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DEGREE'S FINAL THESIS

THESIS TITLE: Future of Datalink applications

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Resumen

Las aeronaves deben volar en un espacio aéreo seguro y esta seguridad se consigue gracias a la información que los proveedores ofrecen a los servicios de control aéreo. En el caso de España el servicio encargado de facilitar dicha información es ENAIRE.

El crecimiento de la aviación desde su primer despegue hasta el día de hoy ha supuesto que la infraestructura necesaria para el desarrollo seguro haya tenido que sufrir transformaciones. Esto se debe a que en un inicio cuando se creó todo este complejo la densidad de tráfico no era tan elevada como en la actualidad. Conscientes de la necesidad de mejora, la Organización de Aviación Civil Internacional (OACI), creó a principios de los años 80 el comité FANS ("Future Air Navigation Service"). Dicha junta, después de una década de estudios y varias reuniones, llegaron a la conclusión de que debían cambiar el concepto de la comunicación aeronáutica basada en voz a un intercambio de información a través del enlace de datos. Esta idea se denominó CNS/ATM (Comunicaciones, Navegación, Vigilancia / Gestión del Tráfico Aéreo) y esta tecnología pretendía automatizar la gestión del tráfico aéreo y optimizarlo, con la finalidad de soportar la creciente demanda a nivel mundial.

El objetivo de esta tesis es poder llegar a la mayor cantidad de usuarios que estén interesados en esta tecnología aplicada al mundo de la aviación.

Este proyecto consta de tres grandes partes, la primera consistirá en la explicación de cómo funciona el mundo ANS (Servicios de Navegación Aérea) y la organización que hay detrás OACI. Una vez tratado ese tema se da paso al segundo y más importante, el cual tratará sobre el enlace de datos. Aquí se explicará el data link, sus aplicaciones en el sector aeroespacial y sus distintas tecnologías. Finalmente, se hablará sobre el futuro de dichas tecnologías y se hará una apuesta sobre la que podrá predominar sobre las demás.

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Overview

Aircraft must fly in safe airspace and this safety is achieved thanks to the information that providers offer to air traffic control services. In the case of Spain, the service responsible for providing this information is ENAIRE.

The growth of aviation from its first take-off to the present day has meant that the infrastructure necessary for safe development has had to undergo transformations. This is due to the fact that at the beginning, when this complex was created, traffic density was not as high as it is today. Aware of the need for improvement, the International Civil Aviation Organisation (ICAO) set up the FANS ("Future Air Navigation Services") committee in the early 1980s. This board, after a decade of studies and several meetings, concluded that they had to change the concept of voice-based aeronautical communication to an exchange of information via data link. This idea was called CNS/ATM (Communications, Navigation, Surveillance / Air Traffic Management) and this technology was intended to automate air traffic management and optimise it in order to support the growing demand worldwide.

The aim of this thesis is to reach as many users as possible who are interested in this technology applied to the world of aviation.

This project consists of three main parts, the first one will consist of the explanation of how the ANS (Air Navigation Services) world works and the organisation behind ICAO. Once this topic has been dealt with, the second and most important part, which will deal with data link, will follow. Here data link, its applications in the aerospace sector and its different technologies will be explained. Finally, the future of these technologies will be discussed and a bet will be made on which one will predominate over the others.

CONTENTS

LIST OF FIGURES

ACRONYMS, ABBREVIATIONS AND DEFINITIONS

AAC: Airline Administrative Communications

ABAS: Aircraft Based Augmentation Systems

ACARS: Aircraft Communications Addressing and Reporting System

ACC: Area Control Centre

ADS: Automatic Dependant Surveillance

ADS-B: Automatic Dependant Surveillance Broadcast

ADS-C: Automatic Dependant Surveillance Contract

AFN: ATS Facilities Notification

AIP: Aeronautical Information Package

AIS: Air Information Service

ALS: Alert services

AMSS: Aeronautical Mobile Satellite Service

ANS: Air Navigation Service

AOC: Airline Operational Control

AOCC: Airline's Operations Control Center

APC: Aeronautical Passenger Communications

ASM: Airspace Management

ATC: Air Traffic Control

ATFM: Air Traffic Flow Management

ATIS: Air Traffic Information Service

ATM: Air Traffic Management

ATN: Aeronautical Telecommunication Network

ATS: Air Traffic Service

CIRC: Aeronautical Information Circular

CMU: Communications Management Unit

CNS: Communications, Navigation, Surveillance

CPDLC: Controller Pilot Data Link Communications

DME: Distance Measuring Equipment

ICAO: International Civil Aviation Organisation

FANS: Future Air Navigation Services

FIS: Flight information services

FMS: Flight Management System

GAT: General Air Traffic

GBAS: Ground Based Augmentation Systems

GNSS: Global Navigation Satellite System

GPS: Global Positioning System

HF: High Frequency

ILS: Instrument Landing System

LDACS: L-Band Digital Aeronautical Communication System

MET: Meteorological Service

MLAT: Multilateration Systems

NDB: Non-Directional Beacon

NOTAM: Notice to Air Missions

OAT: Operational Air Traffic

PSR: Primary Surveillance Radar

SATCOM: Satellite Communication datalink

SBAS: Satellite Based Augmentation Systems

S&R: Search and Rescue Service

SMR: Surface Movement Radar

SSR: Secondary Surveillance Radar

TWR: Tower controller

TMA: Terminal Manoeuvring Area

VOLMET: Weather information for aircraft in flight

VOR: Very High Frequency Omnidirectional Range

VHF: Very High Frequency

VDLM2: VHF Data Link Mode 2

INTRODUCTION

If we go back to the beginnings of aviation, the first daytime flights were flown by observing the terrain and comparing it with a map to obtain the position and course to follow. But for night flights, or when weather conditions worsened, it became necessary to use technical means to continue the flight safely. And so, the different means and methods of air navigation began to be designed, ranging from the use of a chronometer and a map to the current positioning systems using radio signals or those based on inertial platforms and satellites.

From the first take-off to the present day, air traffic has grown exceptionally. This has resulted in the need to direct the flow of aircraft in order to provide safe and reliable navigation during all phases of flight. In order to meet this need in the 1980s, the International Civil Aviation Organization (ICAO) recognized that the traditional Air Navigation and Communication systems and procedures used for civil aviation were reaching their operational limits and the Council took the important decision to establish a committee to study and establish the concepts on which future Air Navigation and Communication Systems would be based.

The committee formed the FANS concept, which later became the CNS/ATM system. The CNS/ATM is a service provided by a complex set of technical and human resources to provide adequate support for the development of air transport, and more specifically air navigation and air traffic.

The purpose of this project is to make a study of the data link applied to the world of aviation. It is intended to reach all audiences interested in this technology, so we have divided the work into the following chapters:

1. **Air Traffic Service Providers:** In this chapter, the different organizations that support air navigation will be explained in detail. Its aim is to give a general idea of how it works and that readers who are not familiar with this world can also understand how it works.

2. **Overview of CNS/ATM:** The aim is to explain what the CNS/ATM scheme is, what its origin was and what improvements it brought to civil aviation.

3. **Datalink:** This section is one of the most important of the project as it will explain what the datalink is and how to work with it in the aeronautical sector. Its relevance lies in the fact that the concepts of this technology must be clear.

4. **The technologies behind the ATN system:** As its title indicates, this chapter will explain all the technologies with which the data link can or will be used to exchange information between air traffic controllers and pilots.

5. **Conclusions:** Finally, the most important section of the thesis will discuss the technology that will prevail over the others in time.

CHAPTER 1. AIR TRAFFIC SERVICE PROVIDERS

Air Navigation Service Provider is the organisation that provide certain services for the safe management of air operations. These services are air traffic management, air traffic services, air traffic flow management, airspace management, communication, navigation and surveillance services, aeronautical information service, meteorological services for air navigation and search and rescue services.

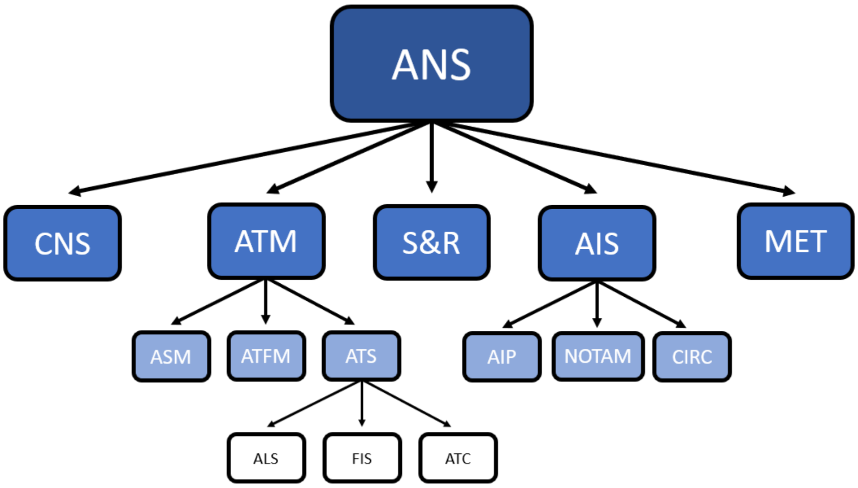

Fig. 1.1 Diagram of the different air traffic service providers

1.1. Communication, navigation and surveillance services

The CNS service consists of three pillars: communications, navigation and surveillance. Its purpose is to support the development of navigation and air traffic, thanks to the knowledge of the aircraft's position and flight plan.[1]

- Communication:

  This service is responsible for providing communications support. A good example would be the optimisation of aeronautical communications systems through the modernisation of infrastructures and associated procedures. This organisation provides the following communications services:

  - Data communication services for air navigation and operational voice applications for air traffic management.
  - Ground-air and ground-ground communications equipment and systems renewal processes including control centre and control tower voice communications.

  - Air-navigation data network evolution projects.
  - Verification and guaranteeing of ground-air communications coverage and radio spectrum management.
  - Projects involving the evolution of ATIS/VOLMET meteorological data systems.
  - Actions related to the datalink service.

- Navigation:

  Its purpose is to provide aircraft with information about the space they are in. In order to give this support, ENAIRE has a network of navaids that are responsible for locating the different aircraft in the airspace. Thanks to the different radio aids, ENAIRE offers the following navigation services:

  - Conventional navigation services: VOR, ILS, DME and NDB services.
  - Satellite navigation services: GBAS services and support for the provision of SBAS services.

- Surveillance:

  Determining the relative positions of aircraft (position, identification, altitude, etc.) in order to establish safe separation distances between them. This information is transferred to the air traffic controllers so that they can communicate the necessary actions to the pilots. The radars that provide such information are the following:

  - <u>PSR (Primary Surveillance Radar):</u> enables detection of non-cooperative targets in en-route and TMA environments.
  - <u>SSR (Secondary Surveillance Radar):</u> enables the detection of cooperative targets in en-route and TMA environments, including Mode S.
  - <u>SMR (Surface Movement Radar):</u> enables detection of non-cooperative targets in airport environments.
  - <u>MLAT (Multilateration Systems):</u> enables cooperative target detection in TMA (WAM) and airport environments.
  - <u>ADS-C (Automatic Dependant Surveillance Contract):</u> automatic dependent surveillance by contract.
  - <u>ADS-B (Automatic Dependant Surveillance Broadcast):</u> automatic dependent surveillance by broadcast.

