Universidad Politécnica de Madrid
Escuela Técnica Superior de Ingenieros de Telecomunicación

CHARACTERIZATION OF THE SATELLITE DATA LINK FOR AIR TRAFFIC MANAGEMENT SYSTEMS

TRABAJO FIN DE MÁSTER

Gustavo Ambrosio Vicente

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Ingeniería de Redes y Servicios Telemáticos

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Resumen

El Trabajo Fin de Máster (TFM) se engloba dentro del área de Diseño de Redes de Comunicaciones por Satélite, aplicado al dominio de la Gestión del Tráfico Aéreo (ATM – "Air Traffic Management").

Los sistemas tradicionales de comunicaciones por satélite utilizan satélites de órbita geoestacionaria (GEO) que actúan como repetidores entre dos puntos de comunicación ubicados sobre la Tierra. En el ámbito de la gestión del tráfico aéreo, los sistemas de comunicaciones por satélite establecen un enlace de comunicaciones entre los aviones en ruta y las estaciones de control en tierra. En las rutas continentales, el avión suele utilizar los sistemas de comunicación terrestres. Pero en las rutas oceánicas, el satélite es la única solución para mantener el enlace de comunicaciones entre el avión y la estación de control en tierra.

Para dar cabida al incremento de la demanda de tráfico aéreo prevista para la próxima década, las instituciones europeas han puesto en marcha varios programas de investigación que tienen como objetivo modernizar la infraestructura de gestión del tráfico aéreo (ATM), teniendo en cuenta los tres pilares básicos del sistema: Comunicaciones, Navegación y Vigilancia (CNS). El satélite juega un papel importante en la renovación de los sistemas de ATM/CNS, mejorando la cobertura y las prestaciones de los sistemas terrestres convencionales: GPS y Galileo reemplazarán algún día los sistemas de radio-ayuda en navegación, los enlaces por satélite servirán como complemento a las comunicaciones aire-tierra entre piloto y estación de control, y los sistemas de vigilancia por radar serán mejorados con nuevos sistemas con tecnología ADS-B (Automatic Dependent Surveillance Broadcast) por satélite.

Este trabajo pretende contribuir al diseño de los nuevos sistemas por satélite que se están planteando para modernizar la infraestructura de gestión del tráfico aéreo, centrándonos en las ramas de Comunicaciones y Vigilancia. El trabajo se centra en la caracterización de los enlaces de comunicaciones de datos por satélite, con especial énfasis en el análisis del ancho de banda (Data Rate) de los distintos enlaces de comunicaciones. El ancho de banda es un parámetro importante para el diseño de la red de comunicaciones por satélite, ya que tiene un impacto directo en el análisis de los balances de enlace, y por extensión en el diseño de la carga útil del satélite y el diseño del segmento de tierra.

El ancho de banda requerido en los enlaces de comunicaciones depende del nivel de calidad de servicio para el que se diseña el sistema (caudal, retardo, disponibilidad, etc). En el trabajo la estimación del ancho de banda requerido se realiza con el objetivo de garantizar un alto nivel de disponibilidad del servicio. La estimación del ancho de banda se basa en la estimación de la cantidad de datos intercambiados entre los aviones y el sistema de control en tierra, teniendo en cuenta los distintos servicios de ATM (comunicaciones, vigilancia, etc). Existe una incertidumbre en el cálculo de esta cantidad de datos, que se debe a la variabilidad del tráfico aéreo: el número de aviones en el espacio aéreo cambia con el tiempo y según la región del espacio aéreo, así como el número de mensajes intercambiados entre un avión y el sistema de control en tierra. Como consecuencia, es necesario definir una distribución de probabilidad que tenga en cuenta esta incertidumbre para la estimación del ancho de banda.

En este trabajo se presenta un nuevo modelo estadístico para estimar el ancho de banda de los enlaces de comunicaciones por satélite ("Data Rate", en bps), modelando la cantidad de datos intercambiada entre un conjunto de aviones y el sistema de control en tierra, dada una región del espacio aéreo y un determinado intervalo de tiempo. El modelo tiene en cuenta dos variables: el número de aviones en una determinada región del espacio aéreo y el número de mensajes intercambiados entre cada avión y el sistema de control en tierra.

El trabajo introduce dos casos de estudio representativos para evaluar el modelo estadístico del ancho de banda. El primer caso de estudio es un sistema de comunicaciones ATM con un satélite GEO, basado en el programa Iris de la ESA. El segundo caso de estudio es un sistema de vigilancia del tráfico aéreo con satélites LEO, basado en la misión Proba-V de la ESA. En ambos casos de estudio, el uso del satélite tiene como objetivo mejorar la cobertura de las comunicaciones aeronáuticas en las rutas oceánicas.

Los casos de estudio se utilizan como referencia para aplicar el modelo propuesto en el trabajo de cara a estimar el ancho de banda de un determinado servicio. Para cada caso de estudio, se identifica un servicio de gestión del tráfico aéreo: en el caso del sistema Iris se analiza el servicio de comunicaciones "Air Traffic Control Clearance" (ACL) mientras que en el caso del sistema Proba-V se analiza el servicio de vigilancia "Surveillance" (SURV) basado en tecnología ADS-B. En el trabajo se estima el ancho de banda requerido para los servicios analizados (ACL, SURV), teniendo en cuenta los enlaces de comunicaciones vía satélite entre los aviones y las estaciones de tierra.

Los resultados del análisis con los casos de estudio son satisfactorios, pero están condicionados a que los supuestos del modelo sean válidos. El principal supuesto es utilizar la distribución de Poisson para representar las variables del modelo (número de aviones, número de mensajes). Este supuesto se justifica con base a las referencias encontradas en la literatura, dentro del ámbito estadístico y también del dominio de la gestión del tráfico aéreo. Como parte de trabajos futuros, se podría realizar la

validación del modelo, utilizando un conjunto de datos reales con los que poder contrastar los resultados.

El modelo estadístico propuesto en este trabajo podría tener varias aplicaciones y se podría explotar dentro del ámbito de ATM. Por ejemplo, se podría utilizar el modelo para desarrollar una herramienta de diseño en el contexto de las nuevas redes de comunicaciones de los sistemas de ATM, con el objetivo de estimar el ancho de banda requerido en los enlaces de comunicaciones teniendo en cuenta un nivel determinado de la densidad del tráfico aéreo.

Abstract

This master thesis belongs to the area of Satellite Communications Network Design, in the scope of the Air Traffic Management (ATM) domain. The traditional satellite communications systems are based on geostationary orbit (GEO) satellites that act as a data relay between two points located in the Earth. In the ATM scenario, a satellite communications system enables the communication between the aircrafts and the ground control stations in the Earth. When flying over continental areas, the aircraft usually communicates with the ground stations using terrestrial datalinks. But in the oceanic routes, the satellite is the only solution to keep the communication link between the aircraft and the ground control station.

In order to address the expected increase of Air Traffic demand in the next decade, the European aeronautical stakeholders are investing a lot of R&D effort towards the modernization of the current Air Traffic Management (ATM) system, taking into account the three main pillars of the system: Communication, Navigation and Surveillance (CNS). The satellite plays an important role in the renovation of the ATM/CNS systems, improving the coverage and performance of the conventional terrestrial systems: GPS and Galileo will replace radio navigation aids, new satellite links will complement the existing air-ground terrestrial links for control-pilot communications, and the traditional radar systems will be enhanced by advanced ADS-B systems (Automatic Dependent Surveillance Broadcast) with satellite technology.

This thesis aims to contribute to the design of the new satellite-based systems that are envisaged for the modernization of the Air Traffic Management infrastructure, focusing on the Communications and Surveillance branches. The thesis addresses the characterization of the satellite datalinks, focusing on the analysis of the data rate for the different communication links. The data rate is an important driver for the design of satellite communication networks, since it has a direct impact in the link budget analysis, the communications payload sizing process and the ground segment design.

The required data rate in the communication datalinks depends on the level of quality of service that is desired for the system (throughput, delay, availability, etc). In this work, the estimation of the required data rate is performed in order to guarantee a high level of service availability. The estimation of the data rate is based on the estimation of the amount of data that is exchanged between the aircrafts and the ground control system. There is an uncertainty in the computation of this data amount, due to air traffic variability: the number of aircrafts in the airspace changes in time and

depends on the airspace region, as well as the number of messages exchanged between an aircraft and the ground control system. As a result, a probability distribution is required to deal with this uncertainty in the estimation of the data rate.

This thesis aims to define a new statistical model for the estimation of the data rate of satellite communications datalinks, modeling the amount of data exchanged between a set of aircrafts and the ground control system, given a certain airspace domain and a specific time interval. The model takes into account two variables: the number of aircrafts in a certain airspace volume, and the number of messages exchanged between each aircraft and the ground control system in the scope of a certain aeronautical service.

The thesis introduces two representative case studies for the evaluation of the data rate statistical model. The first case study is an ATM communications system with a GEO satellite, taking as a reference the ESA Iris Programme. The second case study is a space-based ADS-B surveillance system with LEO satellites, based on the ESA Proba-V experimental mission. In both use cases, the satellite is used in order to improve the coverage of aeronautical communications in the oceanic, remote and polar areas. The evaluation of the data rate model is performed through a set of data loading analyses in which the model is applied to the two different case studies. For each case study, an Air Traffic Management service is identified: the "Air Traffic Control Clearance" service (ACL) is analyzed in the scope of the first case study (ESA Iris Programme) while the ADS-B Surveillance service (SURV) is analyzed in the frame of the second case study (ESA Proba-V mission). As a result of the application of the model, the required data rate is estimated for each of the analyzed services (ACL, SURV), taking into account the satellite communication datalinks between the aircrafts and the ground control stations.

The achieved results with the case studies analysis are satisfactory, but they are conditioned to the validity of the statistical model assumptions. The main model assumption is that the Poisson distribution is good enough for analyzing air traffic data. We support this assumption by theoretical and empirical basis found in both statistical and air traffic management literature. To validate the model, a real sample dataset of air traffic would be required, and to get such dataset is considered as part of future developments of this work.

The statistical model proposed in this thesis could have several applications and could be exploited in the ATM domain. For instance, the proposed model could be applied to develop a design tool for future ATM communication networks, providing the estimation of the required data rate of the communications links taking into account a certain level of air traffic density.

About the author

Gustavo Ambrosio holds a MSc degree in Telecommunication Engineering (2007) and a postgraduate Master in Space Technology (2009) by Universidad Politécnica de Madrid (UPM).

He has expertise in R&D with involvement in several projects within the aerospace sector both at national level (CENIT, Avanza) and European level (ESA, FP7, Artemis).

He has worked at the company Integrasys from 2007 to 2012 as a R&D Software Engineer, participating in several research projects in the scope of Air Traffic Management (ATM) and leading the development of the "System Wide Information Management" (SWIM) system.

Since 2012 he is working in Thales Alenia Space (Deutschland) as a Space Software Engineer, being involved in a research project from ESA in the scope of space-based Air Traffic Surveillance with ADS-B technology.

The motivation for this master thesis arises from his current work in Thales Alenia Space, as a result from the involvement in the ESA project which aims to develop an innovative satellite payload that will demonstrate the reception of ADS-B aircraft signals from space. This project belongs to a recent European initiative which is pursuing to develop a full LEO satellite constellation that would provide Air Traffic Surveillance with worldwide coverage, with particular emphasis on oceanic regions. This new satellite system will need to deliver in real-time a high amount of surveillance data to the ground segment. Therefore a careful analysis will be required for the design of the satellite communication datalinks, selecting an appropriate data rate for the desired quality of service.

This master thesis addresses the characterization of the satellite datalink focusing on the analysis of the data rate, proposing a generic approach that can be applied to several ATM systems. The referred project in the scope of Air Traffic Surveillance is considered as one of the case studies for the master thesis.

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Definitions

This section includes a summary of the definitions and acronyms that are relevant for the understandability of the document. Hereinafter we summarize the relevant definitions.

Aeronautical Services

Within the different flight stages (take-off, cruise, landing), a global set of aeronautical services need to be provided to the aircraft in collaboration with communication peers in ground stations:

- Air Traffic Services (ATS) deal with communication between the cockpit and the controller on the ground for Air Traffic Control (ATC) safety applications.
- Airline Operational Communications (AOC) deal with safety services provided by the airline such flight information, fuel reports, etc
- Aeronautical Passenger Communications (APC) deal mainly with onboard non-safety entertainment applications for passengers.
- Airline Administrative Communications (AAC) deal with messaging non-safety services provided by the airline such as onboard catering, baggage claim, etc.

Airspace Domains

According to [9], the airspace is partitioned into five Airspace Domains:

- Airport (APT): The APT domain consists of an area 10 miles in diameter and up to ~5000 ft consisting of the airport surface and immediate vicinity of the airport.
- Terminal Manoeuvring Area (TMA): The TMA domain consists of the airspace surrounding an airport, typically starting at ~5000 ft up to ~FL245, that is the transition airspace used by Air Traffic Control (ATC) to merge and space aircraft for landing or for entrance into the En-route domain. The TMA domain typically radiates out ~50 nautical miles (NM) from the centre of an airport.
- En Route (ENR): The ENR domain consists of the airspace that surrounds the TMA domain starting at ~FL245 to ~FL600 and is the continental or domestic airspace used by ATC for the cruise portion of the flight.
- Oceanic, Remote, Polar (ORP): The ORP domain is the same as the ENR domain, except that it is associated with geographical areas generally outside of domestic airspace.
- Autonomous Operations Area (AOA): The AOA domain is a defined block of airspace which is associated with autonomous operations where aircraft self-separate (i.e., Air Traffic Control is not used).

Airspace Volumes

According to [9], each Airspace Domain can be partitioned in several Airspace Volumes which are referred to as “Operational Volumes”. An operational volume is a defined operational area in which ATM services are provided.

Eurocontrol [9] defines two types of operational volumes: Service Volumes (SV) and Transmission Volumes (TV):

- Service Volume (SV): A volume of airspace that aligns with ATC sector/position control boundaries. For all domains except the APT, it is a volume of airspace in which all aircraft are controlled by a single Controller position. For the APT, the service volume encompasses all APT airspace sectors/positions in the domain. Service volumes provide the operational context for addressed services such as controller-pilot communication.

- Transmission Volume (TV): A volume of airspace that is based on range or distance. Transmission volumes are most applicable for broadcast services, because broadcasted services reach all users within the range of the broadcast.

Acronyms

The table below summarizes the relevant acronyms for this document.

Acronym	**Description**
AAC	Airline Administrative Communications
ACARS	Aircraft Communications Addressing and Reporting System
ACAS	Airborne collision avoidance system
A-CDMA	Asynchronous Code division multiple access
ACL	ATC Clearance Service
ADS-B	Automatic Dependent Surveillance Broadcast
ADS-C	Automatic Dependent Surveillance Contract
A/G	Air / Ground
AMSS	Aeronautical Mobile Satellite Service
AOA	Autonomous Operations Area
AOC	Airline Operational Communications
APC	Aeronautical Passenger Communications
ATC	Air Traffic Control
ATM	Air Traffic Management
ATN	Aeronautical Telecommunication Network
ATS	Air Traffic Services
APT	Airport Area

CNS	Communication, Navigation and Surveillance
CPDLC	Controller-Pilot Data Link Communication
DME	Distance Measuring Equipment
ENR	En-Route Area
ESA	European Space Agency
FANS	Future Air Navigation System
FL	Flight Level
FRS	Future Radio System
FT	Feet (Unit of length)
GEO	Geo Stationary Orbit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HF	High Frequency
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IP	Internet Protocol
ISL	Inter Satellite Link
ISO	International Organization for Standardization
LEO	Low Earth Orbit
MF-TDMA	Multi-Frequency, Time Division Multiple Access
MLS	Microwave Landing System
NDB	Non-Directional Beacon
NM	Nautical Miles
NRA	Non Radar Airspace
ORP	Oceanic Remote and Polar Areas
OSI	Open Systems Interconnection model

PIAC	Peak Instantaneous Aircraft Count
PSK	Phase Shift Keying
PSR	Primary Surveillance Radar
RA	Radar Airspace
R&D	Research and Development
SATCOM	Satellite Communications System
SSR	Secondary Surveillance Radar
SURV	Surveillance Service
SWIM	System Wide Information Management
SV	Service Volume
TMA	Terminal Maneuvering Area
TTC	Telemetry, Tracking and Command
TV	Transmission Volume
VDL	VHF Data Link
VHF	Very High Frequency
VOR	VHF Omni directional Range

Table 1. Acronyms

1 Introduction

1.1 Motivation and context

The Aeronautical community expects a notable increase of Air Traffic demand on European skies within the next decade. In order to address such expected increase, the European aeronautical stakeholders are investing a lot of R&D effort towards the modernization of the current Air Traffic Management (ATM) system. In this context, the core R&D Programme at European level is SESAR, the Single European Sky ATM Research initiative [23], with the participation of Eurocontrol, Air Traffic Regulators and Aeronautical industry at European level.

The Space community is also committed to the modernization of the ATM system with the involvement in several R&D projects such as the ESA Iris Programme [16] and the space-based ADS-B Programme [24], aiming to develop new satellite-based systems for the future SESAR ATM infrastructure.

In order to achieve this modernization, it is necessary to address the three main pillars of the ATM infrastructure: Communication, Navigation and Surveillance (CNS). Traditionally, the operation of CNS aeronautical systems relies on terrestrial based technologies. The satellite technology has been recently introduced and it will play a very important role in the modernization of the CNS/ATM infrastructure: GPS and Galileo will replace conventional radio navigation aids, Air-Ground communications and surveillance services will rely on a satellite datalink, etc.

Table 2 includes an overview of terrestrial and satellite-based technologies used in CNS systems.

The modernization of Air Traffic Management (ATM) system will lead to a new radio system that will combine both terrestrial-based and satellite-based solutions. This new system is referred by Eurocontrol [9] as the "Future Radio System" (FRS).

The new FRS includes several improvements such as (1) the adoption of datalinks instead of analog voice channels for Air/Ground communications, (2) the adoption of ADS-B technologies instead of traditional radar for surveillance procedures and (3) the introduction of the SWIM platform (System Wide Information Management) in order to handle information exchange among ATM actors. In general, the adoption of these new technologies will lead to the automation of ATM procedures, resulting in a reduction of Air Traffic Controller load.

	Terrestrial-based Technologies	**Satellite-based Technologies**
Communications	VHF, HF (Voice); ACARS VDL (Data) ATN/CPDLC, AMSS, Mode-S	Satcom FANS 1/A: CPDLC **Satcom Iris (FRS)**
Navigation	Conventional Radio Navigation Aids VOR/DME; NDB; ILS; MLS	GPS, Galileo and Augmentations (GNSS)
Surveillance	Primary and Secondary Radar (PSR, SSR) ADS-B and Multilateration Airborne ACAS	Satcom FANS 1/A: ADS-C **Space-based ADS-B (FRS)**

Table 2. CNS Systems with Terrestrial and Satellite technologies

Furthermore, the FRS will include the modernization of the Aeronautical Telecommunication Networks (ATN), where there are many technical challenges to be addressed such as (1) the introduction of a new network topology including ground and onboard aircraft sub-networks, (2) the adoption of new protocols leading to an IPv6-based architecture, (3) the analysis of bandwidth requirements for aeronautical services and (4) the analysis of Mobility Management strategies for the aircraft. These issues need to be standardized at European level by international organisms including Eurocontrol and the International Civil Aviation Organization (ICAO).

