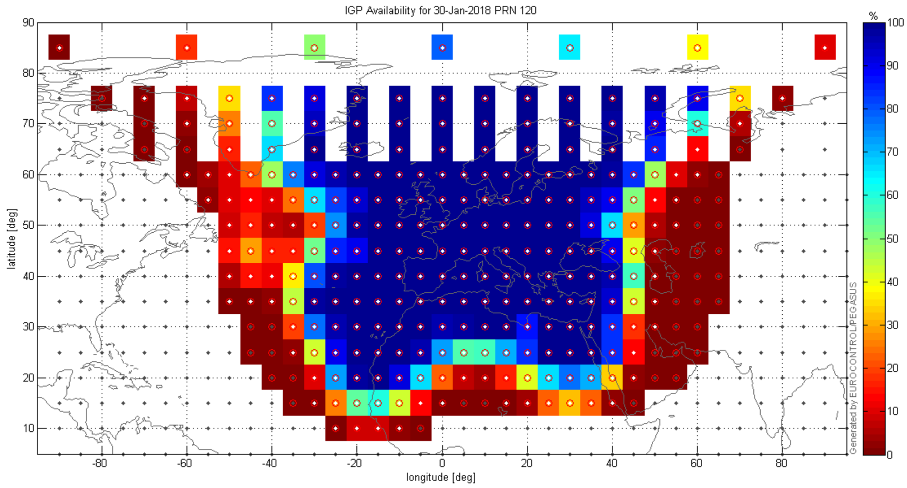

Figure B.11: Availability map PRN 120 (030)

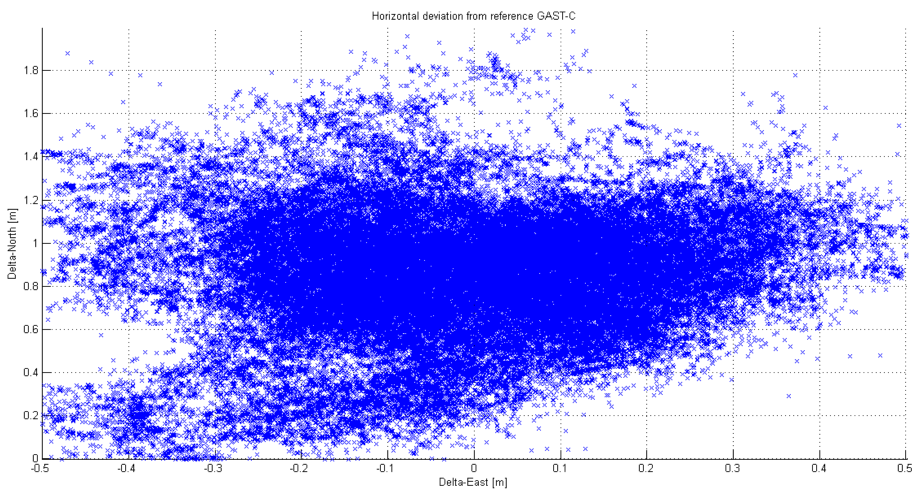

Figure B.12: North-East deviation statistics (030)

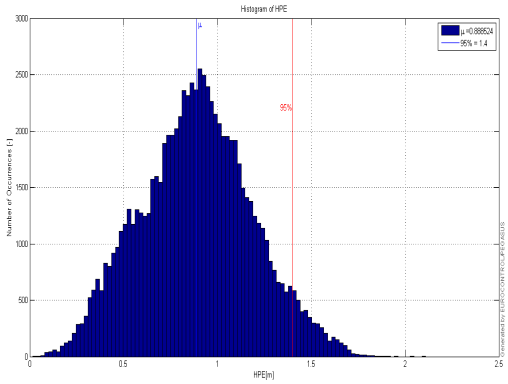

Figure B.13: HPE distribution (031)