1.2. Air traffic management

The ATM services consist of air traffic and airspace management, including air traffic services, airspace management and air traffic flow management, in a safe, economical and efficient manner, through the provision of seamless facilities and services in cooperation with all parties and involving air and ground functions.

As can be seen in the diagram above, air traffic management provides three main services:

- Airspace management:

  The objective is to manage airspace as efficiently as possible to satisfy its many users, both civil and military. This service concerns both how airspace is allocated to its various users (through routes, zones, flight levels, etc.) and how it is structured to provide air traffic services.

  An essential concept within this ASM function is that of Flexible Use of Airspace (FUA), which is based on the consideration that airspace cannot be understood as purely military or civil but must be a continuum in which the needs of all users can be accommodated to the maximum extent possible.

  The ASM is developed at three levels depending on the coordination tasks between civilian and military authorities:

  - Level 1 (Strategic): The objective of the first level is the definition of national airspace polices and the establishment of pre-determined airspace structure.

  - Level 2 (Pre-tactical): At this second level, airspace structures and areas are allocated daily according to user needs. It is coordinated through the civil-military Airspace Management Cell (AMC).

  - Level 3 (Tactical): At this last level, the airspace is used in real time, allowing the safe and coordinated operation of operational and general traffic (OAT/GAT).

- Air traffic flow management:

  The main objective is to contribute to a safe and orderly flow of air traffic by ensuring that air traffic control capacity is utilised to the maximum extent possible, and that traffic volume is compatible with the capacities declared by the air traffic services authority. The purpose of such ATFM measures, is to:

  - Increase safety of operations and avoid excessive air traffic demand compared to the declared capacity of sectors and aerodromes.

    - Optimise the efficiency of the network in order to provide the maximum possible capacity and to minimise the workload of air traffic controllers as much as possible.

    - Assist in the management of critical situations.

- Air traffic services:

  The purpose of this service is to ensure a safe and orderly flow of traffic, thanks to the indications and information provided by air traffic controllers to the flight crew. In summary, this service is divided into three main groups:

    - Air traffic control (ATC): The main functions of air traffic controllers are to avoid collisions between aircraft and between aircraft and obstacles by applying appropriate separation rules and providing timely clearances and instructions that create an orderly and safe flow. For example, accommodating crew requests for desired flight levels and trajectories, ensuring continuous climb and descent operations, reducing wait times in the air and on the ground.

      As is well known, airspace is very extensive and in order to manage everything correctly, this mission is divided into three teams. The first team oversees managing the flights in a limited area of airspace. The mission of the second team is to manage the entry and exit of controlled flights in a control area and in the areas determined in the terminal control areas (holding, approach, take-off and landing phases). Finally, the function of the last team is to manage aircraft in and around the airport.

    - Flight information services (FIS): The purpose of this service is to advise and provide information useful for the safe and efficient conduct of flights. This service is provided to air traffic controllers so that they can report necessary changes, such as weather conditions or the status of navigation aids.

    - Alert services (ALS): Its purpose is to notify and assist the relevant agencies of aircraft in need of search and rescue assistance. This alert service is indispensable in support of the Air Rescue Service (SAR).

1.3. Air information services

The goal of the Air Information Service (AIS) is to provide the aeronautical information and data necessary for the safety, regularity and efficiency of air navigation. This information, which includes the availability of air navigation facilities and services and associated procedures, must be provided to flight operations personal, as well as to ATS units responsible for the flight information service and services responsible for pre-flight briefing.

In order to achieve the standardisation necessary for the operational use of this information by international civil aviation, existing regulations define how aeronautical information is collected and managed, and specifically how an aeronautical information service should receive and/or originate, collate or assemble, edit, format, publish/store and distribute specified aeronautical information/data.

ICAO Annex 15 specifies that aeronautical information shall be published as an integrated aeronautical information package (IAIP), composed of the following elements according to the type of information to be distributed:

- Aeronautical Information Publications (AIP):

  The AIP is the basic aeronautical information manual, published by a state or its authority, containing aeronautical information of a permanent nature and temporary changes of long duration essential to air navigation. Its use is essential for air navigation and airport operations.[2]

  The structure and content of the document is standardised by international agreement through ICAO. AIPs usually have three parts: GEN (general, containing administrative and explanatory information), ENR (en route, containing information relating to airspace such as ATS procedures and rules, airspace description, etc.) and AD (aerodromes, containing information relating to aerodromes/heliports in the territory like geographical and administrative data, physical characteristics, associated cartography, etc.).

  AIPs are cumbersome documents, not usually intended for use in the air. Commercial organisations produce relevant extracts to form flight information publications of convenient size for use on aircraft.

- Notice to Air Missions (NOTAM):

  The NOTAM is a notice containing information concerning the establishment, condition or change of any aeronautical facility, service, procedure or hazard, timely knowledge of which is essential to personnel concerned with flight operations. These notices are communicated by the most expeditious means available to all recipients to whom the information is considered to be of direct operational importance.[3]

- Aeronautical Information Circular (CIRC):

  The CIRC is a notice containing information that does not qualify for the origination of a notice to air mission or for inclusion in the AIPs, but which relates to flight safety, air navigation, technical, administrative or legislative matters.[2]

1.4. Meteorological Services

The Meteorological Service is provided thanks to the State Meteorological Agency (AEMET) through which aeronautical users can access updated reports and forecasts, both for areas and aerodromes, which will inform them of the existing and forecast weather for their flight.

These users will be able to access the following information:

- Aeronautical maps: Significant maps (SIGWX) and/or wind and temperature maps can be found here.
- METAR, TAF and Aerodrome warnings: Observations and weather forecasts for airports.
- TAF colour matrix: The TAF table is a temporal representation of the weather conditions forecast for national airports.
- SIGMET: Warnings about significant weather phenomena en route.
- GAMET and AIRMET: Forecast and area warnings for low altitude flights.
- AIREP: Special reports issued based on notifications by aircraft in flight of adverse weather phenomena observed during their trajectory.
- Volcanic ash warnings: Images with the latest warnings, in graphic format, from volcanic ash warning centres (VAAC) around the world.
- Ash and Cyclone SIGMET: World map with the location of FIR areas reported with a volcanic ash or tropical cyclone SIGMET.

1.5. Search & Rescue

Search and Rescue Service (S&R) is provided to survivors of aircraft accidents, as well as to aircraft in distress (and their occupants), regardless of their nationality. The basic elements include a legal framework, a responsible authority, organised available resources, communication facilities and a workforce trained in coordination and operational functions. This service performs the functions of relief, communication, coordination and search and rescue, initial medical assistance or medical evacuation, through the use of public and private resources, including aircraft, ships and other cooperating vessels and facilities.

The S&R service, although related to the warning service, is not part of air traffic services (ATS), as it does not fulfil any of the ATS objectives. However, close cooperation with ATS units is ensured through the establishment of relevant procedures.

States define the regions in which the S&R service is provided. These regions do not overlap and normally coincide with the corresponding flight information regions (FIRs). However, neighbouring states are advised to develop common S&R plans and procedures to facilitate the coordination of these operations.[4]

CHAPTER 2. Overview of CNS/ATM

2.1. Historical background of the CNS/ATM system

In order to talk about how the CNS/ATM system was formed, it goes back to the increase of traffic in the aerospace sector. Due to this consequence and the limitations of the air navigation system at the time, in the early 1980s ICAO recognised the need for urgent improvements and created the FANS committee. At that meeting (FANS phase I) they reached the following conclusions:

a) The main obstacle was the increase in air traffic in certain geographical areas, which reached a point of saturation that prevented the navigation systems from giving an adequate response to each aircraft.

b) While it is true that the technology had reached a very remarkable level of development, it could not be applied to its full extent because there were areas where the coverage of the systems did not reach and others where they could not be implemented to their full extent.

c) Finally, it was noted that air navigation was deficient due to a lack of information and the capacity to process it. This made it difficult to solve certain required operations.

In 1989, ICAO established a special committee on Future Air Navigation Systems (FANS Phase II). The objective of this meeting was to ensure the proper implementation of future CNS/ATM systems worldwide in a cost-effective and balanced manner. The following points were discussed at this meeting:

a) Identify and make recommendations for concrete institutional arrangements for the global airborne navigation system of the future, considering funding, ownership and management.

b) To develop a coordinated, transition-oriented global plan, including recommendations necessary to ensure the progressive and orderly implementation of the global air navigation system of the future.

Finally, in September 1991, the 10th conference brought together numerous representatives from different states to consider and approve the concept of a future air navigation system developed by the FANS committees. The FANS concept, which became known as the communications, navigation, surveillance/air traffic management (CNS/ATM) systems.

In the following image we can see a summary of the different meetings that took place until the global air navigation plan for CNS/ATM system

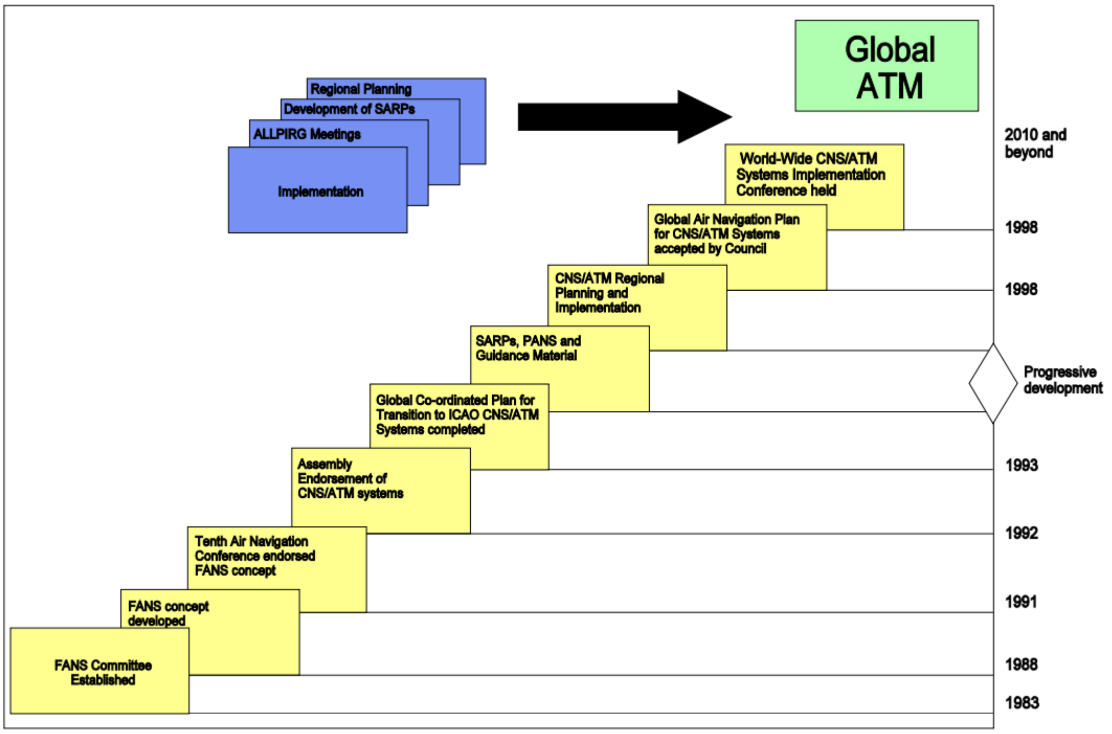

Fig. 2.1 Chronological scheme of the different meetings that took place until the creation of the CNS/ATM system.[5]

The approval of CNS/ATM systems established the beginning of a new era for international civil aviation and the main benefits they would contribute are the following:

- Increased aircraft capacity, especially in congested airspace.
- Increased schedule flexibility.
- Improv the levels of safety.
- Better flight path efficiency.
- Less disruption due to delays and diversions.
- Increased efficiency from reduced separation minimum.
- Minimize aircraft engine fuel consumption and emissions.