In the scope of this thesis, we will focus on the analysis of bandwidth requirements for aeronautical services within the FRS. The goal is to assess the data amount generated by ATM/CNS aeronautical systems, particularly by the Communication and Surveillance branches of the ATM infrastructure, in order to estimate the required bandwidth that must be provided by the Future Radio System (Data Loading Analysis). Referring back to the Table 2, our analysis will focus on two particular use cases in the scope of the FRS satellite-based solutions: the Satcom Iris system and the space-based ADS-B infrastructure.

1.2 Purpose and Scope

This master thesis belongs in general to the area of Networks Design and in particular to the area of Satellite Communications Networks.

The design of satellite-based communication system is defined by the geometry between the satellite and the ground station (GEO, LEO, etc) and the function of the system (TTC, Data Collection, Data Relay). The design process starts with the definition of the different communication datalinks (uplink, downlink, etc) and continues with the calculation of the data rate for each link. The next step is to perform the link design (link budget calculation for each link). Finally, the communications payload sizing process is addressed (TTC subsystem design) [1].

The Data Rate is thus a very important parameter for the design of Satellite Communication Networks, since it has a direct impact in the design of the communication links (Link Budget Analysis) and the communications payload sizing process.

This thesis aims to contribute to the design of the Future ATM Radio System (FRS) introducing a new statistical model for the estimation of the Data Rate in the communication datalinks. The model takes into account the number of aircrafts in a certain airspace volume, and the number of messages exchanged between the Aircraft and Ground ATM system in the scope of a certain aeronautical service.

The Data Rate model will be evaluated in two representative satellite-based system architectures in the scope of the Future ATM Radio System (FRS):

a. Case Study 1: a Satellite Communications System, taking as a reference the ESA Iris Programme [16]

b. Case Study 2: a Space-based ADS-B Surveillance System, taking as a reference the ESA Proba-V experimental mission [17]

As a result of the model evaluation, the Data Rate will be derived for both case studies, taking into account (a) the fixed communications datalink from Satellite to Ground Earth station (downlink), (b) the data communication profile of a certain ATS service in each case study and (c) the amount of air traffic estimated in the ORP regions.

1.2.1 Case Study 1: satellite communications system

A typical satellite communications system is based on GEO satellites that act as a data relay, enabling the communications between two points in the Earth through the satellite links (uplink, downlink). In the ATM scenario, a Satcom System enables the communication between the aircraft and a ground earth station in order to exchange information about the flight. The satellite is the only solution to cover the ATM communications in oceanic, remote and polar areas (ORP).

Nowadays, there is an operative Satcom system for ATM which is referred to as "FANS 1/A", providing Control-Pilot Data Link Communications (CPDLC) for several aeronautical services (ATS/AOC).

The first case study of the thesis is based on the Satcom system proposed by the ESA Iris Programme. This R&D Programme aims to define a new architecture for the A/G communication datalink, leveraging from the existing terrestrial network, and proposing a new satellite communication system (SATCOM) in the scope of the Continental Airspace (ENR/TMA) and Oceanic, Remote and Polar areas (ORP). The Iris project proposes using GEO satellites as a data relay for the ATS/AOC aeronautical services. Figure 1 depicts the general ATM scenario addressed in the scope of the ESA Iris Programme.

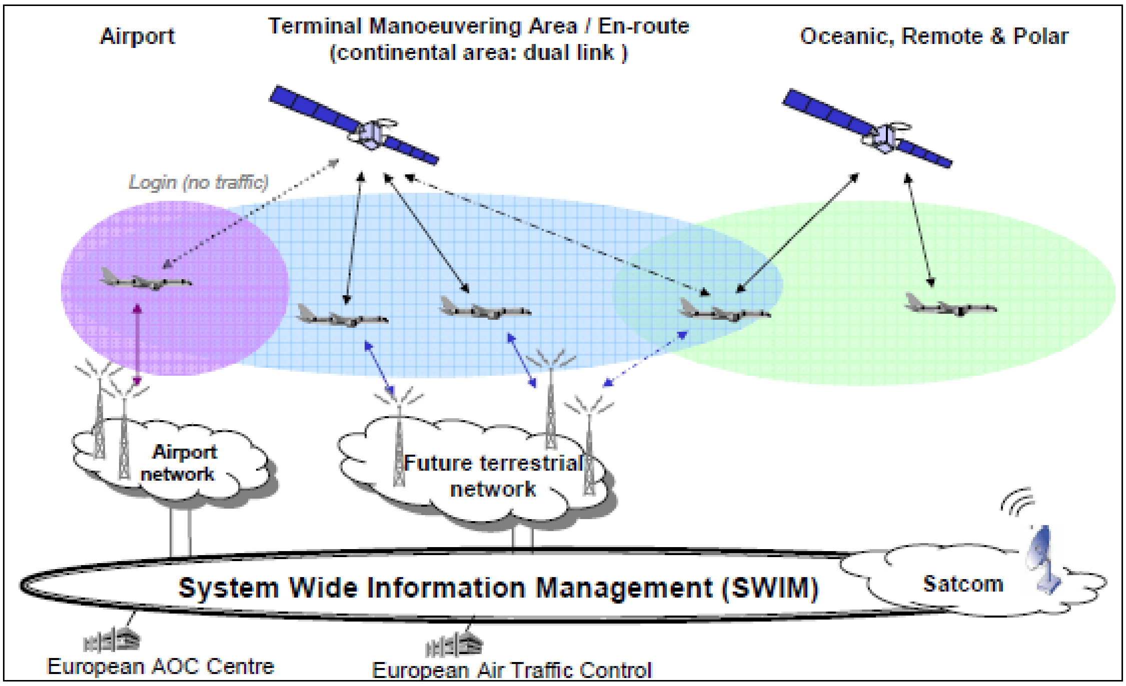

Figure 1. ATM future scenario proposed by ESA Iris [16]

The Satcom Iris system will serve as reference architecture to evaluate the Data Rate model which is derived in this thesis. The Data Rate will be estimated taking into account the following scope:

a. Characterization of the fixed communications datalink from Satellite to Ground Earth station (downlink part)

b. Analysis of the communication traffic profile of a single Air/Ground ATS Service: the Air Traffic Control Clearance Service (ACL).

c. Air Traffic estimation in the ORP airspace domain

1.2.2 Case Study 2: space-based surveillance system

Nowadays, air traffic surveillance is primarily performed using conventional radar systems, combined with a more recent technology which is referred to as ADS-B (Automatic Dependent Surveillance Broadcast). These systems cover the terrestrial areas which are referred to as radar airspaces (RA). For the non-radar airspaces (NRA) like the oceanic areas, it is needed to use satellite-based systems in order to be able to get information about the position of the aircrafts.

Currently, there is only one operative service in oceanic areas which is known as ADS-C (Automatic Dependent Surveillance Contract). This service is supported by the Satcom FANS 1/A system, and it provides aircraft position reports roughly every 10 minutes when the aircraft flies over the ocean.

A new space-based surveillance system is currently under development in order to overcome the limitations of the ADS-C existing system, aiming to provide aircraft position reports with an update rate of 5 to 10 seconds. This new system is based on ADS-B technology and it is planned to be developed both in the USA [14] and in Europe [24].

ESA has already an experimental mission referred to as Proba-V[17], in which an ADS-B Payload is being used as a starting point for the proof of concept of the new space-based surveillance system. Figure 2 depicts an image published by ESA with the first ADS-B aircraft data captured by the Proba-V payload.

The second case study of this thesis is based on the ESA Proba-V experimental mission. In this case, the Proba-V ADS-B system will serve as reference architecture to evaluate the Data Rate model which is derived in this thesis. Unlike in the first case study where we were dealing with GEO Data Relay satellites, in this second case study we have a typical Data Collection architecture with LEO satellites.

In the second case study, the Data Rate estimation will be addressed taking into account the following scope:

a. Characterization of the fixed communications datalink from Satellite to Ground Earth station (downlink part)

b. Analysis of the communication traffic profile of a single Air/Ground ATS Service: Surveillance Service (SURV) based on ADS-B technology

c. Air Traffic estimation in the ORP airspace domain

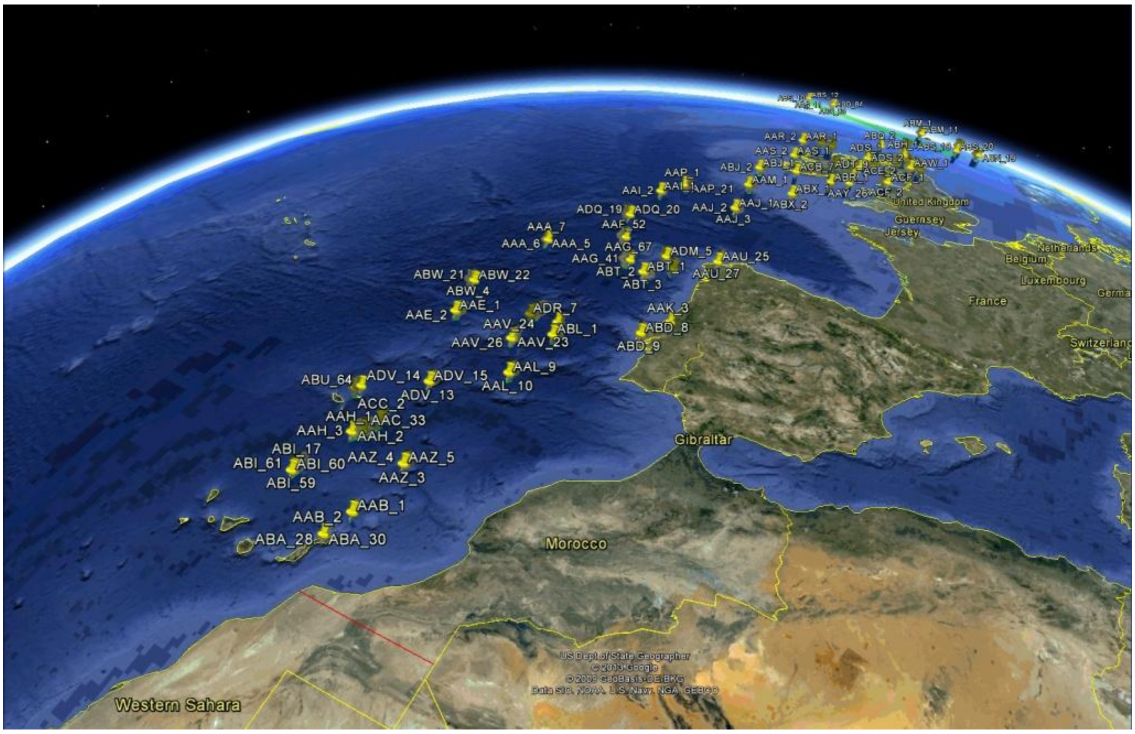

Figure 2. Proba-V ADS-B aircraft detection in Europe [18]

Image published by ESA[18]. Copyright DLR/SES TechCom. An experimental receiver on ESA's Proba-V satellite pinpointing the location of aircraft in flight over the Atlantic approach to western Europe and the UK through their ADS-B signals. Automatic Dependent Broadcast – Surveillance (ADS-B) signals are regularly broadcast from equipped aircraft, giving flight information such as speed, position and altitude. On 23 May this DLR-contributed experiment was switched on for the first time, recording over 12000 ADS-B messages within two hours at an altitude of 820 km.

1.3 Organization of the TFM

This section introduces the organization of the master thesis with the description of the scope of the different chapters.

Chapter 2 introduces the two reference case studies to be analyzed in the scope of the characterization of the satellite datalinks within the Future ATM Radio System: the satellite communications system proposed by the ESA Iris Programme, and the space-based ADS-B surveillance system driven by the ESA Proba-V experimental mission. The architecture of both systems will be presented together with the data rate analysis for the communications links.

Chapter 3 presents the statistical methodology that leads to a Data Rate model as a contribution to the satellite datalinks characterization. The Data Rate model is applied to the two case studies under analysis: the satellite communications system and the space-based surveillance system.

Chapter 4 presents the conclusions of the thesis and introduces some guidelines to develop future work in the scope of the characterization of satellite datalinks for ATM/CNS systems.

2 Data Link Characterization for the Future ATM Radio System

This chapter presents the general strategy to design a satellite communications architecture (section 2.1) and then introduces the two use cases to be analyzed in the thesis: the satellite communications system proposed by the ESA Iris Programme (section 2.2) and the space-based ADS-B surveillance system driven by the ESA Proba-V experimental mission (section 2.3).

2.1 Design process

This section describes the strategy to design a satellite communications architecture according to the general process presented in the book "Space Mission Analysis and Design " (Chapter 13, [1]) .

A communications architecture is defined as a network of satellites and ground stations interconnected by communications links, where the term ground station is equivalent to an Earth terminal which includes land, airborne and ship-borne terminals. The ground station to satellite link is the forward link, and the satellite to ground station link is the return link.

Figure 3 below depicts the general approach for the design workflow of a satellite communications architecture.

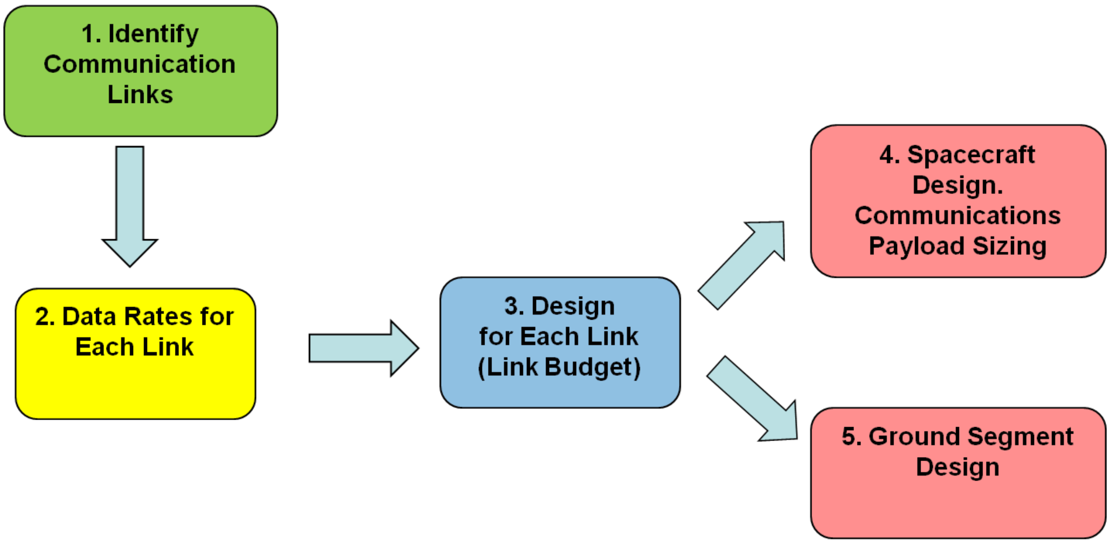

Figure 3. Communications Architecture Design Process

The first step in the design process (Step 1 in Figure 3) is to identify the communication links in the system architecture. The number of communication links depends on the selected architecture type, which can be classified according the following criteria:

a. Architecture defined based on the geometry formed between satellite orbits and ground stations, leading to different architectures such as Geostationary orbits (GEO) and Low altitude orbits (LEO).

b. Architecture defined based on the function performed by the satellite, which can be Data Collection, Data Relay or TTC (Tracking, Telemetry and Telecommand). In the Data Collection function, the satellite acts as an earth observation sensor collecting data and sending it to the ground station. In the Data Relay function, the satellites forward data originating on ground (or in another satellite) to the ground station.

Once the communication links have been identified, the next step is to determine the Data Rate for each communication link (Step 2 in Figure 3). The Data Rate is proportional to the quantity of information per unit time transferred between satellite and ground station. It is measured in bits per second (bps). The Data Rate is an input parameter for the link design, driving the payload sizing process: the higher the data rate, the larger the transmitter power and antenna size will be required.

The next step is to perform the design of each communications link, once the data rate is known (Step 3 in Figure 3). This step involves the selection of the frequency band, the selection of the modulation and coding scheme, and the calculation of the link budget, which is used to compute the required signal-to-noise ratio of the communications system, based on a relationship among data rate, antenna size, propagation path length and transmitter power. The link budget has to be calculated for each link, including forward and return links.

As a result of the links design, we are aware of the satellite transmitter power and antenna aperture size required for the communications system. These parameters have the greatest on the satellite mass, and thus on the cost of the system. This is then the next step in the design, the sizing of the communications payload in terms of mass and power (Step 4 in Figure 3).

Finally, the link design has also an impact in the Ground Segment, which needs to be designed in order to be compliant with the link budget calculations in the Step 3. The design of the Ground System is the Step 5 in Figure 3.

The scope of the current thesis is the analysis of the data rate for satellite communication links. In this section, we have seen that the Data Rate is a very important design driver for the Satellite Communication Payload, since it has a direct influence in the Link Design (Link Budget) determining the required transmitter power and antenna size.

2.2 Case Study 1: satellite communications system

This section describes the architecture of the ESA Iris Satcom system (2.2.1) and introduces the satellite datalink characterization in the scope of the data rate analysis (2.2.2).

2.2.1 Architecture

The standard communication between an air traffic controller and a pilot is voice radio, using either VHF or HF bands. This traditional approach has been recently replaced by Control-Pilot Data Link Communications (CPDLC), a new means of communication between controller and pilot using data link for ATC communication.

Nowadays, the CPDLC is available in continental areas (ENR/TMA) relying on VDL networks for air-ground communications (ATN/CPDLC system). Furthermore, CPDLC is also operative in oceanic routes using the FANS-1/A implementation, which is an ACARS based service that uses satellite communications provided by the Inmarsat (Classic Aero) service.

ESA has launched the Iris Programme in order to improve the current state-of-the-art in Air Traffic Management communications. This ESA program is supported by the SESAR initiative (Single European Sky ATM Research) under the umbrella of the "Advanced Research in Telecommunication Systems" (ARTES) program, having the objective to design, develop, validate and standardize a new satellite-based communication system for the provisioning of ATM safety communications, in accordance with the future ATM concept on the basis of the SESAR requirements.

The Iris system coverage is planned to be worldwide, with special emphasis on the Oceanic and Remote Areas (ORP). In the continental areas (ENR/TMA), the Iris system will be also operative, serving as a complement to the existing terrestrial infrastructure that relies on air-ground datalinks. The concept of a "dual-link" is thus defined for the continental areas, using both terrestrial and satellite datalinks for the ATM communications.

Figure 4 depicts the architecture of the Iris satellite communications system [11]. According to classification described in section 2.1, the architecture has a Data Relay function in which a GEO satellite (Space Segment) enables the communications between the aircrafts (User Segment) and the Ground Segment. Hereinafter we describe in more detail the different segments of the Iris system: Space Segment, Ground Segment and User Segment [11].

The Space Segment (SPS) is composed of a GEO satellite carrying the dedicated ATM payloads operating in L-band for the satellite-to-aircraft mobile link and in Ku-band for the satellite-to-ground fixed link. The on-board ATM payloads are transparent, which means that they are not equipped with On-Board Processing (OBP) capabilities. In the mobile link, the SPS is a multi-beam system, while for the fixed link, a single beam is considered as reference architecture.

The Ground Segment (GS) is mainly composed of the Network Control Centre (NCC), the Ground Earth Station (GES) providing the interface with the SPS, and the Network Management Centre (NMC).

The User Segment is composed of the mobile User Terminals (UTs) or Aeronautical Earth Stations (AES), which are the avionics equipment in charge of implementing the Iris communication protocol, including antenna and transmitter/receiver.