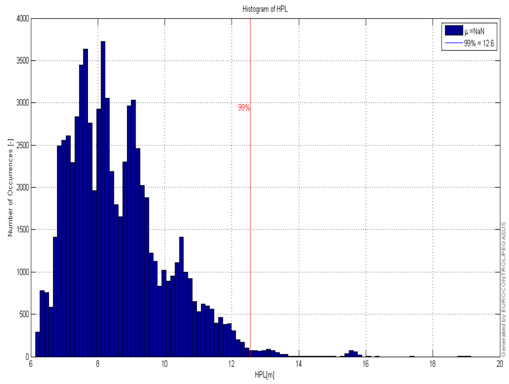

Figure B.14: HPL distribution (031)

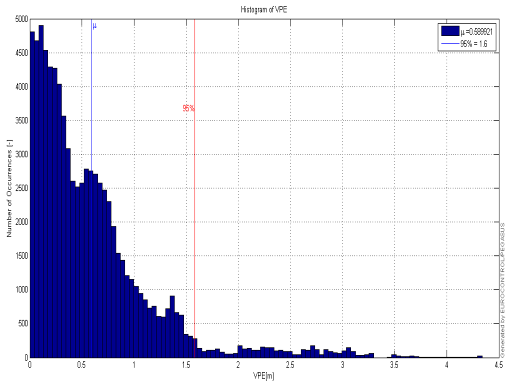

Figure B.15: VPE distribution (031)

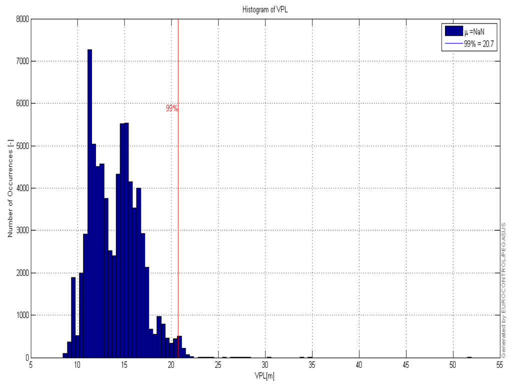

Figure B.16: VPL distribution (031)

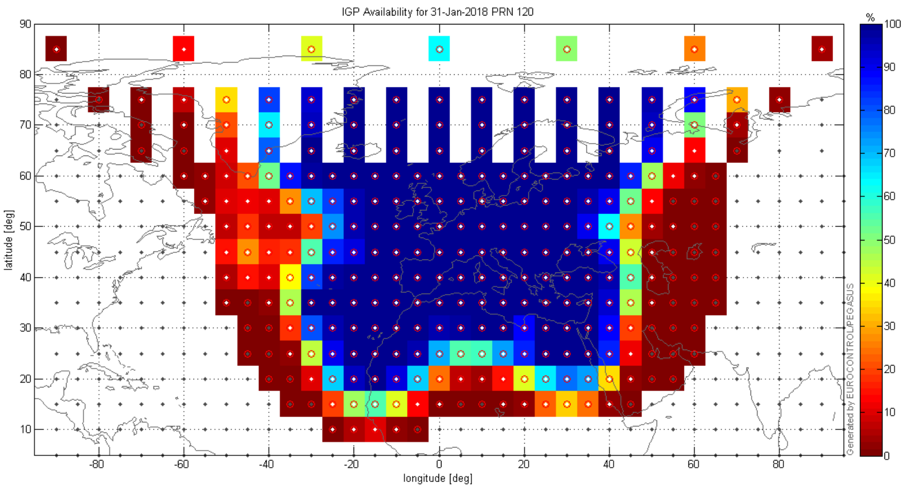

Figure B.17: Availability map PRN 120 (031)