2.2. How the CNS/ATM plan would improve civil aviation

2.2.1 Communication

Currently, communications used in air navigation are based on the use of very high frequency (VHF) channels. However, these same channels will be used to transmit digital data.

In addition to VHF communication, data and voice communications via satellites and data transmission on high frequency (HF) channels are also being introduced. These new communication technologies are used in order to achieve global coverage.

Within the aeronautical communications section we can distinguish two categories:

- Air-ground communications:

  Air-ground communications are understood to be those established between aircraft and stations or located on the ground.

  In this category it is expected that communications in the en-route phase of flight will be carried out through the exchange of digital data. This process consists of the user selecting a particular message from a set of pre-built messages via an on-screen menu. Once the message is selected, some parameters or free text can be added to the message to send the desired information. In addition to the messages sent manually, information would also be transferred automatically. However, this tool would not be useful in crowded areas and, therefore, it is probably that in those areas the use of voice communications would still be preferred. It is also known that the exchange of information by digital data will considerably reduce the volume of voice communications, which will be a great help for both air traffic controllers and pilots.

  In the following two images you can see how the display that supports this technology would look like and the path that the message follows.

  The first image shows a screen with very intuitive buttons to generating the message as well as read it. This is because the technology must be used during the flight and cannot be a distraction for the pilots, so the information to be transmitted must also be brief and clear.

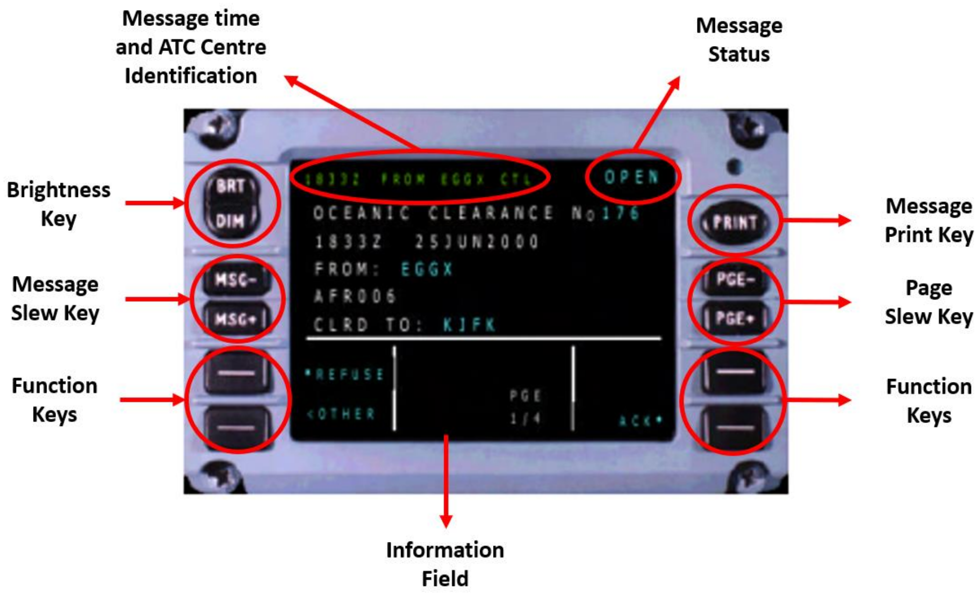

Fig. 2.2 Display that supports the Datalink technology.

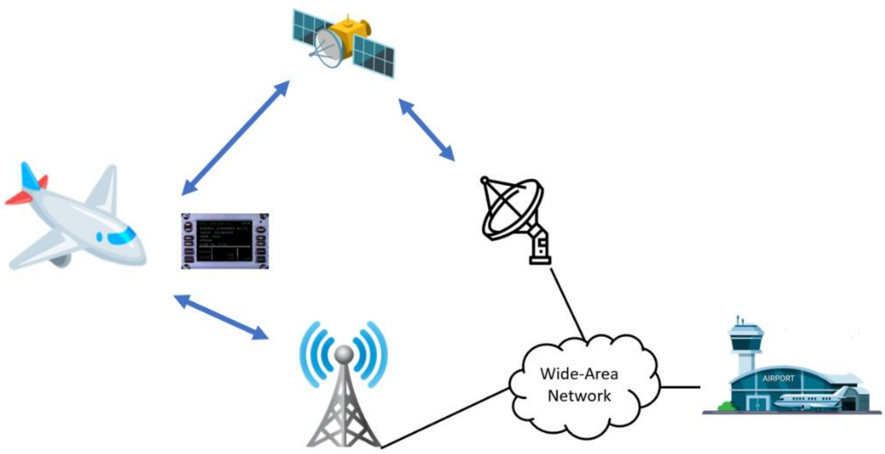

Fig. 2.3 The path that the message follows.

The second figure shows in a simplified way the path taken by the message generated by the pilot or by the air traffic controller. Firstly, the message would be generated on the display, where the buttons can be used to choose between prescribed text or to generate one's own with the desired information. Once the text has been decided it will be sent to the nearest satellite or to an antenna, depending on the protocol being followed at the time. Finally, the message will reach a wide-area network from where it will be transmitted to the company or a control tower depending on its destination. If the message was generated in the control tower, the path it would follow would be the same but in the opposite direction.

- Ground-ground communications:

  Ground/ground communications are defined as communications between air traffic controllers for coordination, and between air traffic controllers and support (emergency), management and administrative personnel.

  It is expected that most routine communications between users and aeronautical ground systems will be by digital data exchange. For example, communications between entities such as meteorological offices, NOTAM offices, aeronautical databanks, ATS units, etc.[6]

  It is true that, for emergencies or non-routine communications, voice communication will continue to be the main means of communication.

To some up, the following image show how through the CNS/ATM plan the communications system would be improved and would have the following benefits:

- Channel congestion for radio communication is reduced.
- Compression failure is reduced as much of the information is sent by message instead of being transmitted by voice.
- An additional communication path is provided.
- Reduced workload for both pilots and air traffic controllers.
- It increases the availability of communications.

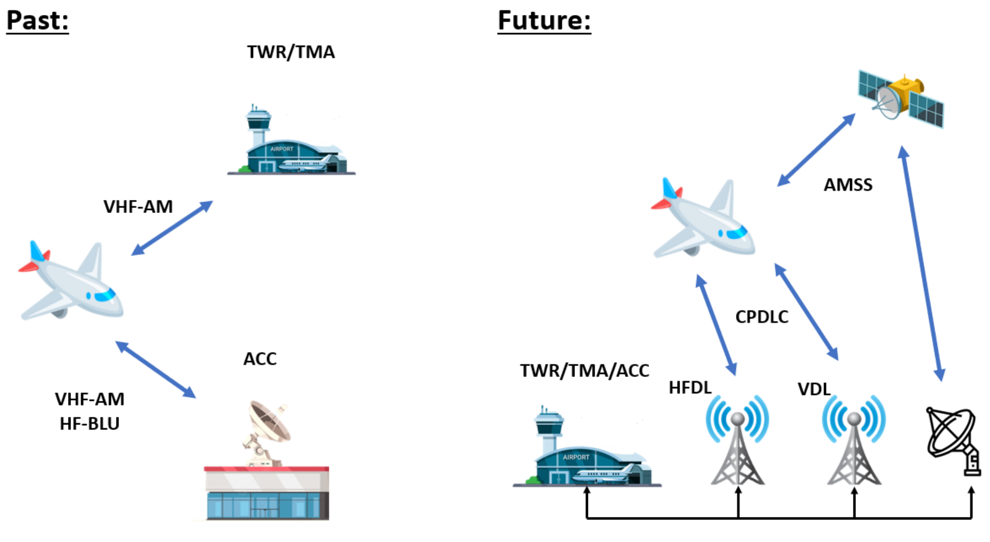

Fig. 2.4 Upgrade of the communication system through the CNS/ATM plan.

2.2.2 Navigation

In 2001, operational performance requirements are to be met, therefore ICAO requires that CNS/ATM systems responsible for improving air navigation provide the capability to determine aircraft position accurately, reliably and seamlessly throughout all phases of flight and around the world. This will be achieved through the introduction of aeronautical satellite navigation and interoperable augmentations (GNSS).

- GNSS (Global Navigation Satellite System):

  The GNSS system is a generic term for satellite navigation systems that provide geospatial positioning with global coverage, both autonomously and with augmentation systems. The first operational system was the GPS system, managed by the United States Army, which is why, despite the development of other systems, in today's social culture it is such a widespread term that it is confused with the term GNSS, which includes other satellite navigation systems such as GLONASS, GALILEO, BEIDOU, etc.

  Being a system where a small error can cause many problems, the correct functioning of the system must be guaranteed. To this purpose, having a way of alerting users that the GNSS is behaving incorrectly is essential for the safety of the system and its users. GNSS avionics have software to provide timely warnings to the user when the system cannot be used for the intended operation.

  Apart from this software, aircraft, satellite and ground-based augmentation systems can ensure integrity. Various augmentation systems can be used to enhance the navigation performance provided by GNSS constellations.

  GNSS augmentation is a technique in which the use of ground stations and/or receiver processors (GPS, GLONASS and Galileo) improves the accuracy, integrity, availability and continuity of navigation, communication and/or surveillance equipment.

  - Types of augmentation:

    - Satellite Based Augmentation Systems (SBAS)

    - Aircraft Based Augmentation Systems (ABAS)

    - Ground Based Augmentation Systems (GBAS)

By way of summary, the following image shows how air navigation has been improved thanks to CNS/ATM systems. As can be seen, in the past, navigation was lacking in many aspects, it was not accurate, as it did not cover the entire airspace, it could not provide continuity, availability or integrity to all aircraft, and this was due to the absence of satellites or augmentation systems. If you look at the part of the picture that refers to the future, all these weaknesses are solved thanks to the systems that are now in place.

