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Master Degree Course in Aerospace Engineering

Master Degree Thesis

New Advance Civil Navigation's solutions to increase the compliance of military fighters A/C with civil aviation in future global airspace

Advisors

Prof.ssa Nicole Viola
Ing. Roberto Demarchi

Candidate

Martina Membola

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Ai miei genitori.

Through chances various,
through all vicissitudes,
we make our way...
Virgil, The Aeneid

Abstract

The wave of interest since RNAVs (Area Navigation)/RNP (Required Navigation Performance) procedure congestion, that has limited the deployment and operational use of military aircrafts, changed plans: particular attention is devoted to the definition of an Advance Civil Navigation solution applicable to fighters with specific consideration to mandates issued by the main competent authorities for civil aircraft (EASA, FAA, ICAO) and concerning in particular Nav DB, A-RNP, RNP-0.3, RNP APCH, CPDL, ADS-B Out and ADS-B In, RVSM and V-NAV.
This is in line with perspectives, new functionalities and applicability to fighters of the SESAR and NextGen proposals which aim to provide growth in various key sectors, including environment, capacity, cost efficiency, safety, and predictability.
Following the work done by NATO NIAG SG 222 which provided a Performance Equivalence process for the use of Alternative Means of Compliance aimed at demonstrating the possibility of integrating military aircraft into General Air Traffic (GAT), a survey was carried out on the public domain documentation regarding Human Machine Interface (HMI), avionics, cockpit and operating modes of the navigation system relating to fighter A/C.
The purpose of this document is to provide an overview of the civil sector requirements that concern avionic architecture, especially as regard navigation systems, introducing the functionalities and temporal priorities.
Through the study of existing military aircraft and a trade off on the reuse of military avionics, it is emphasized how the mandates can be applicable to fighters using customizations and/or mitigations relating to the HMI, Human Factor/Single Pilot aspects, managing to obtain a target compliance level of military aircraft with civil requirements.
Indications are provided on the contents, priorities, and introduction to managing change, regarding fighter cockpit configuration, HMI and Single Pilot Workload, necessary for the integration of fighters into GAT, also analysing aspects concerning the approaches to measuring workload and training of military pilots. As the skills required of military pilots in general aviation change, training must also be renewed and adapted to ensure the pilot situational awareness during the flight. To support likely situations of high pilot workload, the concept of aviation actor refocusing (captain, ground operators) and also new key personell have been introduced.
Furthermore, an outline of the investment and potential return (cost and benefits) is given, associate to new avionic equipment lauch. That, coupled with a focus on the obsolescence management problem, could be resolved by introducing COTS components in military aircraft. Sharing of civil and military services and convergence of technology are recommended as key elements, as well as a joint consultation for avionics development to facilitate future maximum system compatibility between civil and military applications.

Definitions[1]

Air traffic management (ATM). The dynamic, integrated management of air traffic and airspace (including air traffic services, airspace management and air traffic flow management) - safely, economically and efficiently - through the provision of facilities and seamless services in collaboration with all parties and involving airborne and ground-based functions.

Air traffic management system. A system that provides ATM through the collaborative integration of humans, information, technology, facilities, and services, supported by air and ground- and/or space-based communications, navigation and surveillance.

Automatic dependent surveillance-broadcast (ADS-B). ADS-B is a surveillance application transmitting parameters, such as position, track and ground speed, via a broadcast mode data link, at specified intervals, for utilization by any air and/or ground users requiring it. ADS-B is a data link application.

Controller-pilot data link communications (CPDLC). A data link application that provides a means of communication between controller and pilot, using data link for ATC communications.

Flexible use of airspace (FUA). An airspace management concept based on the principle that airspace should not be designated purely as civil or military, but rather as a continuum in which all user requirements are accommodated to the greatest possible extent.

General Air Traffic (GAT). Flights conducted in accordance with the rules and provisions of ICAO.

Next generation air transportation system (NextGen). NextGen is an umbrella term for the ongoing, wide-ranging transformation of the United States National Airspace System (NAS). At its most basic level, NextGen represents an evolution from a ground-based system of air traffic control to a satellite-based system of air traffic management.

Operational Air Traffic (OAT). Flights which do not comply with the provisions for GAT and for which rules and procedures have been specified by the appropriate authorities.

Performance-based navigation (PBN). Area navigation based on performance requirements for aircraft operating along an ATS route, on an instrument approach procedure or in a designated airspace.

Performance Equivalence (PE)[2]. For Military aircraft, ability to meet the required func-

[1] ICAO Circular 330-AN/189, ICAO Doc 9694-AN/955
[2] From AC/92(EAPC)D(2016)0001 dated 13 May 2016

tional attributes of ATM/CNS systems against the performance, safety, security and interoperability requirements of regulated airspace. This includes the measurable (e.g. metrics from regulations and standards) and non-measurable functional requirements (e.g. procedures or technical architecture), demonstrated through the evaluation of accuracy, integrity, continuity of function and availability.

Remote pilot. The person who manipulates the flight controls of a remotely-piloted aircraft during flight time.

Remotely-piloted aircraft (RPA). An aircraft where the flying pilot is not on board the aircraft.

Segregated airspace. Airspace of specified dimensions allocated for exclusive use to a specific user(s).

Single European sky ATM research (SESAR). SESAR is the European air traffic management (EATM) modernization and restructuring programme.

Standards and Recommended Practices. Standards and Recommended Practices are adopted by the Council in accordance with Articles 54, 37 and 90 of the Convention on International Civil Aviation and are defined as follows:

- *Standard*. Any specification for physical characteristics, configuration, matériel, performance, personnel or procedure, the uniform application of which is recognized as necessary for the safety or regularity of international air navigation and to which ICAO Member States will conform in accordance with the Convention; in the event of impossibility of compliance, notification to the Council is compulsory under Article 38.
- *Recommended Practice*. Any specification for physical characteristics, configuration, matériel, performance, personnel or procedure, the uniform application of which is recognized as desirable in the interests of safety, regularity of efficiency of international air navigation, and to which ICAO Member States will endeavour to conform in accordance with the Convention.

Acronyms and Abbreviations

ACARS	Aircraft Communications, Addressing and Reporting System
ACAS	Airborne Collision Avoidance System
ACL	Air Traffic Clearance
ADAPT	ADS-B Deviation Authorization Pre-Flight Tool
ADS-B	Automatic Dependent Surveillance - Broadcast
ADS-C	Automatic Dependent Surveillance - Contract
AFM	Aircraft Flight Manual
AFUA	Advance Flexible Use of Airspace
AHRS	Attitude and Heading Reference System
AMC	Acceptable Means of Compliance
A-MOC	Alternative Method of Compliance
AOC	Aeronautical Operational Control
ASE	Altimetry System Error
ATC	Air Traffic Control
ATM	Air Traffic Management
ATN	Aeronautical Telecommunication Network
ATS	Air Traffic Service
CAPE	Cost Assessment and Program Evaluation
CBA	Cost-Benefit Analysis
CDI	Course Deviation Indicator
CDM	Collaborative Decision-Making
CMU	Communications Management Unit
CNIS	Communication, Navigation, Identification and Surveillance

CNS	Communications, Navigation and Surveillance
COTS	Commercial Off-The-Shelf
CPDLC	Controller Pilot Data Link Communication
CPFH	Cost Per Flying Hour
CRM	Crew Resource Management
CVR	Cockpit Voice Recorder
DA	Design Assurance
DME	Distance Measuring Equipment
DoD	Department of Defense
EASA	European Union Aviation Safety Agency
ETSO	European Technical Standard Order
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FDP	Flight Duty Period
FHP	Flying Hours Program
FIR	Flight Information Region
FMS	Flight Management System
FUA	Flexible Use of Airspace
GAT	General Air Traffic
GFE	Government Furnished Equipment
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPS PPS	Global Positioning System Precise Positioning
HGO	Hybrid Ground Operator Unit
HITS	Highway-In-The-Sky
HMI	Human Machine Interface
HUD	Head Up Display
ICAO	International Civil Aviation Organization
IFF	Identification Friend or Foe
ILS	Instrument Landing System

IMA	Integrated Modular Avionics
INS	Inertial Navigation Systems
IRU	Inertial Reference Unit
LNAV	Lateral Navigation
LP	Localizer Performance
LPV	Localizer Performance with Vertical Guidance
MASPS	Minimum Aviation System Performance Standards
MC	Mission Computer
MCDU	Multipurpose Control Display Unit
MFD	Multi-Function Display
MMS	Military Mission System
MTTA	Military Transport-Type Aircraft
MTBF	Mean Time Between Failures
MTOW	Maximum Take-Off Weight
NAVAID	Navigational Aid
NextGen	Next Generation Air Transportation System
NDB	Non-Directional Beacon
NM	Nautical Miles
OAT	Operational Air Traffic
OEM	Original Equipment Manufacture
OTS	Organized Track System
PAI	Primary Aircraft Inventory
PBN	Performance Based Navigation
PBN IR	Performance Based Navigation Instrument Rating
PE	Performance Equivalence
PF	Pilot Flying
PFD	Primary Flight Display
PIC	Pilot-In-Command
PM	Pilot Monitoring

PM-CPDLC	Protected Mode Controller-Pilot Data-Link Communications
RA	Resolution Advisory
RNAV	Area Navigation
RNP	Required Navigation Performance
RPAS	Remote Piloted Aerial System
RVSM	Reduced Vertical Separation Minimum
SBAS	Space-Based Augmentation System
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure Route
SPO	Single Pilot Operations
SSR	Secondary Surveillance Radar
STAR	Standard Arrival Route
SWIM	System Wide Information Management
TA	Traffic Advisories
TACAN	Tactical Air Navigation Aid
TAWS	Terrain Awareness and Warning System
TBO	Trajectory Based Operations
TC	Taxonomy Condition
TCAS	Traffic Alert and Collision Avoidance System
TCO	Two Crew Operations
TEM	Threat and Error Management
TLX	Task Load Index
TMA	Terminal Manoeuvring Area
TSO	Technical Standard Order
UAS	Unmanned Aircraft System
ULD	Unit Load Devices
VNAV	Vertical Navigation
VOR	VHF Omnidirectional Radio Range
WAAS	Wide Area Augmentation System
WOCL	Window Of Circadian Low

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Chapter 1

Introduction

1.1 Airspace Organization and Management

The civil and military aircrafts are the two airspace users today. Civil and military operations differ in nature and in purpose and, through the years, have learned to live in a symbiotic relationship, each responding to its own rules under the Chicago Convention (only the State Aircraft are not covered by ICAO requirements because of any characteristics and configuration of avionic equipment on board).

The civil aviation sector includes private, commercial and government-owned aircraft that are primarily transporting cargo and passengers, both nationally and internationally.
Military aviation comprises State-owned aircraft engaged in transport, training, security and defence. Both aviation sectors are essential to global stability and economies. However, both usually cannot operate simultaneously within the same block of airspace, thus requiring the establishment of boundaries and segregation.[1]

Military aviation operates a wide range of aircraft types either:

- as GAT and being equipped to civil standards in the same way as civil GAT flights (in particular, transport aircraft operations may in general be considered as similar to those of commercial airlines);
- as GAT, but not being equipped to civil standards (in particular, fighters and training aircraft) because of the limited space available or technical impossibility of fitting the equipment to enable them to conform fully to civil standards;
- as OAT flights, equipped or not to civil standards;
- exclusively in segregated airspace to perform in particular Air Defence and Air Combat manoeuvres, equipped or not to civil standards.

Currently, restrictions have generally inflexible flight level and boundary limits, that is a loss of efficiency by both.

- *Civil operations affected by military restrictions:*
  - Civil flights may not be able to fly near optimum flight levels and fly on the most efficient airways.
  - Airport/Airspace closures may affect schedules and air services.

[1] ICAO, *Civil/Military Cooperation in Air Traffic Management*, 2011.

  - Additional fuel and cost.

- *Military operations restricted by civil considerations:*
  - Longer flight times to reach training areas.
  - Loss of training.
  - Lateral/vertical limits may restrict certain maneuvers.

Lack of civil/military coordination of airspace management has resulted in inefficient airspace use and limited use of aircraft capabilities. For these reasons, there has been a shift from historical bias with a consequence need to integrate military and civil aviation. This results in growing demand to include military flights in civil airspace, as the rapid increase in congestion and complexity of RNAVs (Area Navigation)/RNP (Required Navigation Performance) is potentially limiting the deployment and operational use of military aircraft.

To meet the increasing need for access to airspace by both types of actors and ease congestion in busy airspace, civil and military sectors should be identify a way to improve civil/military cooperation, through sharing of common navigation facilities and interoperability of civil and military Air Traffic Management systems, tools and information flow.

1.2 Civil/Military Collaboration

Historically, agreements between military and civil aviation have focused on the needs of defence, security and emergency. Now, as mentioned before, there is a need to establish procedures that support integration of military and civil aviation in day-to-day operations.
While worldwide collaboration is desirable for matters pertaining to civil aviation, others are best approached on a regional basis, since operating conditions vary a great deal from region to region (for example, in the North Atlantic long-range ocean flying predominates, whereas in Europe many flights are short-haul).
That's why ICAO has mapped a regional planning for Air Navigation that cover nine regions: Asia/Pacific, Middle East, Europe, Africa, Latin America and the Caribbean, South America, North Atlantic, and North America. ICAO's plans are regularly revised or amended to meet the needs of increasing traffic and to take into account technical developments in aviation. So, also the hopefully civil/military cooperation must adapt to nine different regions.

The following best practices are common in States which have implemented effective civil-military cooperation and coordination:

- military participation at relevant civil ATM, CNS and safety meetings to enhance strategic liaison and facilitate holistic planning;
- the integration of civil and military CNS/ATM systems, including the joint procurement and sharing of ATS surveillance data, where possible;
- the joint provision of civil-military navigation aids;
- joint and common training conducted between civil ATS units and military units providing ATS in areas of common interest;
- common rules, procedures and training programmes as far as practical;

- legal agreements and specific provisions established between stakeholders within State and/or with other States;
- participation of military aviation authorities in ICAO global and regional meetings through inclusion in State delegation.[2]

Military authorities should align with future evolutions in civil aviation technology, while at the same time civil aviation to factor in military requirements into future infrastructure modernisation projects.

1.3 FUA and AFUA Concept

In describing the concept of Flexible Use of Airspace (FUA), EUROCONTROL said *"Airspace should be considered as a single continuum, planned and used in a flexible way on a day-to-day basis by all categories of airspace users"*.
The management of flexible airspace is an highly complex exercise, necessitating a process that equitably balances different civil and military interests through the daily allocation of flexible airspace structures.
The ultimate goal of FUA is to have system accomodates short-notice unplanned requirements and allow civilian users temporary access to military restricted and reserved airspace, and viceversa.
Coordination between civil and military authorities should be carried out at the strategic, pre-tactical and tactical levels (see Figure 1.1).

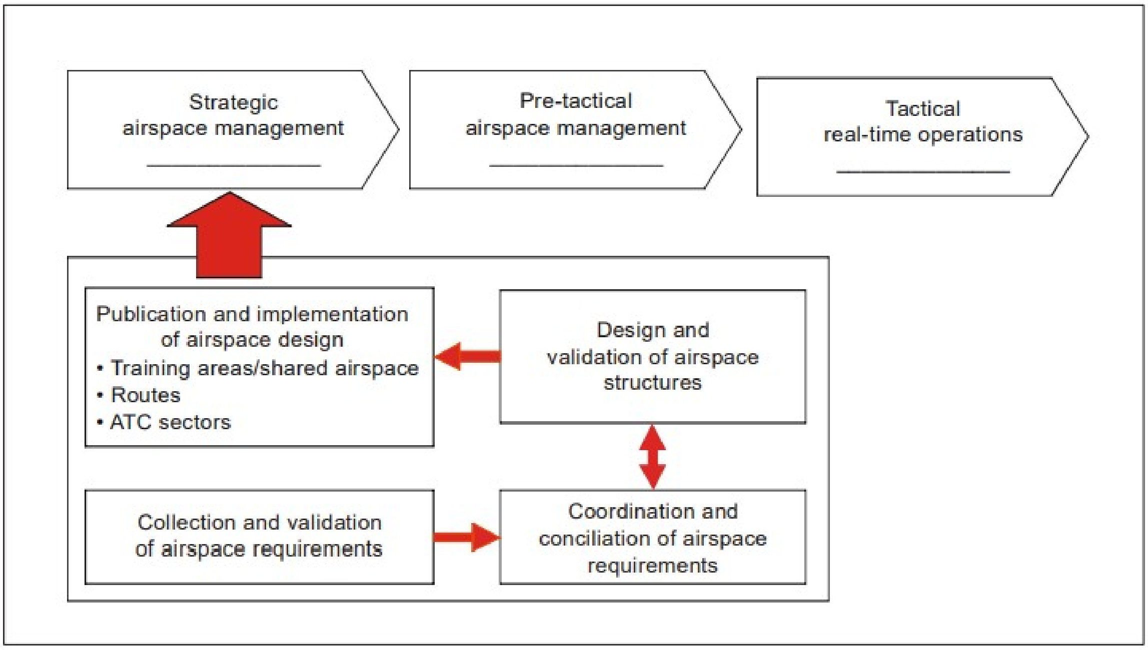


Figure 1.1: Coordination between civil and military authorities carried out at the strategic, pre-tactical and tactical levels

Direct communication between civil and military units should be available to permit the resolution of specific traffic situations if and where civil and military controllers are providing services in the same airspace. If required to meet minimum safety levels, exchange of flight

[2]ICAO, Doc 10088, *Manual on Civil-Military Cooperation in Air Traffic Management*, First Edition, 2020

data, including the position and flight intention of the aircraft, should be available between civil ATC units and controlling military units.

The FUA concept was introduced in 1996 but it has been replaced by the Advance Flexible Use of Airspace (AFUA) concept which is now integrated into Network Manager/CDM (Collaborative Decision-Making) procedures.
Collaborative Decision-Making (CDM) (see Figure 1.2) brings together airlines, civil and military aviation authorities and airports in an effort to improve sharing all information relevant to air traffic operations.