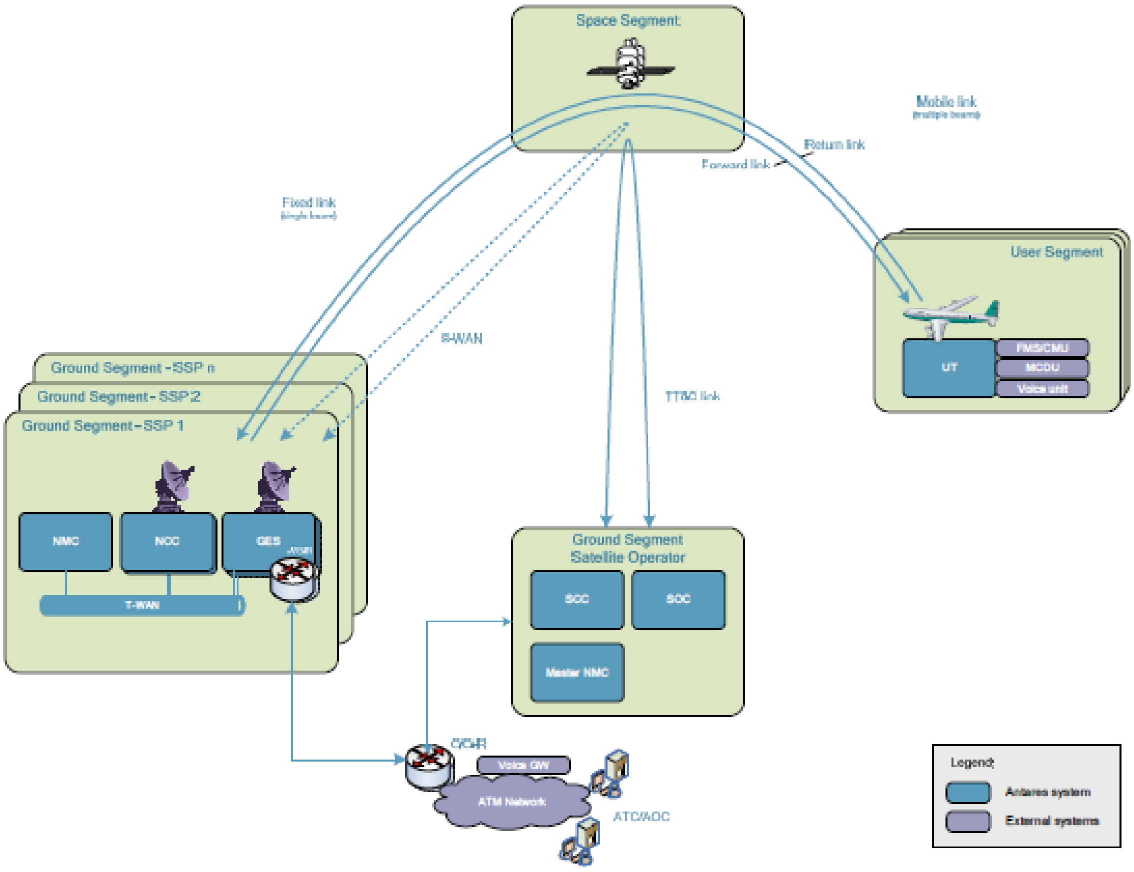

Figure 4. ESA IRIS System Architecture [11]

According to Figure 4, the Iris system from ESA relies on a complex Aeronautical Telecommunications Network (ATN) with the following communication links [11]:

- Forward link: communication link from the Ground Earth Station to aircraft, where:

    - Uplink is the communication link from ground to the satellite
    - Downlink is the communication link from satellite to aircraft
- Return link: communication link from aircraft to Ground Earth Station where:
    - Uplink is the communication link from aircraft to the satellite
    - Downlink is the communication link from satellite to ground
- TTC link: communication link for satellite control by ground operators

The Iris communication standard [12] defines the technologies used in the different communication layers, including the Physical, Link and Network layers.

The Physical layer must be able to counteract the aeronautical channel impairments such as multipath propagation phenomena and Doppler effect and, at the same time, be spectral and energy efficient. On the forward link, linear modulations (QPSK, 8-PSK and 16-APSK) are combined with certain code rates in the LDPC coding family (LDPC: low-density parity-check). On the return link, O-QPSK modulation scheme is combined with Turbo Codes.

In the Link layer, the MF-TDMA multiple access scheme is used in the forward link, while an A-CDMA scheme based on an Enhanced Spread Spectrum ALOHA is proposed for the return link.

In the Network Layer, the current standards for aeronautical networking in the Aeronautical Telecommunication Network (ATN) are based on the ISO OSI networking stack. The International Civil Aviation Organization (ICAO) has recognized that an ATN based on OSI lacks the widespread commercial network support required for the successful deployment of new, more bandwidth-intensive ATN applications, and has recently been working towards a new IP-based version of the ATN [10]. As a result, the Iris Programme keeps both network layer stacks, ATN/IPS and ATN/OSI, allowing co-existence of both stacks in the same system.

2.2.2 Satellite data link characterization

This section describes the satellite datalink characterization of the Satcom ESA Iris system focusing on the analysis of the data rate. The goal is to introduce the Iris scenario that will serve as a basis for the Data Rate model evaluation that is described in Chapter 3 (section 3.3.1).

As it was introduced in section 2.1, the design flow of a satellite communications architecture starts with the identification of the communications links. In the Figure 4 above, we have identified several communication links in the Iris architecture: forward link (uplink/downlink) and return link (uplink/downlink).

The next step in the design is the computation of the data rate of the communication links. In order to determine the data rate, it is necessary to take into account the data communication traffic profile of the different ATM services that need to be provided in the Iris system, considering both ATS and AOC services [9]: Data Communications Management Services, Clearance/Instruction Services, Flight Information Services, Advisory Services, Emergency Services, etc.

In this case study, we will simplify the analysis to a single ATS service which belongs to the Clearance/Instruction group: the "Air Traffic Control Clearance" (ACL) service. This service specifies dialogue exchanges via air-ground addressed communications between Flight Crews and ATC Controllers, dealing with the control of the aircraft flight plan [9]. The ACL service may be initiated by either the ground Automation/Controller or the Avionics/Flight Crew. ACL is available in all flight phases (APT, TMA, ENR, ORP).

The ACL service uses addressed communications relying on a bi-directional communication system: a forward path from the Ground Station to the Aircraft and a return path from the Aircraft to the Ground Station. The ACL service consists of the following types of exchanges:

- Forward Path: ATC clearances, instructions, notifications, and requests
- Return Path: flight crew requests, reports, notifications, and compliance indications

In order to address the computation of the Data Rate required for the ACL service, it is necessary to define a model of the number of aircrafts which are using the service in order to exchange information with the Ground Station. The model used in this case study is the one defined in the COCR [9] for the addressed services: the model estimates the number of aircrafts for each of the different airspace domains (APT, TMA, ENR, ORP), dividing each airspace domain in individual units of observation called "Service Volumes" SVi.

Each Service Volume SVi (1) is a generic airspace volume of a certain domain (APT, TMA, ENR, ORP), in which all aircraft are controlled by a single controller position of the ATC system. The aircrafts in a certain volume SVi are exchanging ATC messages

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[1] "Service Volume" is defined in the section *Definitions,* at the beginning of the document.

with the Ground ATC system via a single transponder within the GEO satellite of the Iris system. It is assumed that the GEO satellite has several communication transponders, and that each transponder is assigned to a single Service Volume of the airspace.

Figure 5 depicts the Satcom Iris scenario for the characterization of the satellite datalinks. In this particular case, only the oceanic and remote areas (ORP) are considered, and we have divided this airspace domain in "N" Service Volumes $[SV_1, SV_2, \ldots SV_i, \ldots SV_N]$. The GEO satellite has several transponders, one per service volume, providing communications in the forward/return links. In principle only the ACL service is considered for the characterization, but the scenario could be generalized to have all the ATS/AOC services.

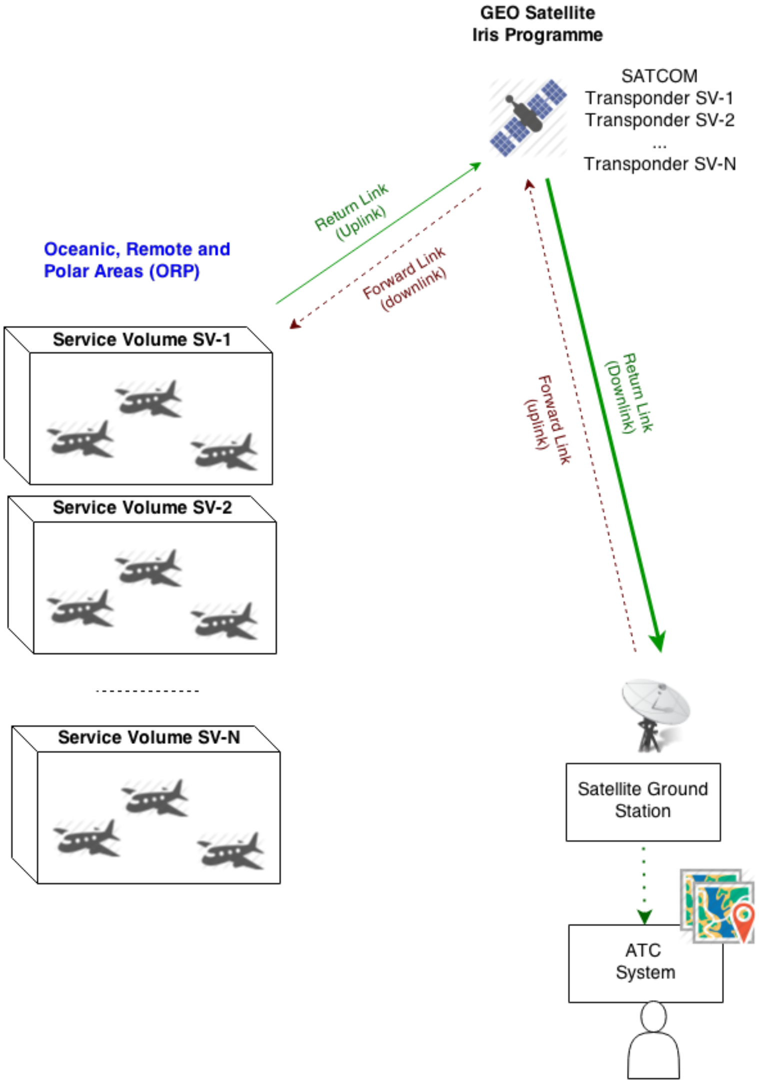

Figure 5. Case Study 1. Satellite Datalink Characterization

The Data Rate computation is performed in this particular case for the fixed downlink in the return path (from satellite to ground). The computation is done at Service Volume level (SVi), using as a reference factors (a) the number of aircrafts in the service volume (ACi), (b) the number of messages transmitted per aircraft (NMsg), (c) the message size (MS in bits) and (d) a time interval (flight duration in seconds). For the ACL service, the deterministic calculation of the data rate for the SVi in the fixed downlink would be:

$$R_{SVi-ACL}(bps) = \frac{AC_i \times NMsg_{ACL} \times MS_{ACL}(bits)}{TimeInterval(\sec)}$$

We could also generalize the computation to a set of ATS/AOC services, for instance a set of "M" services {1, 2, …j, …,M}. In this case the computation of the data rate for a SVi in the fixed downlink would be:

$$R_{SVi}(bps) = \frac{AC_i \times \sum_{j=1}^{M}(NMsg_j \times MS_j)(bits)}{TimeInterval(\sec)}$$

The latter would be the data rate for a single transponder in the GEO satellite. Finally, it could be possible to calculate the total data rate in the fixed downlink accumulating the computations of all the transponders considering all the individual Service Volumes SVi:

$$R_{TOTAL}(bps) = \sum_{i=1}^{N} R_{SVi}$$

In this section we have introduced the characterization of the satellite datalinks for the Satcom Iris system, focusing on the data rate analysis of the fixed downlink from satellite to ground. The next steps in the characterization would be the design of each link (Link Budget) and the communications payload sizing, completing the whole design process described in section 2.1.

The characterization of the Satcom Iris system will be completed in Chapter 3 (section 3.3.1), where we will use statistical methods to estimate the data rate. In this case we will use a simplified scenario with a single Service Volume (SVi) in the ORP domain, focusing on the fixed downlink from the GEO satellite to the Ground Station.

2.3 Case Study 2: space-based surveillance system

This section describes the architecture of the ADS-B satellite system based on the Proba-V mission (2.3.1) and introduces the satellite datalink characterization in the scope of the data rate analysis (2.3.2).

2.3.1 Architecture

Besides the traditional radar systems for surveillance (PSR, SSR), the aim of the current work is to study a more recent technology which is referred to as ADS "Automatic Dependent Surveillance" (ADS). Using this ADS technology, the aircrafts are able to transmit positional information to the Ground Segment for monitoring and surveillance purposes. The information can be provided via broadcast, (i.e., ADS – Broadcast [ADS-B]), or via addressed contracts which require a dialogue between the ATC ground station and the aircraft, (i.e., ADS – Contract [ADS-C]).

In this thesis we will on the ADS-B technology, which is defined according to the following:

- **Automatic**: Periodically transmits information with no pilot or operator input required.
- **Dependent**: Position and velocity are derived from Global Positioning System (GPS) or a Flight Management System (FMS).
- **Surveillance**: A method of determining position of aircraft, vehicles or other assets.
- **Broadcast**: Transmitted information available to anyone with the appropriate receiving equipment.

The ADS-B conventional system consists of two main elements: (1) a ground based receiver and (2) an aircraft transponder/transceiver. The aircraft is able to determine its position based on GPS (*Dependent definition*), and then use the ADS-B transponder to send the corresponding surveillance report to a Ground Station. The Ground Station has an ADS-B receiver that decodes the information and forwards the surveillance reports to the Air Traffic Control (ATC) centre. The ADS-B conventional system relies on a terrestrial data link to enable the communication between the aircraft transponder and the ground-based receiver using the 1090 Mhz frequency band.

Nowadays, the ADS-B service is operational in Airport areas (APT) and in Continental areas, including Terminal Maneuvering Areas (TMA) and En-Route Areas (ENR). In particular, the ADS-B service is operative in Australia, America, Canada and some European countries.

However, the ADS-B service is not operational in Oceanic, Remote and Polar areas (ORP). Figure 6 depicts the coverage of the ADS-B service according to the database Flight-Radar-24 [20], which uses the data from several ground receivers all around the world.

Figure 6. Coverage of terrestrial ADS-B system [20]

In order to cover the gap of the ORP areas, it is necessary to introduce a satellite communications system that will enable worldwide coverage complementing the existing ADS-B terrestrial infrastructure. Currently, the Inmarsat satellite system is providing the ADS-C service in some oceanic regions, relying on the FANS-1/A platform. But the ADS-C service only provides an update of the aircraft position roughly every 10 minutes, and it requires an addressed communication protocol with the Ground ATC system.

In order to overcome the limitations of the ADS-C service, it is envisaged to develop a new satellite system which provides the ADS-B service with continuous availability in oceanic regions and an update rate of around 10 seconds. This is a very innovative solution that is currently under development in the scope of several initiatives in Europe [5, 15, 17, 24] and the USA [6, 8, 14, 22].

From the Air Traffic Management point of view, the capability of global coverage provided by the future ADS-B system, will enable the optimization of dense oceanic routes, resulting in aircraft fuel savings, a reduction in greenhouse gas emissions, and enhanced safety in airspace when ADS-B reporting aircraft can be displayed on a radar screen at an Air Traffic Control Centre.

In Europe, the ESA Proba-V experimental mission is the first initiative in the scope of the development of the future space-based ADS-B system [17]. The Proba-V has a single LEO satellite in Sun-synchronous polar orbit (820 Km altitude), and the main payload is designed to map land cover and vegetation growth across the entire planet. The satellite has a secondary payload with an ADS-B aircraft signal detector.

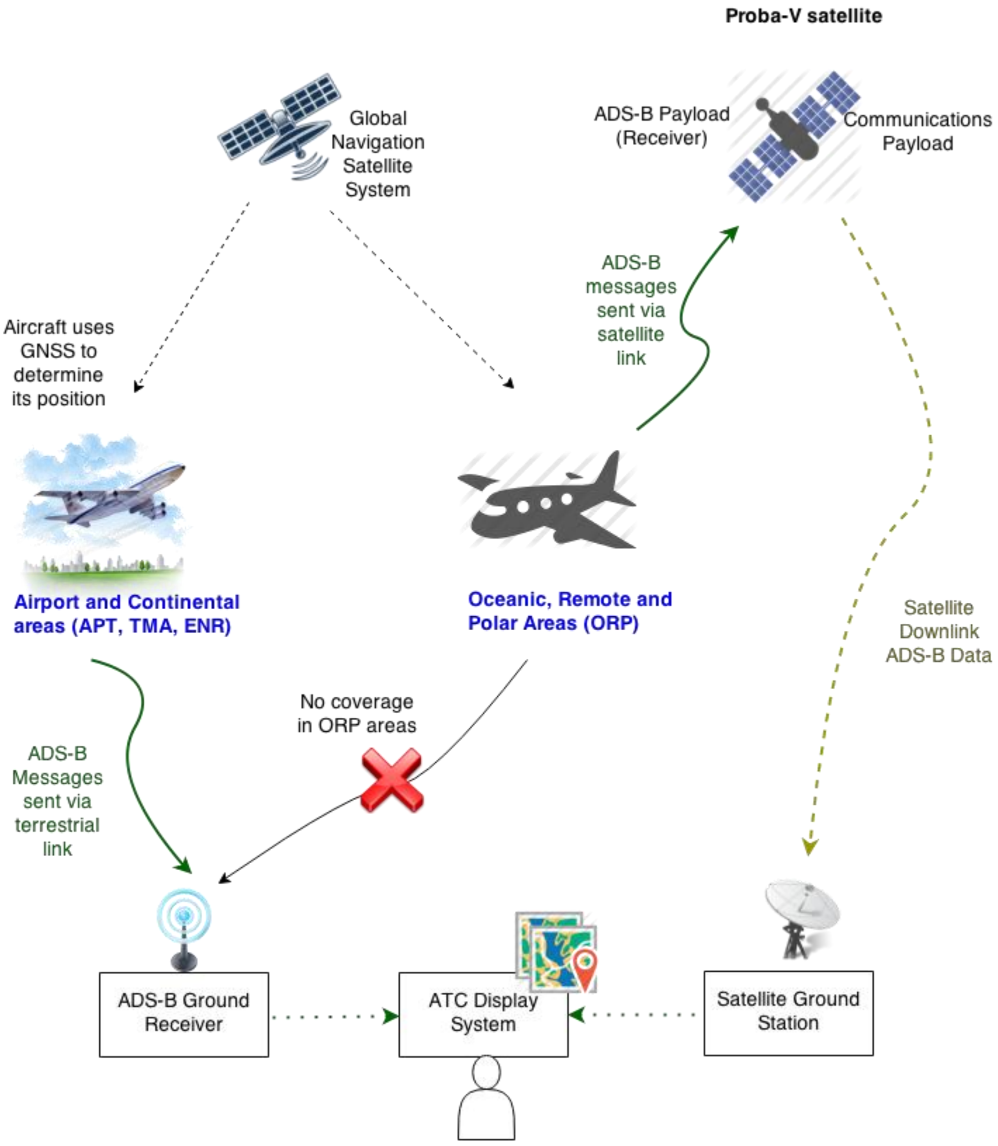

Figure 7. Proba-V System Architecture

Figure 7 depicts the architecture of the Proba-V system architecture. The figure depicts the Proba-V satellite which is intended to provide ADS-B service over ORP areas, together with the ADS-B terrestrial-based solution which is operational in the APT/TMA/ENR areas.