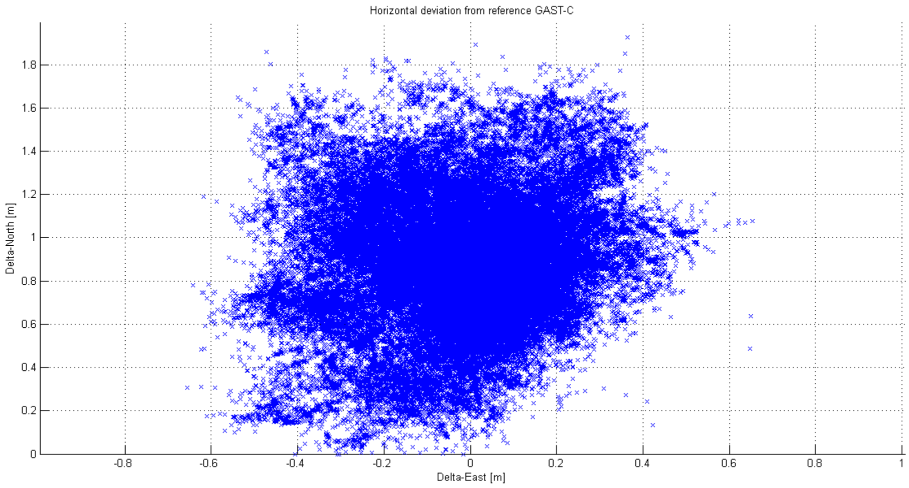

Figure B.18: North-East deviation statistics (031)

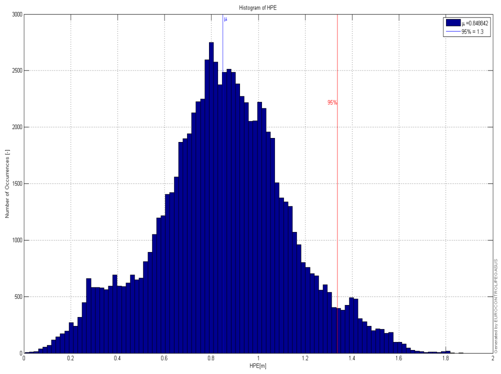

Figure B.19: HPE distribution (032)

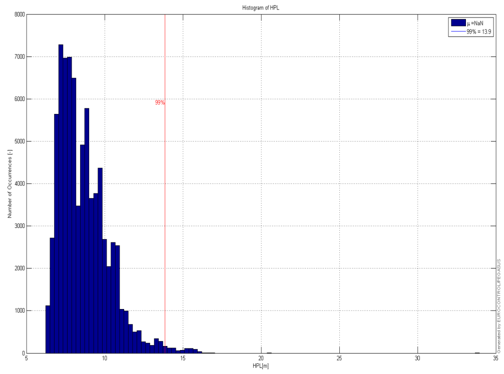

Figure B.20: HPL distribution (032)

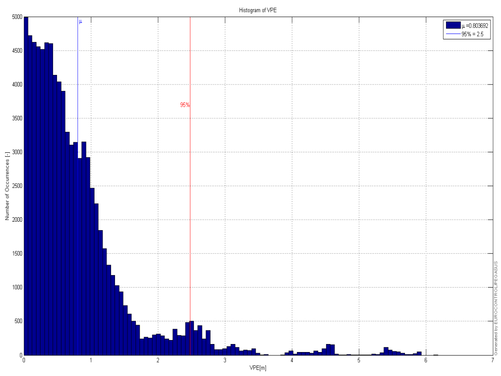

Figure B.21: VPE distribution (032)

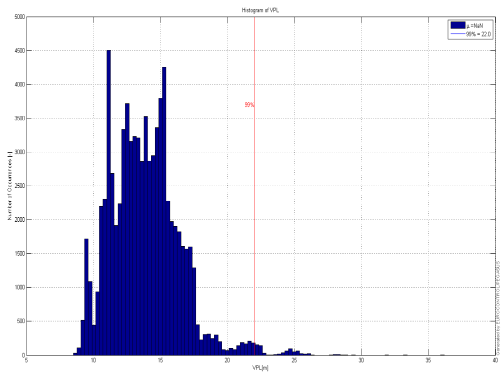

Figure B.22: VPL distribution (032)