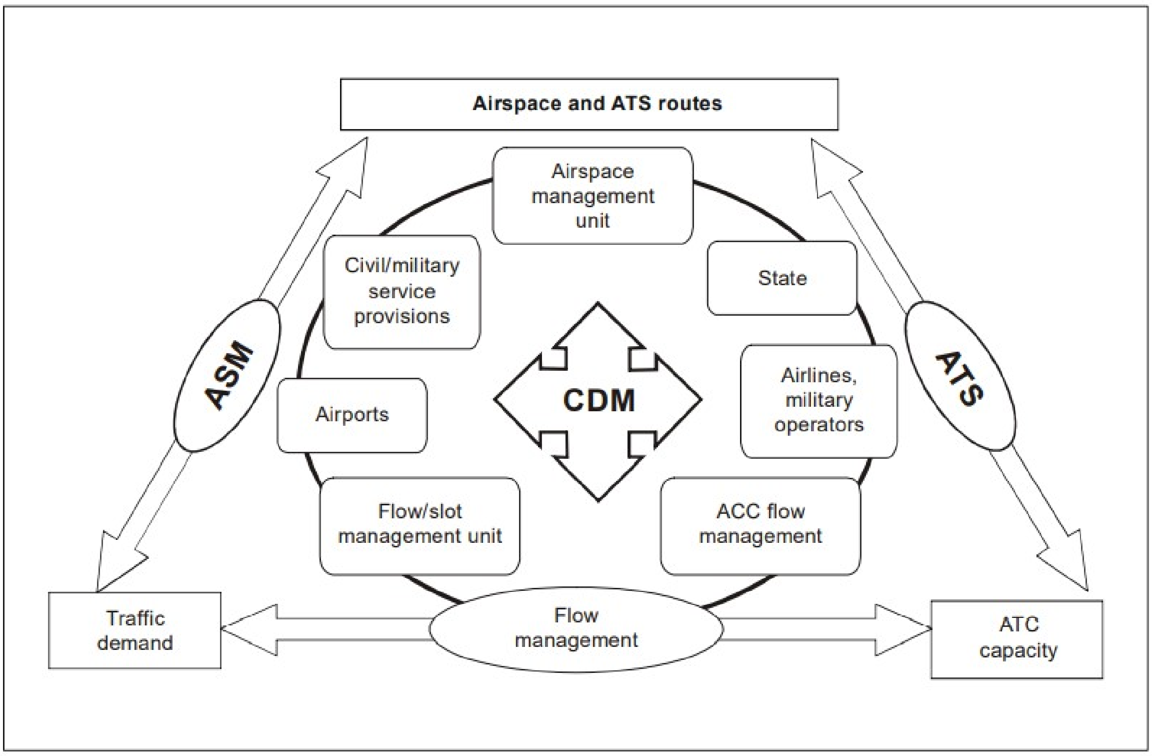


Figure 1.2: Collaborative decision-marking

1.4 Advance Use of Airspace

The actual aim is to overcome the FAU/AFAU concept and explore the military aviation's journey towards civil general flight operations, studying how meeting mandates by EASA, FAA and ICAO, through promoting and sharing of civil and military services and convergence of technology.

During the years, the evolution of technology has led to increased requirements on civil aircraft when operating in certain airspace (for example RVSM, ADS-B, RNP procedures), so increased compliancy with civilian standards will facilitate access to airspace for military aircraft. Also, the common application of standards and equipment will enable joint training and utilization of operational, administrative and technical personnel.
Military necessity is to will be as compliant as possible with civil requirements but it is equally

important to ensure military-to-military interoperability is maintained.

When considering retrofit/upgrades of their fleet or new aircraft acquisition, authorities should consider the following options to aim for technical compliance:

- the certification of the appropriate modules of military systems taking into account/based on civil standards (for example the A330 MRTT and the A400M which were certified by EASA, installation of civil certified ACAS on board military transport aircraft);
- the existence of military certificates that match, as a minimum, civil standards (for example the United States Department of Defence certification of some models of military Mode 5 Level 2 transponder that meet Annex 10, ADS-B provisions);
- performance equivalence process when military certificates do not meet civil standards (EUROCONTROL, the European Defence Agency and the North Atlantic Treaty Organization, at the time of writing were developing such processes); and
- the implementation of an acceptable alternative means of compliance based on tailored standards. [3]

[3] ICAO, Doc 10088, *Manual on Civil-Military Cooperation in Air Traffic Management*, First Edition, 2020

Chapter 2

SESAR and NextGen

Today, access to the airspace and the management of air traffic rely on principles and technology that were developed 40 years ago.
The U.S. and Europe are modernising their ATM systems through the NextGen and SESAR programmes respectively that develop new capabilities introducing new enabling technologies and operational procedures.
The planned evolution of today's aviation ecosystem towards a new (digital) ecosystem covering all aviation operations is presented in the following Figure 2.1:

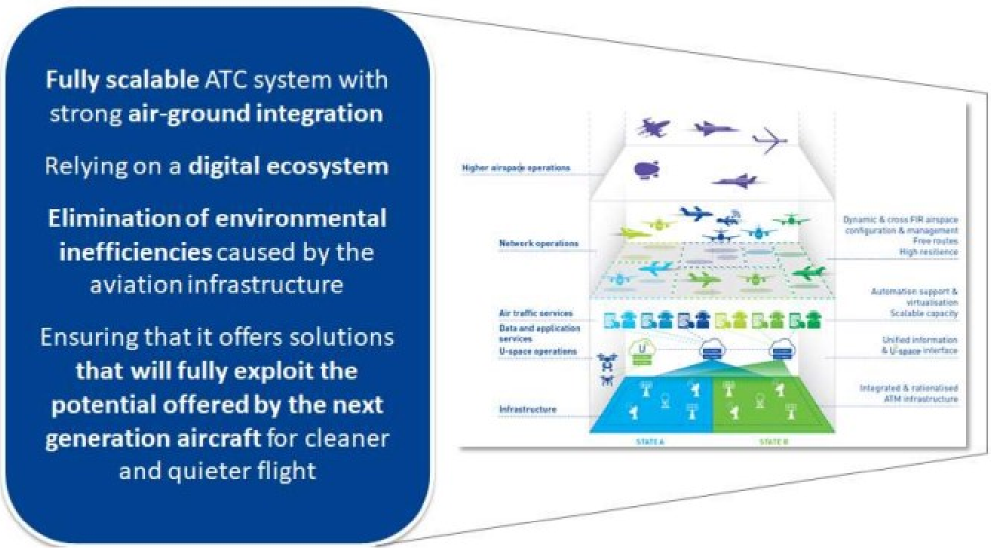


Figure 2.1: A new ecosystem for aviation

This view remains as relevant post COVID-19 as it was before, and there is now also an opportunity to accelerate its priority characteristics.
Both SESAR and NextGen will evolve and adapt to changing needs to always reflect the current state of the two concepts.

A key element of both SESAR and NextGen is System Wide Information Management (SWIM), which is a focus on how the technologies and systems will enable shared awareness for operations.
The planned technology is very similar: ADS-B, Data Link, Extended Conflict Detection.
ADS-B equipment has been successfully tested in operational environments, and is an example of a developed SESAR and NextGen technological component. The United States is further

along on the surveillance part, known as Automatic Dependent Surveillance - Broadcast (ADS-B) Out, while Europe's SESAR is further advanced on datalink communications. As said before, Europe and the U.S. clearly are moving toward the same goal, although the pace and emphasis during the transition to next-generation traffic management still must be worked out. Both systems recognize the primacy of data communications to the cockpit and amongst ground systems ("voice by exception"), while maintaining the requirement for voice for emergency purposes, back up, and for communications with less equipped aircraft.

Both systems embrace a network-centric infrastructure with shared services and distributed data environments that interact semi-autonomously to achieve system-level efficiencies, but have differences that are presented in the next section.

2.1 Differences between SESAR & NextGen

SESAR and NextGen differ in their implementation frameworks because they are tied to very different European and US industry structures.
First of all, the SESAR Operational Concept time horizon is 2020+, while the NextGen time horizon is 2025+.
NextGen tends to be closely tied to government in a hierarchical framework whereas **SESAR** appears to be a more collaborative approach, including, but not limited to, ATM ground activities. NextGen, while having a longer timeline to implement, takes a broader approach to transforming the entire air transportation system, including ground activities.
SESAR operational concepts place the business trajectory at the core of the system, with the aim to execute each flight as close as possible to the intention of the user. This is seen as a move from airspace to trajectory focus whereas introducing a replacement approach to airspace design and management. New separation modes will allow for increased capacity. Using these new integrated and collaborative features, humans will be central in the future European ATM system as managers and decision makers.
And also, the SESAR concept essentially has a strict ATM focus, while NextGen also deals with other elements that may impact ATM either directly or indirectly.

Another difference lies in the treatment of information: while both indicate that data and information are key to integration and net centrality, SESAR, being a more decentralized model, calls for the establishment of a Reference Model for data and for data normalization and standardization. NextGen, envisioning a more centralized government-run approach describing not only data but the provision of "information services" in a service-oriented and networked environment.

Difference in time where various parts will be developed and implemented:

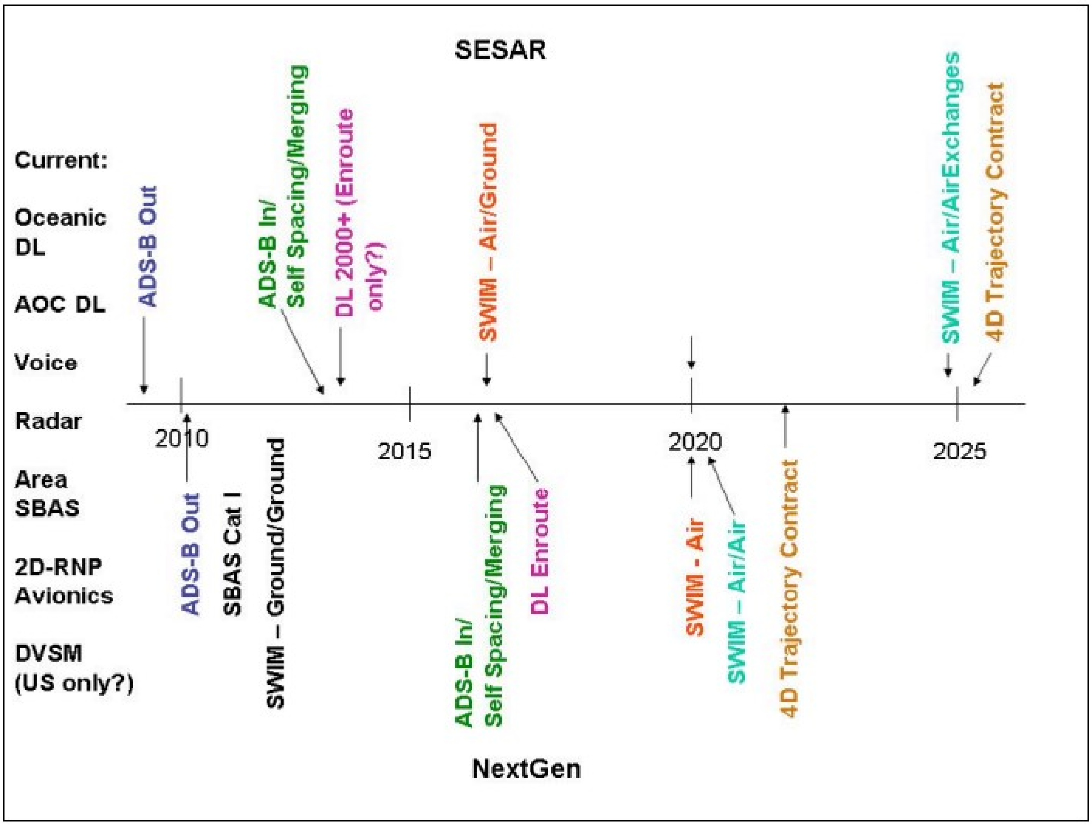


Figure 2.2: Difference in time between SESAR & NextGen

2.2 The military in SESAR/NextGen

The military operate in their multiple roles as Air Navigation Service provider, airspace user, airport operator and regulator under State responsibility every day.
Military aircraft fly approximately 170,000 flights across European airspace and through high density TMAs per year. With the planned increases in sizes of TMAs and introduction of extended arrival profiles the pressure on these aircraft to be "as civil as possible" is increased. SESAR/NextGen programme has committed to military activities in cooperation with the defence industry to shape the future of military aviation towards a civil-military performance. Especially, definition, development and validation of technical and operational solutions for integrating in the current and future airspace the following categories of vehicles:

- Regional aircraft;
- Military aircraft, with the aim of assuring the coexistence of military/civil aircraft;
- Helicopters;
- Unmanned.

Even though not mandatory, non-compliance with SESAR/NextGen by the military would create risks. Core network performance could be degraded, with negative consequences for States. The military might notice it troublesome to access bound airspace, that might have an impact on daily training. Most importantly, the military, through non-compliance, might be perceived as a potential danger to civilian traffic.

2.2.1 Benefits of military involvement in SESAR/NextGen

Military and civil aviation face similar challenges. In addition, military airspace users have very specific needs stemming directly from the different types of missions that are assigned to them by public authorities. They strive to be “as civil as possible” while remaining “as military as necessary”.
SESAR, NextGen and similar initiatives which support increased civil-military connectivity have the potential to aid the introduction of fighters A/C in the future.

An increasing number of military flights needs to be accommodated in common airspace volumes, shared with civil traffic and don’t require a segregated environment, relying on a common Air Traffic Management/Communications, Navigation and Surveillance (ATM/CNS) infrastructure.
Military operators strive for the recognition that the capabilities available onboard modern military aircraft can sustain civil ATM/CNS requirements.
Launching a modernisation programme of military ATM systems is an important opportunity leading to potential economies of scale: the reutilization of military avionics to support ATM functions can reduce retrofits, integration costs, technical impact and cost upon military from civil aviation infrastructure modernisation initiatives. But the dual use systems available for both civilian and military stakeholders can bringdown costs for both (e.g. fuel and time savings and improving the efficiency of military missions).
Military ‘transport-type’ aircraft can be handled by Air Traffic Controllers (ATC) with the same procedures as equipped civilian aircraft, contributing to the reduction of workload.

In the next section reference will be made to research approach and opportunities for civil-military ATM/CNS interoperability reported in Directorate European Civil-Military Aviation, Civil-Military Coordination Division, *Dual Use CNS Concept for Military Research approach and opportunities for civil-military ATM/CNS interoperability*, 2018.
SESAR’s civil-military requirement to seek "interoperability of infrastructures on the basis of solutions/synergies that **enable the highest level of reuse of existing military capabilities**", rather than equipment exemptions, becomes a key factor in ensuring the required levels of military connectivity and performance in a context of global interoperability.

This mindset will lead to developing the next thesis chapters and proposing new considerations and solutions.

2.2.2 Dual Use CNS Concept

The Dual Use CNS approach[1] (illustrated in Figure 2.3), was recognized in the European ATM Master Plan and to large extent followed in the Single European Sky Research (SESAR) Programme in respect to civil-military:

As seen in Figure 2.2, between 2009 and 2015 a particular SESAR 1 research project defined and validated a specific solution for Automatic Dependent Surveillance – Broadcast (ADS-B) to be enabled on board military aircraft using existing military transponders.
This work included the assessment of interoperability opportunities offered by the re-utilisation of different types of military Identification Friend or Foe (IFF) equipment.
This project culminated with a series of live flight trials, in September 2014, using airborne

[1] Directorate European Civil-Military Aviation, Civil-Military Coordination Division, *Dual Use CNS Concept for Military. Research approach and opportunities for civil-military ATM/CNS interoperability*, 2018

prototypes that provided unprecedented evidence that modern military aircraft can be interoperable within a civil ADS-B environment in a cost-effective way. These successful validations indicated that military aircraft compliance with civil ATM/CNS requirements must be progressed by decoupling equipage from performance and making use of low-cost interfaces for avionics already in operation.

Avionics Modularity

The functional architectures of some military aircraft can be compared with civil mainline aircraft as far as ATM/CNS components are concerned. Additional functions fulfilled by military aircraft, specific to their mission, are not of interest for ATM/CNS.

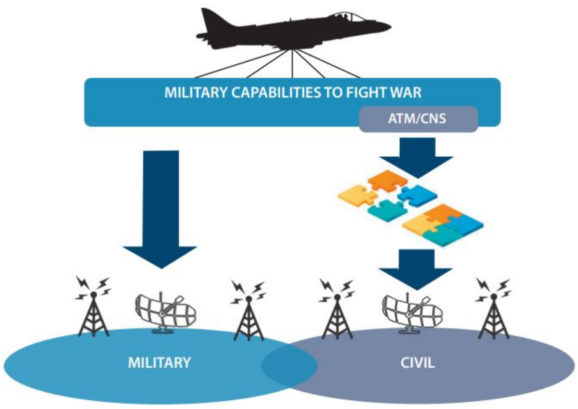


Figure 2.3: Dual CNS Approach

It is important to highlight that the state-of-the-art Integrated Modular Avionics (IMA) architecture, first developed in the context of a military fighter programme in the U.S. and used for civil mainline aircraft, now widely used by Airbus and Boeing and for multiple civil and military aircraft. IMA became the most important architecture principle for aircraft avionics.
The IMA Core System relies on a set of standard modules communicating across a common backbone bus/network (Figure 2.4).

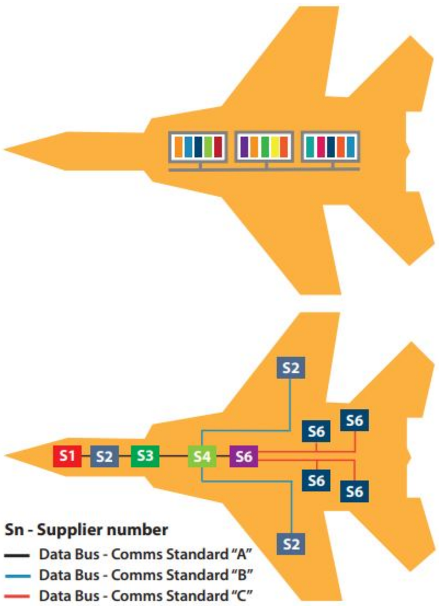


Figure 2.4: Integrated Modular Architecture (IMA)

The IMA Core System can be viewed as a single entity comprising many integrated processing resources that may be used to build any avionics system function regardless of its size and complexity. Therefore, "consideration of IMA to support Dual Use CNS may require additional research but it surely offers a promising option to address the challenges put by the increasing avionics predominance and functional allocation principles of 5th generation fighter aircraft due to its modularity and multimode avionics principles of the relevant AoR".

Flight Management System

Military aircraft are typically equipped with a Mission Computer (MC) or Military Mission System (MMS) that are different from civil Flight Management Systems (FMS). The MC enables the crew to create, retrieve, modify and store flight plans. When flight plan is to be executed, the MC calculates the parameters, and provides estimated times along the route with estimated fuel burn rates. The flight plan and data are displayed on the control panel display. The MC provides also an interface for the pilot/co-pilot flight instruments and for the auto-pilot/flight director.
When implementing 4D trajectory management functions, eventually deemed to be implemented in military aircraft, it may be required the support by MC/MMS, similar to FMS, or emulated by ground systems. This is an aspect that should warrant the fullest attention in

future research.