Figure 7 depicts the remote sensing payload which includes the ADS-B Receiver able to detect the signals from the aircrafts. Furthermore, the satellite has a standard communications payload (SATCOM transponder, TTC subsystem), which is dealing with the communications with the Ground Segment and enables the ADS-B data download. According to classification described in section 2.1, Figure 7 depicts a point-to-point "Data Collection" architecture, where the satellite is sensing ADS-B signals and forwarding the information to the Ground via the downlink.

As a result, two communication links have been identified in the Proba-V satellite system architecture: uplink from aircraft to satellite, and downlink from satellite to ground. Both links belong to the return path which is established between the Aircraft and the Ground Segment; in this case there is no forward path from the Ground Segment to the Aircraft.

The Proba-V mission is only an experimental mission which is used as a proof of concept to demonstrate the reception of ADS-B signals from space. However the surveillance data is not available in real-time and it is needed to wait one day to achieve full coverage of the Earth. The next step would be to plan the deployment of a full commercial constellation of LEO satellites with ADS-B payloads. This constellation would provide the ADS-B service with continuous availability of the surveillance data in real-time and worldwide coverage. In this context, there are several new initiatives in the USA [14] and in Europe [24] which are working in this direction towards the development of a new satellite-based ADS-B system.

2.3.2 Satellite data link characterization

This section describes the satellite datalink characterization of the space-based ADS-B system focusing on the analysis of the data rate. The goal is to introduce the Proba-V scenario that will serve as a basis for the Data Rate model evaluation that is described in Chapter 3 (section 3.3.2).

As it was introduced in section 2.1, the design flow of a satellite communications architecture starts with the identification of the communications links. In the Figure 7 above, we have identified several communication links in the Proba-V architecture: uplink from aircraft to satellite and downlink from satellite to ground.

The next step in the design is the computation of the data rate of the communication links. In order to determine the data rate, it is necessary to take into account the data communication traffic profile of the different ATM services that need to be provided in the Proba-V system. In this case study there is only one aeronautical service which is referred to as "Surveillance" (SURV) and it is based on ADS-B technology.

The SURV service uses Automatic Dependent Surveillance (ADS) positional information which is provided via broadcast (ADS-B) by equipped aircraft [9]. The aircraft providing the data must have the capability to broadcast out, and the recipient for the ADS data (a ground ATC system) must have the capability to receive and process ADS-B reports. The SURV service thus uses broadcast communications to deliver ADS-B messages containing position reports, from the Aircraft to the Ground ATC System. In the case of the Proba-V ADS-B system the messages are transmitted via the LEO satellite, while in a terrestrial ADS-B system the messages are transmitted via a RF datalink.

The SURV Service can be characterized according to several parameters which are briefly described in the following [9]:

- Update Interval: This is the time interval within which there is a percentile probability of receiving at least one report update.
- Expiration Time: The expiration time is the maximum time between updates beyond which a service interruption is declared.
- Latency: the one-way latency is the time taken from the reception of the navigational signal (GNSS) by an aircraft antenna to the output of positional information at a Ground Controller position. It includes the reception of the raw navigational signal, processing of it to determine position, transmission of the position information via the aircraft ADS-B transmitter, reception and processing by the surveillance processing system on the ground. In the case of the satellite-based ADS-B system the latency is higher than in the terrestrial case, since the signal needs to travel via the satellite.
- Continuity: This is the probability that a system will continue to perform its required function without unscheduled interruption, assuming that the system is available when the procedure is initiated.

In order to address the computation of the Data Rate required for the SURV service, it is necessary to define a model of the number of aircrafts which are using the service in order to report positional information to the Ground Station. The model used in this case study is the one defined in the COCR [9] for the broadcast services: the model estimates the number of aircrafts for each of the different airspace domains (APT, TMA, ENR, ORP), dividing each airspace domain in individual units of observation called "Transmission Volumes" TVi.

Each Transmission Volume TVi (2) is a generic airspace volume of a certain domain (APT, TMA, ENR, ORP), which is within the range of coverage of the ADS-B receiver that is mounted in a LEO satellite. For the ORP region, we assume that the receiver covers a range of 200 Nautical Miles in the pointing direction of the satellite antenna [9]. It is assumed that the aircrafts in TVi are transmitting SURV messages via ADS-B and that all SURV messages are detected by the ADS-B receiver onboard a LEO satellite.

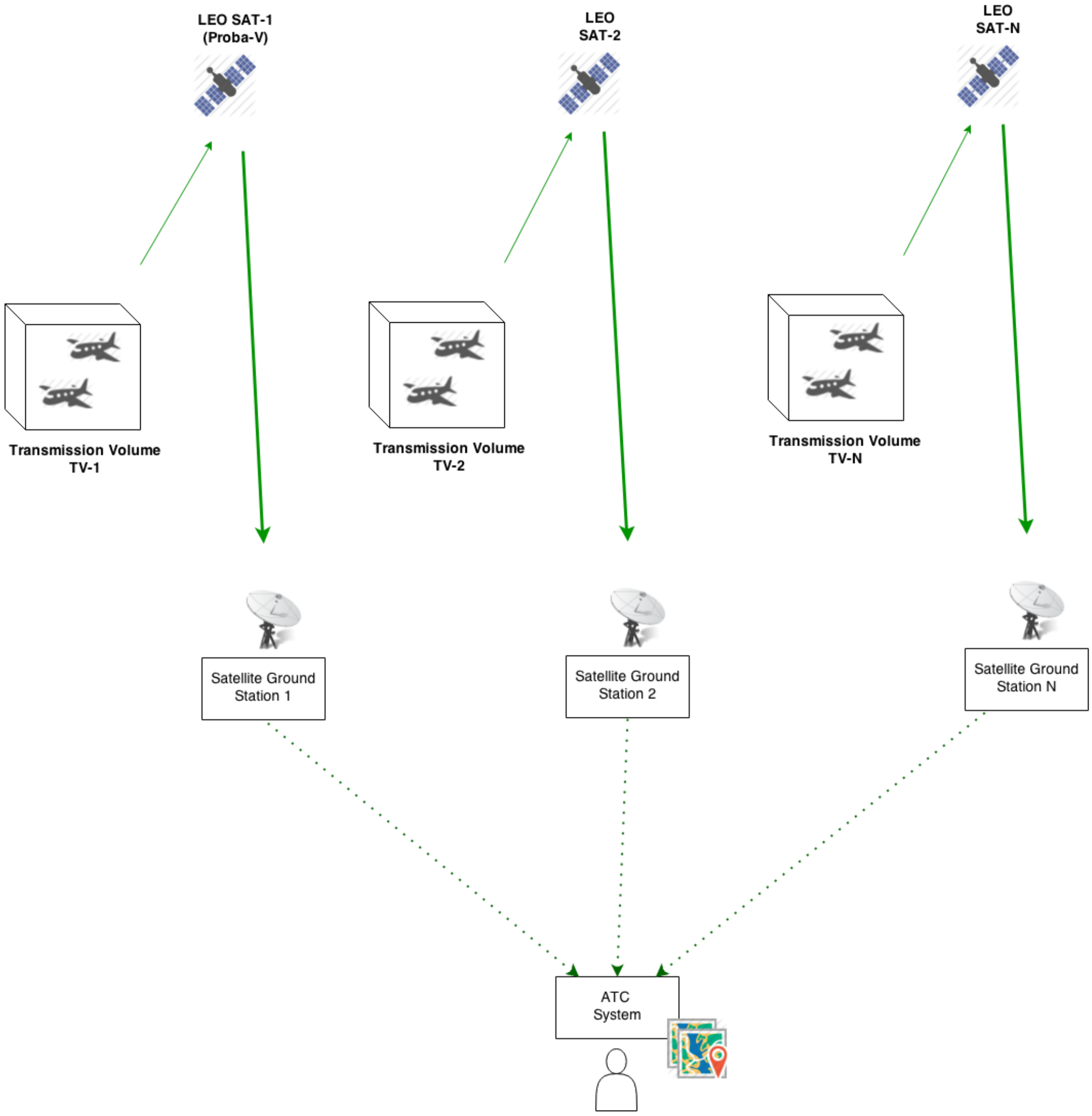

Figure 8. Case Study 2. Satellite datalink characterization

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2 "Transmission Volume" is defined in the section *Definitions*, beginning of the document.

Figure 8 depicts a generic scenario for the characterization of the satellite datalinks of the space-based ADS-B system. In this case we represent one step beyond the Proba-V mission, anticipating the LEO constellation which is planned for the future. The figure depicts a constellation of N satellites in LEO orbit $[SAT_1, SAT_2, ...SAT_i, ...SAT_N]$. We assume that we are targeting the oceanic and remote areas (ORP), and we have divided this airspace domain in "N" Transmission Volumes $[TV_1, TV_2, ...TV_i, ...TV_N]$. In this particular case, we perform a one-to-one assignment between the satellites of the constellation (SATi) and the transmission volumes (TVi): each satellite SATi detects the ADS-B messages from the aircrafts confined in the transmission volume TVi.

The Data Rate computation is performed in this particular case for the downlink from each satellite (SATi) to the ground segment. The data rate computation implies a capacity assessment concerning which is the amount of data that needs to be downloaded to the ground segment for each of the satellites in the constellation. The capacity assessment is done at Transmission Volume level (TVi), considering the following factors:

a) The Aircraft Count (ACi): number of aircrafts that are detected by each satellite (SATi) in the constellation, in the scope of the Transmission Volume TVi of the ORP airspace.

b) The ADS-B message distribution per aircraft, including the message size (MS in bits) and the message update rate (i.e. rate of messages per second)

For the SURV service, the deterministic calculation of the data rate for a transmission volume TVi in the downlink of the satellite SATi would be:

$$R_{TVi}(bps) = \frac{AC_i \times MS_{SURV}(bits)}{UpdateRate_{SURV}(\sec)}$$

As an alternative architecture to the one shown in Figure 8, we could think about the deployment of a LEO constellation which uses a GEO satellite as a data relay. In this case, instead of sending the ADS-B data directly to the Ground, the individual LEO satellites SATi would send the captured ADS-B messages to the GEO data relay satellite. The GEO satellite would then be responsible to download to the Ground Segment all the ADS-B data collected by the satellites in the LEO constellation (SATi). Assuming this alternative architecture, we could calculate the required data rate for the downlink of the GEO relay satellite, accumulating the contributions of each LEO satellite SATi for the Transmission Volume "TVi":

$$R_{Data\,\mathrm{Re}\,lay}(bps) = \sum_{i=1}^{N} R_{TVi} \text{ , where } R_{TVi}(bps) = \frac{AC_i \times MS_{SURV}(bits)}{UpdateRate_{SURV}(\sec)}$$

In this section we have introduced the characterization of the satellite datalinks for the space-based ADS-B system, focusing on the data rate analysis of the fixed downlink from satellite to ground. The next steps in the characterization would be the design of each link (Link Budget) and the communications payload sizing, completing the whole design process described in section 2.1.

The characterization of the space-based ADS-B system will be completed in Chapter 3 (section 3.3.2), where we will use statistical methods to estimate the data rate. Although at the moment we have considered a complete LEO constellation to illustrate the space-based ADS-B system, in the next chapter we will address a simpler scenario with a single LEO satellite like in the Proba-V mission. The data rate will be then estimated for a single Transmission Volume (TVi) in the ORP domain, focusing on the fixed downlink from the Proba-V LEO satellite to the Ground Station.

3 Statistical Models for Data Link Characterization

This thesis aims to define a new statistical model that enables the estimation of the Data Rate for satellite communications datalinks in the scope of Air Traffic Management (ATM).

To estimate the Data Rate required in the satellite communications datalinks, the amount of ATM data that needs to be exchanged between the aircrafts and the Ground ATC System must be estimated. There is uncertainty about this data amount, due to air traffic variability: the number of aircrafts in the airspace changes in time and space, as well as the number of ATM messages exchanged between an aircraft and the Ground ATC System. As a result, the total number of ATM messages transmitted per second, in a given airspace domain (APT, TMA, ENR, ORP) and at a given time interval, is variable.

Hence, the satellite network design should take into account uncertainty conditions and therefore a probability distribution is required to deal with this uncertainty. This thesis aims to estimate the amount of ATM data exchanged between the aircrafts and the Ground ATC system, given a certain airspace domain and a specific time interval, taking into account uncertainty conditions.

This chapter presents an analysis of the state-of-the-art of this topic (section 3.1) and the rationale and the methodology behind the Data Rate statistical model (section 3.2), together with a set of data loading analyses (section 3.3) that are used to apply the Data Rate model in the scope of the case studies introduced in chapter 2.

3.1 State-of-the-art models

Several state-of-the-art studies have been identified, addressing a satellite datalink characterization and a capacity assessment in the scope of a Data Rate Analysis for ATM/CNS services:

- Datalink characterization performed by the University of Salzburg in the scope of the ESA Iris project [7]
- Analysis performed by CNES and ESA in the scope of the "Satcom for ATM" project [19]
- Identification of future ATM/CNS services and communications data loading analysis presented in the COCR report from Eurocontrol [9].

Relative little work has been done on the analysis of the Data Rate for satellite communications systems in the scope of ATM, taking into account its uncertainty. The study of the University of Salzburg [7] deals with scenarios of future communication air traffic volumes, but they do not associate a probability to each scenario and, as a result, it is not possible to deal with the underlying uncertainty. Here in the current thesis, a probability function will be considered to model the air traffic variability, in such a way that it is possible to assess the uncertainty surrounding the global network design.

The study performed by the University of Salzburg [7] provides a characterization of the data communication traffic profile for the future ATM system, using a statistical air traffic model that relies on the Eurocontrol forecasts for 2020/2030 and the databases from the CFMU (Eurocontrol Central Flow Management Unit). Furthermore, the study derives initial bandwidth estimation for the satellite-based ESA Iris system providing ATS/AOC services in the European airspace. The simulation results of the paper show that the information volume requirements over the European region for 2030 are in the order of 4.5 Mbps in the forward link (from ground to aircraft) and less than 1 Mbps in the return link (from aircraft to ground).

Besides the ESA Iris project, there is a joint study "Satcom for ATM" between CNES and ESA [19] that presents some results in the scope of the estimation of the required data rate for a satellite-based ATM system. In particular, the related research work presented by CNES in [13] describes an alternative model of the air traffic data communications profile relying on Poisson and Exponential stochastical message generation patterns. The simulation results of the CNES work [13] are very similar to the ones obtained by the University of Salzburg [7], around 4 Mbps for the forward link (from ground to aircraft) and 1 Mbps for the return link (from aircraft to ground).

The main reference document for this master thesis is the COCR report prepared by Eurocontrol: "Communications Operating Concepts and Requirements" [9]. This document has been developed primarily to identify the future Air Traffic Services (ATS) and estimate the ATM operational requirements that are expected to be implemented in 2020 (Phase 1) and 2030 (Phase 2). Furthermore, the COCR is used to determine candidate data communications technologies that can meet these requirements.

The COCR provides an estimate of the communication load of the future radio system considering ATS and AOC services. The estimation is divided in three communication data loading analysis: Voice Loading Analysis, Addressed Data Loading Analysis and Broadcast Data Loading Analysis. Each analysis estimates the information transfer rate needed for an operational volume, which can be either a service volume (used in addressed communications) or a transmission volume (used in broadcast communications). The analyses are intended to be technology independent, and the derived capacity requirements for each ATM service are intended to provide a sense of overall information transfer rates (bits per second).

The current master thesis takes as a reference the COCR Addressed Data Loading Analysis (in the satellite communications use case) and the COCR Broadcast Data Loading Analysis (in the surveillance use case).

The COCR Addressed Data Loading Analysis provides the estimated communication load associated with addressed data communications in a service volume. ATS and AOC traffic load is evaluated in the uplink and downlink transmissions. A queuing model is developed in order to estimate the Message Arrival Rate for a certain ATS/AOC service according to the following:

MsgArrivalRate = (PIAC * NumberMessagesPerAircraft) / FlightDuration

where PIAC is the "Peak instantaneous aircraft count", the highest number of aircraft in a selected service volume during the selected window of time). In the COCR, the PIACs are predicted for the years 2020 and 2030 using two separate air traffic computer models:

- EUROCONTROL's System for Traffic Assignment and Analysis at a Macroscopic Level (SAAM)
- The MITRE Corporation's Center for Advanced Aviation System Development Mid Level Model (MLM)

On the other hand, the COCR Broadcast Data Loading Analysis looks at broadcast communication loading associated primarily with surveillance services (e.g. SURV). This analysis assumes uses a transmission volume. Here the information transfer rate is calculated by multiplying the PIAC by the message size and dividing the result by the latency: DataRate = (PIAC*MessageSize) / Latency

3.2 Methodology: a new model for ATM

The statistical analysis of the Data Rate is based on modeling the amount of ATM data exchanged between the aircrafts and the Ground ATC system, given a certain airspace domain and a specific time interval.

From now on this amount of data is referred to as the "*ATM traffic quantity*" and it is defined according to the following:

ATM traffic quantity = NumberMsg * SizeMsg where “NumberMsg” is the total number of ATM messages transmitted by the aircrafts to the Ground ATC System, and “SizeMsg” is the size of each message in bytes.

The Data Rate is derived dividing the *ATM traffic quantity* by the time interval that is considered for the data transmission.

The statistical analysis defines a confidence level $(1-\alpha)$, which characterizes the quality of service in terms of service availability for the satellite communications system, taking into account the data rate (link capacity measured in bps). The parameter α defines the probability of system overflow, i.e., when the amount of data to be transferred overflows the capacity (bps) of the communication link. The system overflows with a probability α, when the *ATM traffic quantity* is higher than expected according to the system design.

The parameter α is given by an external agent as a requirement for the system design, and it can be defined as low as desired $(0<\alpha<1)$. In this work the Data Rate of the communications system is modeled for a given confidence level $(1-\alpha)$. Note that the best case, $\alpha=0$, and the worst case, $\alpha=1$, are excluded because they are implausible: the former corresponds to the impossibility of overflow and the latter to the certainty of overflow.

3.2.1 Modeling the ATM traffic quantity

The statistical model defines Y as a random variable for the number of messages (NumberMsg), and X as the average size of a message (SizeMsg). Then the *ATM traffic quantity* is defined as $Z = XY$.

Let $Z_{(1-\alpha)}$ be an *ATM traffic quantity* such that the equality, $P(Z \le Z_{(1-\alpha)}) = 1-\alpha$, holds. In other words, with a confidence level $(1-\alpha)$, the *ATM traffic quantity*, Z, is less or equal to $Z_{(1-\alpha)}$. Thus, with a confidence level $(1-\alpha)$, the required data rate to be designed for the communication link is given by the amount of data $Z_{(1-\alpha)}$.

For instance, if it is assumed that $\alpha = 0.01$, then $(1-\alpha) = 0.99$ and $P(Z \le Z_{0.99}) = 0.99$. This means that in the 99% of the cases the data volume Z will be less than the value $Z_{0.99}$. The probability of system overflow is only 0.01, meaning that in 1% of the cases the system capacity is not enough to transfer the data with the designed data rate: here the data volume Z is higher than the designed threshold $Z_{0.99}$.