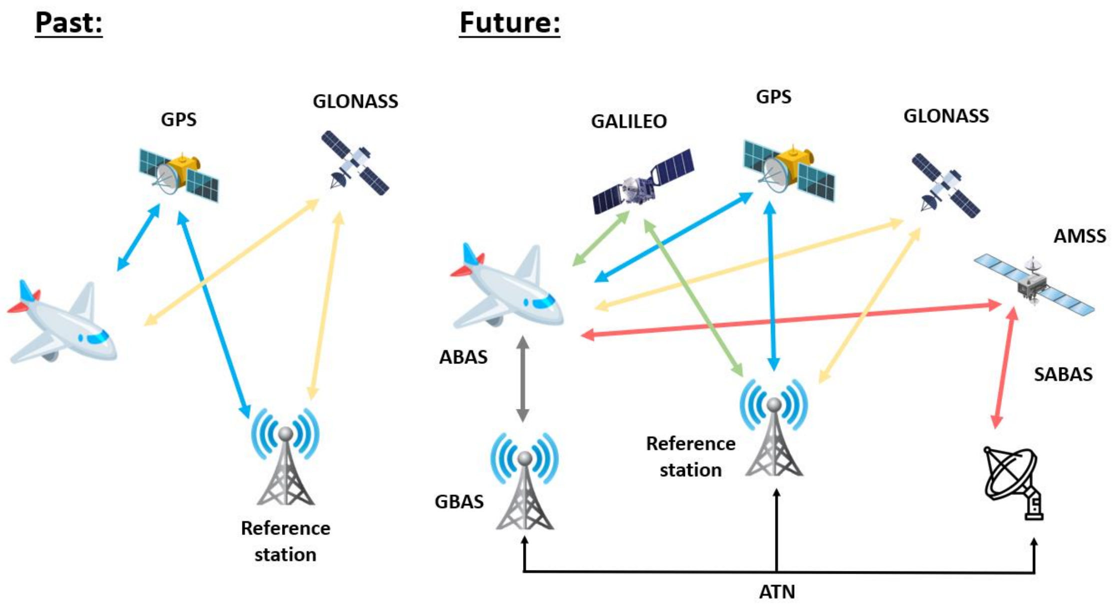

Fig. 2.5 Upgrade of the navigation system through the CNS/ATM plan.

2.2.3 Surveillance

Having explained the improvements that the CNS/ATM project would bring in terms of communication and navigation, it now only remains to see which are the points to be improved in the surveillance sector:

- Limited coverage (visual range).
- Shielding problems.
- Occasional false responses.
- Insufficient data exchange.
- Insufficient surveillance data in the cockpit.
- Lack of ability to monitor vehicle movement.

These weak points will be solved thanks to the implementation of these two new technologies.

- Secondary surveillance radar Mode “S” (SSR):

  Secondary surveillance radars (SSR) allow positioning aircraft in three dimensions, thanks to the implementation of a transponder in the aircraft. The system works as follows: the antenna on the ground encodes a message and sends it in the form of a train of modulated pulses at 1030 MHz. This message called interrogation arrives at the aircraft and decodes it, then the aircraft sends a coded response at 1090 MHz to the station. From this response the ground equipment can calculate the distance between itself and the aircraft by measuring the delay time of the signal sent and received.

  The responses transmitted by the aircraft can be of different modes, for example, mode A we obtain the aircraft identification, mode C we obtain the altitude and mode S which is the one we will focus on in this section. This mode allows us to know new parameters such as position, flight level (barometric), 4-digit octal identity, flight identifier, roll angle and many other parameters, so this SSR radar upgrade is much better.

  Mode S is an advanced selective interrogation system, which was introduced to solve the shortcomings of modes A and C. It is characterized by the ability to selectively interrogate aircraft. Each interrogation is directed to a single aircraft, it examines it to verify its own direction and if it matches, it transmits the appropriate answer. In this way we manage to eliminate the problems of overlapping answers. It is true that the possibility of being able to perform selective interrogations is achieved by knowing the position in which the desired aircraft is located. In order to know this future position, the radar uses both the previous position and the parameters received from the aircraft in order to calculate its future location

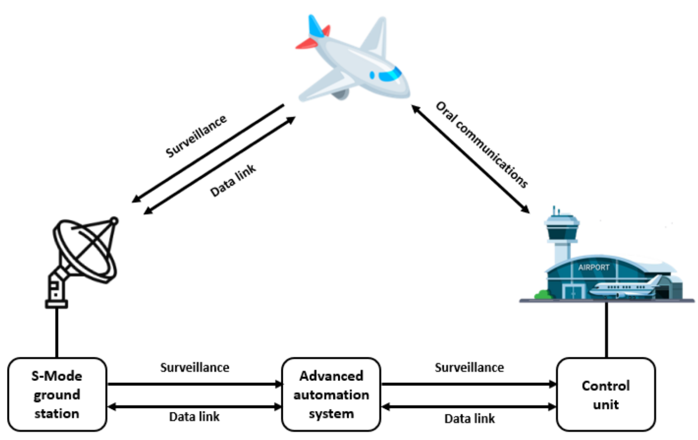

Fig. 2.6 Schematic diagram of SSR operation.

- Automatic dependent surveillance (ADS):

  This new technology will be based on ground-to-air data link. It is a surveillance technique in which aircraft will automatically provide, via a data link, information extracted from on-board navigation and position-fixing systems. That is, the data to be sent are aircraft identification, four-dimensional position and additional data as required. This information will be used by the automated ATC system and thus provide the necessary data to the air traffic controller.

  The ADS is an automatic system because no external stimulus is required; it is dependent because it relies on “on-board” systems to provide surveillance information to other parties.

  The implementation of this technology will bring with it many benefits such as surveillance of aircraft throughout all stages of flight even in remote and oceanic areas, so-called "gate-to-gate", improved flight safety, reduced minimum separation between aircraft and therefore also reduced delays. In addition to all these benefits, one of the most important is that ADS could replace primary or secondary radar in certain areas and thus relieve some of the bandwidth congestion.

  To implement this concept, two data delivery techniques have been defined, ADS-Broadcast (ADS-B) and ADS-Contract (ADS-C).

  - ADS-B is a surveillance technique based on the transmission of parameters such as aircraft identity, position, track, ground speed and other necessary information. The position update rate depends on the phase of flight, for example every 10 seconds in cruise and every second in approach.

    This information is sent in broadcast mode by means of a system known as "ADS-B out" to all interested parties, which will generally be the air traffic control stations, but may also be to other aircraft in order to facilitate knowledge of the air traffic situation, spacing and self-segregation, all this is achieved if these aircraft are equipped with a receiver known as "ADS-B in".

  - The ADS-C, unlike its brother, works in connected mode, which means that a connection must be established between the aircraft and the station interested in knowing its position. This contract can be periodic, per event or on demand.

The following image shows a schematic that summarizes the updates that the surveillance would receive once the CNS/ATM plan was implemented. As can be seen in the left part of the image, the surveillance system lacked precision and was not a secure system. But with the updating of the surveillance system all the problems are solved as explained in this section.

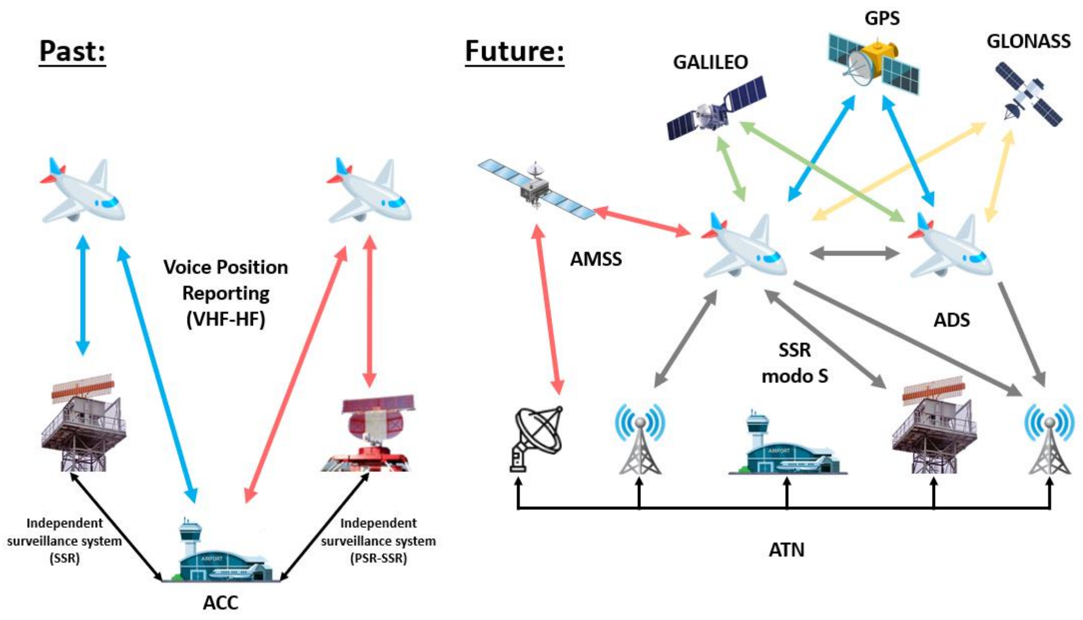

Fig. 2.7 Upgrade of the surveillance system through the CNS/ATM plan.

CHAPTER 3: Datalink

3.1. What is the Datalink?

Data link is a generic term for a communication technique that consists of the actual connection between a system on board an aircraft and a system on the ground or on board another aircraft, or both. This connection allows the exchange of digitized information in different ways (addressable, broadcast) and the message can also be transmitted via different communication media (VHF, HF, satellite).[7]

The following image shows a brief summary of the operation of this technology through a simple scheme where first the message/information is transmitted by the sender through different media. Once the message has been sent, the receiving unit transmits it to the addressee and displays the message on the screen.

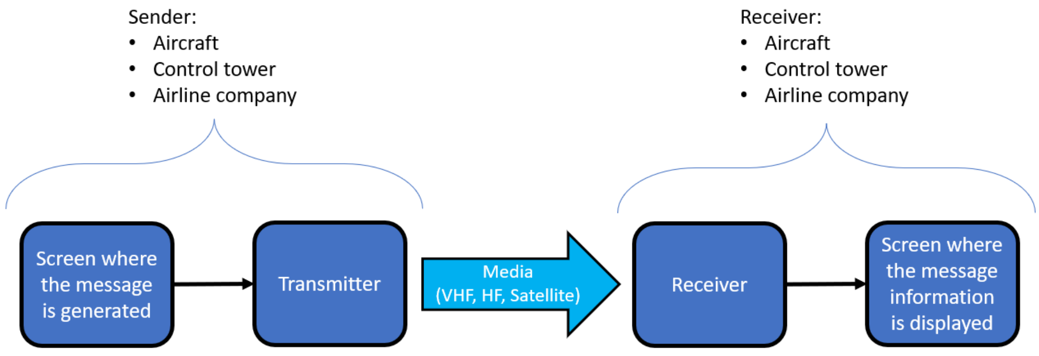

Fig. 3.1 Scheme of how the Datalink works.

The main benefits of this technology are as follows:

- Provide an alternative means of communication to voice.
- To automate communication tasks as much as possible.
- Reduce the workload of both the controller and the pilot.
- Increase ATM efficiency, capacity and safety.
- Provide additional information exchanges by utilizing the capabilities of automated systems on the ground and in the air.
- Provide surveillance in areas that are not suitable for radar coverage.

3.2. How Datalink communications work in the aeronautical sector?

Having explained what datalink is, it is time to explain how this type of communication works in the aerospace sector.

First, before establishing a connection between air traffic controller and pilot, the aircraft sends a first message called AFN (ATS Facilities Notification). Its purpose is to notify the ATC centre that the aircraft supports data link communications and is ready to start exchanging messages. The AFN notification can have the following purposes:

- To notify the ATC centre of the aircraft's data link communication capabilities, i.e., to indicate that CPDLC applications are available.

- Provide the ATC centre with the aircraft identification to allow correlation of the radar tracks with the corresponding flight plan.

Once the AFN message has been successfully completed, two messages are exchanged, which are called connection request and connection confirm. This exchange of messages takes place automatically, without the intervention of either the air traffic controller or the pilot.