Also for redundancy in civil aircraft, each FMS calculates its own navigation solutions independently, comparing its solutions with the other FMS.
It means that, in a military aircraft, the flight management function, where it exists, can be implemented either in a civil-alike Flight Management System or be part of a Mission Computer, which also performs military-specific functions (e.g. threat assessment, weapon delivery, etc.).
Nevertheless, military navigation architectures (where FMS is a crucial element) cannot easily comply with the majority of PBN specifications because military Mission Computers are normally not using the ARINC 424 data structures, and that cannot qualify the aircraft beyond RNAV-5.
Some military computers implement a similar way to ARINC 424 to describe the trajectory with waypoint attributes and guidance laws along the path. In the long term, it might be considered whether starting from the existing ARINC 424 structure and extending it with the specific military path terminators necessary to define military trajectories could be cost-beneficial.

MC/MMS (and FMS) can be a fundamental dual use enabler in military aircraft to sustain Trajectory Based Pperations (TBO) and advanced navigation functions. For Performance Based Navigation, one must recognise that difficult mismatches, like flight path definition using ARINC 424 data, are still to be researched/investigated to determine the best mitigating adaptations.

Communications Equipment

Radio communications between aircraft and ground receiver sites, supporting voice communications between pilots and air traffic controllers, is ensured through VHF radios (HF and SATCOM used in oceanic regions). For similar air-ground voice requirements the military rely on UHF radio communications, which are also provided by certain civil ANSPs when handling State aircraft operating GAT without VHF 8.33 kHz channel spacing capability.
Civil aviation is introducing Controller Pilot Data link Communications (CPDLC) and Trajectory Management that currently are supported by VHF data link radios, namely the ICAO-compliant VDL Mode 2 protocols.
The definition of the next generation of air-ground data link technologies is underway in the context of SESAR and ICAO and comprise a terrestrial segment (LDACS), satellite communications (SATCOM) and airport data link (AeroMACS), with the name of Future COM Infrastructure (FCI). FCI concept offers significant opportunities for civil-military interoperability.

Sensor Equipment

Sensors are the equipment able to provide data, such as position, velocities and accelerations (angular and linear), to onboard computational equipment (i.e. MC/MMS and FMS) and to communication systems (i.e. VDL Mode 2 radio).
The eligibility of sensors available in military aircraft is usually one of the important constraints for military systems compliance with civil ATM/CNS requirements. This is particularly evident in the case of compliance with PBN navigation specifications. The dual use of satellite restricted signals, e.g. GPS PPS, is an important subject to be considered for research efforts. Research investigations must focus on the determination of performance levels to compare with civil navigation requirements, in respect to GPS SPS receivers and hence GNSS.

For military sensors in general, tactical aircraft with airborne architecture constraints could be handled by addressing the equivalence of military TACAN, GPS PPS, GALILEO PRS and INS performances. The determination of military sensors eligibility shall consider existing integration architectures e.g. Multimode Receivers (MMR) and GPS/GNSS coupling. For demanding requirements that imply reliance on augmented GNSS signals, the availability of multifrequency/multiconstellation and multi-tracking capabilities, other specific technical solutions are still to be defined and validated.

Control Panels and Displays

There are various Multi-Function Displays (MFD) located on the main instrument panel of military aircraft. Typically, there are two Primary Flight Displays (PFD) and two Navigation Displays (pilot and co-pilot) or one PFD and one ND, and central system display(s) where aircraft status parameters are showed. All displays are multipurpose and so the pilot can decide the information to be shown in each display.
The Multipurpose Control Display Units (MCDUs), that communicate with MC, provide the primary operator interface via an alphanumeric keyboard, mode select keys, line select keys, annunciators, and a flat panel display.
All avionic systems are interconnected to allow access and control of nearly all flight plan management parameters, as long as one MC and one MCDU are available. The communication radio management function acts through MCDU as the control for the VHF/UHF and HF radios. The navigation radio management function acts also through MCDU as the control for the TACAN, VOR, and ADF navigation radios. MCDUs are also used to control the IFF transponder and to select SAR functions.

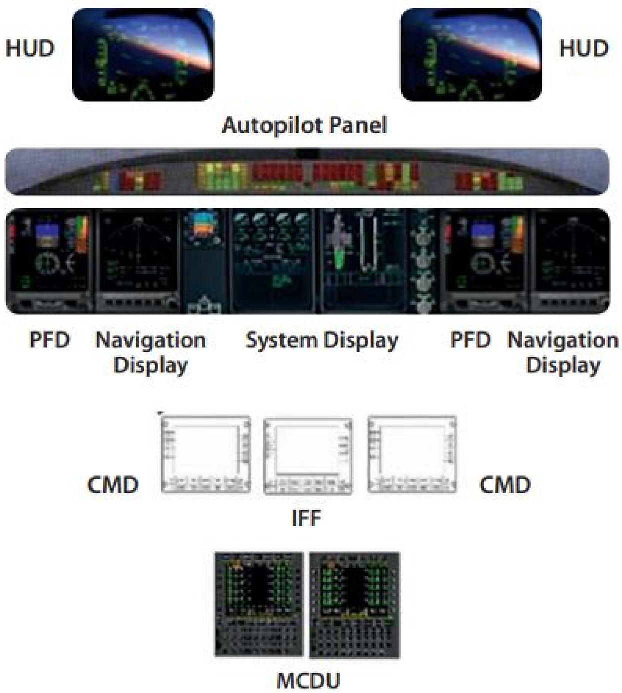


Figure 2.5: Displays and Control Panel

The Communication Management Display (CMD) is used to reduce the pilot workload associated with the MCDU, and to provide pilots with a head up means of using the radios. The CMD is also capable of using the FMS database to tune navigation radios. The CMD can also

control the IFF modes.
IFF Control Panel can be used as an alternative way of controlling CMD. The IFF control panel provides the pilot with power control, mode control, mode test control, code selection, and zeroize control. Available civil surveillance transponder modes are: 3/A, C, S ELS/EHS, while military IFF Modes are: 1, 2, 4, 5.
The Digital Autopilot/Flight Director (DA/FD) system interfaces with the autopilot system control panels and with the other components of the avionics system. Two identical and interchangeable DA/FD Automatic Flight Control Processors (AFCPs) are connected to the aircraft avionics data buses.

Adaptation of airborne displays and integration with multiple avionics is a key constraint to the potential military compliance with civil ATM/CNS functions, because this functions require innovative approaches at the level of software applications. For the particular case of PBN, this matter needs to be subject of in-depth studies to propose mitigations.

Other Dual Use CNS Opportunities

In the **communications** domain it is important to continue research efforts on how Future Communications Infrastructure (Future COM) technologies can be enabled and used by military aircraft to sustain potential interoperability requirements in terms of air-ground CPDLC and Trajectory Management.

In terms of advanced **navigation** the implementation of Performance-Based Navigation offers substantial opportunities to apply a Dual Use CNS approach but technical solutions are still to be defined and validated in the context of European research.

In the context of **surveillance**, the main interoperability area relates to ADS-B implementation in military aircraft. In this respect, the future research efforts must complement the work conducted in SESAR 1 to conclude the validation of the feasibility of using military transponders (Mode S component) to support ADS-B.

Other areas that remain open for research initiatives are the eventual use of multi-mode avionics relying on software defined radios and reliance on enhanced visual systems and airborne surveillance to mitigate airborne collision functions.

The advent of Unmanned Aircraft Systems (UAS) / Remote Piloted Aerial Systems (RPAS) represents a huge challenge for aviation: accommodating UAS/RPAS in non-segregated airspace, without any increase in risk to other airspace users, calls for focused research on the technologies to find advanced data link solutions, new collision avoidance alternatives, and low-cost navigation-related technical solutions, as well as determining parameters for autonomous flying operations.

The compliance of the core system software to the civil standards for software design assurance level can be anticipated as crucial for equipment approval. Some aspects of those research domains would require strong involvement of National Authorities to address the specific security and institutional constraints.

2.2.3 Comments

To comply with civil ATM/CNS requirements, a significant number of transport military type aircraft may simply be forward fitted as civil mainline. In fact, modern military large (no significant limitations in terms of cockpit space and aircraft integration) transport-type aircraft will be expected to feature equipage solutions that cope simultaneously with civil and military requirements.
Nevertheless, Dual Use CNS technical solutions have to be defined for those aircraft types, validated and industrialised to avoid overlapping equipage fittings through avionics rationalisation and by taking advantage of multi-mode performance-based solutions.

Combat aircraft are war-fighting platforms that have limited on-board space for additional avionics fit, so the integration of civil ATM/CNS on-board equipment is often problematic. For fighters, the preferred approach to attain the desired levels of civil-military interoperability should be on the basis of maximum reutilisation of available capabilities, performance-level solutions and multi-mode avionics.

Dual Use CNS can bring significant benefits to military operators when facing the modernization of civil aviation infrastructure. In the past, some studies quantified the potential impact of SESAR upon military as very substantial. With the emergence of PBN, trajectory based operations and other concepts and technology evolution trends, with clear impact on certain military operations, it can be inferred that cost benefits of Dual Use CNS approaches allowing maximum reutilization of available military aircraft capabilities may need to be measured in the same order of magnitude. Limitation of technical impacts as well as enhanced interoperability and safety benefits will be paramount to justify future research.

The concepts proposed by SESAR/NextGen, as seen above, aim to improve civil/military collaboration in future airspace while maintaining a separation concerning the technology adopted. These studies, in the following chapters, are used to demonstrate the possibility of integrating military fighters into civil airspace but with a slightly different purpose: military aircraft are able to meet civil avionics standards and requirements and have performance comparable to commercial aircraft.

Chapter 3

Standards and Regulations Research

To promote and development an advance use of airspace where military aircrafts meet the standards of general aviation, a different solution must seek it through the study of standards, regulations, requirements and mandates issued by EASA, FAA and ICAO.

3.1 Performance Based Navigation (PBN)

Methods of navigation have improved to give operators more flexibility. Under Area Navigation, there are Legacy and Performance Based Navigation (PBN) methods, see Figure 3.1.

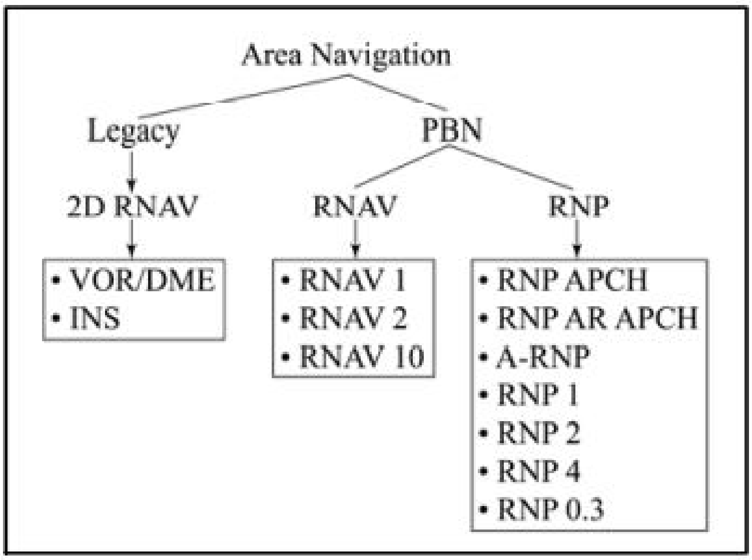


Figure 3.1: Area Navigation tree structure

The legacy methods include operations which allows two-dimensional area navigation (2D RNAV) in terms of both VOR/DME dependent systems and self-contained systems such as Inertial Navigation Systems (INS).
Many operators have upgraded their systems to obtain the benefits of PBN. Within PBN there are two main categories of navigation methods: Area Navigation (RNAV) and Required Navigation Performance (RNP), that is an RNAV system that includes onboard performance monitoring and alerting capability. The RNP capability of an aircraft will vary depending upon the aircraft equipment and the navigation infrastructure. "For example, an aircraft may be eligible for RNP 1, but may not be capable of RNP 1 operations due to limited NAVAID/ATC

coverage or avionics failure. The Aircraft Flight Manual (AFM) or avionics documents for your aircraft should specifically state the aircraft's RNP eligibilities" (U.S. Department of Transportation - FAA, *Aeonautical Information Manual - Official Guide to Basic Flight Information and ATC Procedures*, 2017). For both RNP and RNAV designations, the numerical designation refers to the lateral navigation accuracy in nautical miles which is expected to be achieved at least 95 percent of the flight time.
This information is introduced in International Civil Aviation Organization's (ICAO) Doc 9613, Performance Based Navigation (PBN) Manual (Fourth Edition, 2013) and the FAA AC 90-105A, Approval Guidance for RNP Operations and Barometric Vertical Navigation in the U.S. National Airspace System and in Remote and Oceanic Airspace (2016). For any particular PBN operation, it is possible that a sequence of RNAV and RNP applications is used, as shown in Figure 3.2.

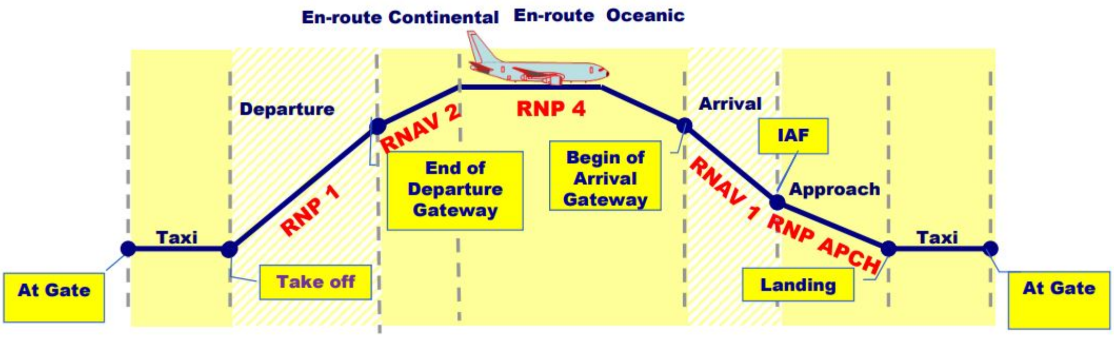


Figure 3.2: Example of Application of RNAV and RNP specifications

3.2 RNP Operations

Please note that on 1 May 2011 entered into force the Agreement between the EU and the USA on cooperation in the regulation of civil aviation safety, so EASA and FAA mandates are based upon sufficiently similar principles.

Lateral Accuracy Values. The lateral accuracy value is typically expressed as a distance in nautical miles from the intended centerline of a procedure, route, or path.

- **Nav Specs and Standard Lateral Accuracy Values.** U.S. standard values supporting typical RNP airspace are as specified below. Other lateral accuracy values as identified by ICAO, other states, and the FAA may also be used. (See Figure 3.1).
  - **RNP Approach (APCH).** RNP APCH procedures are titled RNAV (GPS) and offer several lines of minima to accommodate varying levels of aircraft equipage: either lateral navigation (LNAV), LNAV/Vertical Navigation (LNAV/VNAV), and Localizer Performance with Vertical Guidance (LPV), or LNAV, and Localizer Performance (LP). GPS or WAAS can provide the lateral information to support LNAV minima. LNAV/VNAV incorporates LNAV lateral with vertical path guidance for systems and operators capable of either barometric or WAAS vertical. Pilots are required to use WAAS to fly to the LPV or LP minima. RNP APCH has a lateral accuracy value of 1 in the terminal and missed approach segments and essentially scales to RNP 0.3 in the final approach.

- **RNP AR APCH.** RNP AR (Authorization Required) APCH procedures are titled RNAV (RNP). RNP AR APCH vertical navigation performance is based upon barometric VNAV or WAAS. RNP AR is intended to provide specific benefits at specific locations. It is not intended for every operator or aircraft. RNP AR capability requires specific aircraft performance, design, operational processes, training, and specific procedure design criteria to achieve the required target level of safety. RNP AR APCH has lateral accuracy values that can range below 1 in the terminal and missed approach segments and essentially scale to RNP 0.3 or lower in the final approach. Operators conducting these approaches should refer to AC 90-101A, Approval Guidance for RNP Procedures with AR.
  RNP AR operations are GNSS based but with a provision that DME/DME may be used if approved by the State regulator.
- **Advanced RNP (A-RNP).** Advanced RNP includes a lateral accuracy value of 2 for oceanic and remote operations but not planned for U.S. implementation and may have a 2 or 1 lateral accuracy value for domestic enroute segments. Except for the final approach, A-RNP allows for scalable RNP lateral navigation accuracies. Its applications in the U.S. are still in progress.
  * **Additional A-RNP Functions.** Additional functions may be required for an operation in given airspace:
    - Vertical navigation (Baro-VNAV or LPV);
    - Parallel Offset (Intended for en route tactical use only; strategic offsets will be by route definition);
    - Fixed Radius Transition (Removes the variability of the fly-by transition; Standard radius is 22.5 NM for FL200 and above and 15 NM for FL190 and below; Radius to be used will be loaded from the database);
    - Holding (A hold is defined by a point, the turn direction, an inbound track and an outbound distance);
    - Time of Arrival Control.

    Parallel Offset, Fixed Radius Transition and RNP Holding are defined in RTCA DO-236B.
- **RNP 1.** RNP 1 requires a lateral accuracy value of 1 for arrival and departure in the terminal area and the initial and intermediate approach phase.
- **RNP 2.** RNP 2 will apply to both domestic and oceanic/remote operations with a lateral accuracy value of 2.
- **RNP 4.** RNP 4 will apply to oceanic and remote operations only with a lateral accuracy value of 4.
- **RNP 0.3.** RNP 0.3 will apply to rotorcraft only, with the exception of RNP APCH. This Nav Spec requires a lateral accuracy value of 0.3 for all phases of flight except for oceanic and remote and the final approach segment.
  Requires TSO C145a/146a/196 GNSS equipment.

- **Application of Standard Lateral Accuracy Values.** U.S. standard lateral accuracy values typically used for various routes and procedures supporting RNAV operations may be based on use of a specific navigation system or sensor such as GPS, or on multi-sensor RNAV systems having suitable performance.

- **Depiction of Lateral Accuracy Values.** The applicable lateral accuracy values will be depicted on affected charts and procedures.

- **Other RNP Applications Outside the U.S.** The FAA and ICAO member states have led initiatives in implementing the RNP concept to oceanic operations. For example, RNP10 routes have been established in the northern Pacific (NOPAC) which has increased capacity and efficiency by reducing the distance between tracks to 50 NM.
- **Aircraft and Airborne Equipment Eligibility for RNP Operations.** Aircraft meeting RNP criteria will have an appropriate entry including special conditions and limitations in its Aircraft Flight Manual (AFM), or supplement. Operators of aircraft not having specific AFM-RNP certification may be issued operational approval including special conditions and limitations for specific RNP lateral accuracy values [1].