The goal of the design is to find the threshold value of the *ATM traffic quantity* $Z_{(1-\alpha)}$ that will determine the data rate of the communication link.

To find $Z_{(1-\alpha)}$, an upper bound "x" for the size of a message is established and, as a result, $X \le x$. This implies $P(Z \le Z_{(1-\alpha)}) = P\left(Y \le \frac{Z_{1-\alpha}}{x}\right)$. Thus, with a confidence level $(1-\alpha)$, the number of messages, Y, is less or equal to $Y_{(1-\alpha)} = \frac{Z_{(1-\alpha)}}{x}$ and the *ATM traffic quantity*, Z, is less or equal to $Z_{(1-\alpha)} = xY_{(1-\alpha)}$.

To find $Y_{(1-\alpha)}$, we use the statistical distribution of Y. Let $F_Y(y) = P(Y \le y)$ be the distribution function of Y. Thus, $P(Y \le Y_{(1-\alpha)}) = F_Y(Y_{(1-\alpha)})$ and $Y_{(1-\alpha)}$ is found solving the equation $F_Y(Y_{(1-\alpha)}) = 1-\alpha$: the solution is $Y_{(1-\alpha)} = F_Y^{-1}(1-\alpha)$.

Finally, $Z_{(1-\alpha)} = xF_Y^{-1}(1-\alpha)$ and with a confidence level $(1-\alpha)$, the *ATM traffic quantity*, Z, is less or equal to $xF_Y^{-1}(1-\alpha)$.

3.2.2 Modeling the Number of ATM Messages per Volume

This section describes the statistical model of the total number of messages transmitted by the aircrafts to the Ground ATC system.

As it is stated above, there are several airspace domains: APT, TMA, ENR, ORP, etc. Here we use "d" $\{d = 1, 2, \cdots, L\}$ to identify the airspace domain and a_d to denote the unit of observation within the airspace domain "d": from now on we call this unit "airspace volume" and we assume that the aim is to estimate the *ATM traffic quantity* in an airspace volume. This assumption is based on the approach adopted by Eurocontrol [9] for the data loading analysis using airspace volumes ([3]).

We model as a random variable the total Number of Messages, $Y_d(t)$, transmitted by the aircrafts to the Ground ATC system, in a given airspace volume a_d at a given time interval $(t, t+\Delta t)$, where Δt is assumed to be a reference flight interval representing the duration of a certain flight phase (in the order of seconds).

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[3] The "Airspace Volume" definition can be found in the section *Definitions* at the beginning of the document, including the classification in Service and Transmission Volumes.

The statistical distribution of the random variable $Y_d(t)$ is defined as a mixed distribution of the statistical distributions of two air traffic variables:

a) The Number of Aircrafts that are present in the airspace volume a_d at a given time interval $(t, t+\Delta t)$. From now on this will be referred as the "Aircraft Count" and it is modeled with the variable $N_d(t)$.

b) The Number of Messages transmitted per Aircraft in the airspace volume a_d at a given time interval $(t, t+\Delta t)$. This is modeled with the variable $Y_{di}(t)$.

Hereinafter we describe in detail the statistical model for the variables $N_d(t)$, $Y_{di}(t)$ and $Y_d(t)$.

Aircraft Count per Airspace Volume

The Aircraft Count, $N_d(t)$, in a selected airspace volume a_d $\{d = 1, 2, \cdots, L\}$, at a given time interval, $(t, t+\Delta t)$, is modelled using a Poisson distribution: $N_d(t) \rightarrow \mathrm{P}(\lambda_{dt})$, where λ_{dt} is the air traffic density in the airspace domain d within the time interval $(t, t+\Delta t)$ (average number of aircrafts per unit of volume a_d within the time interval $(t, t+\Delta t)$). Note that it is assumed that λ_{dt} is the same for every airspace volume, a_d, within the airspace domain "d", but it depends on the time point t.

Poisson distribution is a paradigmatic model of populations where individuals are distributed at random either in space or time. It is used in the empirical treatment of count data: its basic assumption is that the counts (number of aircrafts) in disjoints sets of space or time are independent, and this is a reasonable assumption in many real populations, including air traffic.

A number of references can be found in the statistics literature providing theoretical and empirical evidence supporting this model for analyzing count data in many areas [3, 4]. Also, references can be found in Air Traffic Management literature [9, 13]. The validation of this model would be part of the future work derived from this thesis, providing additional empirical evidences to the existing ATM literature (see Appendix 6.2).

The probability function of the Aircraft Count is defined according to the following Poisson distribution:

$$P(N_d(t)=n_{dt})=\frac{e^{-\lambda_{dt}}\lambda_{dt}^{n_{dt}}}{n_{dt}!}$$

Equation 1. Probability function of Aircraft Count

Number of ATM Messages per Aircraft

The number of transmitted messages, $Y_{di}(t)$, by an aircraft i chosen at random among those $N_d(t)$, in a selected airspace volume a_d within the time interval $(t,t+\Delta t)$, is modelled using a Poisson distribution: $Y_{di}(t)\rightarrow \mathrm{P}(\phi_{dt})$, where ϕ_{dt} is the message density in the airspace domain d within the time interval $(t,t+\Delta t)$ (average number of messages exchanged between an aircraft and the Ground ATC System in the airspace volume a_d within the time interval $(t,t+\Delta t)$).

The assumption that the number of messages emitted in disjoints time intervals are independent is reasonable and, as a result, it can be expected that the Poisson distribution fits reasonably well this number. Note that it is assumed that ϕ_{dt} is the same for every aircraft in the airspace volume a_d within the airspace domain "d", but it depends on the time point t .

As it will be shown later on, the assumption of the Poisson distribution for the model of the number of ATM messages will be only valid in the scope of the Case Study 1 (see section 3.3.1). For the case study 2 a different approach will be applied (see section 3.3.2).

Number of ATM Messages per Airspace Volume

The total number of ATM messages transmitted by the $N_d(t)$ aircrafts, in the airspace volume a_d and the time interval $(t,t+\Delta t)$, is $Y_d(t)=\sum_{i=1}^{N_d(t)} Y_{di}(t)$. This random variable $Y_d(t)$ is modelled as a (finite) mixture distribution:

$$P(Y_d(t)=y_{dt})=\sum_{n_{dt}} P(N_d(t)=n_{dt})P(Y_d(t)=y_{dt}\,|N_d(t)=n_{dt})$$

This distribution is based on the $N_d(t)$ equally distributed components $\{Y_{di}(t)\rightarrow \mathrm{P}(\phi_{dt}); i=1,2,\cdots\}$, with mixing weights $P(N_d(t)=n_{dt})$, where $n_{dt}=0,1,2,\cdots$ is a non-negative natural number and $\sum_{n_{dt}} P(N_d(t)=n_{dt})=1$.

Here, $P(Y_d(t)=y_{dt}\,|N_d(t)=n_{dt})$ denote the probability function of the random variable $Y_d(t)=\sum_{i=1}^{n_{dt}} Y_{di}(t)$, conditionally to $N_d(t)=n_{dt}$. Assuming that the variables

$\{Y_{di}(t) \to \mathrm{P}(\phi_{dt}); i = 1, 2, \cdots, n_{dt}\}$ are independent and identically distributed, it is well known that $Y_d(t) \to \mathrm{P}(n_{dt}\phi_{dt})$ and hence, $P(Y_d(t) = y_{dt} \,|\, N_d(t) = n_{dt}) = \dfrac{e^{-n_{dt}\phi_{dt}} (n_{dt}\phi_{dt})^{y_{dt}}}{y_{dt}!}$.

Thus, the probability function of the random variable $Y_d(t)$ is, $P(Y_d(t) = y_{dt}) = \sum_{n_{dt}} P(N_d(t) = n_{dt}) P(Y_d(t) = y_{dt} \,|\, N_d(t) = n_{dt})$, where $P(N_d(t) = n_{dt}) = \dfrac{e^{-\lambda_{dt}} \lambda_{dt}^{n_{dt}}}{n_{dt}!}$ and $P(Y_d(t) = y_{dt} \,|\, N_d(t) = n_{dt}) = \dfrac{e^{-n_{dt}\phi_{dt}} (n_{dt}\phi_{dt})^{y_{dt}}}{y_{dt}!}$ and, as a result:

$$P(Y_d(t) = y_{dt}) = \sum_{n_{dt}} \frac{e^{-\lambda_{dt}} \lambda_{dt}^{n_{dt}}}{n_{dt}!} \frac{e^{-n_{dt}\phi_{dt}} (n_{dt}\phi_{dt})^{y_{dt}}}{y_{dt}!}$$

Equation 2. Probability Function of the Number of ATM Messages

This is known as the Neyman Type A distribution [see [3], Sec. 6]. We will use it to estimate the *ATM traffic quantity*. The Appendix section 6.1 contains more details of this statistical distribution, including the mean and the variance.

Figure 9 depicts the probability function of the variable $Y_d(t)$, from $y_{dt} = 0$ to $y_{dt} = 20$, for $\lambda_{dt} = 2$ and $\phi_{dt} = 3$.

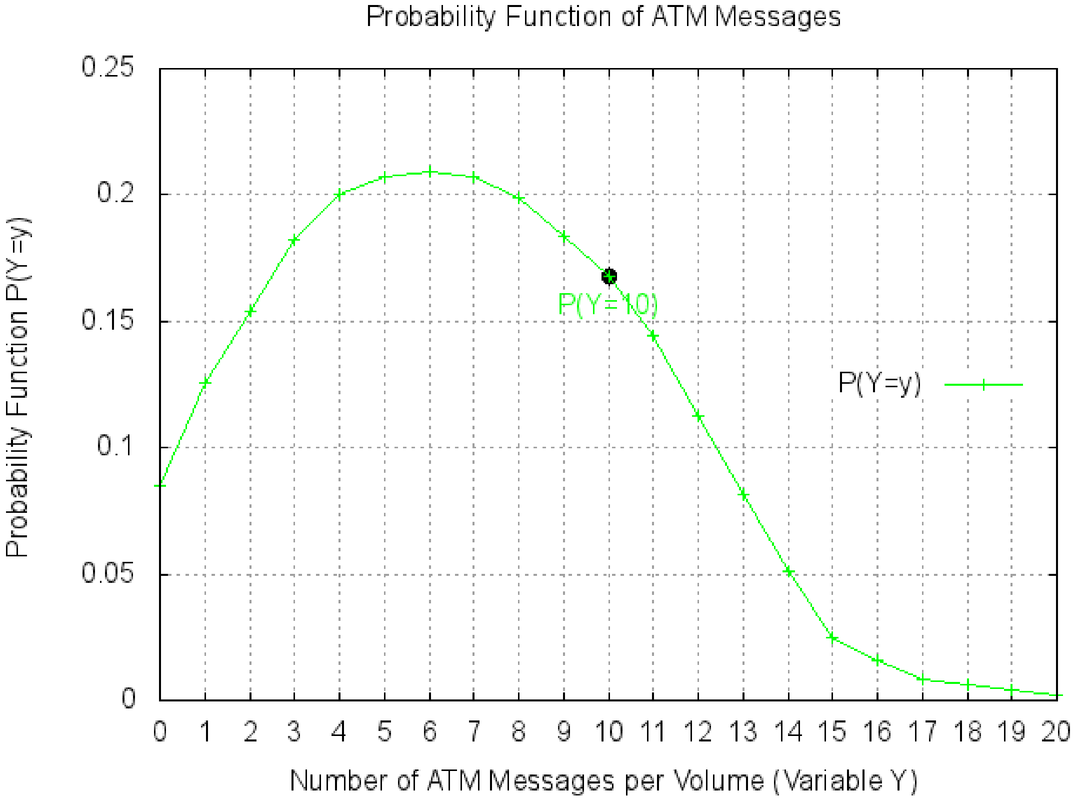

Figure 9. Probability Function of the Number of ATM Messages

3.2.3 Estimation of the ATM Traffic Quantity and Required Data Rate

The estimation of the data rate for a communication link is given by the *ATM traffic quantity* in a certain time interval.

Following the model of section 3.2.1, the *ATM traffic quantity* is derived from a set of calculations based on the Distribution Function of the variable $Y_d(t)$:

$$F_{Y_d(t)}(y_{dt}) = P(Y_d(t) \leq y_{dt}) = \sum_{y_{dt}=0}^{y_{dt}} P(Y_d(t) = y_{dt} \,|\, \lambda_{dt}, \phi_{dt})$$

Equation 3. Distribution Function of the Number of ATM Messages

Figure 10 depicts a reference distribution function for the variable $Y_d(t)$.

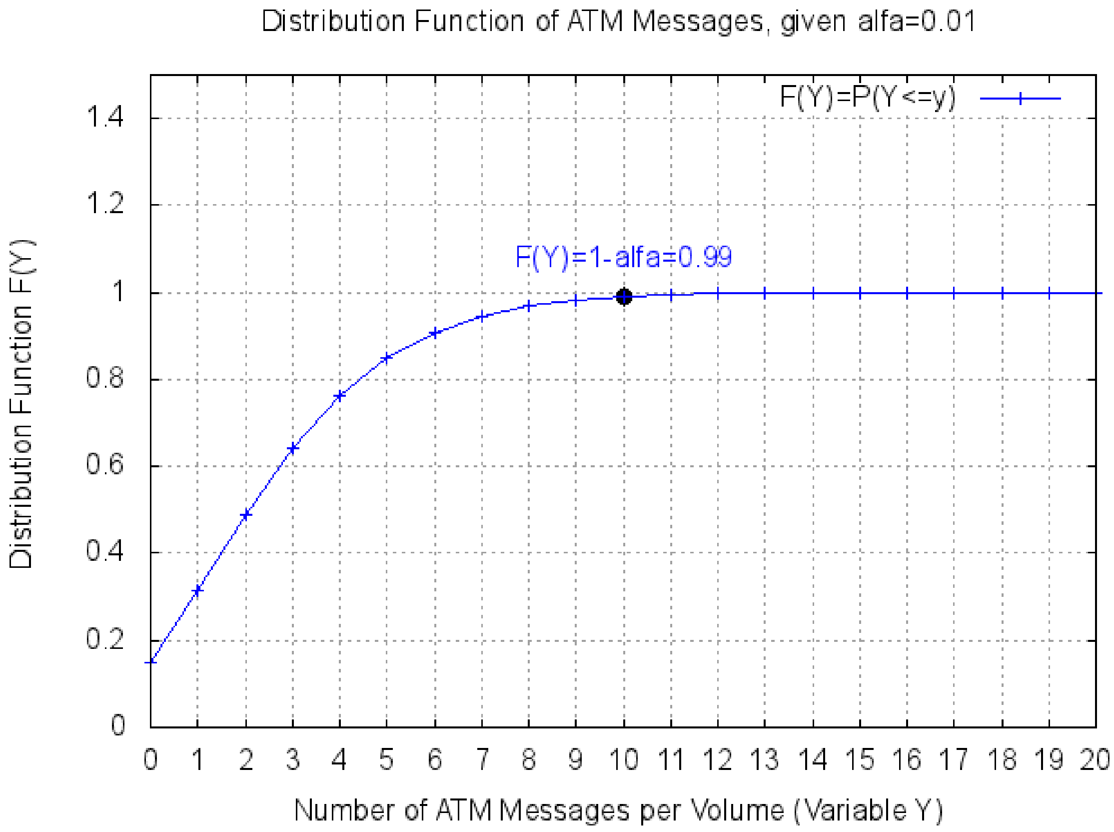

Figure 10. Distribution Function of the Number of ATM Messages

As shown in section 3.2.1, with a confidence level $(1-\alpha)$, the *ATM traffic quantity* is less or equal to $Z_{dt(1-\alpha)} = xY_{dt(1-\alpha)}$, where $Y_{dt(1-\alpha)}$ is found using the distribution function of $Y_d(t)$. The distribution function value in $Y_{dt\,(1-\alpha)}$ is:

$$F_{Y_d(t)}(Y_{dt(1-\alpha)}) = P(Y_d(t) \le Y_{dt\ 1-\alpha}) = \sum_{y_{dt}=0}^{Y_{dt(1-\alpha)}} P(Y_d(t) = y_{dt})$$

The $Y_{dt(1-\alpha)}$ value is estimated solving the equation $\sum_{y_{dt}=0}^{Y_{dt(1-\alpha)}} P(Y_d(t) = y_{dt} \mid \lambda_{dt}, \phi_{dt}) = 1-\alpha$, where

$$P(Y_d(t) = y_{dtj} \mid \lambda_{dt}, \phi_{dt}) = \sum_{n_{dt}} \frac{e^{-\lambda_{dt}} \lambda_{dt}^{n_{dt}}}{n_{dt}!} \frac{e^{-n_{dt}\phi_{dt}} (n_{dt}\phi_{dt})^{y_{dt}}}{y_{dt}!}$$

In practice, the parameters $(\lambda_{dt}, \phi_{dt})$ have to be estimated from a sample dataset. Appendix 6.2 provides details on how these parameters can be estimated. In the data loading analyses addressed in this thesis (see section 3.3), the parameters $(\lambda_{dt}, \phi_{dt})$ are estimated taking reference values from Eurocontrol [9].

Let $Y_{dt(1-\alpha)}$ be the estimated value obtained by accumulating the probability values $P(Y_d(t) = y_{dt} | \lambda_{dt}, \phi_{dt})$ from $y_{dt} = 0$ to $y_{dt} = Y_{dt(1-\alpha)}$ in such a way that $\sum_{y_{dt}=0}^{Y_{dt(1-\alpha)}} P(Y_d(t) = y_{dt} | \lambda_{dt}, \phi_{dt})$ is equal or slightly less than $(1-\alpha)$.

Figure 10 shows a reference example, given $\alpha = 0.01$, in which the estimate value of $Y_{dt(1-\alpha)}$ is ten messages:

$$F_{Y_d(t)}(Y_{dt0.99}) = 0.99 \Leftrightarrow Y_{dt0.99} = F^{-1}_{Y_d(t)}(0.99) = 10$$

The *ATM traffic quantity* estimate is then: $Z_{dt(1-\alpha)} = xY_{dt(1-\alpha)}$. The estimation of the required data rate is driven by the *ATM traffic quantity* $Z_{dt(1-\alpha)}$. The data rate is calculated per unit of time according to the following:

$$DataRate = \frac{Z_{dt(1-\alpha)}}{\Delta t} = \frac{xY_{dt(1-\alpha)}}{\Delta t}$$

Equation 4. Data Rate

The Data Rate is measured in bits per second (bps), provided that "x" is given in bits per message and "Δt" in seconds.

3.3 Data Loading Analysis: applications of the ATM model

The ATM model introduced in section 3.2 can be applied to the case studies presented in Chapter 2 in order to illustrate its usefulness for the estimation of the data rate for a certain aeronautical service.

In this section we perform a data loading analysis in order to derive the data rate of two particular ATS services, which were already introduced in Chapter 2: the ATC Clearance Service (ACL) and the Surveillance service based on ADS-B (SURV). The ACL service is analyzed in the scope of the first case study (Iris Programme) while the SURV service is analyzed in the frame of the second case study (Proba-V mission).

To do a data loading analysis, models of the air traffic flow in the main airspace domains (APT, ENR, ORP, etc) are required. We apply the ATM model presented in section 3.2, assigning values to the model parameters: the air traffic density λ_{dt} and the average number of messages exchanged with the Ground ATC System ϕ_{dt}.

In the Appendix 6.2, we provide details about how the parameters (λ_{dt}, ϕ_{dt}) could be estimated in practice, and how the proposed model could be validated. Here in this section we assume that the ATM model holds, and we use the reference model that is considered by Eurocontrol [9] to assign values to these two parameters. The GNU Octave tool [21] is used for the mathematical operations that are performed in the data loading analyses.