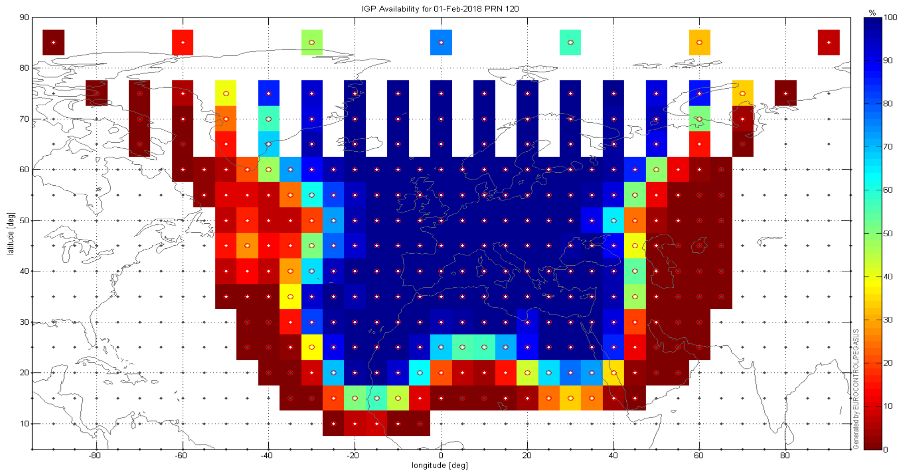

Figure B.23: Availability map PRN 120 (032)

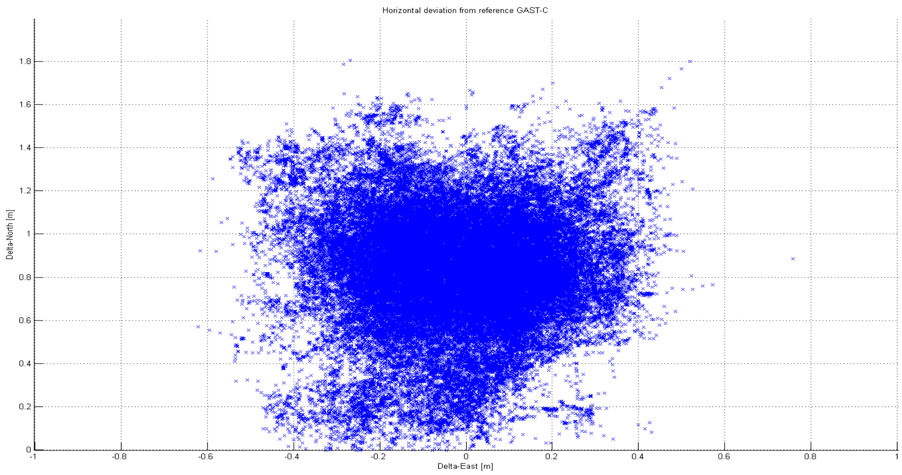

Figure B.24: North-East deviation statistics (032)

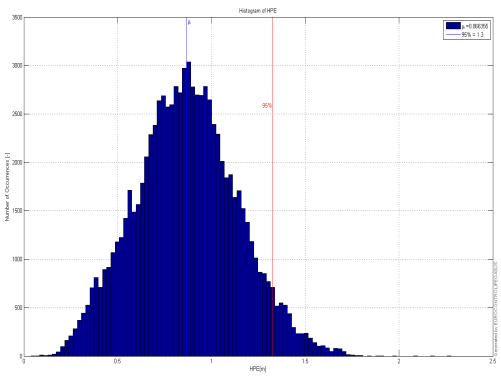

Figure B.25: HPE distribution (033)

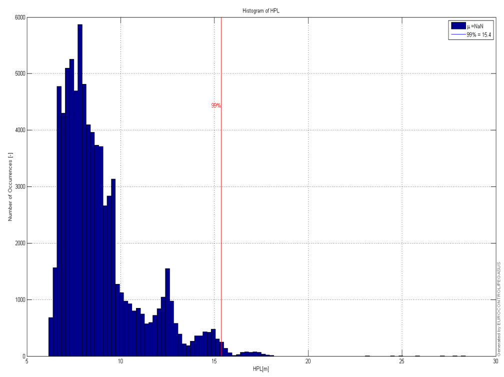

Figure B.26: HPL distribution (033)