RNP Level	Typical Application	Primary Route Width (NM) – Centerline to Boundary
0.1 to 1.0	RNP AR Approach Segments	0.1 to 1.0
0.3 to 1.0	RNP Approach Segments	0.3 to 1.0
1	Terminal and En Route	1.0
2	En Route	2.0
4	Projected for oceanic/remote areas where 30 NM horizontal separation is applied.	4.0
10	Oceanic/remote areas where 50 NM lateral separation is applied.	10.0

Figure 3.3: U.S. Standard RNP Levels

3.2.1 The future requirements

Regulation (EU) 2018/1048 describes the laying down airspace usage requirements and operating procedures concerning Performance Based Navigation (PBN). In this regulation it is stated that from 1 June 2030 all approaches and SIDs should be based on PBN, only in the case of contingency other means than PBN are allowed.
A pilot will have to still be able to fly an NDB/VOR/ILS approach, however NDB's and VOR's will disappear.

3.3 Navigation Databases

Most navigation specifications require a navigation database, except for RNAV 10 and RNAV 5, because RNAV 10 and RNAV 5 Navspecs support legacy navigation systems (INS) which do not use an airborne Nav database.
PBN is dependent on Nav Data, that is critical to flight safety but there is opportunity for error/corruption at each stage so procedures for checking, validating, managing data is necessary. Navigation database must be obtained from a qualified supplier that complies with RTCA DO-200A/EUROCAE ED-76A standard.It must be appropriate for the region of intended operation i.e. must include the navaids and waypoints required for the route.
The Navigation database allows an FMS or GPS navigator to create a continuous display of navigation data, thus enabling an aircraft to be flown along a specific route. Vertical navigation can also be coded. The data included in an airborne navigation database is organized into

[1] U.S. Department of Transportation - FAA, *Aeronautical Information Manual*, 2017

ARINC 424 records. Nav DB is updated every 28 days (Figure 3.4), in order to ensure that its contents are current.

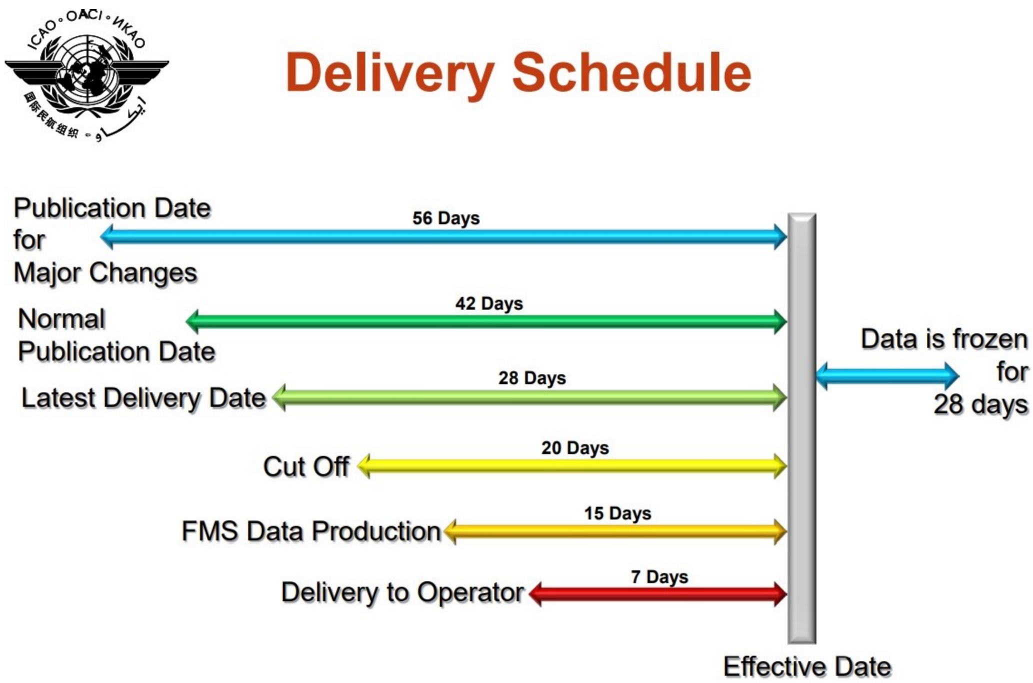


Figure 3.4: Nav Database, delivery schedule

3.3.1 Data generation in Nav Database

The navigation database must guarantee the *integrity* and *accuracy* of nav data.
Long chain from origin to aircraft (see Figure 3.5) represents, as said before, an opportunity for error/corruption at each stage, so sound QA procedures need to be in place and also consider that operators are responsible for managing their own safety.

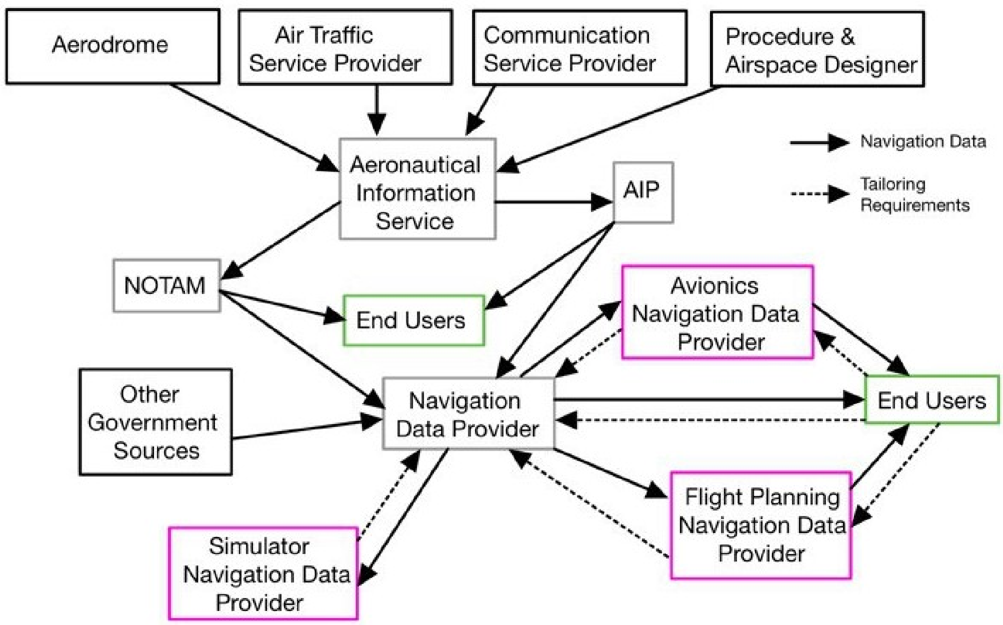


Figure 3.5: Navigation Data Chain

In military aircraft, three levels of data generation are considered: military, civil and tactical. Figure 3.6 considers the data generation process in case of a civil type, but a similar chain can be considered in the military and/or tactical case where in the former category embraces military airport data and the latter involves tactical classified data as target or air-defence data.

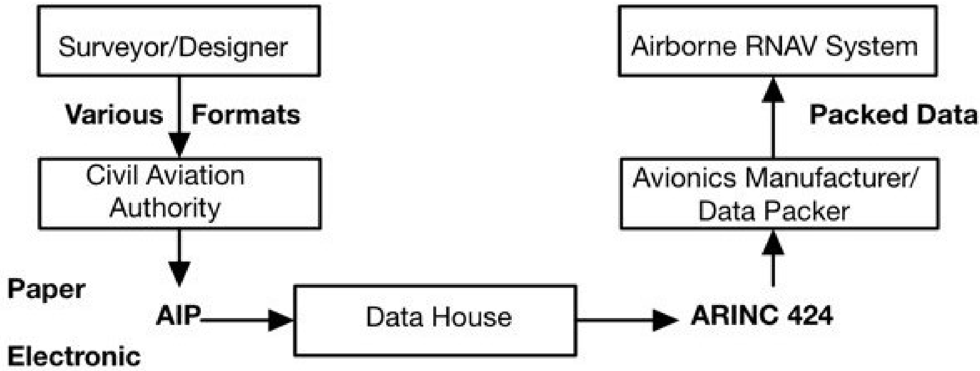


Figure 3.6: Civil Navigation Data Formats

3.3.2 Navigation Service Requirements

- **Global Navigation Satellite System (GNSS).** Required to begin any RNP AR APCH.
- **Inertial Reference Unit (IRU).** Required for any RNP AR APCH with accuracy value less than 0.3 NM or missed approach with RNP less than 1.0 NM.
- **Distance Measuring Equipment (DME).** DME/DME updating may serve as reversionary mode where infrastructure and aircraft can provide required missed approach performance.
- **VHF Omni-Directional Range (VOR) Stations.** The RNAV system may not use VOR/DME updating.

3.4 Controller Pilot Data Link Communication (CPDLC)

CPDL stands for Controller Pilot Data Link Communication and automates routine ATC processes replacing verbal ATC instructions and pilots read-backs over datalink rather than the VHF or HF radio.
There are CPLDC programs (referred to as Air Traffic Clearance -ACL-) Service in the Link2000+ terminology) on going in the NAT and SoPAC (FANS), as well as USA and Europe (ATN). The CPDLC is being globally implemented and currently is in different implementation stages. The global communication procedures are detailed in the ICAO Provisions: Annex 10 Volume III Part 1 Chapter 3. The CPDLC message set is contained in ICAO Doc 4444: PANS-ATM, Annex 5.

3.4.1 Benefits of CPDLC

- Less communication on the ATC frequency;

- Increased sector capacities;
- More pilot requests can be dealt with simultaneously;
- Reduced probability of miscommunication;
- Safer frequency changes, hence fewer loss of communication events.

3.5 Automatic Dependent Surveillance - Broadcast (ADS-B)

ADS-B stands for Automatic Dependent Surveillance - Broadcast:

- *Automatic* because it periodically transmits information with no pilot or operator involvement required;
- *Dependent* because the position and velocity vectors are derived from the Global Positioning System (GPS) or other suitable Navigation Systems (i.e., FMS);
- *Surveillance* because it provides a method of determining 3 dimensional position and identification of aircraft, vehicles, or other assets;
- *Broadcast* because it transmits the information available to anyone with the appropriate receiving equipment.

The ADS-B system is composed of aircraft avionics and a ground infrastructure.
ADS-B replaces radar technology with satellites, bringing major advantages: ADS-B uses satellite signals to track aircraft movements.
On-board avionics determine the position of the aircraft by using the GNSS and transmit its position along with additional information about the aircraft to ground stations for use by ATC and other ADS-B services. This information is transmitted at a rate of approximately once per second.

ADS-B equipment may be certified as a surveillance source for air traffic separation services using ADS-B Out.
ADS-B equipment may also be certified for use with ADS-B In advisory services that enable appropriately equipped aircraft to display traffic and flight information.

Successful completion of ADS-B certification depends on performance of joint avionic characteristics and successful execution and certification of the development chain. However, certification of the development process can be a problem for military aircraft with non-certified navigation systems.

3.5.1 ADS-B Out

ADS-B Out works by broadcasting information about an aircraft's GPS location, altitude, ground speed and other data to ground stations and other aircraft, once per second. Air traffic controllers and aircraft equipped with ADS-B In can immediately receive this information. This offers more precise tracking of aircraft compared to radar technology, which sweeps for position information every 5 to 12 seconds.
Radio waves are limited to line of site meaning radar signals cannot travel long distances or

penetrate mountains and other solid objects. ADS-B ground stations are smaller and more adaptable than radar towers and can be placed in locations not possible with radar. With ground stations in place throughout the country, even in hard to reach areas, ADS-B provides better visibility regardless of the terrain or other obstacles.
For example, aircraft operating in most controlled U.S. airspace must be equipped with ADS-B Out.

3.5.2 ADS-B In

ADS-B In provides operators of equipped aircraft with weather and traffic position information delivered directly to the cockpit. ADS-B In equipped aircraft have access to the graphical weather displays in the cockpit as well as text-based advisories, including Notices to Airmen and significant weather activity.
The information that is received both air-to-air and ground-to-air by the ADS-B In receiver is for situational awareness use only.

3.5.3 ADS-B: Where are we now

The following is an overview of which countries already require ADS-B and those who have upcoming [2]:

1. **Europe**

ADS-B is mandated for all aircraft. Requirements apply only to Instrument Flight Rule (IFR) flights and only for aircraft with a Maximum Take-Off Weight (MTOW) of 5700 kg (12,566 lbs.) or greater and/or max cruising True Airspeed (TAS) greater than 250 knots (kts).
The transitional phase ends on June 7th, 2023.
Exemptions available to old aircraft (CoA before 7 June 1995), aircraft operating maintenance or export flights and aircraft that will cease operations in Airspace by 31 October 2025. For a detailed breakdown of the rule, see the dedicated section on CIR (EU) 2020/587.

Evolution of airborne equipage [3]
In this diagram (Figure 3.7), we show the continued evolution of the equipage, categorized in the three populations as effectively created by the most recent amendment of the mandate. The diagram is updated monthly and is based on airline planning data covering 60% of the EU-based, mandated fleet, responsible for at least 85% of monthly IFR movements. The evolution of the actual equipage (solid green curve) is monitored by EUROCONTROL.

[2] Jason Davidson, *ADS-B UPDATE 2021 – WHERE ARE WE NOW*, 2021
[3] SESAR, Automatic Dependent Surveillance - Broadcast, 2021

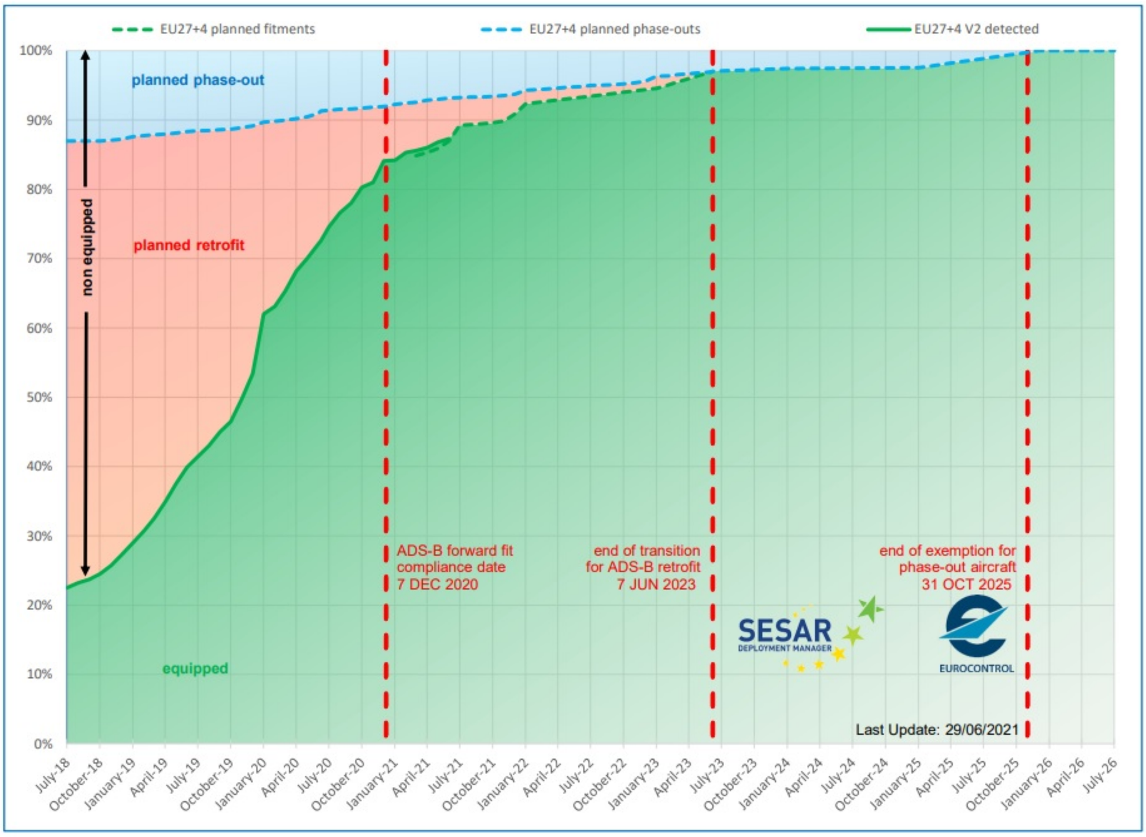


Figure 3.7: Evolution of airborne ADS-B equipage

Note

- CIR (EU) 2020/587 creates an indefinite exemption for airframes with first individual CoA dated before 7 June 1995. This fleet is excluded from the diagram from data point 07-Dec-2020.

- Following the publication of CIR (EU) 2020/587, SDM re-surveyed a portion of airspace users for their updated implementation plans. Due to a lack of near-term planning stability, brought on by the COVID crisis in the aviation industry, the diagram respects the results of the survey as of data point 01-Jan-2022.

- SPI IR also includes a mandate on Mode S surveillance; Mode S ELS must be fitted from 7 Dec 2020, whereas Mode S EHS regime is similar to the ADS-B regime depicted in the diagram.

EASA released AMC/GM to the SPI IR regulation giving further information, definitions and recommendations on several articles and paragraphs as shown in the Figure 3.8 below, ordered by the addressed stakeholder groups.

Reference	Headline	Stakeholder	Content
Article 5 AMC3	Interoperability requirements	Air Operator	How to benefit from transitional arrangements, required verification documents
Article 5 GM3	Interoperability requirements	Air Operator	Definition of 'Serviceable Transponder'
Article 5 GM4	Interoperability requirements	Air Operator	Exemption conditions, such as early build, planned phase-out, maintenance/export; required documents, conditions
Article 14a AMC1	Flight Plans	Air Operator	Flight Plan amendment with ELS/ADS-B/EHS function non equipped or temporarily inop *
Article 5 AMC2	Interoperability requirements	Design Organization	Certification guidelines
Article 5 GM1	Interoperability requirements	Design Organization	Definition of continuity for certification
Acceptable Means of Compliance and Guidance Material to Commission Implementing Regulation (EU) No 1207/2011			
Article 4 AMC1	Performance requirements	ANSP	Applicable separation minima for seamless operation
Article 4 GM1	Performance requirements	ANSP	Separation minima determination methodology
Article 5 AMC1	Interoperability requirements	ANSP	ASTERIX data format usage for transfer of surveillance data
Article 5 GM2	Interoperability requirements	ANSP	Capability to establish individual aircraft identification (1206/2011)
Article 5 GM5	Interoperability requirements	ANSP	Business case development for the most effective solution determination
Article 6 GM1	Spectrum protection	ANSP	Compliance monitoring of Transponder performances
Article 6 GM2	Spectrum protection	ANSP	Prevention, reporting and management of harmful interference
Article 7 GM1	Associated procedures	ANSP	Recommendation for performance assessment of surveillance systems

* ELS exemption applicable to EU MS State A/C only

Figure 3.8: Related Acceptable Means of Compliance and Guidance Material

For more information, see (EU) No 1207/2011 and (EU) No 1028/2014 and (EU) 2017/386 and (EU) 2020/587, the latter 3 are amendments to (EU) No 1207/2011 | EASA AMC | ADS-B Europe.