For the connection to be secure, the aircraft performs several checks to approve or reject the link:

- The connection is accepted if there is no previously established connection.

- The connection is accepted if it is requested by the next ATC centre that is going to take control of the aircraft.

The last important concept that remains to be explained is the message frame. This frame is composed of two major parts, the header and the message elements.

- Header:

    - Message Identification Number: For each connection, the aircraft and the ground system assign an identifier to each uplink and downlink message, known as a message identification number. This identification number is an integer in the range 0 to 63. The ground system assigns the identification numbers for the uplink messages, and the aircraft assigns the numbers for the downlink messages.

    - Reference Number: All response messages shall also contain within their header a reference number. This number links it to the message to which it is being replied and is identical to the initial message identification number to which it refers.

- Date/Time: In all messages the date and time must be sent in the following format: YYMMDD HHMMSS

- Message Elements:
  - Element ID: Each of the elements of the frame is preceded by an element identification number, which is specific to each of the said elements and different from the message identification number.
  - Element data: This part is designated to the pre-constructed information to be sent to the air traffic controller for downlink messages or to the pilot for uplink messages.
  - Message attributes: These define the treatment to be applied by the CPDLC user receiving a message. There are three attributes: urgency, alert and response.

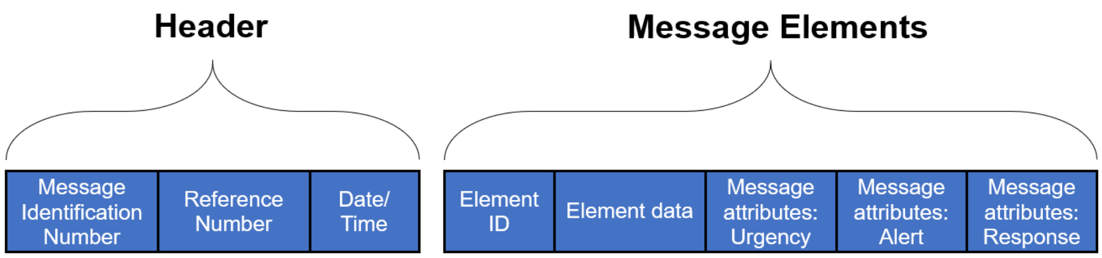

Fig. 3.2 Scheme the Datalink message frame.

3.3. Aeronautical data link communication categories

In the communication through the data link between air and ground, three categories are defined depending on who the message is addressed to. These categories are as follows:

- Air Traffic Services communications, between aircraft and ATC centers (CPDLC):

  Controller Pilot Data Link Communications (CPDLC) is a two-way data link system between pilot and controller. The purpose of this link is to transmit non-urgent strategic messages to the aircraft and thus free up voice communications. As explained in section "2.2.1", these text messages are displayed to pilots on a cockpit screen and allow them to communicate with air traffic controllers through a series of pre-built text exchanges.

This type of communication, by relying on text messaging, reduces workload and increases efficiency because the air traffic controller can be attending to other aircraft while waiting for other aircraft to respond.

The messages that are usually exchanged depend on the phase of flight the crew is in and the importance of the message. For example, if the aircraft is on take-offs, as departure time approaches, the pilot/co-pilot will send a departure request (indicating aircraft type, gate number and ATIS code) via the display and ATC will respond with the departure clearance. In addition, if we were in the cruise phase, the messages sent by the controllers would be flight level, speed and deviation assignments.

On the other hand, depending on the importance of the message, the information is grouped into three groups:

- Urgency → For very important messages.
- Alert → If the information conveyed by the message is severe.
- Response → When the message is an answer.

- Airlines Datalink Communications (AOC & AAC):

Airline Operational Control (AOC) communications refers to the transfer of data between the aircraft and the airline's operations control center. The role of the AOCC in this communication is to monitor and resolve operational problems.[8] To achieve this, the most common support functions in an AOCC are as follows:

- Flight Dispatch: They prepare flight plans and request new flight slots from Air Traffic Control entities.
- Aircraft Control: Their role is to coordinate aircraft in the event of various problems. For example, in a disruption situation, they try to minimize delays by changing aircraft, diverting or merging flights, among other actions.
- Crew control: Their role is to manage the crew. That is, they monitor crew check-in and check-out, update and modify the crew roster according to disruptions that may occur during the operation.
- Maintenance services: They are responsible for unplanned maintenance services and short-term maintenance scheduling.
- Passenger Services: Decisions will have an impact on passengers. The responsibility of this function is to consider and minimize the impact of decisions made by the AOCC on passengers, thereby seeking to minimize flight time.

Airline Administrative Communications (AAC): Consists of crew rostering and cabin provisioning. They are essential to the airlines' business but do not affect flight operations. A clear example would be passenger lists, catering, baggage handling, etc.

- Aeronautical Passenger Communications (APC):

  Aeronautical Passenger Communications refers to communication services offered to passengers such as e-mail, Internet access and telephony, access via seat screens, airline-provided equipment or passengers' own laptops or other mobile equipment.

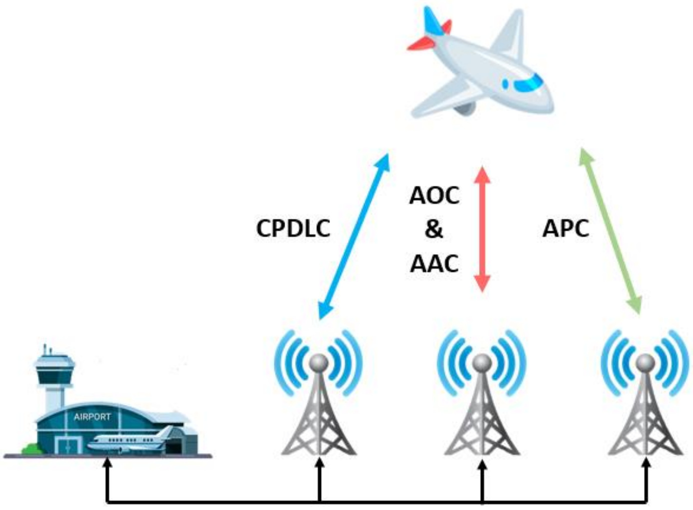

Fig. 3.3 Overview of the different Aeronautical data link communication categories.

3.4. First steps towards the use of Datalink communications in aviation

In the early days of aviation, aircraft did not have computers and the only way to exchange information was by radio. For this reason, when aircraft began to be fitted with computers, the way of communicating was updated and a digital system appeared, capable of communicating via data, this technology was called ACARS (Aircraft Communications Addressing and Reporting System). This system, connected to on-board communications equipment working in the VHF (Very High Frequency) and HF (High Frequency) bands or to satellite communications equipment (Satcom), allows messages to be sent and received.

3.4.1 Aircraft Communications Addressing and Reporting System (ACARS)

ACARS was originally developed in response to a requirement from Piedmont Airlines to find a better way to measure flight crew duty times. The application was called "OOOI" and provided aeronautical operational control (AOC) communications. "OOOI" gave the actual times Out (from gate), Off (take-off), On (touch down) and In (arrival at gate or parking position). As the system matured, organizations discovered that other sensitive information could be transmitted and received through the ACARS system, and expansion got underway.[7]

The following table lists the messages that were originally sent by ACARS. The first column refers to the name associated with each acronym. The second and third columns contain the precondition and the action required for the pilot to send this message. Finally, the last column contains the content of the message.

Table 1. "OOOI" Message

Name	Trigger Condition	Action	Message contents
Out	Parking brake released; all doors are closed.	Leaving gate or parking position	Out time
Off	Air or ground sensor on landing gear to "airborne" state.	Take off	Out time, Off time, initial and ETA
On	Air/ground sensor on landing gear to "ground" state.	Touch down	On time
In	Parking brake seat, any door is opened.	Arrival at gate or parking position	On time, In time

When ACARS was developed, it was modeled on the Telex System. Therefore, the system architecture is based on three main components:

- The Aircraft Equipment

  The ACARS equipment on board an aircraft is called Management Unit (MU) or, in the case of more modern versions with more functionalities, Communications Management Unit (CMU). The aircraft equipment consists of airborne end systems and a router. The end systems are the source of information for downstream messages and the destination for upstream commands. The function of the router is to automatically select the most efficient air/ground transmission method.

Typical airborne end systems found in aircraft are:

  - Flight Management System (FMS) --> Flight plan change requests, position reports, clearances and controller instructions.
  - Printer --> There will be a printer on the flight deck and there may also be a terminal for the cabin crew. It can be directed from the ground to automatically print an ascending message.
  - Maintenance computer --> Its function is to send diagnostic messages. This information is essential as even in advanced systems some problems can be solved by ground technicians.
  - Cabin terminal --> Commonly used by flight attendants to communicate passenger needs, gate changes due to delays, etc.

- The Service Provider

  The role of the data link service provider (DSP) is to move messages across one of the three air/ground sub-networks:

  - VHF/VDL (VHF Data Link) --> Its coverage is limited as transmission is through the field of view. Even so, it is the most widely used.
  - SATCOM --> Its coverage is partially global as it does not provide service to the polar regions. This is due to the layout of the satellite network. In addition, as it is an area with little aircraft flow, it is not interesting to provide coverage with this service due to its high cost.
  - HF/HFDL (HF Data Link) --> This sub-network complements the SATCOM coverage as its range will cover the polar regions. This service is cheaper than the previous one and more modern.

  There are currently two main service providers in the world (ARINC and SITA), although some countries have implemented their own network, with the support of ARINC or SITA.

- The Ground processing end system

  The final ground system is the destination for downlinks and the origin for uplinks. It is the responsibility of an ANSP or an airline operator. The end systems that are addressed to an ANSP provide air traffic services, such as take-off clearances. While the messages that are addressed to the airlines supply the data necessary for the airline to operate efficiently.

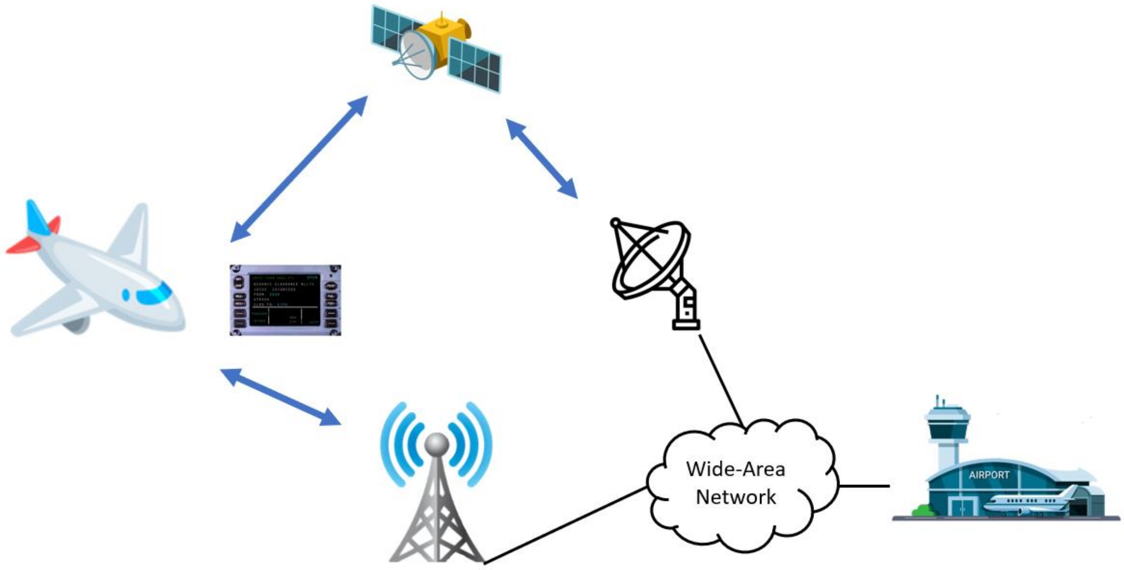

Fig. 3.4 The path that the ACARS message follows.