We will generate simulations of the total number of messages emitted in a given airspace volume a_d of a certain airspace domain "d" $\{d = 1, 2, \cdots, L\}$ within a given time interval $(t, t + \Delta t)$, using the probability function of aircraft count (Equation 1) and the probability function of the number of messages exchanged with the Ground ATC system (Equation 2). For simplicity, we can assume that we have only 5 known airspace domains and then make the following assignment for "d": $\{d = APT, TMA, ENR, ORP, AOA\}$. The following assumptions are considered for the data loading analyses:

- Only the ORP airspace domain is considered: "h=ORP".
- It is evaluated only one airspace volume within the ORP domain: a_{orp}. Note: see the definition of "Airspace Volume" in the section *Definitions*, at the beginning of the document.
- The average air traffic density λ_{dt} and the average number of messages ϕ_{dt} are assumed to be constant within the reference time interval $(t, t + \Delta t)$.

3.3.1 Case Study 1. ATC clearance service (ACL)

In the first case study we consider the Satcom Iris system (section 2.2) as reference architecture. The case study uses the aeronautical service "ATC Clearance" (ACL) in order to illustrate the usefulness of the proposed ATM model (section 3.2) within the Satcom Iris architecture.

Figure 11 depicts the particular scenario which defines the scope of this case study. The scope is to perform a data loading analysis of the ATC Clearance Service (ACL) taking into account the satellite downlink in the return path. Figure 11 depicts in green color the communications link under study: the downlink of the return path, from satellite to ground station.

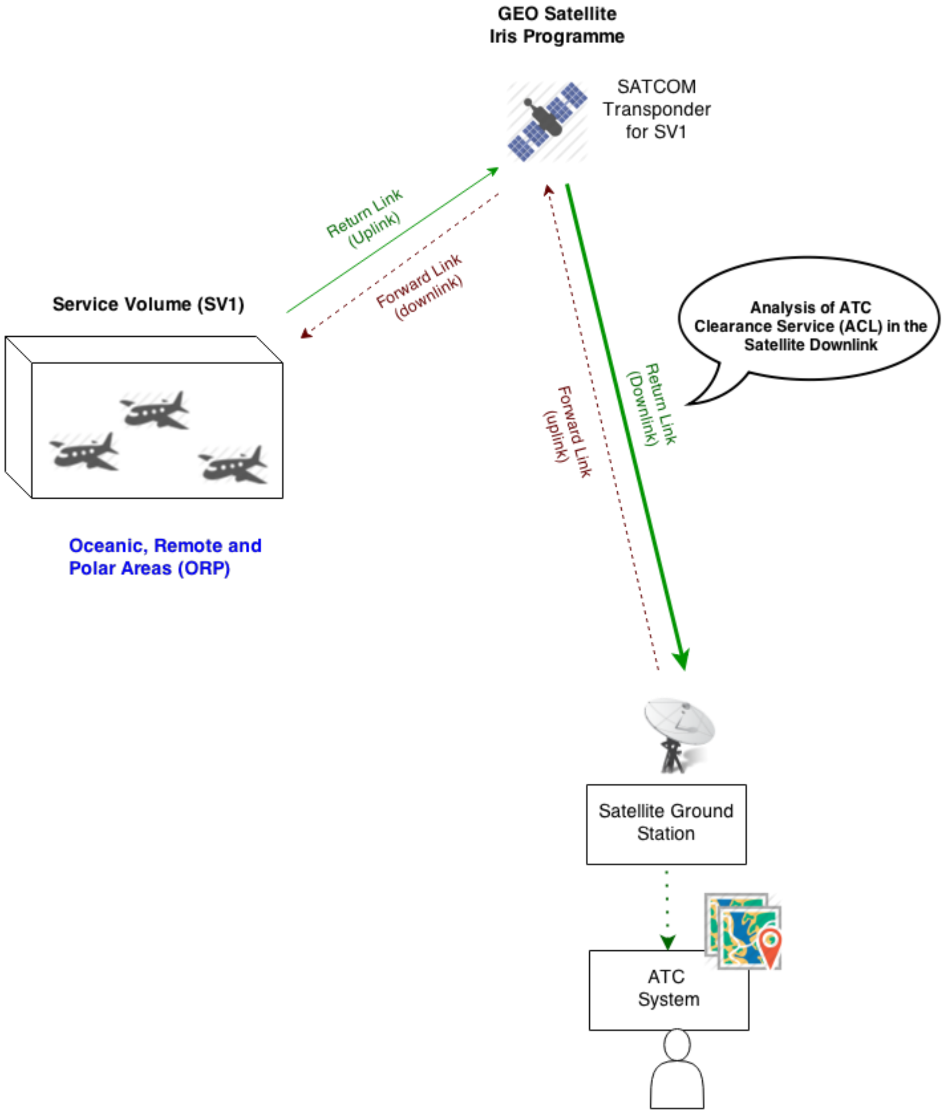

Figure 11. Case Study 1. ACL scenario for Data Loading Analysis

Figure 11 depicts the single Service Volume (SV1) that is considered for the ACL addressed service. We only consider a single service volume SV1. For the application of the ATM model to the ACL service, we need to know the following parameters:

- The average number of aircrafts in the selected Service Volume (SV1) within the interval $(t, t+\Delta t)$. This corresponds to the λ_{dt} parameter of the model.
- The average number of ACL messages transmitted per aircraft in the selected Service Volume (SV1), within the interval $(t, t+\Delta t)$. This corresponds to the ϕ_{dt} parameter of the model.
- The size of the ACL messages. This corresponds to the "x" parameter of the model.

We provide in Appendix 6.2 details about how these parameters can be estimated in practice and how the proposed ATM model could be validated. Here we assume that the ATM model holds and, in order to assign values to these parameters, we considered the estimation performed by Eurocontrol in the "COCR" document [9], in the scope of the so-called "Phase 1, Horizon 2020" and the ORP airspace domain. Table 3 depicts the parameter values that are considered for the ACL data loading analysis.

Parameter	**Description**	**Reference Value for ORP domain**	**Eurocontrol COCR document reference [9]**
λ_{dt}	Average Number of Aircrafts in a service volume (SV1), during a flight interval of Δt =60 seconds	5 aircrafts in Δt =60 sec	Table 6-7. Service Volume PIACs (ORP LD, NAS). Table 6-5. Phase 1 and Phase 2 Flight Durations and Sectors/ATSUs Traversed (ORP, Sector Flight Time, Phase 1)
ϕ_{dt}	Average Number of ACL messages transmitted per aircraft in a service volume (SV1), during a flight interval of Δt =60 seconds	2 messages in Δt =60 sec	Table 6-2. Phase 1 ATS Service Instances per Aircraft (ORP).
x	Size of the ACL messages	93 bytes	Table 6-15. ATS Message Quantities and Sizes per Instance (Downlink).

Table 3. Case Study 1. Parameters for ACL Data Loading Analysis

Probability of Aircraft Count

The probability function of aircraft count (Equation 1) according to the parameters given in Table 3 ($\lambda_{dt} = 5$) is:

$$P(N_d(t) = n_{dt} | \lambda_{dt} = 5) = \frac{e^{-5} 5^{n_{dt}}}{n_{dt}!}$$

Figure 12 depicts this probability function, from $n_{dt} = 0$ to $n_{dt} = 20$. The figure shows that the maximum value of the probability function is given for $n_{dt} = 5$. The detailed results are presented in Appendix 6.3.1, Table 5.

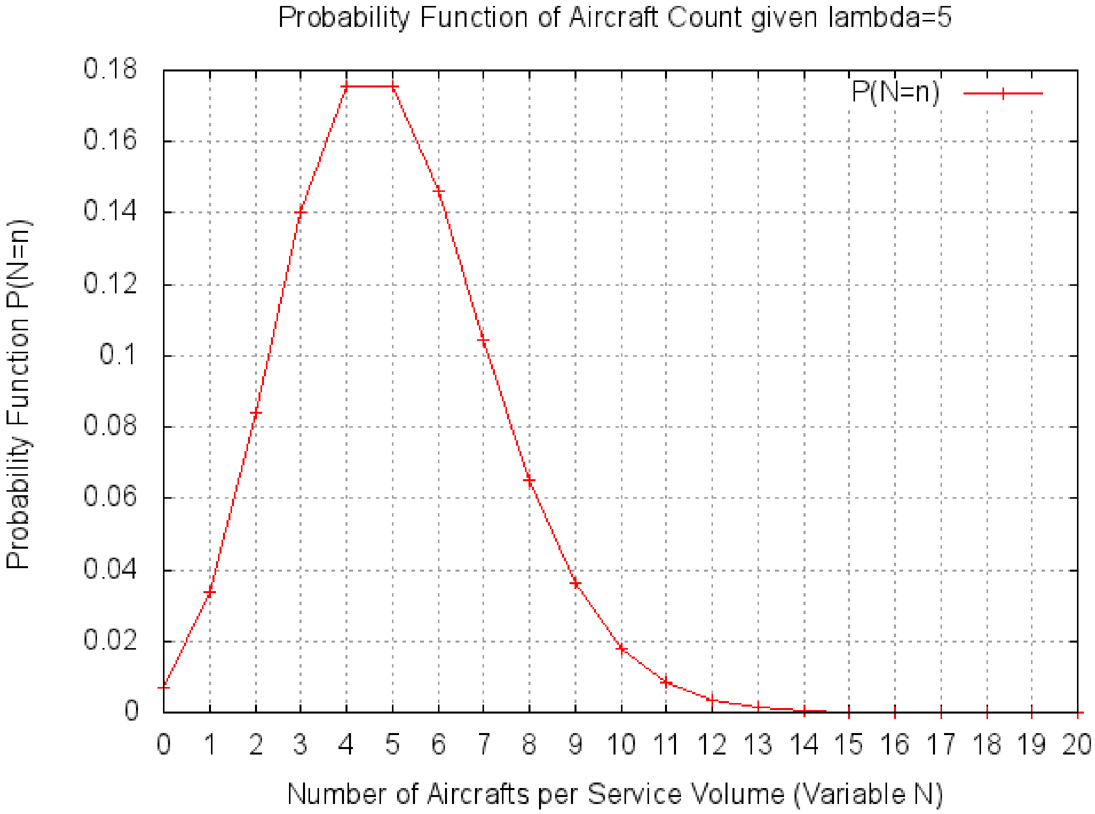

Figure 12. Probability Function of Aircraft Count given lambda=5

Probability of the Number of ACL Messages

The probability function of the Number of ACL Messages is calculated according to the parameters given in Table 3 ($\lambda_{dt} = 5$ and $\phi_{dt} = 2$) from $n_{dt} = 0$ to $n_{dt} = 20$ (Equation 2):

$$\textit{Probability Function: } P(Y_d(t) = y_{dt} | \lambda_{dt} = 5, \phi_{dt} = 2) = \sum_{n_{dt}=0}^{20} \frac{e^{-5} 5^{n_{dt}}}{n_{dt}!} \frac{e^{-n_{dt} 2} (n_{dt} 2)^{y_{dt}}}{y_{dt}!}$$

Figure 13 depicts this probability function. The figure shows that the maximum value of the probability function is given for $y_{dt} = 8$. The detailed results are presented in Appendix 6.3.1, Table 6.

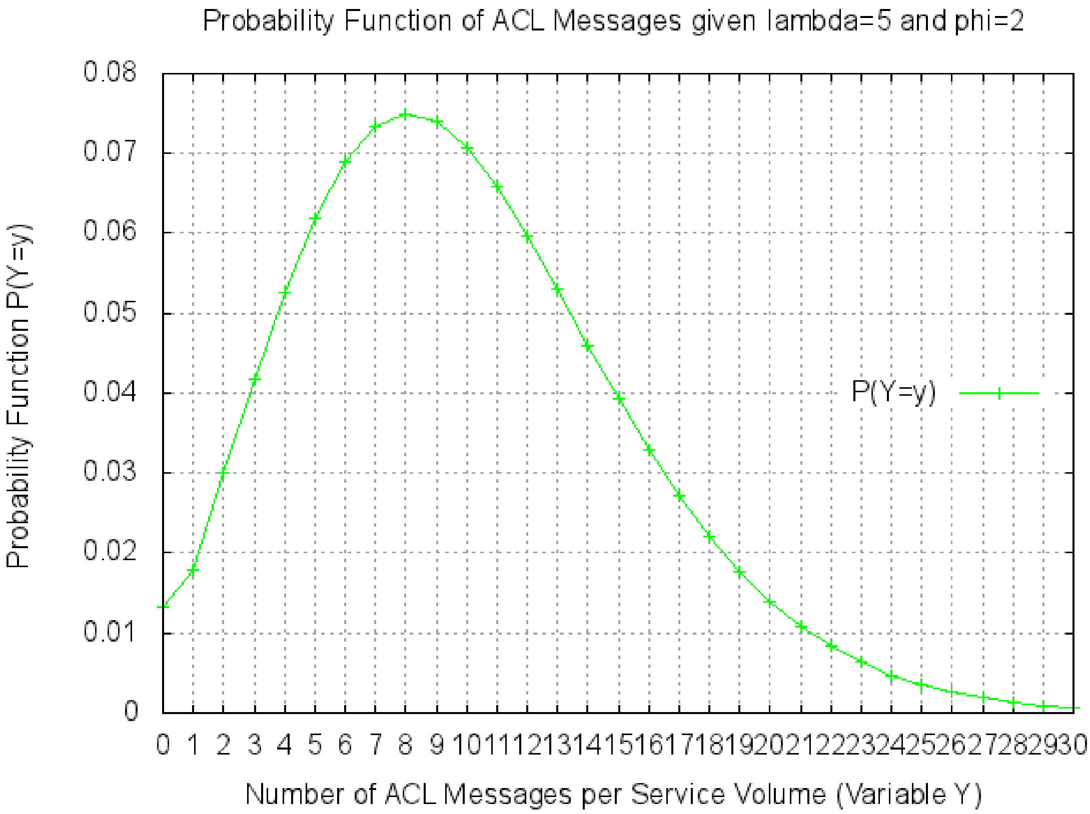

Figure 13. Probability Function of ACL Messages

Estimation of ACL Data Rate

To estimate the required data rate for the ACL service, the distribution function of the ACL Messages is calculated according to the following (Equation 3):

$$\textit{Distribution Function:}\ F_{Y_d(t)}(y_{dt}) = \sum_{y_{dt}=0}^{y_{dt}} P(Y_d(t) = y_{dt} \mid \lambda_{dt} = 5, \phi_{dt} = 2)$$

Figure 14 depicts this distribution function. See Table 6 for more details.

If we consider a value of $\alpha = 0.01$, then with a confidence level of 99.0 % the number of ACL messages is less than 25:

$$Y_{dt(1-\alpha)} = Y_{dt(1-0.01)} = Y_{dt(0.99)}$$

$$F_{Y_d(t)}(Y_{dt0.99}) = 0.99 \Leftrightarrow Y_{dt0.99} = F^{-1}_{Y_d(t)}(0.99) = 25.$$

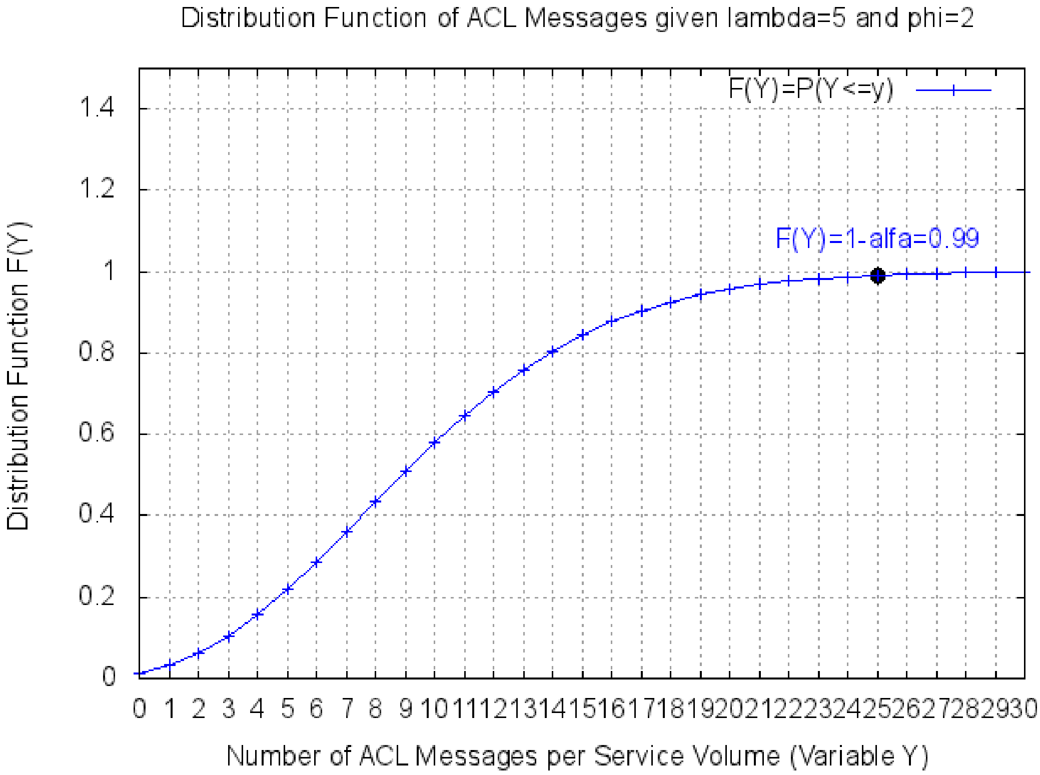

Figure 14. Distribution Function of ACL Messages

As a result, the ACL traffic quantity is $Z_{dt(1-\alpha)} = 25x$, where x is the upper bound established for the ACL message size. The ACL data rate is then calculated for a time interval "Δt", taking into account the data amount corresponding to the ACL traffic quantity $Z_{dt(1-\alpha)} = 25x$.

Considering the reference values in the Table 3, the message size is "x = 93 bytes = 93*8 bits" and the flight duration is "Δt =60 seconds". The data rate is then calculated according to the following (Equation 4):

$$DataRate = \frac{Z_{dt(1-\alpha)}}{\Delta t} = \frac{25*93*8}{60} = 310bps$$

In this case study we have then estimated the data rate required for the ACL service for the ORP regions in the satellite downlink. An additional estimation could be performed for the satellite uplink (forward path in Figure 11), following the same process described above for the calculation of the data rate. In this case the input parameters for the model may be different, depending on the estimation of the number of ACL messages in the uplink.

3.3.2 Case Study 2. Surveillance service (SURV)

In the second case study we consider the Proba-V LEO system (section 2.3) as reference architecture. The case study uses the aeronautical service "Surveillance" (SURV) based on ADS-B technology, in order to illustrate the application of the ATM model (section 3.2) within the Proba-V LEO system.

Figure 15 depicts the particular scenario which defines the scope for this case study. The scope is to perform a data loading analysis of the Air-Ground Surveillance Service (SURV) taking into account the satellite downlink.