2. United States

ADS-B is required when operating overall 48 continuous states, within airspace at or above FL 100 (excluding airspace from 2,500 ft AGL). At or below FL100 ADS-B will be required:

- While operating within class B or C airspace;
- While operating within 12NM of the coastline in the Gulf of Mexico, at or above 3,000 ft MSL.

Requirements for areas outside the 48 Contiguous States can be found in the FAA Notices to Airmen.

ADS-B Exemption

ADS-B is required when operating over the U.S. as of Jan. 1, 2020. However, aircraft without the necessary ADS-B capabilities can still operate in U.S. airspace with a single-use route deviation authorization obtained through the FAA's ADS-B Deviation Authorization Pre-Flight Tool (ADAPT).

ADAPT facts:

- Applies to U.S. airspace route segments only;
- Only valid for a single route;

- Applications can be submitted 24 hrs. to 1 hr. in advance of departure;
- Authorizations are only valid within a +2 hour window of approved ETD.

For more details, please read through these references: FAA ADS-B | 14 CFR 91.225 | 14 CFR 91.227 | FAA Final Rule | Airspace.

3. Australia
ADS-B is required for all IFR operations at all flight levels over continental Australia, the Arafura Sea (bounded on the north by airway B598), the Great Australian Bight (bounded on the south by airway Q27/L513), and the Bass Strait (bounded on the east by airway H20 and to the southwest by L513).
More information can be found on AIP GEN 1.5 | CAO 20.18, 82.1, 82.3, and 82.5 | CASA 61/14.

4. Hong Kong
ADS-B is required for all operations above FL 285.
For more information, see AIP GEN 1.5 and ENR 1.10.

5. Indonesia
ADS-B is required for all flights within Jakarta (WIIF) and Ujung Pandang (WAAF) flight information regions (FIRs) at and above FL 245. Below FL245 ADS-B is required in multiple TMA and CTR airspace as well as parts of Class D and E airspace.
More information can be found at AIP ENR 1.6.

6. Seychelles
The initial mandate that was supposed to go into effect on June 7th, 2020, has been delayed indefinitely per AIC 10/20. Based on AIC 01/19, the mandate that is to be applied sometime in the future is as follows: all flights within the Seychelles (FSSS) FIR require ADS-B. Some automatic exemptions are available such as State aircraft, small aircraft, and others.
See AIC 01/19 and AIC 10/20 for more information.

7. Singapore
ADS-B is required for all operations at or above FL 290 within the area bounded by:
073605N 1090045E, 040713N 1063543E, 041717N 1061247E (MABLI), 044841N 1052247E (DOLOX), 045223N 1041442E (ENREP), 045000N 1034400E, thence north along the Singapore FIR boundary to 070000N 1080000E.
This area includes the following airways: L642, L644, M753, M771, M904, N891, N892, Q801, Q802, Q803, and T611.
For more information, see AIP ENR 1.8.

8. Sri Lanka
ADS-B is required within a prescribed area (See AIP SUP 02/20 for more details).
Aircraft manufactured before 01-JAN-2020 must have ADS-B (Out) 1090 MHz applicable to RTCA DO-260, DO-260A, or DO-260B. Aircraft manufactured on or after 01-JAN-2020 and has an MTOW exceeding 12,566 lbs (5,700 kgs) or having a maximum cruising true airspeed (TAS) greater than 250 knots must have ADS-B (Out) 1090 MHz applicable to RTCA DO-260B.

9. Vietnam
ADS-B is required for all flights at or above FL290 within the VVTS FIR whose MTOW is

5,700 kgs (12,566 lbs) or heavier. All flights operating along airways L625, L628, L642, M765. M768, M771, N500, and N892 require ADS-B at or above FL290.

10. Taiwan

ADS-B is mandatory for all aircraft operating within the Taipei FIR, at or above FL 290.
For more information, see ENR 1.8.13.

11. China

ADS-B is currently required for all flights at and above FL290 if operating in one of the following Urumqi CTA sectors. ZWWWAR02, ZWWWAR03, ZWWWAR05 and ZWWWAR06.
For more information, see AIP SUP 08/18.

11. Colombia

Colombia was initially supposed to go live with its mandate on January 1st, 2020. However, this has been delayed until April 30th, 2022. ADS-B is required for all flights within Colombia airspace, at all flight levels.
For more information, see RAC 4 4.2.2.6.

12. India

The current requirement is for aircraft to be ADS-B equipped to operate at or above FL285 on ATS routes in Indian continental airspace with designators L, M, N, P, Q, T and routes A201, A347, A465, A474, A791, B211, B466, G450, R457, R460, R461, W15, W19, W20, W29, W41, W43, W45, W47, W56S/N, W67, W111, W112, W114, W115, W118, W153.
For more information, see AIP SUP 148/18.

13. Malaysia

Malaysia has multiple phases for its ADS-B implementation. Phase 1 is a trial that is currently going on. Phase 2 will start on 25-MAR-2021. ADS-B is required to operate from FL290 to FL410 (inclusive) within a specified area that will affect the following airway segments:

- B466 (ANOKO-TOSOK)
- L510 (EMRAN-GIVAL)
- L645 (SAMAK-SAPAM)
- N571 (IGOGU-VAMPI)
- P574 (NOPEK-ANSAX)
- P627 (POVUS-RUSET)
- P628 (IGREX-GIVAL)

Phase 3 starts on 25-MAR-2022 and will require ADS-B in the entire WMFC and WBFC FIRs at all altitudes.
More information may be found within AIP SUP 01/20.

14. New Zealand

All flights operating within New Zealand where at or above FL245 where Transponder Mandatory Controlled Airspace exists require ADS-B. A second phase to begin on December 31st, 2021, will extend this requirement all the way to the surface.

More information may be found at https: //www.nss.govt.nz/ads-b.

15. French Polynesia / Tahiti (NTTT) FIR

All aircraft flying at or above FL200 will require to be ADS-B equipped. Starting on January 1st, 2022, the mandate will then expand to include the entire NTTT FIR.
More information is located at AIC PAC-P A06/19.

16. Canada

Space-based ADS-B will be used for surveillance in Class A airspace. Then on January 27th, 2022 will expand into Class B airspace. Non-ADS-B Out equipped aircraft will be accommodated within the airspace until a performance requirements mandate can be implemented.

17. UAE

The ADS-B mandate has been delayed until 02-DEC-2021 (AIP SUP 02/21). As per U.A.E. AIP GEN 1.5 and CAR Part IV Aircraft Operations, CAR OPS 1.867 ADS-B is mandated in the Emirates FIR for all IFR aircraft.

18. Saudi Arabia

As per GACAR 91.477 (b)(1)(vi) ADS- B will be mandated starting on January 1st, 2023, in class A, E, and B/C/D (around major airports).

19. South Africa

As of January 2020, the decision for an ADS-B mandate has been delayed until 2022.

20. Mexico

Starting on January 1st, 2022, ADS-B will be mandated for all Mexican airspace IFR operations.
More information at Advisory CO AV-91.2/19

21. Curacao FIR

As per AIC 10/19, all flights operating at and above FL290 requires ADS-B. On 01-JAN-2023, this requirement will extend all the way to the surface.

22. Mongolia

Starting 17-JUN-2021, as per AIRAC SUP 01/18, all flights operating at and above FL207 (6300 meters) requires ADS-B.

23. New Caledonia / NFFF FIR

Starting on 01-JAN-2022, all flights operating within the New Caledonia sector of the Nandi (NFFF) FIR requires ADS-B. For more information, see AIP PAC-N GEN 1.5.

3.5.4 Equipment Versions

All mandates in effect currently require ADS-B equipment to meet the requirements for 1090ES (1090 MHz), while some areas (USA) also allow 978 UAT (978 MHz) equipment to be used.

3.6 Reduced Vertical Separation Minimum (RVSM)

RVSM was implemented to reduce the vertical separation above Flight Level (FL) 290 from 2000-ft minimum to 1000-ft minimum. It allows aircraft to safely fly more optimum profiles, gain fuel savings and increase airspace capacity.
Between 1997 and 2005 RVSM was implemented in all of Europe, North Africa, Southeast Asia, North America, South America, and over the North Atlantic, South Atlantic, and Pacific Oceans.
An operator shall ensure that aeroplanes operated in RVSM airspace are equipped with:

- Two independent altitude measurement systems;
- An altitude alerting system;
- An automatic altitude control system;
- A secondary surveillance radar (SSR) transponder with altitude reporting system that can be connected to the altitude measurement system in use for altitude keeping. (IR-OPS SPA.RVSM.110, EU-OPS 1.872)

3.7 Vertical Navigation (VNAV)

VNAV stands for Vertical Navigation and is an autopilot feature that allows the aircraft to adjust vertical speed to meet a predetermined altitude at a specified waypoint. All SIDs, STARs, and Approaches have altitudes restrictions that have to be met; and VNAV is available (currently for descent only) to help meet these restrictions and reduce your workload.
Provided flight plan has at least one waypoint with an altitude restriction, VNAV will calculate a desirable rate of climb/descent and adjust this as conditions change. The following parameters are used for this calculation:

- Groundspeed;
- Distance to the next waypoint;
- Difference in altitude between initial altitude and target/final altitude.

During the descent, an Altitude Arc will be displayed on the map which indicates the predicted position at which the aircraft will be level at the altitude currently displayed in the Autopilot FCU ALT button. If this arc is not at the desired position, VNAV may not be working correctly and manual intervention could be required.
Vertical Navigation (VNAV) utilizes an internally generated glideslope based on the Wide Area Augmentation System (WAAS) or baro-VNAV systems. Minimums are published as a Decision Altitude (DA).

3.8 Mandates and regulatory framework

The next step consists in the identification of mandates issued by EASA, FAA, ICAO analysing the relevant impact on the pilot workload considering the functional and temporal priorities in America, Europe, New Zealand and the Asia Pacific.

- United States

- North America
    * **Automatic Dependent Surveillance-Broadcast (ADS-B) Out** equipage beginning January 1, 2020. ADS-B is the next generation GPS-based surveillance system the FAA is using to supplement, and in some cases replace, ground-based radar surveillance. The equipment required to comply with the 2020 mandate is an advanced transponder, an accurate GPS position source, an interface mechanism, and annunciators. The transponder has to be DO-260B compliant, which is the highest ADS-B Out equipment standard in the world.
    * Currently, all aircraft operating on or at any point along two specified tracks within the NAT (North Atlantic) Organized Track System (OTS) between FL360 to FL390 (inclusive) during the OTS validity period are required to be fitted with and using **Future Air Navigation System (FANS) 1/A** (or equivalent), **Controller to Pilot Data Link Communications (CPDLC)** and **Automatic Dependent Surveillance-Contract (ADS-C)** equipment.
- Canada
    * **Crew Resource Management (CRM)** in January 31, 2019 includes the concept of Threat and Error Management (TEM). TEM "advocates the careful analysis of potential hazards and taking the appropriate steps to avoid, trap, or mitigate threats and manage errors before they lead to an undesired aircraft state." The new standards relate to the training of crews for commercial aircraft operations, including air taxis.
- Mexico
    * **TCAS/ACAS 7.1** upgrade, On January 1, 2020, in compliance with International Civil Aviation Organization (ICAO) Annex 10.
    * **ADS-B Out** requirements are delayed until Jan. 1, 2022.
- Columbia
    * **ADS-B Out**: Starting on April 30, 2022, unless specifically authorized by ATC, no person may operate an aircraft within Colombian territory in any controlled airspace or other airspace in which a transponder is required, without ADS-B Out operational capability.

• Europe

- **Automatic Dependent Surveillance-Broadcast (ADS-B) Out** equipage in June 8, 2016 for new aircraft and June 7, 2020 for aircraft needing retrofits.
  On ADS-B, the European Commission has aligned more with the United States.
- **Traffic Alert and Collision Avoidance System (TCAS II) version 7.1** equipage in December 1, 2015 that enables mitigation of mid-air collision risk in situations where aircraft separation is reduced, such as with FANS 1A airspace.
- **Protected Mode Controller-Pilot Data-Link Communications (PM-CPDLC)** equipage in February 5, 2015. It is an air/ground data-link application that enables direct text messaging communications for revised clearances and rerouting instructions between the aircraft FMS and Air Traffic Controllers.
- **Cockpit Voice Recorders (CVRs) and Underwater Locating Devices (ULDs)** upgraded in January 1, 2019.

- **CPDLC Link 2000+** equipage in February 5, 2020, which was implemeted to serve as a high-speed CPDLC connection for aircraft flying above Flight Level 28,500 (FL285) to decrease radio frequency congestion within en route airspace. It is supported by the ground-based Aeronautical Telecommunications Network (ATN) Baseline 1, which operates over the VHF Data Link Mode 2 (VDL M2) subnetwork.
- **Cockpit voice recorders** with a recording duration of at least 25 hours is required on commercial airplanes with a maximum takeoff weight (MTOW) of 60,000 pounds or more manufactured from Jan 1, 2021.

- Australia
  - Any aircraft registered on or after February 6, 2014 operated under Instrument Flight Rules, is required to carry **ADS-B** transmitting equipment compliant with the Australian Civil Aviation Safety Authority's (CASA) Civil Aviation Order 20.18.
  - Beginning in February 2016, any aircraft operated under IFR in Class A-E airspace and within the arc of a circle that starts 500 nautical miles true north from Perthaerodrome and finishes 500 nautical miles true east from Perth Airport must carry serviceable ADS-B transmitting equipment that complies with Civil Aviation Order 20.18.
  - Starting in February 2017, all aircraft registered before February 6, 2014 operated under IFR requires ADS-B equipage complying with Civil Aviation Order 20.18.
  - **Duty and Rest Time Rules**: Starting July 1, 2021, affected operators (include all those with Australian commercial certifications, including airlines, charter and air taxi companies, flight schools, and aerial application firms) are required to follow new regulations establishing flight duty and pilot rest times.
- China
  - As of December 2014, **ADS-B Out** is required above FL290 in Hong Kong airspace.
  - Commercial operators are required to equip 50 percent of their aircraft fleet with **HUDs** beginning in 2020.
  - Commercial operators are required to equip 100 percent of their aircraft fleet with **HUDs** beginning in 2025.
- New Zealand
  - **ADS-B Out** already mandatory for aircraft flying above 24,500 feet, will apply in the rest of New Zealand's controlled airspace by December 31, 2022.
- Asia Pacific region
  - *Singapore*: The Civil Aviation Authority of Singapore (CAAS) started mandating **ADS-B Out** equipage to the DO-260 standard in 2014 above FL 290.
  - *Indonesia*: Starting January 1st, 2018, The Republic of Indonesia Ministry of Transportation is requiring all aircraft flying within the Jakarta FIR and Ujung Pandang FIR at or above FL290 to carry serviceable **ADS-B equipment**, including a **Mode S transponder and GNSS source position**.

- *Taiwan*: The Taiwan Civil Aeronautics Administration currently requires aircraft operating along airways B576 and B591 above FL290 to be equipped with **ADS-B** to the DO-260 standard. All aircraft operating in the Taipei FIR at or above FL290 will be required to carry ADS-B equipment starting January 1, 2017.

The mandates of the different states show one common vision of the future airspace, as there is a need to introduce avionics changes in/within a fairly long/short time frame.
SESAR, NextGen and similar initiatives which will support increased connectivity have the potential to aid single pilot operations (and also fighter A/C) in the future in this respect via the use of non-voice ATC communications.

Chapter 4

One sky for all

The military approach is to be “as civil as possible” while remaining “as military as necessary” for its aviation and ATM operations.
When the military operate a day to day routine training of air forces, must retain freedom of movement in European airspace to deploy air assets nationally, within the most dense and complex areas of Europe. Missions often launch with very short notice.
Military must be able to operate in non-segregated parts of airspace by:

- using military systems, recognised by the EU as providing an equivalent level of performance as the one required for civil aviation;
- improving the coordination between civil and military controllers (e.g. collocation of civil and military controllers).

4.1 Military versus Civil Aircraft

Previously, military organizations utilized their own standards for hardware and software development. Their rationale for such was:

- Military projects were more complex than commercial DO-178;
- Military projects needed higher reliability in harsh environments than civilian projects;
- Military projects had numerous varied suppliers to manage;
- Military projects required specialized military/sensitive functionality and complex integration cycles;
- Military projects had long airframe lifetimes to account for.

Today, consider the commonality between Military and Commercial avionics software/hardware:

- Both utilize high complexity and complex integrations;
- Both utilize hundreds of suppliers (many supplying nearly equivalent avionics to both Military and Commercial clients) with long project lifetimes;
- Both require access to leading-edge commercial technologies;
- Both are increasingly concerned with re-usability, quality, and increased cost-effectiveness;

- Both require a high level of operability, reliability, maintainability, and safety;
- Military aircraft are now utilized more and more in commercial airspace (they do not want to be restricted in flight paths or hours).

So, sharing of civil and military services and convergence of technology must be promoted, as well as a joint consultation for avionics development to facilitate future maximum system compatibility between civil and military applications.
The military community should define dual use technical solutions, enabling the reutilisation of available military capabilities hence reducing integration and technical constraints.
To overcome the difficulties caused by the mismatch of civil and military standards and certification, an alternative certification process based on the principles of performance equivalence can utilize available military capabilities to comply with civil CNS/ATM requirements expressed as performance levels and attributes.

4.2 Meeting Aviation Mandates

To meet the mandates concerning avionics and on-board systems, seen in the previous chapter, there are two alternatives: introduction of COTS (Commercial off-the-shelf) products or use of current avionics but which are certified with an alternative certification process based on the principle of performance equivalence. However, there is recognition that, sometimes, re-utilisation of avionics and other on-board systems could not necessarily meet an absolute equivalent level of performance because of lack of components.
Understanding the complexity and diversity of standards for military and aerospace components is a challenge in itself. It is therefore not surprising that securing qualification and testing processes contributes substantially to increased costs. Obviously from a military perspective, when applications are not particularly mission critical, the use of COTS components (that meet civil requirements) is preferable from an economic point of view, also considering that it is always possible to use versions of COTS designs intended for difficult or hostile operating conditions.
Is COTS' introduction really preferable from an economic point of view? It is necessary a trade-off analysis: in order to fit COTS there must be space required on the military aircraft, and this is possible if the aircraft is new and sizeable, whereas existing fighters, probably, are not be able to be retrofitted, which is why it is desirable to use PE process.
Performance-based certification must not lower certification standards, rather it must deliver better requirements on the basis of a performance-based approach which would benefit all airspace users.
The objective is to discuss the access of military aircraft to common non-segregated airspace volumes relying on systems which meet the performance requirements and which do not hinder the safety level associated with that airspace and to support mutual recognition of certificates from different certification environments.