3.5. Aeronautical Telecommunication Network (ATN)

ATN is a data communications network that provides a reliable, robust and seamless communication service for all ATC and AOC applications.

ICAO Annex 10 defines the ATN as an inter-network architecture that enables the interoperability of ground, ground/air and avionics data sub-networks through the adoption of services and protocols with common interfaces based on the ISO (International Organisation for Standardisation) OSI (Open Systems Interconnection Reference Model). By relying on internationally recognised data communications standards, the development of harmonised systems is facilitated, thus encouraging the provision of competitive network services.[9]

The objectives to be achieved with the implementation of ATN, which will address the requirements of the civil aviation community, are as follows:

- Objective 1: ATN must be designed in such a way that it provides a highly available network. This means that it must guarantee multiple alternative paths to the same destination so that there is no single point of failure, and the message reaches its destination.

- Objective 2: The ATN must optimise existing resources as much as possible. This is achieved by using the existing communications infrastructure.

- Objective 3: ATN must be robust against message saturation. This is achieved by giving a different priority to each message. This ensures that when the network is close to collapse, high priority data reaches its destination in less time.

3.5.1 ATN architecture & components

The elements that make up the ATN architecture are routers, sub-networks and end systems.

- Routers: They oversee routing the different messages through the different sub-networks connected to them. Based on two parameters, the availability of the network infrastructure and the class of service requested.
- Subnetwork: Used as a physical medium to transfer information between the different systems in the ATN. A subnetwork is defined as a separate communications network that would not be part of the ATN but are interconnected through the ATN. This provides the ability to provide multiple data paths between end systems.
- End systems: These are responsible for hosting the applications, as well as the upper layer protocol stack to communicate with the end systems.

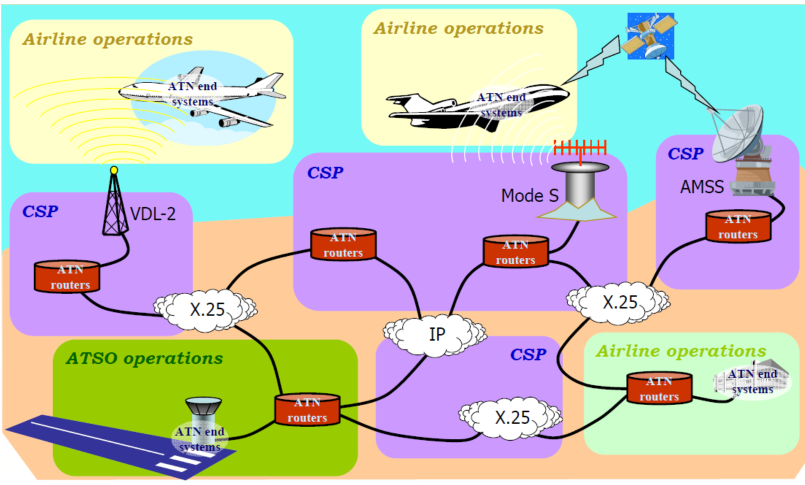

Fig. 3.5 The ATN network.[10]

3.5.2 Transition to ATN

As explained in the previous section, the pioneer of using Datalink technology in aviation was ARINC, the problem is that this communication system was not standardized by ICAO and was initially only used for the exchange of information between the aircraft and the airline (AOC/AAC). Until some ATS providers started to use this platform for very limited ATS applications, e.g., pre-departure clearance, ATIS, etc. At that point they realized that if they wanted to use the same technology for CPDLC communication they had to upgrade the platform or even develop a new one. Finally, it was decided to develop the ATN platform standardized by ICAO.

However, before the full development of the ATN platform, BOING created the FANS-1, and at the same time AIRBUS produced the FANS-A platform. The use of FANS-1/A in the intermediate period to ATN served as an alternative while it was being implemented and to gain experience.

Thanks to all this knowledge provided by ACARS and FANS-1/A, the ATN will give more confidence as it will provide its customers with the following advantages:

- Bandwidth use will be more efficient.
- Routing protocols will provide more efficient use of routes between the aircraft and the air traffic center.
- The integrity of data transmission is improved.
- Increased safety in high traffic density areas.

CHAPTER 4: The technologies behind the ATN system

Before starting to discuss the different link technologies that could become part of the ATN platform, mention should be made of the expected requirements and characteristics required by the ICAO Global Air Navigation Plan and the SESAR European ATM Master Plan.

- Network compatible with the internet protocol suite using IPv6.
- Increased network capacity compared to the old sub-networks.
- Support for aeronautical voice and data applications.
- Network interoperability functions and CNS integration.

Having clarified the points that the different technologies need to meet, it is now time to take a closer look at the different candidates to support the ATN system.

4.1. VDL Mode 2

- Overview

  The Very High Frequency (VHF) Digital Link (VDL) communications system is one of several sub-networks that the aircraft can use to communicate with the ground base via the Aeronautical Telecommunications Network (ATN). This technology is intended to become the replacement for the outdated low-speed ACARS.

  As seen above, for many years ACARS has been the forerunner of ground-to-air VHF data communications. However, the global increase in air travel, as well as the demand for more bandwidth hogging data applications, has also led to an increase in demand for aeronautical VHF communication channels. To meet this demand, several adjustments have been made, e.g., the bandwidth of aeronautical voice channels has been reduced to 8.33 kHz, new data modes have been considered which will replace some of the voice applications and thus relieve the radio spectrum and improve safety. One of the results of these considerations has been the introduction of VHF Data Link Mode 2.[11]

  The following table shows in detail all the VDL Mode 2 characteristics:

Table 2. VDL Mode 2 characteristics

Parameters	Characteristics
Bandwidth	[118.000-136.975] MHz
Modulation	D8PSK
Minimum transmission rate	4 kbps
Maximum transmission rate	31 kbps
Transmission type	Half duplex
Channel bandwidth	25 kHz

- Architecture

The VDL system is based on the OSI reference model and, therefore, has been designed in a modular fashion which separates the functions of the physical, data link and lower sub-layer of the network layers. The modulation scheme that has been defined for the VDL physical layer can interoperate with the upper layers without affecting the protocol stack.[12]

VDL-M2 supports connectivity to the Aeronautical Telecommunications Network ATN). The ATN provides an architecture which basically sees a VDL-M2 station onboard an aircraft as just another node in the ATN, a router in sky so to speak.

In the following image you can see the ATN architecture scheme, where we would also find the layers that would make reference to the VDL.

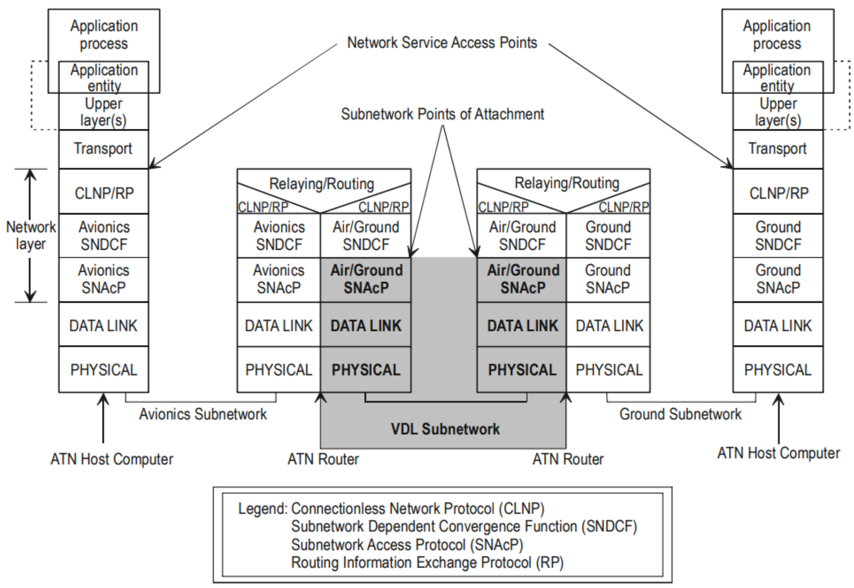

Fig. 4.1 ATN protocol architecture.[12]

4.2. AeroMACS

- Overview

The airport mobile communications system (AeroMACS) is an emerging wireless technology that helps airlines (AOCs), airport authorities and air navigation service providers (ANSPs) to cope with increasing volumes of data exchange on busy airport surfaces. In addition, AeroMACS has to support network management services (NET) and, in a second implementation phase, other services such as VoIP or video streaming1 in connection with specific needs. All services must be managed according to a priority policy, where NET has the highest priority, followed by ATC and finally AOC. As a summary, the following image shows the set of systems that are connected thanks to AeroMACS.

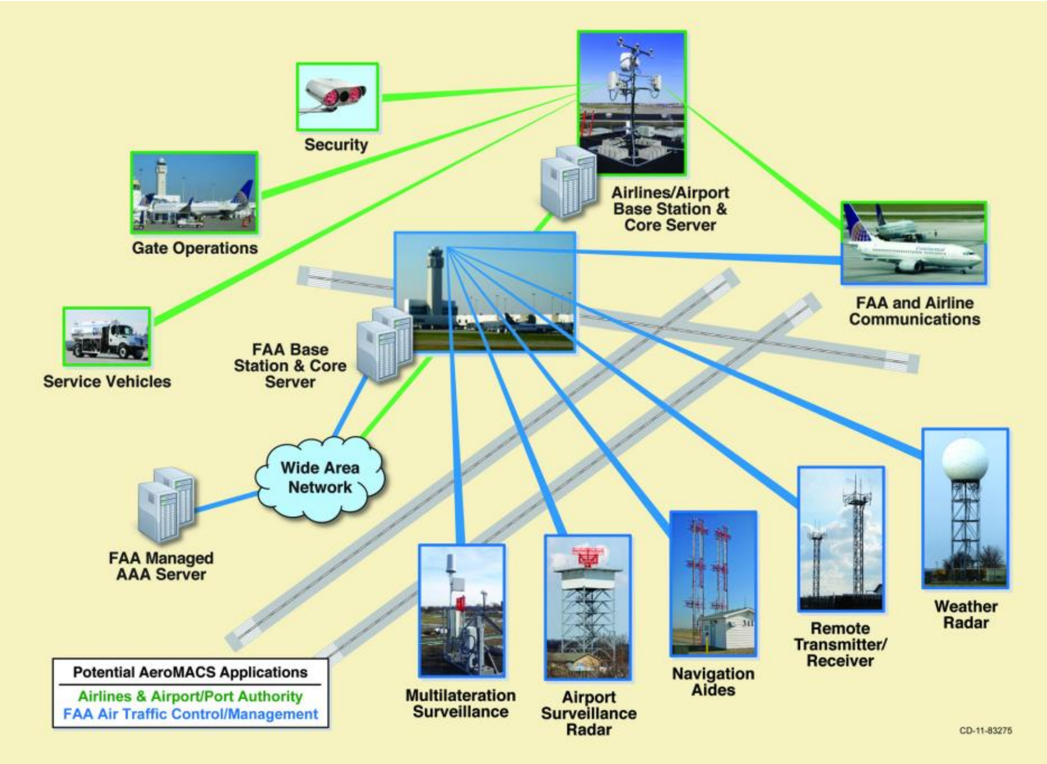

Fig. 4.2 Airport point-to-multipoint communications service.[13]

AeroMACS is an international standard operating in the protected and licensed aeronautical C-band from 5091 MHz to 5150 MHz for short-range, high data rate communications, which has been designated globally by the International Telecommunication Union (ITU). It is based on commercial 4G technology using the WiMAX standard (IEEE 802.16). It provides a broadband IP data link with worldwide interoperability, enabling the integration of critical communications for air traffic services, airline operational communication and airport authority communications.