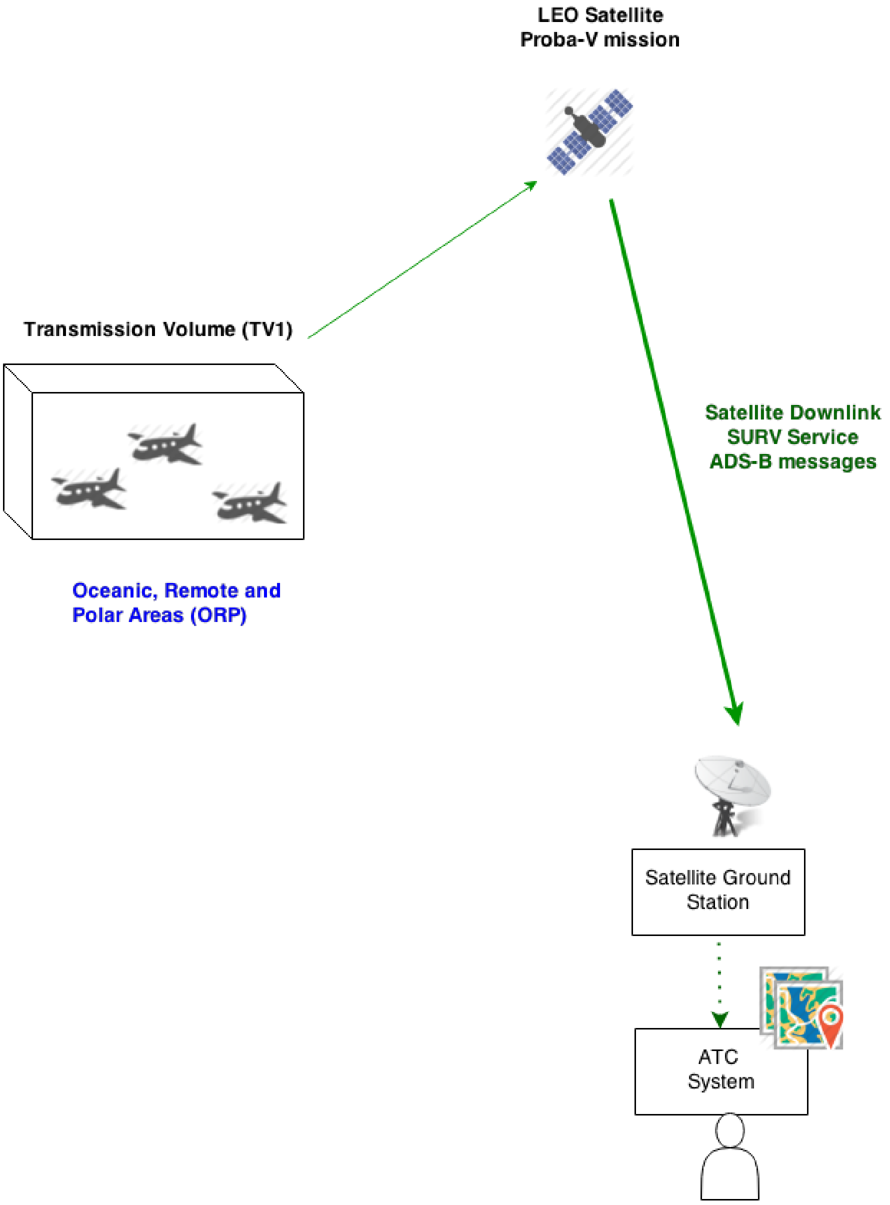

Figure 15. Case Study 2. SURV scenario for Data Loading Analysis

Figure 15 depicts in green color the communications link under study: it is the downlink from the satellite to the ground station. Unlike in the first study, here the model considers a Transmission Volume (TV1) instead of service volume, since in the SURV case study we are dealing with a broadcast communication system based on ADS-B. We evaluate the number of SURV messages transmitted by the aircrafts in a single volume TV1, considering a range of 200 NM for the ORP region.

For the application of the ATM model to the SURV service, we need to know the following parameters:

- The average number of aircrafts in the selected Transmission Volume (TV1), within the interval $(t, t+\Delta t)$. This corresponds to the λ_{dt} parameter of the model.
- The average number of SURV messages transmitted per aircraft in the selected Transmission Volume (TV1), within the interval $(t, t+\Delta t)$.
- The size of the SURV messages. This corresponds to the "x" parameter of the model.

We provide in Appendix 6.2 details about how to estimate these parameters in practice and how to validate the ATM model. Here we assume that the ATM model holds and, in order to assign values to these parameters, we consider the estimation performed by Eurocontrol in the "COCR" document [9], in the scope of the so-called "Phase 1, Horizon 2020" and the ORP airspace domain. Table 4 depicts the parameter values that are considered for the SURV data loading analysis.

In this case study, the Poisson distribution is not applicable for modeling the number of SURV messages. It is assumed that the SURV messages are transmitted periodically by the aircrafts, with an update rate of 10 seconds. Assuming that there is no transmission failure, the number of SURV messages expected within the time interval $(t, t+\Delta t)$ is deterministic and equal to the constant value $\frac{\Delta t}{10}$. Therefore in this case the model is simplified and the parameter ϕ_{dt} is not needed.

Parameter	**Description**	**Reference Value for ORP domain**	**Eurocontrol COCR document reference [9]**
λ_{dt}	Average Number of Aircrafts in a transmission volume (TV1). The transmission volume range is 200 Nautical Miles (NM) and the transmission time interval corresponds to a flight duration of Δt =60 seconds	3 aircrafts in Δt =60 sec	Table 6-11. Transmission Volume PIACs (ORP, P1). Table 6-1. Transmission Volume Ranges (Air-Ground SURV, ORP) Table 6-5. Phase 1 and Phase 2 Flight Durations and Sectors/ATSUs Traversed (ORP, Sector Flight Time, Phase 1)
N/A	Average Number of SURV messages transmitted per aircraft in a transmission volume (TV1), during an interval Δt =60 sec. **Note**: The SURV messages are transmitted periodically with an update rate of 10 seconds. Hence the Number of SURV messages is a constant, assuming that there is not transmission failure	6 messages in Δt =60 sec $(\frac{\Delta t}{10}=6)$	Table 6-2. Phase 1 ATS Service Instances per Aircraft (ORP). Table 5-3. ATS Broadcast Service Update Intervals (ORP, Phase1).
x	Size of the SURV messages	34 bytes	Table 6-15. ATS Message Quantities and Sizes per Instance

Table 4. Case Study 2. Parameters for SURV Data Loading Analysis

Probability of Aircraft Count

The probability function of aircraft count (Equation 1) according to the parameters given in Table 4 ($\lambda_{ht}=3$) is:

$$P(N_d(t)=n_{dt}\,|\,\lambda_{dt}=3)=\frac{e^{-3}3^{n_{dt}}}{n_{dt}!}$$

Figure 16 depicts this probability function, from $n_{dt} = 0$ to $n_{dt} = 20$. The figure shows that the maximum value of the probability function is given for $n_{dt} = 3$. The detailed results are presented in Appendix 6.3.2, Table 7.

Note the long tail of this distribution and the low probability (1.10E-03) of having ten or more aircrafts in the considered airspace region. The probability of a number larger than 20 is nearly zero.

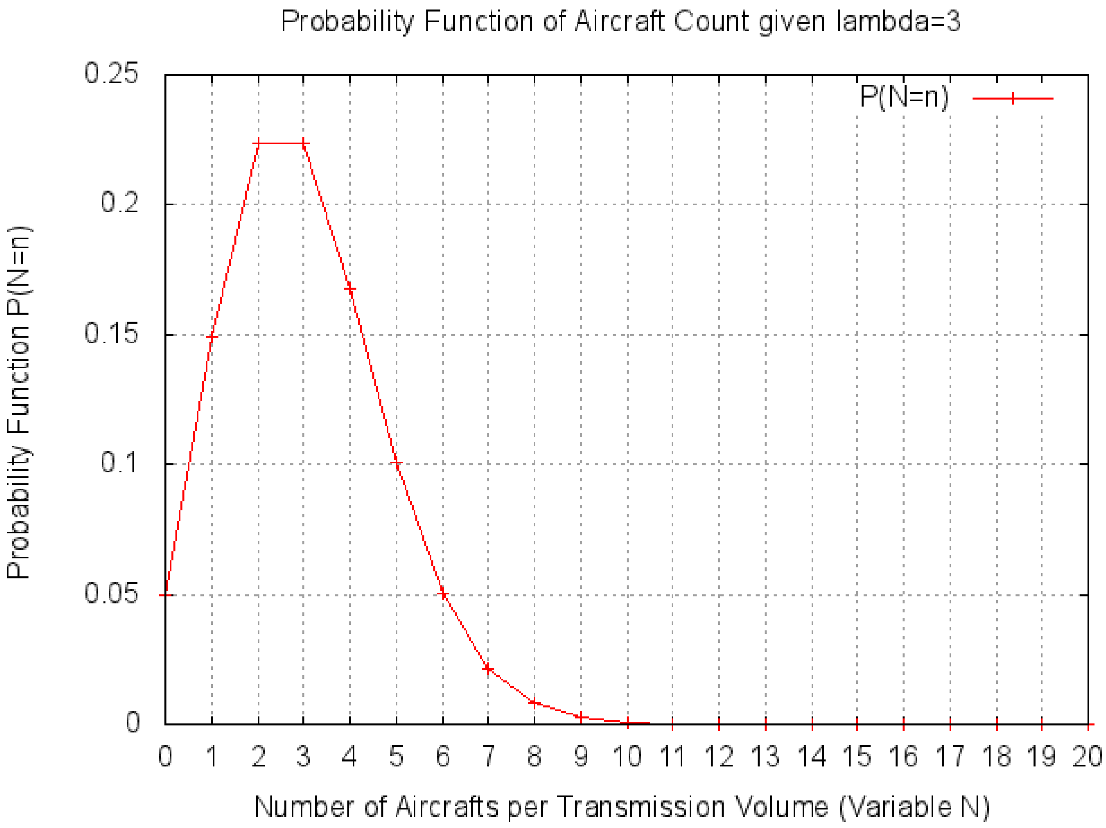

Figure 16. Probability Function of Aircraft Count given lambda=3

Probability of the Number of SURV Messages

The SURV messages are transmitted periodically with a given update rate (10 seconds according to Table 4). Hence, if there is no transmission failure then there is no uncertainty about the Number of SURV messages, $Y_{di}(t)$, transmitted by an aircraft within the time interval $(t, t+\Delta t)$: it is the constant $Y_{di}(t) = \frac{\Delta t}{10}$. As a result, the total number of ATM messages transmitted by the $N_d(t)$ aircrafts, in the Transmission Volume a_d and the time interval $(t, t+\Delta t)$, is $Y_d(t) = N_d(t)\frac{\Delta t}{10}$. And there is uncertainty about $Y_d(t)$ since there is uncertainty about $N_d(t)$.

We model $Y_d(t)$ uncertainty as before (Equation 2):

$$P(Y_d(t)=y_{dt})=\sum_{n_{dt}} P(N_d(t)=n_{dt})P\ \ Y_d(t)=y_{dt}\left|N_d(t)=n_{dt}\right.$$

If $N_d(t)=n_{dt}$ then $Y_d(t)=n_{dt}\frac{\Delta t}{10}$ with probability equal to one, since it is a constant as explained above: $P(Y_d(t)=n_{dt}\frac{\Delta t}{10}\left|N_d(t)=n_{dt}\right.)=1$.

As a result, assuming that $\lambda_{dt}=3$ (Table 4), we have the following: $P(Y_d(t)=n_{dt}\frac{\Delta t}{10})=P(N_d(t)=n_{dt}\left|\lambda_{dt}=3\right.)=\frac{e^{-3}3^{n_{dt}}}{n_{dt}!}$

Figure 17 depicts the probability function of the SURV Messages, which as it can be seen coincides with the probability function of the variable $N_d(t)$ (Figure 16).

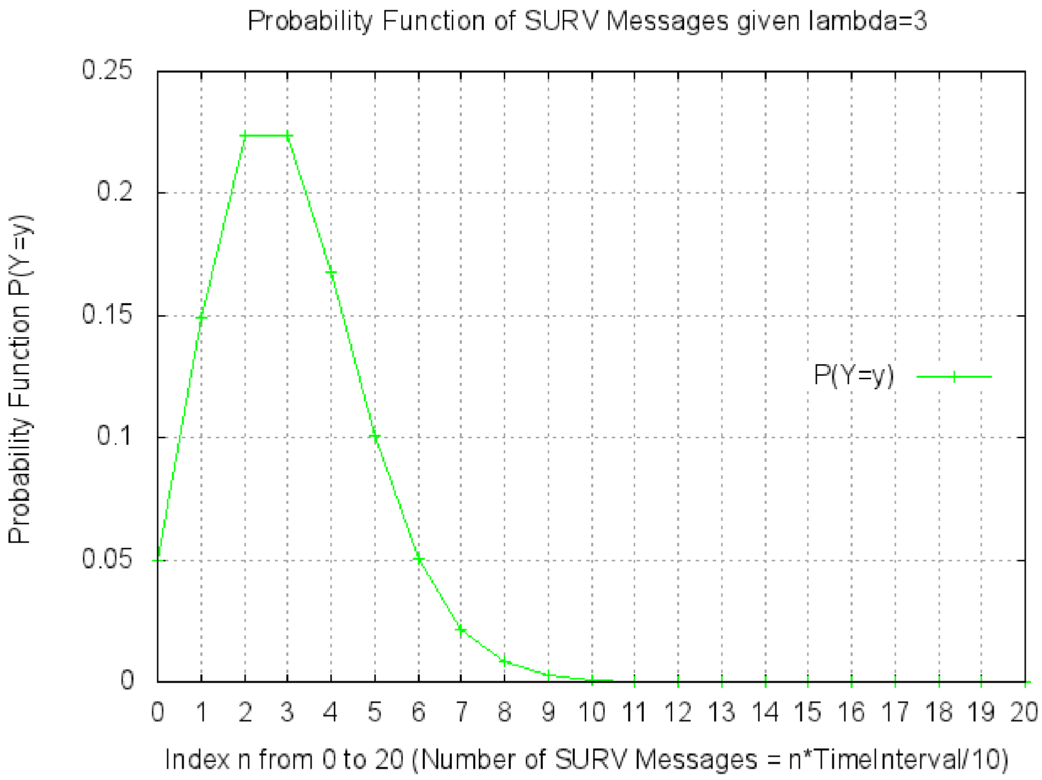

Figure 17. Probability function of SURV Messages

Estimation of SURV data rate

The distribution function of the SURV Messages is calculated according to the following (Equation 3):

Distribution Function, depicted in Figure 18:

$$F_{Y_d(t)}(y_{dt} = n_{dt}\frac{\Delta t}{10}) = \sum_{y_{dt}=0}^{n_{dt}\frac{\Delta t}{10}} P(Y_d(t) = n_{dt}\frac{\Delta t}{10}\bigg|\lambda_{ht} = 3) = \sum_{y_{dt}=0}^{n_{dt}} P(N_d(t) = n_{dt}\,|\,\lambda_{dt} = 3) = \sum_{y_{dt}=0}^{n_{dt}} \frac{e^{-3}3^{n_{dt}}}{n_{dt}!}$$

Note that the $Y_d(t)$ distribution function is the same than the $N_d(t)$ distribution function: $F_{N_d(t)}(n_{dt}) = \sum_{n_{dt}=0}^{n_{dt}} P(N_d(t) = n_{dt}\,|\,\lambda_{dt} = 3) = \sum_{n_{dt}=0}^{n_{dt}} \frac{e^{-3}3^{n_{dt}}}{n_{dt}!}$.

If we consider a value of $\alpha = \mathbf{1.0 \times 10^{-03}}$ (a confidence level of 99.9 %), we get that the number of SURV messages is less than $Y_{dt(0.999)} = 9\frac{\Delta t}{10}$, with a confidence level of 99.9 % (see Appendix 6.3.2, Table 8):

$$Y_{dt(1-\alpha)} = Y_{dt(1-0.001)} = Y_{dt(0.999)}$$

$$F_{Y_d(t)}(Y_{dt0.999}) = 0.999 \Leftrightarrow Y_{dt0.999} = F^{-1}_{Y_d(t)}(0.999) = 9\frac{\Delta t}{10}$$

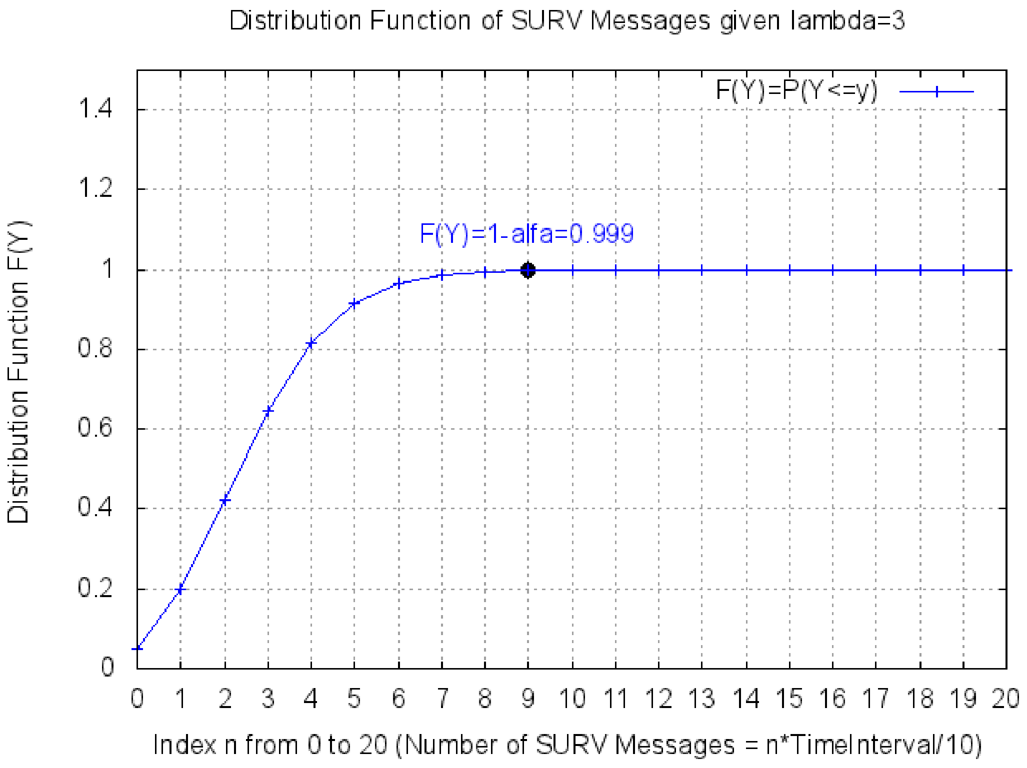

Figure 18. Distribution Function of SURV Messages

As a result, the SURV traffic quantity is $Z_{dt(1-\alpha)} = 9\frac{\Delta t}{10}x$, where x is the upper bound established for the SURV message size. The SURV data rate is then calculated for a time interval "Δt", taking into account the data amount corresponding to the SURV traffic quantity $Z_{dt(1-\alpha)} = 9\frac{\Delta t}{10}x$.

Considering the reference values in the Table 4, the message size is "x = 34 bytes = 34*8 bits" and the time interval is "Δt=60 seconds". The data rate is then calculated according to the following (Equation 4):

$$DataRate = \frac{Z_{dt(1-\alpha)}}{\Delta t} = \frac{9\frac{\Delta t}{10}x}{\Delta t} = \frac{9x}{10} = \frac{9*34*8}{10} = 244.8bps$$

In this case study we have then estimated the data rate required for the SURV service for the ORP regions in the satellite downlink.

4 Conclusions and Future Work

This chapter includes the conclusions of the master thesis and the analysis of the future work to be done in the scope of the research area of the thesis.