Both alternatives will be considered in order to reach a conclusion through a gap analysis.

4.2.1 Performance Equivalence Concept

The concept of Performance Equivalence is used with different meanings, so it is underline the necessity to quote the following high-level definition from AC/92(EAPC)D(2016)0001 dated 13 May 2016: *"For Military aircraft, Performance Equivalence is the ability to meet the required functional attributes of ATM/CNS systems against the performance, safety, security and interoperability requirements of regulated airspace. This includes the measurable (e.g. metrics from regulations and standards) and non-measurable functional requirements (e.g. procedures or technical architecture), demonstrated through the evaluation of accuracy, integrity, continuity of function and availability."*

Performance Equivalence is a methodology for achieving Alternative Means of Compliance (A-MOCs) when Acceptable Means of Compliance (AMCs) cannot be met or when there is an operational and/or technical advantage of not using it.
The concept of performance-based certification is designed to focus on the technical performance of the system rather than its architecture or components, and is thus intended to define tailored means of compliance in support of the certification activity.
The flow chart in Figure 4.1, extracted from the JFR, illustrates the high level concept on which the process for determining compliance, equivalence or exemption is based.

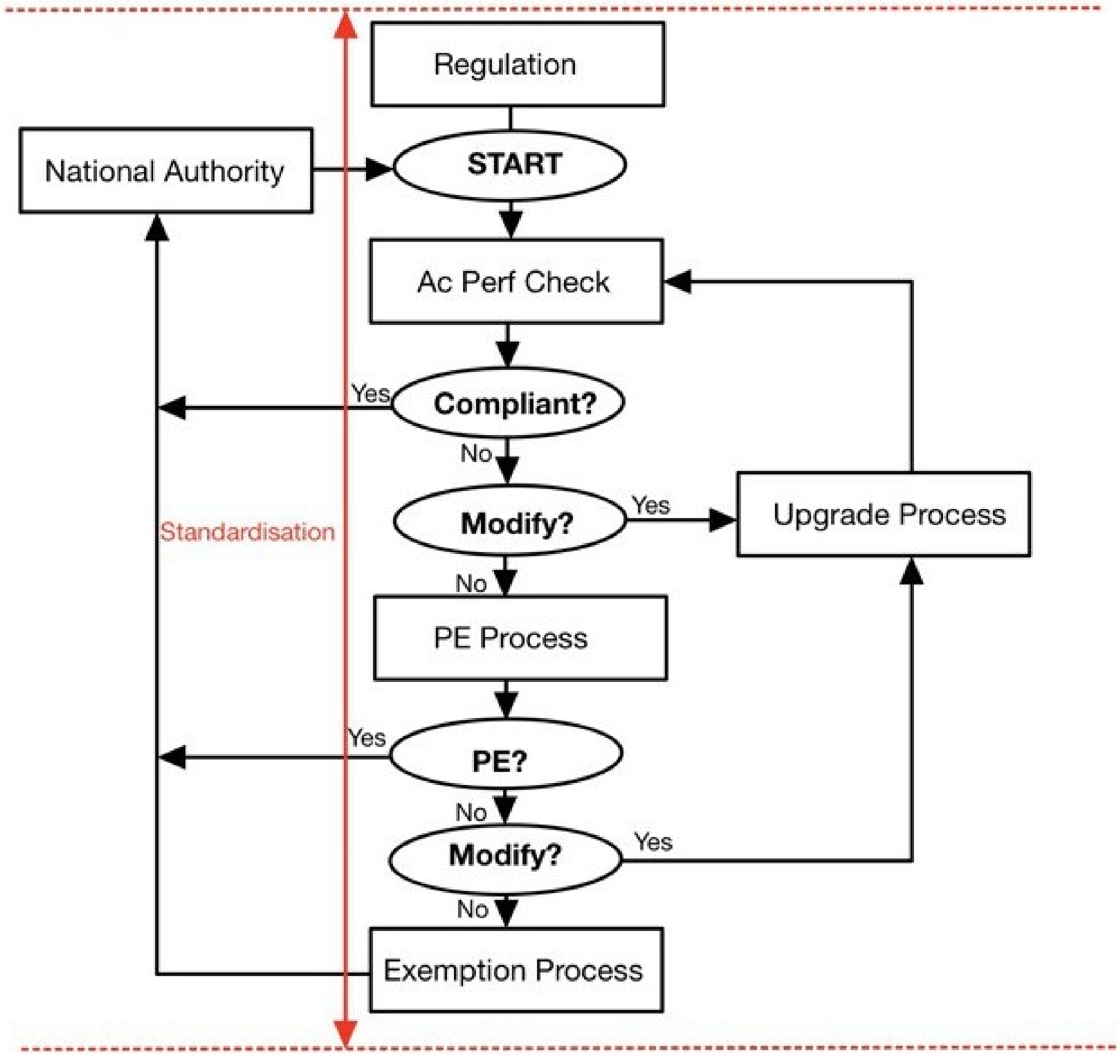
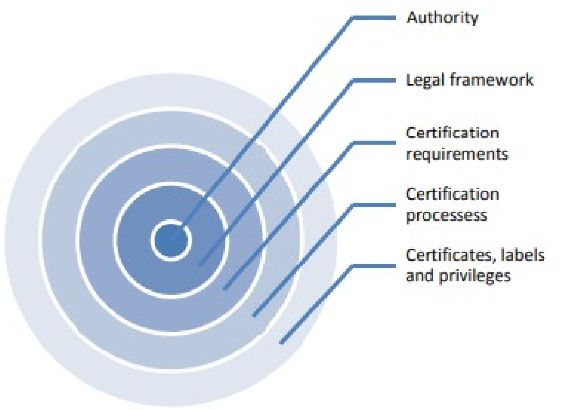


Figure 4.1: Process for Determining Compliance, Equivalence or Exemption

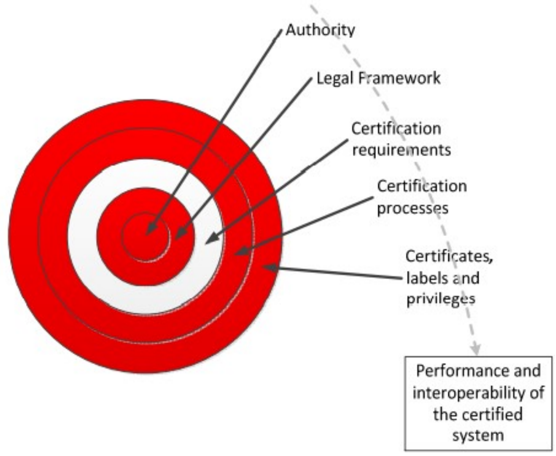
Generally up to now, no military equipment is Technical Standard Order (TSO)/European Technical Standard Order (ETSO) compliant, so an alternative compliance strategy can be applied to submit it to civil certification.
In order to solve the absence of TSO or ETSO approval, an extensive analysis of the equipment documentation (Specifications, Equipment Test Results, etc.) provided by the Original Equipment Manufacturer (OEM) can be done in order to show the level of compliance with regards to the civil standards.

4.2.2 The certification environment

The certification environment (Figure 4.2) is depicted functionally below using a five-ring display.



(a) Certification processes and certificates, labels and privileges



(b) Certification processes and certificates, labels and privileges modified and not

Figure 4.2: Certification environment

The certification of military systems is no different from that of civil systems: it follows the same strict rules and requires a legal framework supporting the actions of the certification authority.
As seen in Figure 4.2(a), the certification requirements are the basis for certification, the documented certification processes ensure that the certification is performed according to the expected standards and the certificates, labels and privileges are the outcome of the certification processes applied to a system (or individuals).
In aviation, the certification environment is the cornerstone for the performance and interoperability of the certified systems.

Being the architecture of military aircraft different from that of civil airliners, many requirements could be prejudicial to the certification of the operational capabilities of military aircraft although safety, performance and interoperability requirements, which are at the heart of the objective of certification, are met.

In Figure 4.2(b), the aspects identified in the red-coloured circles will not be modified in the performance-based certification.
Each ring is analysed: military authorities are assumed to be as reliable as civil authorities, so there is no need or no requirement for modifying the legal framework and that part of the

certification environment of the military authorities.
That is why in Figure 4.2(b), the authority and the legal framework are both coloured in red to show that they will not be modified by performance-based certification. And so for other rings.

4.2.3 Applicability of requirements to fighter aircraft: timing and priorities

The target is to outline key elements of a strategic approach for the military towards compliance with civil PBN/RNP requirements to enable safe, unrestricted and timely access to airspace. Avionics and on-board systems required for military aircraft to be integrated into the GAT are analysed, including from the PE point of view, assigning priority based on previous experience or time of implementation issued by mandate's point[1].

Depending on the available expertise and access to public domain information, analysis could be performed on *EF Typhoon*, so that analysis activity acts as a case study to derive a generic process for other military aircrafts assessment.
It is noted that avionics and CNIS (Communication, Navigation, Identification and Surveillance) systems provided by Leonardo Spa are analysed [2].

1. ADS-B Out & ADS-B In

As previously seen, the Commission Implementing Rule (EU) Nº 1207/2011 establishes the date for the mandate of Mode S Elementary, Enhanced and ADS-B Out capabilities in European Airspace and specifies the airborne equipage requirements.
The Commission Implementing Regulation (EU) No 2017/386 establishes the new applicability date for operators to comply with the transponder requirements as the *7 June 2020* (previously 7 December 2017). This date also applies to state aircraft.

ADS-B uses a *transponder*, typically combined with a *GPS*, to transmit highly accurate position information to ground controllers and also directly to other aircraft. Therefore transponders and GPS must be certified.

Firstly, **transponder** is considered.

- **PE.** The performance equivalence process is applicable to a single equipment or to a part of the equipment itself, but also to subsystems or to a whole systems. With regard to the applicable civil regulation at transponder level, the same level of compliance of a TSO or ETSO equipment can be demonstrated by the analysis and test for military equipment. Sometimes the PE demonstration can be very expensive and not usable if its use is extended to the whole avionics.

- **COTS.** If compliance with civil regulation at transponder level cannot be demonstrated, the equipment must be redesigned or replaced with other equipment that complies with civil requirements.
  COTS can be introduced with three levels: military, tactical (with characteristics similar

[1] *Note*: Timing and priorities are indicated by order of treatment.
[2] ©Leonardo products, www.leonardocompany.com

to those of current products) and civil (to meet civil requirements). Accuracy, continuity and integrity must be guaranteed.
The “ADS-B Out” capability on board is enabled by transponders interfaced with the relevant avionics systems (such as GNSS, pressure altimeters etc.).
The relevant certification documents are EASA AMC 20-24 for ADS-B in Non-Radar Airspace or CS-ACNS for “ADS-B out”.

Furthermore, work on the future ADS-B applications (spacing, separation and self-separation) is ongoing or planned by SESAR (Europe) and NextGen (USA). The standards of future applications will be developed also by EUROCAE/RTCA joint work.

- **Mixing Performance.** In addition to PE and COTS, a third case study (which we introduce here for the first time) could be added, which we will call "Mixing Performance" and which represents a mixed approach. This approach is the main key in the avionics choice and the trade-off analysis is based on the level of mix considered.
  "Mixing performance" means having military components, including COTS, function as a whole as civilian equipment.

  To support the use of Company products, the **M428 IFF Transponder** (Figure 4.3), certified by the US Department of Defense, could used to be as reference in this analysis. Compatibility with the latest ATC standards is provided by a Mode S (up to Enhanced Surveillance) that includes an ADS-B Out capability (compliant to DO-260B) and ADS-B In growth capability.

Figure 4.3: M428 MKXIIA & MODE S IFF COMPACT TRANSPONDER

  Multiple options are available in order to interface the host platform; all interfaces are available in the same unit and are automatically selected at power-up. These options are:

  – MIL-STD-1553 to interface an avionic bus;
  – RS 485 to interface an FMS or dedicated Control Panel;
  – ARINC 429 to interface an FMS;
  – Ethernet (Growth capability).

The M428 transponder also provides next market demand as the integration of the ADS-B In functions inside the military transponder. Through the Mode S ADS-B In function, aircraft will be able to receive surveillance information (about civil tracks) without the need to switch on the radar and the interrogator (if available on the platform).

So the functions required in the civil field are satisfied by this equipment.
Defining dual use technical solutions enables the utilisation of available military capabilities hence reducing integration and technical constraints.

The **GPS** issue is now addressed.
Military GPS is not TSO holder[3] and as regards the Navigation Database only route waypoints supported (For RNP-1 the use of military waypoints is not authorised)[4].

- **PE.** GNSS receivers that use Global Positioning System Precise Positioning (GPS PPS) signals contain Government Furnished Equipment (GFE) elements, with associated documentation that cannot allow a direct demonstration of compliance with civil requirements. However, to demonstrate meeting those performance requirements, the Government Furnished Equipment (GFE) elements could treat as a black box.
  State aircraft were developed following customer requirements and modifications are not foreseen, so the civil compliance is to be demonstrated by means of a Performance Equivalence approach. Accuracy, Integrity and Continuity requirements are analysed.

  Accuracy. Verifyed.
  In civil requirement it is usually described as the 95% probability for an aircraft to actually fly into the RNP/RNAV corridor.

  Continuity. The problem is the different Design Assurance between military and civil requirements. However, it should be considered that the military authority might authorise Design Assurance concepts, e.g. SW and HW development, that differ from those that the civil authority might authorise.
  It should take into account navigation equipment architecture, equipment design standard, resulting MTBF, redundancy, monitoring functions and the ability of the system to recognize true and false alarm.

  Integrity. The problem is EF Typhoon GPS unit is not TSO compliant. Here too, it must be borne in mind that the Military Authority may make exceptions that the Civil Authority cannot.
  Integrity completes the definition of continuity: the navigation data are to be available (with a probability) and they are to be reliable (with a probability).

  Next section provides a detailed analysis of this last points.

- **COTS.** Considering the aircraft currently in development, where some changes are possible, and future development, the best way is to use COTS.

[3] *Note*: TSO is not mandatory, however further analysis would be necessary to show compliance with Accuracy, Integrity and Continuity requirements.

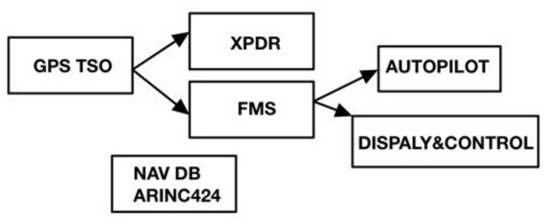
[4] *Note*: This could be mitigated by modifying the Mission Planning System to load the ARINC data with the required integrity to the existing EF Typhoon navigation database.

Advantages: Buying already certified equipment the certification process of the entire chain will be easier.

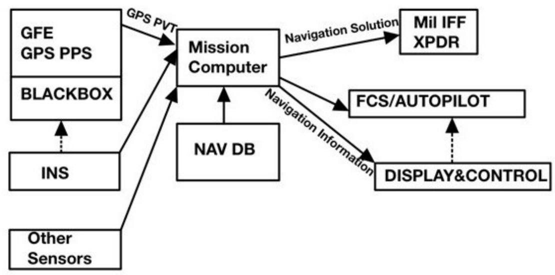
- **Mixing Performance.** Again, as in the case of the transponder, the third approach of "Mixing Performance" is examined. If a TSO GPS on military aircraft is considered, the whole chain has to be certified, so a TSO certified antenna should also be implemented. The problem could be that a military TSO certified antenna can not available, so we refer to the mixed approach where a civil TSO certified antenna can be used to complete the avionics.
  Here is another example of Mixing Performance: military GPS PPS used to power the COTS "M428 IFF Transponder" which is civil certified.

GPS compliance: definition of the problem

The primary source of position (GPS) cannot be verified in accordance with civilian rules, because the data bus, mission computer, Nav DB, etc., are not civil certified and cannot be used to verify the position.
Infact, to analyse the different aspect of the Navigation System performance requirement, the complexity of the required work is reported by comparison.



(a) Minimal Civil Avionic Configuration



(b) Example of Military Avionic Configuration

Figure 4.4: Comparison between different avionic configuration

As seen in Figure 4.4 it follows that a complex analysis about the different aspects (Accuracy, Continuity and Integrity) must be addressed.

Accuracy. To qualify military GPS accuracy, the performance is evaluated with a flight test activity (performed on population of samples singularly evaluated) in order to guarantee the respect of the specification / customer requirement. For this reason, statistical parameters are usually available and can be used as means of evidence to demonstrate compliance with civil accuracy requirements.

Continuity. Performance Equivalence can be used to demonstrate the continuity requirement using:

- Analysis on Mean Time Between Failure (MTBF) vs. Architecture;
- Analysis on monitoring systems to demonstrate the capacity to detect as soon as possible any lack of continuity and to activate backup measures;

- Design Assurance (DA);
- Service history can be used to mitigate lack of DA performed in line with civil standards (DO-178, DO-254).

Integrity. The integrity depends on three main aspects:

- Sensor/Navigation System error (unnoticed error should not exceed the required threshold with the required occurrence probability);
- Undetected HW failures (in terms of Performance Equivalence, the evidence to be provided and the level of mitigation placed in act have to be determined case by case);
- Design Assurance (gap analysis on industrial standards used during equipment development [DO-254 and DO-178]).

The integrity fails if any of these contributions affect the Navigation System, therefore the total probability of integrity failure is the sum of the single probabilities.

Comments

The Performance Equivalence approach is based on flight test. If a GPS sensor system has been validated, the results are valid also for another aircraft with the same antenna/amplifier/receiver. From other hands, civil certification should take into account the peculiarity of a military evolution: the FMS military equivalent is continuously updated for customer requirement and function adding. In this case, the civil certification remains valid if the civil navigation related functions are not modified.

So, State Aircraft compliance to accuracy, integrity and continuity requirements can be validated using alternative methods for example flight test data, statistical analysis, gap analysis, failure test ect.
A modern aircraft following military Design Assurance standards can easly follow this approach compared to older aircrafts where Design Assurance standards are obsolete.

2. VNAV

The flight paths that an aircraft is allowed to fly depend on its avionics capabilities, both laterally and vertically. While the concept of lateral guidance is more intuitive (what path we fly from A to B), vertical guidance concerns when an aircraft climbs or descends, and how fast. Vertical guidance is useful in optimizing climbs and descents, minimizing environmental impact.
While legacy Instrument Landing Systems (ILS) provide guidance based on radio navigation signals transmitted from the ground, PBN Area Navigation (RNAV) approaches rely on Distance Measuring Equipment (DME) or Global Navigation Satellite System (GNSS) positioning for lateral guidance, and barometric altimeter systems for vertical guidance. This guidance is internal, calculated by the aircraft's Flight Management System (FMS) computer. The "quality" of internal guidance is based on the capability of the aircraft's computer (and sensors -GPS above all-) and its validation process. Thus, the presence of LNAV and VNAV on aircraft means that the operator is no longer dependent on a ground-based Navigation Aid infrastructure.
Impacted areas associated with upgrade to LNAV/VNAV or LPV capability include:

- Aircraft Systems;
  - Flight Management System;
  - Displays and Control Panels;
  - Flight Director/Autopilot;
  - Air Data and GNSS;
  - Others, Depending on Configuration;
- Simulation and Training;
- Technical Publications.