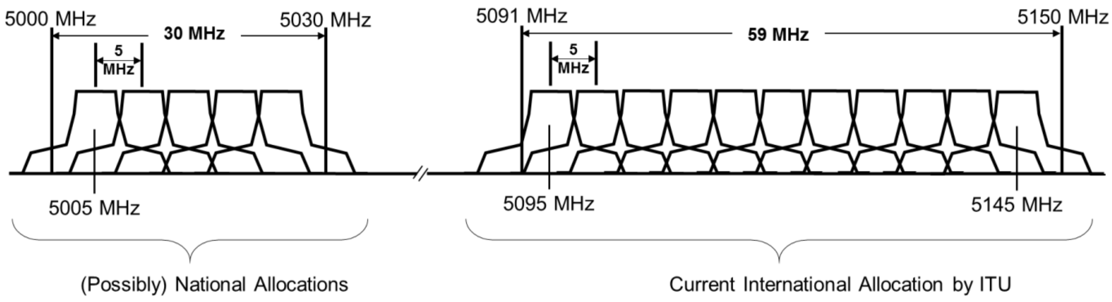

Fig. 4.3 AeroMACS frequency spectrum.[14]

- Architecture

The AeroMACS network is based on the IEEE 802.16-2009 communications standard. The primary mode of operation of a system based on this standard is a point-to-multipoint architecture. This is based on the Internet Protocol (IP), which means that it relies on IP addressing to provide secure connectivity between users and access to common services.[15]

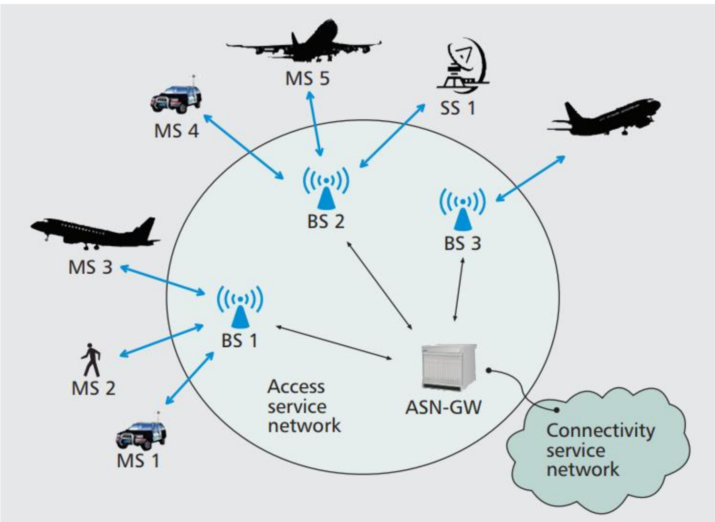

Fig. 4.4 AeroMACS network architecture.[15]

The entities found in an AeroMACS network architecture, represented in the image below, are the following:

- MS nodes refer to anything mobile such as aircraft, service or emergency vehicles and pedestrians. On the other hand, SS nodes are fixed elements that can be surveillance weather stations, radar sites or airline equipment. MS & SS nodes are linked through wireless connections to BS access points. There can be several MS & SS nodes assigned to a single BS. Mobile MS nodes are transitory and must be serviced by a handover protocol that allows MSs to maintain connected service as they move between access point coverage areas.

- The Base Station nodes (BS) identified in this architecture represent the network access point for the MS/SS nodes.

- The ASN-GW aggregates subscriber and BS control traffic within an access network. It plays an important role in subscriber management, network optimization and forwarding of all MS traffic.

- The connectivity service network (CSN) provides connectivity to the airport's closed intranet and firewall-protected access to the open Internet. The airport intranet hosts local IP-based servers that provide various data services and applications to authorized airport users.

4.3. Satellite communication datalink (SATCOM)

- Overview

Satellite communication is already used in oceanic and remote regions, where the coverage of other systems is not sufficient. In parallel to its use in these regions, this service can coexist with existing services in the European sky and thus increase its robustness and resilience to failures. In addition, satellite communication will provide additional bandwidth and consequently increased capacity. This is an added value that gives great importance to this technology since, as is well known, bandwidth in the aerospace sector is reaching its limits.

The technology we are talking about in the previous paragraph already exists and has a name, Iris. The Iris satellite system is a data link service funded and promoted by the European Space Agency. It runs on the upgraded Inmarsat SwiftBroadband Safety (SB-S) service and the global wideband area network for air traffic service use and in the near future will be extended for use in continental airspace.

For this emerging technology to be reliable and endure over time, it must meet the following points:

- Compliance with ATS safety and performance requirements, both in the short and medium term.

- Immediate coverage of Europe and scalability to become a worldwide component to support air-to-ground ATM communications.

- High capacity, guaranteeing the required performance for ATS and AOC services.
- Future-proofing, as upgrades to the existing system can be implemented gradually to meet future requirements for enhanced performance in compliance with upcoming ATN-IPS standards.
- Resistance to malicious attacks, thanks to secure and redundant end-to-end mechanisms.

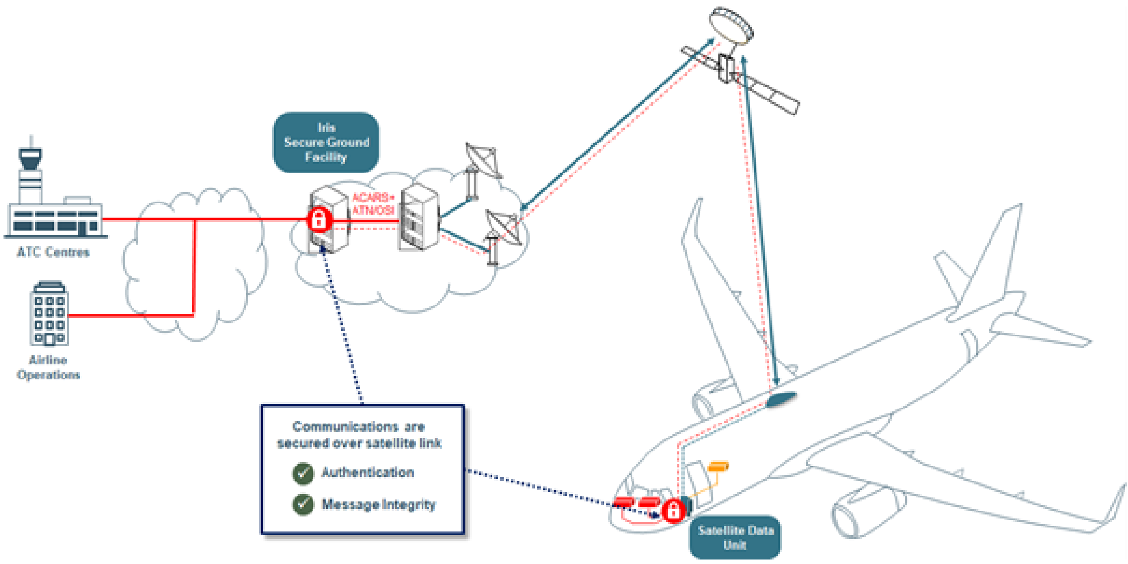

Fig. 4.5 Diagram of the Iris end-to-end system.[16]

- Architecture

  The Iris architecture consists of three main components, the ground segment, the space segment (satellite) and the air segment (aircraft). The following image and definitions are extracted from the Iris white paper.[17]

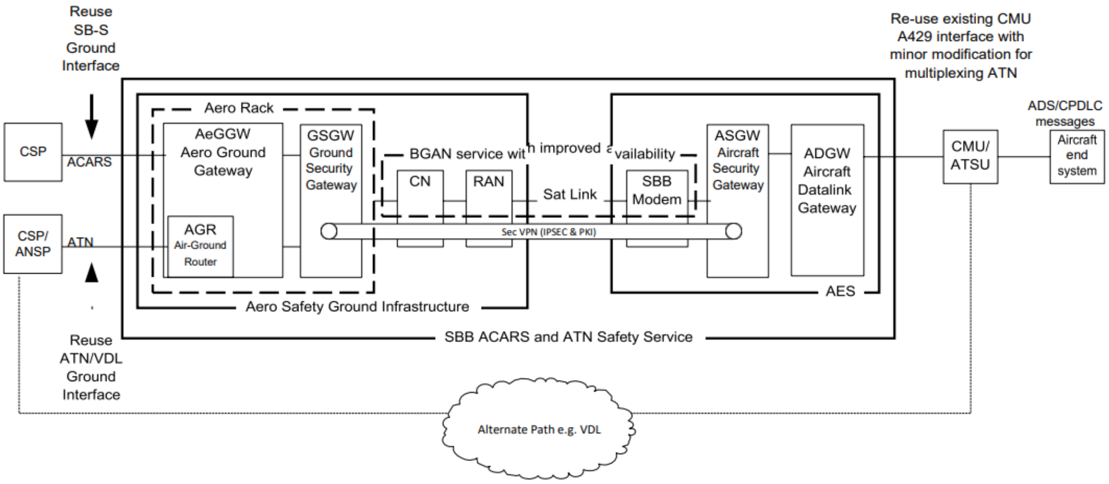

Fig. 4.6 Iris network architecture.[17]

- **<u>Ground segment:</u>**

  <u>The Aero Ground Gateway (AeGGW):</u> is the physical entity that handles ATN/ACARS traffic to/from an aeronautical ground station (AES).

  <u>The Air-Ground Router (AGR):</u> is an ATN/OSI routing software function within the AeGGW that interfaces with the ATSU/CMU on the aircraft.

  <u>The Ground Security Gateway (GSGW):</u> responsible for establishing the secure VPN tunnel to the aircraft.

  <u>The Ground Datalink Gateway (GDGW):</u> supports the combined delivery of ATN and ACARS traffic over the satellite link, extending similar functions developed and operational for SB Oceanic Safety's ACARS service.

- **<u>Aero segment:</u>**

  <u>The Aircraft Security Gateway (ASGW):</u> responsible for establishing the secure VPN tunnel between the aircraft and its GSGW.

  <u>The Aircraft Datalink Gateway (ADGW):</u> is a functional block within the AES that is responsible for encapsulating the ATN/ACARS messages in an IP wrapper to allow them to be sent to the ground via the SBB; and for de-encapsulating the received ATN/ACARS IP messages for transmission to the aircraft CMU.