The aeronautical community is facing a modernization of the Air Traffic Management infrastructure in order to improve the existing Communications, Navigation and Surveillance systems. The satellite technology is playing an important role in this modernization, and a lot of new initiatives are arising in order to develop new satellite systems that will require a careful design to meet the expected requirements.

This thesis aims to contribute to the design phase of the new satellite communication systems in the ATM domain, providing a new statistical model which enables the characterization of the satellite communications datalinks focusing on the estimation of the Data Rate. The proposed model serves as an alternative to the existing state-of-the-art solutions currently in use by ESA and CNES, having as main added-value that the new model takes into account the uncertainty that is derived from air traffic variability in terms of (1) the number of aircrafts in a certain region and (2) the associated data communications load.

4.1 Summary of the achieved results

The statistical analysis presented in this work is based on modeling the amount of ATM data exchanged between the aircrafts and the Ground ATC system (*ATM Traffic Quantity*), given a certain airspace domain (APT, TMA, ENR, ORP) and a specific time interval. The model of the *ATM Traffic Quantity* takes into account two air traffic variables:

a) The Number of Aircrafts ($N_d(t)$) that are present in the airspace volume a_d, within the airspace domain d, at a given time interval $(t, t+\Delta t)$. This variable is modeled with a Poisson distribution with parameter λ_{dt}.

b) The Number of ATM Messages transmitted per Aircraft ($Y_{di}(t)$) in the airspace volume a_d, within the airspace domain d, at a given time interval $(t, t+\Delta t)$. This variable is modeled with a Poisson distribution with parameter ϕ_{dt}.

The statistical model combines these two variables and as a result derives the total total number of ATM messages transmitted by the $N_d(t)$ aircrafts, in the airspace volume a_d and the time interval $(t, t+\Delta t)$. The result is modeled as the variable $Y_d(t)$ and the thesis addresses the computation of the probability function and distribution function for this variable.

The estimation of the data rate is derived from the distribution function of $Y_d(t)$, taking into account a certain confidence level $(1-\alpha)$ which is used to characterize the communications service availability in the ATM system. The data rate is selected to guarantee a high level of service availability, so that a high percentage of the aircraft messages can be delivered through the communication link.

The master thesis evaluates the resulting statistical model of the data rate using two representative satellite-based system architectures in the ATM domain. The first case study of the thesis is a satellite communications system based on the ESA Iris Programme, using a GEO satellite as a data relay for ATS/AOC aeronautical services. The second case study of this thesis is a space-based ADS-B surveillance system based on the ESA Proba-V experimental mission (LEO satellite). In each case study, a certain aeronautical service is analyzed in order to evaluate the statistical model: the "Air Traffic Control Clearance" service (ACL) is analyzed in the scope of the first case study (Satcom Iris Programme), while the ADS-B Surveillance service (SURV) is analyzed in the frame of the second case study (Proba-V mission).

The evaluation performed with the case studies aims to show the applicability of the statistical model in two different scenarios, which illustrates how the model could be applied to analyze the communications requirements in an ATM system with several aeronautical services (ACL, SURV). We use reference estimations from Eurocontrol in order to assign values to the model parameters λ_{dt} (air traffic density) and ϕ_{dt} (number of messages per aircraft). As a result of the application of the model, we derive the required data rate for each aeronautical service (ACL, SURV), finalizing the data loading analysis.

The achieved results with the case studies analysis are satisfactory, but they are conditioned to the validity of the statistical model assumptions. The main model assumption is that the Poisson distribution is good enough for analyzing air traffic data. We support this assumption by theoretical and empirical basis found in both statistical and air traffic management literature. The validation of the model could be addressed using a real sample dataset of air traffic, although this is not addressed in the thesis and could be considered as part of the future work. As part of the validation process, the real sample dataset could be used to obtain a more accurate estimation of the parameters λ_{dt} and ϕ_{dt}. This would serve to refine the assumptions taken in the data loading analysis of the thesis, enhancing the air traffic model accuracy based on real measurements.

4.2 Application and exploitation of the results

The model presented in this thesis could have several applications in the ATM domain and it could be exploited as a solution to improve the characterization of satellite communication datalinks for ATM systems.

As a first application, the statistical methodology proposed in this thesis could be used to implement an air traffic analysis tool that would contribute to the design of future communication networks in the ATM domain. As it has been explained through this work, there are many new initiatives such as the satellite communications Iris Programme and the space-based surveillance Proba-V Programme. In this context, every new deployment of a communications system could leverage from the usage of this tool in order to estimate the required data communications load and select the most suitable data rate for the communications links in the new design.

Furthermore, the aeronautical stakeholders could benefit from the statistical model proposed in this work in order to obtain forecast estimations of the air traffic in a certain timeframe. The number of aircrafts per airspace domain could be estimated taking into account the uncertainty which is due to the air traffic variability in the time and space domains. The application of the model proposed in this work could then be compared with the forecast estimations that are currently considered by organisms such as Eurocontrol.

4.3 Future Work

In this work, the air traffic flow has been modeled for elemental time intervals, $(t, t+\Delta t)$, assuming that the air traffic density, λ_{dt}, and the message density, ϕ_{dt}, are constant within this time interval. Furthermore, the analysis assumes that the airspace domains (APT, TMA, ENR, ORP, etc) are divided in homogeneous airspace volumes a_d, and that the parameters λ_{dt} and ϕ_{dt} are the same for every airspace volume, a_d, within the airspace domain d, at the given time interval $(t, t+\Delta t)$. The scope of the analysis is the "peak hour" time interval as a reference, considering the corresponding estimations from Eurocontrol for the time interval in which it is expected to have the peak number of aircrafts.

In future developments of this work, it would be interesting to model air traffic flow over daily and yearly cycles, using (logarithmic and linear) models of λ_{dt} and ϕ_{dt} changing in the time and space domains. In this case λ_{dt} and ϕ_{dt} would be variable during the time interval $(t, t+\Delta t)$, and they will be different for each airspace volume a_d within the domain d.

Using these models, the required data rate that must be supported by the ATM Future Radio System will be estimated over daily and yearly cycles. These long term models are useful to associate probabilities to scenarios in the future ATM system, in such a way that the uncertainty surrounding forecasts about the future communication traffic profile could be taken into account at the moment of making decisions regarding the network design.

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6 Appendixes

6.1 Mean and Variance of the statistical distribution

Mean Value (Expectations)

The expected value of $Y_d(t)$ is $EY_d(t) = \sum_{y_{dt}} y_{dt} P(Y_d(t) = y_{dt}) = \sum_{n_{dt}} P(N_d(t) = n_{dt}) \sum_{y_{dt}} y_{dt} P(Y_d(t) = y_{dt} \,|N_d(t) = n_{dt})$ where, $\sum_{y_{dt}} y_{dt} P(Y_d(t) = y_{dt} \,|N_d(t) = n_{dt})$ is the expected value of $Y_d(t)$ conditionally to $N_d(t) = n_{dt}$, denoted by $E(Y_d(t) | N_d(t) = n_{dt})$, so that $EY_d(t) = \sum_{n_{dt}} P(N_d(t) = n_{dt}) E(Y_d(t) | N_d(t) = n_{dt})$, where $E(Y_d(t) | N_d(t) = n_{dt}) = n_{dt}\phi_{dt}$.

Finally, the expected number of messages emitted (exchanged with the air ATM system) is

$$EY_d(t) = \sum_{n_{dt}} \frac{e^{-\lambda_{dt}} \lambda_{dt}^{n_{dt}}}{n_{dt}!} n_{dt}\phi_{dt}$$

Variance

The variance of $Y_d(t)$ is $VY_d(t) = \underset{N_d(t)}{V} E(Y_d(t) | N_d(t)) + \underset{N_d(t)}{E} V(Y_d(t) | N_d(t))$, where, $\underset{N_d(t)}{V} E\,Y_d(t) | N_d(t) = \underset{N_d(t)}{V} n_{dt}\phi_{dt} = \lambda_{dt}\phi_{dt}^2$. Assuming that the variables $\mathrm{Y}_{di}(t) \to \mathrm{P}(\phi_{dt}); i = 1, 2, \cdots, n_{dt}$ are independent and identically distributed, then $V\,Y_d(t) | (N_d(t) = n_{dt}) = \sum_{i=1}^{n_{dt}} VY_{di}(t) = \sum_{i=1}^{n_{dt}} \phi_{dt} = n_{dt}\phi_{dt}$ and $\underset{N_d(t)}{E} V\,Y_d(t) | (N_d(t) = n_{dt}) = \underset{N_d(t)}{E} n_{dt}\phi_{dt} = \lambda_{dt}\phi_{dt}$.

Thus,

$$VY_d(t) = \lambda_{dt}\phi_{dt}^2 + \lambda_{dt}\phi_{dt} = \lambda_{dt}\phi_{dt}(1 + \phi_{dt})$$

The standard deviation is $\sqrt{VY_d(t)} = \sqrt{\lambda_{dt}\phi_{dt}(1 + \phi_{dt})}$

6.2 Validation of the ATM model

Referring back to the methodology described in section 3.2, the main assumption for the ATM model is that the Poisson distribution is good enough for analyzing air traffic data (aircraft count, number of messages). To validate and justify the Poisson-based model, the statistical hypothesis can be verified using an empirical dataset of air traffic, using for instance non-parametric tests such as the Chi-Squared test [2].

The validation of the model can be also performed estimating the model parameters λ and ϕ, taking as a reference a real sample dataset of air traffic. The estimated values $\hat{\lambda}_{dt}$ and $\hat{\phi}_{dt}$ would serve to refine the assumptions taken in the data loading analysis of the thesis (see section 3.3), enhancing the air traffic model accuracy based on real measurements. This statistical methodology would be used as a tool for the control of the process defined by Eurocontrol [9] in the scope of the forecast estimations of the air traffic.

Hereinafter we briefly describe a methodology to estimate the model parameters based on a real sample dataset of air traffic.

Several methods have been proposed in the literature to estimate the two parameters, λ and ϕ, of the Neyman Type A distribution presented in Equation 2 (see [3], Sec. 6.4]. The most usual are the maximum likelihood method and the moments' method.

Given a sample of the number of messages $y_{dtj}; j = 1, 2, \cdots, m_{dt}$, of size m_{dt} , observed in a_d and Δt, the maximum likelihood estimators, $\hat{\lambda}_{dt}$ and $\hat{\phi}_{dt}$, are found solving the maximum likelihood equations:

$$\frac{1}{m_{dt}} \sum_{j=1}^{m_{dt}} y_{dtj} = \bar{y}_{dt} = \hat{\lambda}_{dt} \hat{\phi}_{dt}$$

$$\sum_{j=1}^{m_{dt}} \frac{(y_{dtj} + 1) P(Y_d(t) = y_{dtj} + 1 \mid \hat{\lambda}_{dt}, \hat{\phi}_{dt})}{P(Y_d(t) = y_{dtj} \mid \hat{\lambda}_{dt}, \hat{\phi}_{dt})} = m_{dt} \bar{y}_{dt}$$

These equations can be solved iteratively, using a Newton-Raphson approach. The resulting moments' estimators are:

$$\hat{\lambda}_{dt} = \frac{\bar{y}_{dt}}{\hat{\phi}_{dt}}$$

$$\hat{\phi}_{dt} = \frac{s_{dt}^2 - \bar{y}_{dt}}{\bar{y}_{dt}} ,$$

where $s_{dt}^2 = \frac{1}{m_{dt}} \sum_{j=1}^{m_{dt}} (y_{dtj} - \bar{y}_{dt})^2$

Moments' estimate can be used as initial values in the iterative Newton-Raphson procedure to found the maximum likelihood estimators.

The estimator's uncertainty can be assessed using their variances: if the sample size m_{ht} is large, they are:

$$V\hat{\lambda}_{dt} \simeq \frac{\lambda_{dt}\left[2+\phi_{dt}^{2}+2\lambda_{dt}(1+\phi_{dt})^{2}\right]}{\phi_{dt}^{2}m}$$

$$V\hat{\phi}_{dt} \simeq \frac{\lambda_{dt}\left[2+\phi_{dt}+2\lambda_{dt}(1+\phi_{dt})^{2}\right]}{\lambda_{dt}m}$$

6.3 Data Loading Analysis using Octave

6.3.1 Results for the Case Study 1

a) Probability of Aircraft Count given $\lambda_{dt}=5$, **from** $n_{dt}=0$ **to** $n_{dt}=20$:

$$P(N_d(t)=n_{dt}|\lambda_{dt}=5)=\frac{e^{-5}5^{n_{dt}}}{n_{dt}!}$$

$N_d(t)=n_{dt}$	$P(N_d(t)=n_{dt}\|\lambda_{dt}=5)=\frac{e^{-5}5^{n_{dt}}}{n_{dt}!}$
0	0.0067379
1	0.033690
2	0.084224
3	0.14037
4	0.17547
5	0.17547
6	0.14622
7	0.10444
8	0.065278
9	0.036266
10	0.018133
11	0.0082422

12	0.0034342
13	0.0013209
14	4.7174e-04
15	1.5725e-04
16	4.9139e-05
17	1.4453e-05
18	4.0146e-06
19	1.0565e-06
20	2.6412e-07
Total	0.971

Table 5. Case Study 1. Probability Function of Aircraft Count

b) Probability of ACL Messages given $\lambda_{dt}=5$ and $\phi_{dt}=2$, **from** $n_{dt}=0$ **to** $n_{dt}=20$:

Probability Function: $P(Y_d(t)=y_{dt}\,|\,\lambda_{dt}=5,\phi_{dt}=2)=\sum_{n_{dt}=0}^{20}\frac{e^{-5}5^{n_{dt}}}{n_{dt}!}\frac{e^{-n_{dt}2}(n_{dt}2)^{y_{dt}}}{y_{dt}!}$

Distribution Function: $F_{Y_d(t)}(y_{dt})=\sum_{y_{dt}=0}^{y_{dt}}P(Y_d(t)=y_{dt}\,|\,\lambda_{dt}=5,\phi_{dt}=2)$

$Y_d(t)=y_{dt}$	$P(Y_d(t)=y_{dt}\,\|\,\lambda_{dt}=5,\phi_{dt}=2)$	$F_{Y_d(t)}(y_{dt})=\sum_{y_{dt}=0}^{y_{dt}}P(Y_d(t)=y_{dt}\,\|\,\lambda_{dt}=5,\phi_{dt}=2)$
0	0.013256	0.013256
1	0.017940	0.031196
2	0.030079	0.061275
3	0.041715	0.10299
4	0.052587	0.155577

5	0.061965	0.217542
6	0.069059	0.286601
7	0.073429	0.36003
8	0.075002	0.435032
9	0.073982	0.509014
10	0.070760	0.579774
11	0.065841	0.645615
12	0.059757	0.705372
13	0.053020	0.758392
14	0.046077	0.804469
15	0.039283	0.843752
16	0.032903	0.876655
17	0.027110	0.903765
18	0.022000	0.925765
19	0.017611	0.943376
20	0.013864	0.95724
21	0.010794	0.968034
22	0.0083014	0.9763354
23	0.0063109	0.9826463
24	0.0047451	0.9873914
25	0.0035305	0.9909219
26	0.0026007	0.9935226
27	0.0018982	0.9954208
28	0.0013747	0.9967955

29	9.9172e-04	0.99778722
30	6.9794e-04	0.99848516

Table 6. Case Study 1. Probability of ACL messages.

6.3.2 Results for the Case Study 2

a) Probability of Aircraft Count given $\lambda_{dt} = 3$**, from** $n_{dt} = 0$ **to** $n_{dt} = 20$:

Probability Function: $P(N_d(t) = n_{dt} | \lambda_{dt} = 3) = \dfrac{e^{-3} 3^{n_{dt}}}{n_{dt}!}$

$N_d(t) = n_{dt}$	$P(N_d(t) = n_{dt} \| \lambda_{dt} = 3) = \dfrac{e^{-3} 3^{n_{dt}}}{n_{dt}!}$
0	0.049787
1	0.14936
2	0.22404
3	0.22404
4	0.16803
5	0.10082
6	0.050409
7	0.021604
8	0.0081015
9	0.0027005
10	8.1015e-04
11	2.2095e-04
12	5.5238e-05
13	1.2747e-05
14	2.7315e-06
15	5.4631e-07
16	1.0243e-07
17	1.8076e-08

18	3.0127e-09
19	4.7569e-10
20	7.1354e-11
Total	0.999

Table 7. Case Study 2. Probability Function of Aircraft Count

b) Probability of SURV Messages given $\lambda_{dt} = 3$, from $n_{dt} = 0$ to $n_{dt} = 20$:

Probability Function: $P(Y_d(t) = n_{dt}\frac{\Delta t}{10}) = P(N_d(t) = n_{dt} \middle| \lambda_{dt} = 3) = \frac{e^{-3}3^{n_{dt}}}{n_{dt}!}$

Distribution Function: $F_{Y_d(t)}(y_{dt} = n_{dt}\frac{\Delta t}{10}) = \sum_{y_{dt}=0}^{n_{dt}} \frac{e^{-3}3^{n_{dt}}}{n_{dt}!}$

$N_d(t) = n_{dt}$	$Y_d(t) = n_{dt}\frac{\Delta t}{10}$	$P(Y_d(t) = n_{dt}\frac{\Delta t}{10})$	$F_{Y_d(t)}(y_{dt} = n_{dt}\frac{\Delta t}{10})$
0	0	0.049787	0,049787
1	$Y_d \quad t \ = \frac{\Delta t}{10}$	0.14936	0,199147
2	$Y_d \quad t \ = 2\frac{\Delta t}{10}$	0.22404	0,423187
3	$Y_d \quad t \ = 3\frac{\Delta t}{10}$	0.22404	0,647227
4	$Y_d \quad t \ = 4\frac{\Delta t}{10}$	0.16803	0,815257
5	$Y_d \quad t \ = 5\frac{\Delta t}{10}$	0.10082	0,916077
6	$Y_d \quad t \ = 6\frac{\Delta t}{10}$	0.050409	0,966486
7	$Y_d \quad t \ = 7\frac{\Delta t}{10}$	0.021604	0,98809
8	$Y_d \quad t \ = 8\frac{\Delta t}{10}$	0.0081015	0,9961915

9	$Y_d \quad t = 9\frac{\Delta t}{10}$	0.0027005	0,998892
10	$Y_d \quad t = 10\frac{\Delta t}{10}$	8.1015e-04	0,99970215
11	$Y_d \quad t = 11\frac{\Delta t}{10}$	2.2095e-04	0,9999231
12	$Y_d \quad t = 12\frac{\Delta t}{10}$	5.5238e-05	0,999978338
13	$Y_d \quad t = 13\frac{\Delta t}{10}$	1.2747e-05	1.0
14	$Y_d \quad t = 14\frac{\Delta t}{10}$	2.7315e-06	1.0
15	$Y_d \quad t = 15\frac{\Delta t}{10}$	5.4631e-07	1.0
16	$Y_d \quad t = 16\frac{\Delta t}{10}$	1.0243e-07	1.0
17	$Y_d \quad t = 17\frac{\Delta t}{10}$	1.8076e-08	1.0
18	$Y_d \quad t = 18\frac{\Delta t}{10}$	3.0127e-09	1.0
19	$Y_d \quad t = 19\frac{\Delta t}{10}$	4.7569e-10	1.0
20	$Y_d \quad t = 20\frac{\Delta t}{10}$	7.1354e-11	1.0

Table 8. Case Study 2. Probability Function of SURV messages