The cost of upgrading avionics equipment to enable LNAV/VNAV capability ranges from $75,000 to $350,000 depending on aircraft type, current configuration, and certification type [5].

The VNAV requirement in military aircraft is not currently envisaged and will not be until an advanced level of development of the aircraft itself. However, knowing that VNAV has GPS-based vertical guidance (mitigations have been discussed above), the pilot can be used as a mitigator of the inadequacy of Design Assurance with adequate procedural integration.

To study the pros and cons of PE and COTS introduction of this apparatus, we refer to the literature.

- **PE.** This approach cannot be followed because the GPS PPS does not have satellite-based augmentation systems (SBAS) that are used to enhance adequately the vertical accuracy and precision of an existing GPS system, so VNAV has limitations.

- **COTS.** The substitution of older equipment in legacy fleets becomes more and more difficult as component suppliers eventually abandon their older products to make room for newer equipment lines.

- **Mixing Performance.** This is a significant challenge for two reasons:
  - The cost of re-design is driven by the high specifications associated with development, verification, and certification of aircraft equipment;
  - Unlike consumer products, aerospace avionics manufacturers do not typically justify a business case for components unless it is in association with a new aircraft type.

3. RVSM

Since 2003 a number of issues have arisen regarding the operation of State aircraft flying under general air traffic rules within RVSM airspace, in particular the validation of height-keeping performance requirements for aircraft types and the necessity for an RVSM approval to be issued by the appropriate State airworthiness authority.
The main issues to be conveyed are:

[5] NextGen Advisory Committee, *Vertical Navigation (VNAV), NAC Task 20-2 Report*, 2021

- There is no exemption for State aircraft to operate as GAT within RVSM airspace with a 1000 ft vertical separation minimum without an RVSM approval. The absence of such approval does not mean that State aircraft cannot access RVSM-designated airspace, but it does require a separation of 2000 ft to be observed and a separate flight plan to be filed.

- Any derivative aircraft modified for specific functions must be validated against the RVSM MASPS before being granted an RVSM approval.

- Formation flights are not permitted within RVSM airspace with a 1000 ft vertical separation minimum [6].

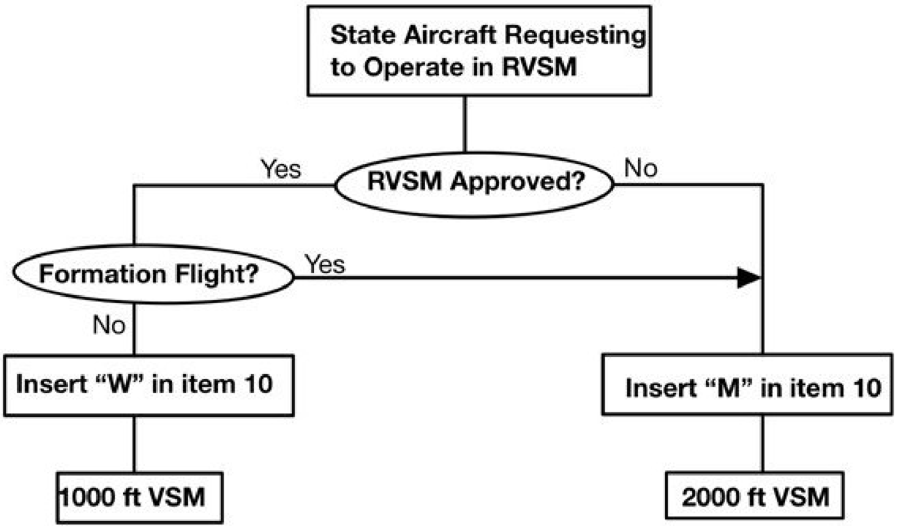


Figure 4.5: Flight planning requirements for State aircraft in EUR RVSM airspace

When non-RVSM compliant State aircraft operate as GAT in RVSM airspace the complexity of the provision of a higher vertical separation minima can lead to operational disadvantages such as non-optimum routes and flight profiles and additional fuel consumption.
Modern military fighters are fitted with a type of altimetry system (especially, FCS provides one), often using multiple static and dynamic pressure sources connected to redundant pressure calculators, which is of a different nature from the civil commercial aircraft independent altitude measurement systems.
The apparent lack of redundancy may be a safety issue if it creates a non mitigated risk. Moreover, their height-measuring performance may be strongly influenced by the aircraft external carriage configuration, which may limit the approved aircraft configurations.

- **PE.** Operator must prove that the certified altitude measurement system is compliant with SPA.RVSM.110 (a) (level of the Implementing Rule, binding) and it must be specified by a certification specification different from the CS-ACNS (non-binding): since the RVSM technical MASPS are included in the CS-ACNS, the military authorities willing to issue an RVSM approval for such aircraft types have to demonstrate that the technical fit of the aircraft is fully compliant with the ICAO provisions and that this aircraft type does not hamper the level of safety in the RVSM airspace.

[6]EUROCONTROL, *Guidance Material for the Certification and Operation of State Aircraft in European RVSM Airspace*, 2014

- **COTS.** Military aircraft should be modify aircraft and the technical feasibility of modification should be assess.
  Minimum Equipment Fit:
  - Two independent altitude measurement systems;
  - One secondary surveillance radar transponder with an altitude reporting system that can be connected to the altitude measurement system in use for altitude keeping;
  - An altitude alerting system;
  - An automatic altitude control system.

  Also military authorities should conduct flight crew training and amend operating practices and procedures [Refs: Appendix 4 of TGL n° 6, Rev. 1 (Training Programmes and Operating Practices and Procedures) and ICAO Guidance Material EUR Doc. 009].

Altimetry System Error (ASE)

The incidence of height keeping errors that can be tolerated in an RVSM environment is small. Altimetry system error is the difference between the altitude indicated by the altimeter display assuming a correct altimeter barometric setting and the pressure altitude corresponding to the undisturbed ambient pressure. Errors in measuring the ambient air pressure or converting this into the altitude readout are major sources of ASE.
In most circumstances ASE is invisible to pilots, ground controllers and other aircraft (TCAS), so that any increased risk due to ASE cannot be mitigated operationally. Also, ASE is extremely difficult to measure in an operational environment (ASE is extensively described in CS-ACNS – Book 2 – Subpart E – Appendix A).
Undetected rapid deterioration of ‘no life limit’ components must be considered, particularly integrated pitot/static probes, and the rapid rate of deterioration associated with them and the inability of some checks to identify faults. This is not a problem because it is handled manually, but it must be taken into account.

4. CPDLC

Currently, more than 23% of the traffic crossing the Maastricht Upper Area Control Centre (MUAC) airspace use CPDLC on a daily basis as a secondary communications medium, complementing VHF voice communications, which remains the primary means for tactical communication.
As of February 2020, CPDLC will be required to operate above FL285 in Europe.
The data link and voice communication requirements for CNS/ATM are being defined by civil aviation authorities and are based on use of commercial communication systems.
Currently, there are two implementations of CPDL:

- FANS-1/A, developed by Boeing, used on trans-oceanic routes. FANS-1/A is based on the ACARS (Aircraft Communication Addressing and Reporting System) system and uses Inmarsat Data-2 (Classic Aero) satellite communication;

- ATN/CPDLC, extended through the Link2000+ program in the EU countries. The system uses VHF Digital Link (VDL) Mode 2 networks, operated by ARINC and SITA.

The military has unique requirements as using CPDLC. These requirements were never considered when the CPDLC message set was being developed.

- **PE.** To support the use of Company products, the **SP 2310 Airborne HFDL**[7] (Figure 4.6), designed in accordance with RTCA DO-178B, could used to be as reference in this analysis. This system provides main airborne platforms with an HF voice and data communications capability and together with an ACARS Management Unit or Communications Management Unit (CMU), it provides the ability to transfer data with other aircraft or ground station supporting AOC, ATS and ATC services.

Figure 4.6: SP 2310 Airborne HFDL

The SP-2310 comprises the following units:

- HF transceiver (HF RT) or HF Data Radio (HFDR) SP-2311, that includes an internal modem for data communications in accordance with Arinc 635;
- Antenna Tuning Unit ATU-2005.

The transceiver is form, fit and function compliant with ARINC standard including interfaces and connectors. The HF data radio is designed to satisfy interoperability requirements.
In double configuration, two SP-2311 units can be linked together (via Cross Link) to automatically provide hot backup of data functions in case of failure.
The SP-2311 has three modes of operation:

- Voice (ARINC 753/719 Mode) where it behaves as a standard AM-SSB transceiver. Voice signals are provided via normal audio I/O, with transmit and receive conditions initiated by the operator with the microphone;
- Analog data (ARINC 753 Mode) where it receives data audio and data key line from analog data unit and send back received data audio;
- Digital data (HFDL as per ARINC 635) where it provides services for Physical, Link and partially Network layers of OSI model.

[7]©Leonardo products, www.leonardocompany.com

- **COTS.** If compliance with civil regulation about CPDLC cannot be demonstrated, the equipment must be redesigned or replaced with other equipment that complies with civil requirements. COTS can be introduced with three levels: military, tactical (with characteristics similar to those of current products) and civil (to meet civil requirements). So, Link2000+ could be proposed in parallel.

5. Airborne Collision Avoidance System (ACAS)

As seen in Chapter 3.8, there is regulatory initiative for the introduction of ACAS II software version 7.1.
ACAS II tracks aircraft in the surrounding airspace through replies from their ATC transponders. If the system diagnoses a risk of impending collision it issues a Resolution Advisory (RA) to the flight crew which directs the pilot how best to regulate or adjust his vertical speed so as to avoid a collision.
Experience, operational monitoring and simulation studies have shown that when followed promptly and accurately, the RAs issued by ACAS II significantly reduce the risk of mid-air collision. ACAS II can issue two types of alerts:

- Traffic Advisories (TAs), which aim to help the pilots in the visual acquisition of the intruder aircraft, and to alert them to be ready for a potential resolution advisory;

- Resolution Advisories (RAs), which are avoidance manoeuvres recommended to the pilot. When the intruder aircraft is also fitted with an ACAS II system, both systems coordinate their RAs through the Mode S data link, in order to select complementary resolution senses.

Back in 2005, the mandatory implementation of ACAS II (TCAS version 7.0 or above) did not apply to State Aircraft.
By that time, the military commitment was voluntary, but Germany has made ACAS II mandatory within its airspace, from 1 January 2000, for all aircraft whether civil or MTTA (Military Transport-Type Aircraft), which meet the Phase 1 criteria, and from 1 January 2005 for all aircraft whether civil or MTTA which meet the Phase 2 criteria (for fixed-wing turbine engine aircraft having a maximum certificated take-off mass exceeding 5,700kgs, or a maximum approved passenger seating configuration of more than 19).
A revised Policy on ACAS for State aircraft is under discussion at the moment to reflect the need to recommend equipage with the latest TCAS logic (version 7.1).

No research has been conducted on safety assurance system alternatives for military aircraft.

- **PE.** Civil safety assurance requirements, as currently defined, are *not* suitable for the direct application of a performance based approach.
  We have to considered that, with on-board sensors (radar, etc.), a fighter aircraft shows a satisfactory situational awareness of the surrounding traffic. Thus, the PE process could be conducted by considering the avionics base on the aircraft and implementing a dedicated SW.

- **COTS.** Modern military platforms evidence awareness capabilities that could be relevant to mitigate the absence of collision avoidance. IFF capability and airborne radars could be important in this respect.

4.2.4 Conclusions

This effort to find ways to meet mandates (both PE and COTS) has been done for implementing common improvements for all stakeholders.
The best alternatives for the various points analysed are listed below:

- As for **ADS-B Out e IN**, the analysis of two components must be considered:
  - *Transponder*, for which the best solution is to use the Mixing Performance process;
  - and for *GPS* the use of COTS is preferred, because the aim is to move towards uniformity between civilian and military with a view to SESAR and NextGen.
- **VNAV**. Having chosen a COTS to have a certified GPS also in the case of VNAV we choose to implement a new equipment.
- **RVSM**. In this case you can decide to seek permission each time or use minimum equipment to meet the mandates.
- **CPDLC**. Present trend is for civil data link capability based on ATN / VDL-2 or FANS / ACARS to be considered the eligible capability for transport-type military aircraft where civil CPDLC capability is considered required.
  Procedures concerning communications to be used by military aircraft to promote harmonisation in CPDLC should be developed using a combination of existing CPDLC message elements and free text.
- **ACAS/TCAS II (version 7.1)**. This equipment with potential to be considered might comprise:
  - SSR Mode A+C Transponder;
  - Military SSR Mode S Transponder (Level 2);
  - Military IFF Mode 5 Transponder (Level 2);
  - Military Combined Interrogator Transponder (CIT);
  - Airborne Radar.

As to **military navigation architectures** cannot easily comply with the majority of PBN navigation specifications due to the eligibility of sensors and to all the issues related to the flight path definition based on ARINC 424 data. It should be noticed that the display systems used on modern military aircraft can easily meet the civil requirements.

Our goal is to achieve: additional flight efficiency, additional throughput and enhanced safety.

Chapter 5

Changes in Military Aircraft

With the evolution of military operations and the expansion of civil aviation, military systems increasingly have to operate in any airspace, including in a mixed environment context, and therefore must meet the common ATM/CNS requirements. What does it mean for fighter cockpit configuration, Human Machine Interface (HMI) and Single Pilot Workoload?

Before we get to this, a quick note about the most defining difference between military and civil sector: the number of necessary pilots.
It seems highly appropriate to address these aspect considering a further reduction of the crew size from two pilots to one has become an option also in civil aviation. The trend in the civil sector will be exploited to assert the introduction feasibility of single pilot military aircraft into GAT landscape.

5.1 Background: from crew operations to single pilot operation in Civil sector

Commercial aircraft are commonly operated by two pilots: the Pilot Flying (PF) and the Pilot Monitoring (PM). This crew configuration could change in the future, considering the historical background in commercial aviation, toward so called reduced-crew or Single Pilot Operations (SPO).
During the past decades, cockpit crews have gradually been reduced from initially five crew members to today's Two Crew Operations (TCO). So far this 'decrewing' has not led to any safety issues when it was accompanied by adequate technological support (Harris, 2007). In light of this historical trend and taking into account the ongoing technological progress, a transition to SPO seems like the logical next step.
Economic factors are the main drivers because airlines want to save costs, gain more operational flexibility and prepare for an expected pilot shortage due to the growing demand for commercial aviation (Bilimoria, Johnson, & Schutte, 2014; Comerford et al., 2013).

A roadmap of the technologies necessary to develop Single Pilot Operation is presented in Figure 5.1.

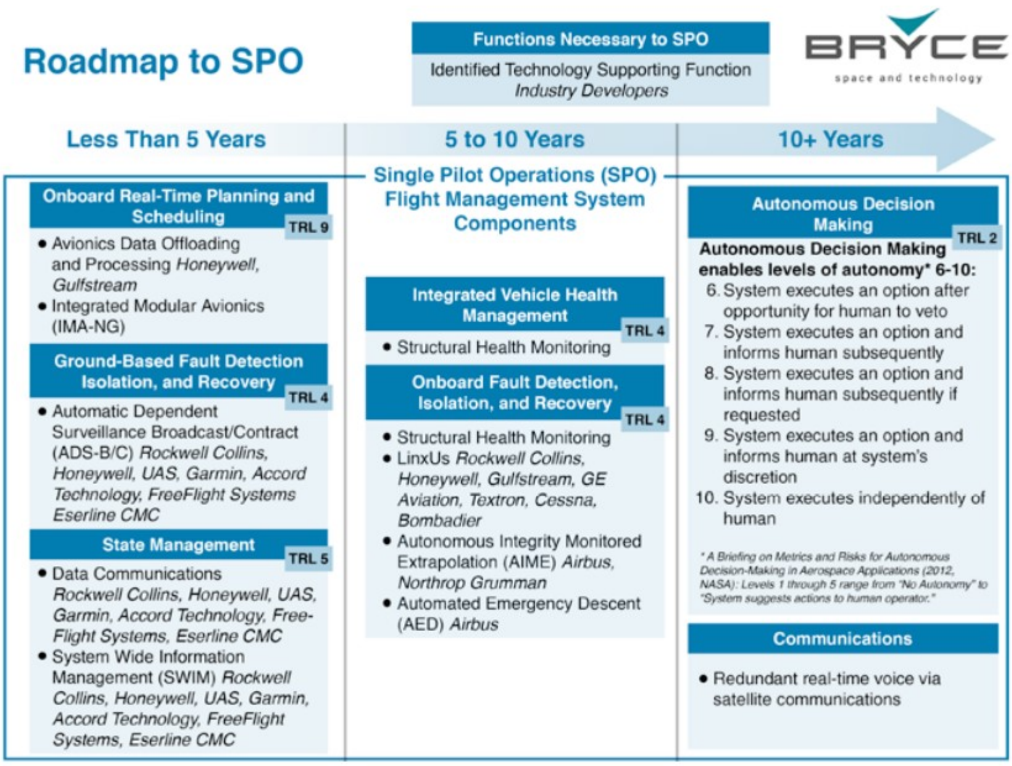


Figure 5.1: A roadmap of the technologies necessary to develop Single Pilot Operation

The characteristics (e.g., roles/responsibilities, tools, procedures) of an SPO will depend in part on the nature of the operating condition.

The question that must be asked is: "Why do we actually need two pilots?". Removing the second pilot does not necessarily means remove second pilot who can be replaced by automation (called as aircraft-centric) but also means re-collocated pilot to the ground (air-ground-centric).

- **Aircraft-centric**: technological solutions replacing the second pilot are based on physical and psychological monitoring of human performance and could be seen as support or associate systems for the single pilot. This approach would make use of advanced technologies (computing power, artificial intelligence, machine advantages over humans) and would not require a considerable change to the aircraft's operations or air transport system;
- **Air-ground-centric**: SPO uses actual technology where the focus is on real-time functionality distribution between the flight deck and the ground station, relocating the second pilot to the ground, with an important development of human-machine interaction.