- **Space segment:**

  The Core Network (CN): provides the services, switching and routing of traffic across the RAN. The CN consists of a set of UMTS network nodes with separate packet and circuit switching domains.

  The Radio Access Network (RAN): is responsible for all radio-related aspects of Inmarsat's terrestrial BGAN system. It controls AES communications through the satellite to the terrestrial network.

4.4. L-band Digital Aeronautical Communications System (LDACS)

- Overview

The L-Band Digital Aeronautical Communication System is a future technology that will allow aircraft to be connected to ATN during all phases of flight. Specifically, LDACS will connect aircraft operating in continental airspace by deploying a network of Ground Stations (LDACS GS), each station covering a part of the airspace called a cell. In a simplified form, each aircraft will carry on board a station (LDACS AS) with which it will be able to connect to the ATN by joining the LDACS GS covering the airspace in which it is operating. This link shall be maintained until the connection to another base is more favourable or until the aircraft leaves the airframe in which it was located. If the two stations remain connected, information can be exchanged via data and voice with different levels of quality of service depending on the communication requirements of each application or user. In this way, LDACS can support a wide variety of applications with different requirements, such as ATC and AOC communications.[18], [19]

LDACS provides a two-way radio link operating in the aeronautical L-band, specifically between 960 and 1164 MHz. Each LDACS cell uses a pair of frequency channels of 495.05 kHz each one for ground-to-air communications, i.e., FL (Forward Link), and one for air-to-ground communications, i.e., RL (Reverse Link). The FL and RL can operate simultaneously, which drastically reduces the latency of messages transmitted by LDACS, all of which is achieved by duplex frequency splitting. In addition, to make efficient use of the scarce spectrum available, the pair of frequency channels used by one cell can be reused by other distant cells.

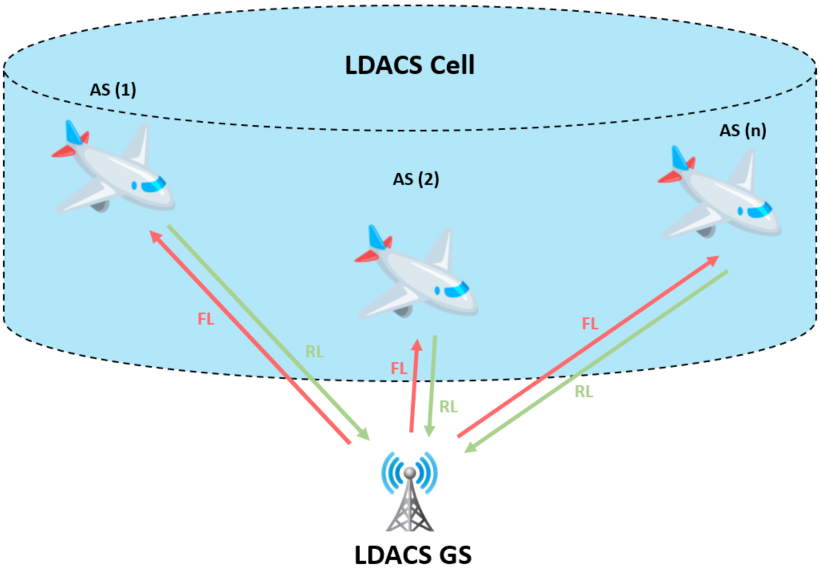

Fig. 4.7 Simplified diagram of LDACS operation.

CHAPTER 5: Conclusions

Before we can conclude which technologies will be further developed and used in the future, a brief comparison of all technologies with their strengths and weaknesses will be made.

- VDL Mode 2
  - Strengths:

    As an already deployed sub-network, it is compatible with all aeronautical communications networks. It is also able to cover current data link flow and applications. Finally, it is a simple and low-cost technology.

  - Weaknesses:

    As mentioned above, it is a transitional technology, i.e., it is suitable for today's needs, but is insufficient for more advanced applications and services that require better connectivity and higher data throughput. This technology consists of very low throughput, lower connection quality and highly variable latency and delays.

- AeroMACS
  - Strengths:

    They are in front of a network that provides connectivity for fixed and mobile assets, thus achieving the location of the different assets on the airport surface.

    This network operates in C-band, which offers relatively high performance. In addition, being in this bandwidth relieves the congested VHF spectrum.

    Finally, this technology helps airport surface communications by optimising airport management, reducing delays and congestion at the airport. In addition, increased security capabilities are achieved through the exchange of private data via a public key infrastructure (PKI).

  - Weaknesses:

    What has been considered a benefit, is now becoming a weakness and that is the use of the C-band as it is starting to become congested due to the heavy use of it in commercial wireless networks (Wi-Fi) and wireless links.

It is true that this is not a technology that needs a large infrastructure to be used, but it requires the installation of new equipment only for vehicles on the airport surface. Therefore, its coverage is limited and its contributions only help airports.

- SATCOM
    - Strengths:

      As a satellite-based network, it achieves almost worldwide availability and coverage. This means that except in polar regions, coverage is guaranteed.

      Another benefit of this technology is that, thanks to being continuously connected, flight plans can be updated throughout the flight path. This makes it possible to maintain an optimal trajectory to the destination and thus minimise the fuel burn and its environmental impact.

      Finally, as air traffic controllers have all this information, they can both schedule landings much further in advance and thus manage to maximise airport capacity, as well as optimise airspace and increase its capacity.

    - Weaknesses:

      This network provides an inadequate service for more advanced applications requiring better connectivity, as it operates at low throughput (low data rate). Naturally this technology is not recommended for use in real-time applications such as emergency communication.

      It is true that this technology has been able to increase coverage, but due to the limited number of satellites and their arrangement, the higher northern and southern latitudes (polar regions) are not served.

      Finally, the antenna that transmits in the K/Ka band, which is installed on the aircraft, is quite large, which implies an additional load for the aircraft and consequently an increase in fuel costs.

- LDACS
    - Strengths:

      As it is a sub-network based on terrestrial antennas, it will be able to provide the communication capability and in addition the navigation capability. This is achieved because the range data is similar to that of DME.

This sub-network provides two clear benefits and these are its increased data transfer capacity and its high spectrum efficiency.

- Weaknesses:

  As it is a very young sub-network, there is a need to invest in the installation of the new infrastructure which would entail a financial investment.

  On the other hand, the performance of this sub-network is rather modest, i.e., it covers the lower limit of the basic broadband connection. This means that some applications may not be supported in the future.

With this comparison we can conclude that each technology brings an essential benefit to the world of aerospace communication. It is true that some of them will tend to disappear over the years, (like the VDLM2) but in the near future they will need to coexist. This means that the most suitable technology, which is already being studied, is Multilink. Moreover, the need for multilink in-flight operations is justified as the required communication performance (safety, efficiency, continuity, etc.) of ATM operations. With this service we would avoid degradations or unexpected interruptions due to loss of connection because we would have another link through which to communicate.

Multilink is defined as the existence of at least two independent air-ground data links. This concept will be based on the technologies explained above and each of them will have a different applicability and availability depending on the phase of flight of the aircraft.

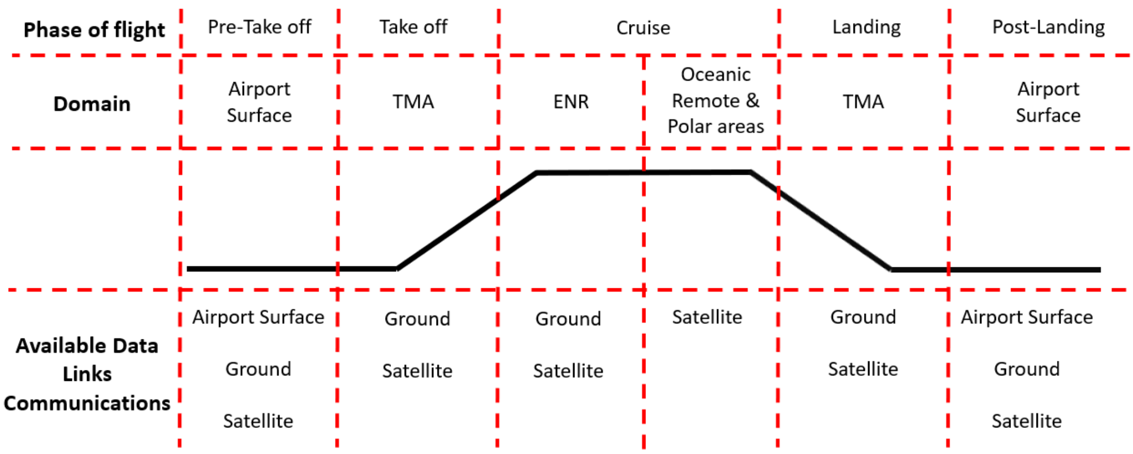

Fig. 5.1 Availability of different surfaces depending on the flight phase of the aircraft.[20]

Figure 5.1 shows a diagram of the availability of these technologies depending on the phase they are in:

- Pre-Take-off and Post-Landing: These phases are the most interesting in relation to the multi-link concept, since the three possibilities for exchanging data between air traffic controllers and pilots are available on the airport surface.

- Take-off and Landing: At this stage, there are two ways to communicate: satellite communication (SATCOM) and ground communication (LDACS & VDLM2).

- Cruise: In this part of the flight, there are two possibilities, the route may be through areas where there is both terrestrial and satellite coverage, or the flight may pass through oceanic, remote or polar areas. In this situation we would lose the availability of the multilink because we could only offer the possibility to exchange data via satellite communication.

In wireless communications, whenever two or more networks are available, there are two types of handover procedures. Vertical handover (VHO), which consists of switching between different technologies, for example just before take-off we would be connected thanks to the AeroMACS technology until the aircraft starts to take-off, when we must then switch to another network (such as LDACS or SATCOM). On the other hand, horizontal handover (HHO) consists of the process of transferring data from one cell to another without changing network, a clear example would be when the aircraft loses coverage from one antenna and switches to another.

In order to work well with this set of networks and to be able to transfer data correctly both horizontally and vertically, the multilink system needs to go through the following processes:

- Log-on

  The first step is the data link login, this process consists of each available network being connected by the multilink system in order to establish a connection. The moment a datalink equipment receives a connection request, it responds by informing its link status.

- Data link selection

  The second step is to decide which data link will be chosen for transmission among the different links that are available at that moment. This decision is based on quality of service (i.e., if a network cannot meet this requirement, it will be discarded) and/or on user preference criteria, which in this case is the carrier (e.g., an airline may prefer to use the LDACS network rather than SATCOM, even though both meet the other requirement).

- Handover

  Finally, the last step will be triggered whenever there is a degradation or failure of the data link used. In that case, a horizontal or vertical handover will be performed.

To sum up, multilink will bring many benefits to the world of aviation, which is why it is expected to be the technology that will flourish over time. A clear example is that it will improve safety levels in the exchange of information between air traffic controllers and pilots, thanks to the possibility of always offering at least one communication channel in all parts of the flight and even in several phases more than one to be used in case of failure or degradation of the signal.

Another advantage of this technology is that, thanks to the ability to be connected throughout the flight, trajectories will be improved, efficiency will be improved and fuel consumption will be minimised. This is important for two reasons: the first is that by consuming less fuel, greenhouse gas emissions can be reduced, thus slowing down climate change, and the second is that this will enable airlines to cut costs and reduce ticket prices.

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