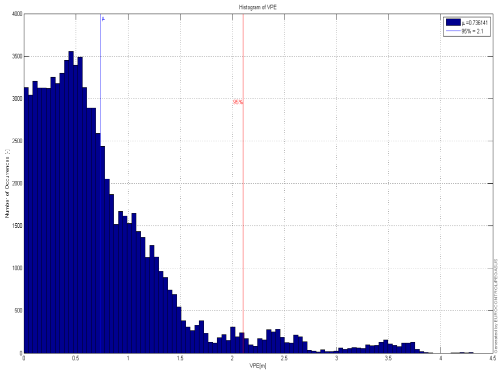

Figure B.27: VPE distribution (033)

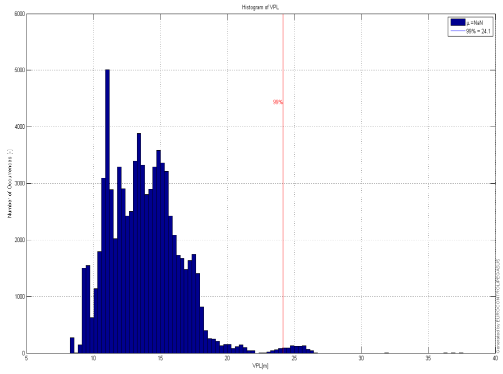

Figure B.28: VPL distribution (033)

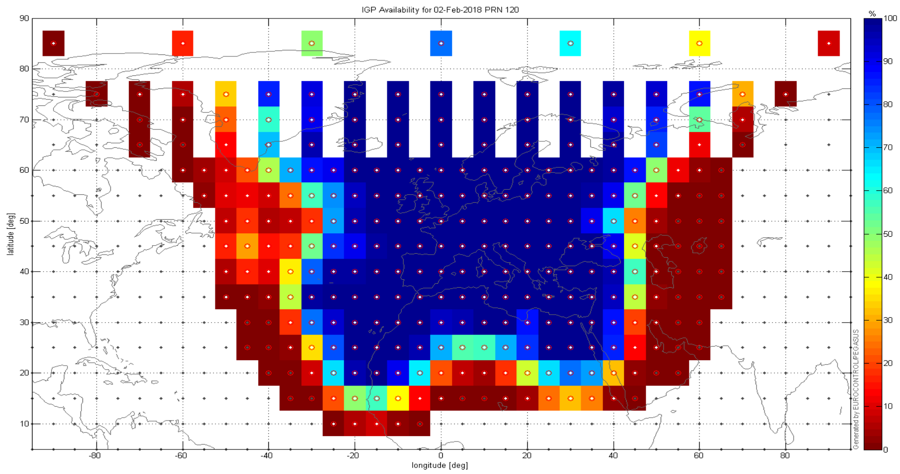

Figure B.29: Availability map PRN 120 (033)

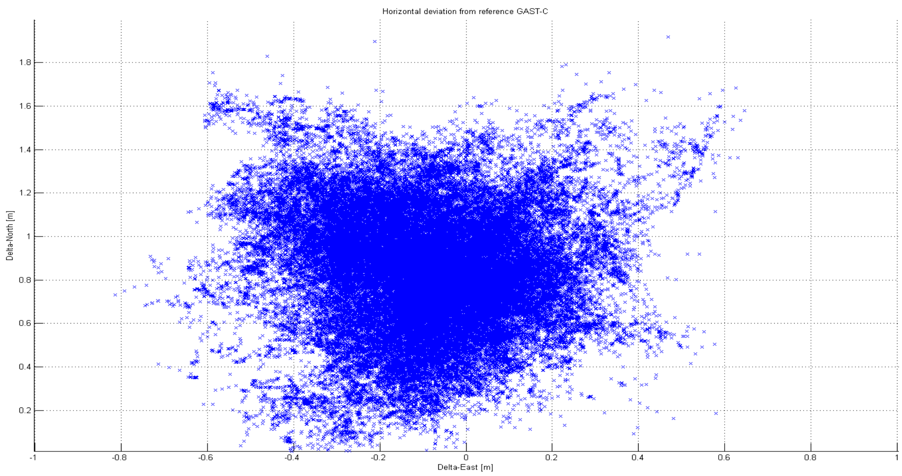

Figure B.30: North-East deviation statistics (033)