The seven proposed civil configurations are shown (see Figure 5.2):

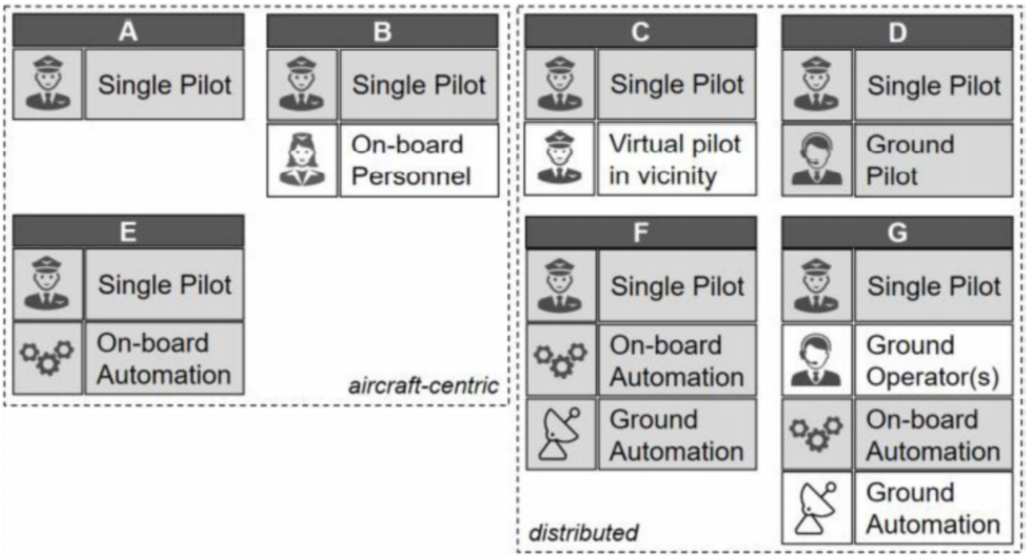


Figure 5.2: Classification of existing concepts. Agents highlighted in grey are always online; those highlighted in white are on standby, acting only on request.

In this context the concepts of greatest interest are:

- **A - Elimination of the second pilot**. This concept involves the removal of the second pilot from the cockpit without change any type of operation, with actual deck layou and or the actual air transport system. But, it leads to an increase in the workload of the SP during some particular flight phases (in particular: taxi, take-off, climb-out, approach and landing), while it could lead to monotony for the operator during long cruises. Both cases would compromise safety and regulations relating to airworthiness and flight certifications may be violated.

- **D - Transfer to the ground of the second pilot**. In this way the second pilot becomes a remote (co)pilot, who takes new benefits compared to the crew: it is not subject to depressurization, to the gravitational force, to the temperature, etc. and he is easily interchangeable. Both pilots, on the ground and in flight, have the same tasks and functions as the current ones and to complete the protocols it is necessary that both know what the other pilot is doing and why, and who is in control of the aircraft. It is required a safe data link connection. If the communication fails, the single pilot should be able to operate as in modes A or B.

- **E - Replacement of the second pilot with the automatisms on board**. This solution is the next logical step relating to the trend of de-crewing and for which there will be a new protocol to proposed. The main problem will be final authority: it will have to be given to automatisms or always to humans? And when the pilot is unable to perform tasks.

- **G - Displacement of the second pilot with one or more (redundancy) ground operator(s) with automatisms on board and on the ground**. Concepts in this category were developed by NASA in cooperation with BOEING, as part of the research project to reduce pilot workload thank to the help of automatism. In fact, for NASA the concept of SPO falls into this category, which includes a SP on board, automatisms on board and on the ground and one or more Ground Operators (GOs).

In SPO, cognitive functions of current PF and PM will be distributed among pilot, ground operators and new avionic systems.
Normal piloting cognitive functions consist in reading checklists, cross-checking life-critical information, trouble-shooting and recovering from failures, fuel monitoring, etc. Ground operators have different cognitive functions that can be named dispatching, ATC coordination, crew scheduling, maintenance triggering, customer service, and weather forecast. Their job will change with SPO and will need piloting cognitive functions in the case of malfunctions in the airspace, including pilot incapacitation and its duality, total system failure. In addition, they will not have to control only one aircraft but, in some cases, several.

A basic taxonomy is presented in Figure 5.3, based on the pilot's physiological and behavioral condition (normal vs. incapacitated) and flight condition (nominal vs. off-nominal). It is noted that the term "flight condition" refers to the myriad factors affecting the flight other than the pilot's condition, such as the status of aircraft systems, weather conditions, and airport availability.
As the taxonomy condition (TC) progresses from 1 to 4, the operating conditions become more challenging, and the requirements for safe implementation of SPO become more complex.

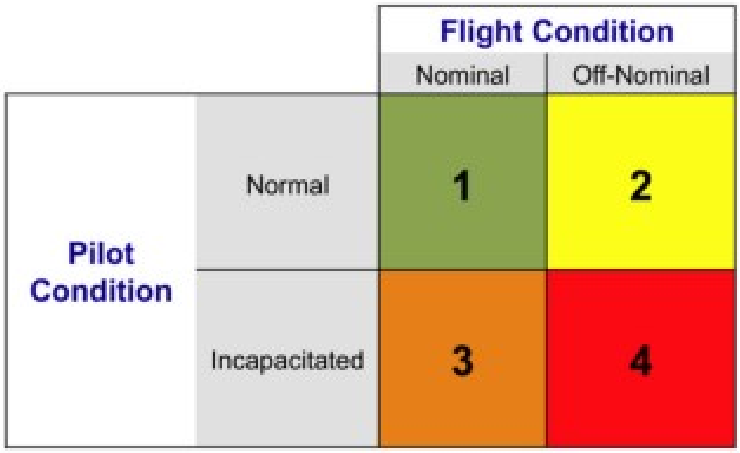


Figure 5.3: A taxonomy of operating conditions for SPO

For example, in TC-1, there may not be much need for ground operator assistance; the cockpit automation could provide most of the assistance needed by the captain. In TC-2, the captain would likely request the assistance of a ground operator, especially in complex off-nominal conditions with high cognitive workload. TC-3 would require a ground operator to assume the role of captain and interact with cockpit automation to land the aircraft. In TC-4 the ground operator acting as captain may need assistance from other ground operators to land the aircraft[1].

5.2 Fighter Cockpit

Most important point concerns cockpit configuration because many military fighters operate with a single pilot in the cockpit (except for training twins or Tornado and F15EX or old non-operational aircraft such as the F4/F14). In fact, for all 4th-5th generation aircraft, the needs of the single-seater pilot were paramount throughout the design process. This has meant high levels of attention have been paid to the control and information interfaces throughout the unique glass cockpit, from the head-up, head-down and head-out systems to all-round vision.
With the introduction of fighters into general aviation, the cockpit configuration will have to adapt to the new requirements and make room for the automation needed to support the

[1]Michael Matessa, Thomas Strybel, Kim Vu, Vernol Battiste, Thomas Schnell, *Concept of Operations for RCO/SPO*, 2017

individual pilot. For this reason also a redefinition of the pilot's workload will be required, which could be mitigated by support operations, such as procedures, automation, and problem-solving skills.

5.2.1 New Cockpit Automation Requirements

In order to introduce a military fighter aircraft in GAT new considerations must be made regarding the division of functions between human operator and automation.
There are two important automation capabilities that require significant advancement:

- interaction and task exchange, and
- pilot health monitoring.

Interaction and Task Exchange

Cockpit automation needs to clearly inform the captain about what it is doing, and to confirm important parameters (e.g., altitude settings). In response to a command from the captain, the automation must repeat the command for error-checking, inform the captain that it is executing the command, and notify the captain when it is done. The automation must follow current best practices for human-to-human CRM.
The automation will be called upon to assist the captain in declarative[2], retrospective[3], and prospective[4] memory items. Required tasks of the automation may include checklists, task reminders, challenge-and-response protocols and recall of information or instructions provided by ATC personnel or ground operators, for example.

Pilot Health Monitoring

The second automation capability that requires development is the monitoring of the captain's physiological and behavioral state. This health monitoring serves two purposes: assessing the capacity of the captain and catching the possible mistakes made by the captain.
Physiological sensors can assess health factors ranging from heart rate variability and pulse oxygen levels to more elaborate measures such as electro-encephalograms (EEG) and functional nearinfrared spectroscopy (fNIRS). The challenge is to make the measurements as non-intrusive and comfortable as possible, because the idea of wiring the body with multiple sensors, non only during training, is highly undesirable for human acceptance. Still, technology continues to advance.
Pilot health monitoring can also be performed by ground operators who can query the captain or watch a video feed of the cockpit to determine the physiological and behavioral state. This assessment, along with health monitoring data provided by the automation, will be the basis for a decision to declare the captain incapacitated and transfer command authority to ground operators and/or cockpit automation to land safely.

Under SPO, it is assumed that an incapacitated pilot condition would be handled as a declared emergency with Air Traffic Control (ATC) providing special handling to the flight which

[2] *Note: Declarative memory* is a type of long-term memory that involves conscious recollection of particular facts and events.

[3] *Note: Retrospective memory* is where the content to be remembered (people, words, events, etc) is in the past, i.e. the recollection of past episodes.

[4] *Note: Prospective memory*is where the content is to be remembered in the future and may be defined as "remembering to remember" or remembering to perform an intended action.

would be directed to land by a ground operator interacting with advanced cockpit automation. The necessity for safely landing an SPO aircraft with an incapacitated pilot will be a key driver of technology requirements for cockpit automation, remote flight-control tools for the ground operator, and air/ground data links. The implementation of these technologies with sufficient reliability/redundancy will likely represent a significant part of the costs of implementing SPO. It is noted that some components of the technologies required for safe landing in an incapacitated-pilot scenario, such as autoland systems, are already available and in current use. For example, Garmin Autoland technology, FAA certified and available on the G3000 integrated flight deck in the Piper M600. In the event of an emergency, Autoland can also activate automatically, and it will control and land the aircraft without human intervention.

The Table 5.1 below provides some indicators of inactivity, alertness, and illness that can be measured for the monitoring of pilot incapacitation.

	Loss of consciousness	**Cardiac**	**Neurological (seizures)**	**Gastro-intestinal**
Pilot Acknowledgement of not feeling well				
Verbal (headche, stomach pain, chest pain, etc.)	x	x	x	x
Action (press button)	x	x	x	x
Inactivity				
Muscle tone (stiff/limp)			x	
No Response-Actions (e.g. Langley model)	x	x	x	x
No Response-Communication	x	x	x	x
No Response-Eye tracking (monitoring and cross-checking of flight instruments)	x	x	x	x
Alertness/Fatigue				
Facial Eye (staring, closing, shut)	x			x
Facial Mouth(drooling)			x	
Irregular EEG activity	x		x	
Subjective Report	x			x
Stress and workload				
Heart Rate	Sudden drop	x	x	
Blood Pressure	Sudden drop	x	x	
Sweating			x	x
Irregular breathing		Shortness of breath		
Premature Ventricular Contractions		x		
(predictive of heart attacks)				
Body temperature	x			x
Other Signs of Illness				
Facial Eye (twitching, blinking, rolling)			x	
Face Mouth (lipsmacking, chewing, swallowing)			x	
Muscle (jerking or twitching movements)			x	
Nausea/vomiting		x		x
Loss of bladder or bowel control			x	x
Reduced blood flow	x			

Table 5.1: Indicators of inactivity, alertness, and illness

5.3 Single Pilot Workload

Higher levels of automation could come to replace human roles in the cockpit, but it must be ensured that Single Pilot Operations (SPO) need to provide at least the same safety standards as today's Two Crew Operations (TCO).
What could change in the military pilots workload with the introduction of single pilot military fighter into GAT landscape? What is the approach to misure the workload?

5.3.1 Approaches to Measuring Workload

From a human-centered perspective, one of the major challenges in the introduction of SPO is workload (Koltz et al., 2015).
The study of workload has resulted in the development of several instruments that measure one's perception of how difficult a particular task is to perform. The information gained can be used with other, less subjective, data to improve training, procedures, or device interfaces to reduce workload.
One of the most well-known instruments is the NASA Task Load Index (Hart & Staveland), more commonly known as the NASA-TLX, that is an instrument that had two main steps. The first assesses the perceived difficulty of a task along six workload subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration level, which are all rated on a scale from 0-100. The second component weights the importance of each subscale to account for individual differences to compute a final TLX score (Hart & Staveland, 1988; Hart, 2006). Over the years, the TLX has been implemented in a variety of ways. One of the variations has included using the unweighted scores for each of the subscales, thereby eliminating the need to complete a secondary rating scale. The result simplifies the analysis procedure for the researcher and makes the scale easier to complete for the respondent. This approach is referred to as Raw TLX, or simply, RTLX (Byers, Bittner, & Hill, 1989; Hart, 2006; Miller, 2001).
Another subjective measure of workload is the Instantaneous Self-Assessment (ISA) technique (Castle & Legget, 2002). The ISA, unlike the TLX, is a unidimensional measure of workload. ISA measures consist of a rating on a scale of one (low) to five (high) of the perceived level of workload, as well as the respondents' reaction time to provide the rating.

5.3.2 Example of Measuring Workload

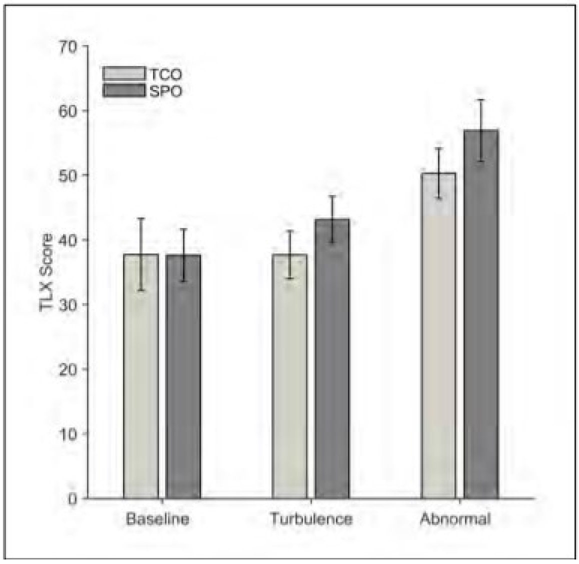
To aim at tackling the above questions and providing a better understanding of workload and performance in SPO, the results obtained by Faulhaber are shown below. The research was conducted within the graduate program *"Gendered configurations of humans and machines. Interdisciplinary analyses of technology"*(KoMMa.G) funded by the federal state of Lower Saxony (Germany) [5].
Note: This example was chosen because it is one of the most recent studies in civil sector.

The study was conducted in a fixed-base A320 flight simulator by fourteen pilots (aged between 26 and 56 years and flying experience ranged from 300 to 22000 flight hours), but the focus of the research was chosen on the approach and landing phases of flight, particularly demanding for pilots.

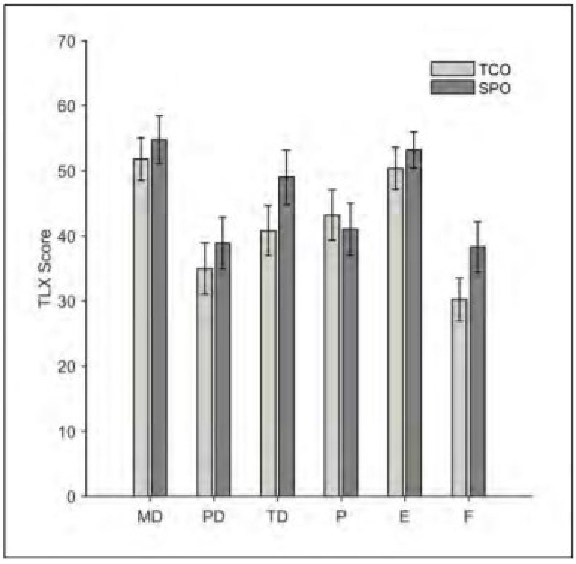
[5]Faulhaber, A. K. (2019), *From Crewed to Single-Pilot Operations: Pilot Performance and Workload Management*, 20th International Symposium on Aviation Psychology, 283-288.

The research aimed at investigating workload and performance in SPO compared to TCO conditions in baseline, turbulence (moderate turbulence was simulated) and abnormal (an engine fire was induced when the participants reached an altitude of 1800 ft) scenario.
Half the participants started with the SPO condition while the other half started with the TCO condition. After each scenario, the PF completed the NASA TLX. The NASA Task Load Index (TLX) was used to assess subjective workload ratings after each scenario.

The results showed that workload was at the same level for SPO and TCO baseline conditions but trended higher for the turbulence and abnormal conditions in SPO (Figure 5.4(a)). The baseline condition yielded nearly the same mean values for TCO (M = 37.74, SD = 20.74) and SPO (M = 37.62, SD = 15.11). In the turbulence condition, there was a small difference with means of 37.68 (SD = 13.81) for TCO and 43.15 (SD = 13.39) for SPO. As expected, the abnormal condition received the highest workload scores and the most prominent difference in ratings with mean scores of 50.3 (SD = 14.36) for TCO and 56.9 (SD = 17.88) for SPO.
The subscales of the NASA TLX were additionally analyzed separately to understand which of them were affected most by the factor crew configuration and which contributed most to the overall workload rating. A look at the unweighted mean scores showed that the subscales for mental demand and effort received the highest mean workload scores in general (Figure 5.4 (b)). With the exception of the performance subscale, scores were consistently higher in SPO as opposed to TCO conditions, even though the difference remains relatively small.



(a) Bar graphs showing NASA TLX unweighted mean composite workload scores representative of the 2x3 factorial design. Error bars show standard errors of the mean.



(b) Bar graphs showing the NASA TLX unweighted mean workload scores for each subscale for the factor crew configuration. Error bars show standard errors of the mean.

Figure 5.4: Workload Results

Results revealed that workload was not perceived as higher in baseline SPO conditions but only in scenarios involving turbulence or abnormal procedures. This is to a certain extent in line with the results from previous studies (Bailey et al., 2017; Etherington et al., 2016).
Qualitative analysis of pilot's behavior patterns during the experiment revealed that participants developed different strategies to manage workload in the SPO condition. The majority of participants (9 out of 14) talked to themselves or called out each step while following the landing checklist. Some of them even made exactly the same calls they were used to from TCO.

Thinking aloud was however never mentioned or asked for during the briefing session and this could hence be interpreted as a way to handle workload. Further analyses of pilot performance showed that checklist usage was more consistent in TCO.
Observation of pilot performance also indicated that higher workload did lead to more errors and less accuracy in the completion of tasks, especially during the abnormal SPO condition.

5.3.3 What could happen in Military sector

Note: In order to present to the competent Authority data that support the introduction of fighters into GAT, it is suggested that the study based on the previous example could be carried out on military simulators or rigs using Instantaneous Self-Assessment (ISA) and NASA TLX. These must feature the avionics implementation (analysed in Chapter 4.2.3) to demonstrate that the workload of the military pilot is similar and comparable to that of the civil pilot. Simulations may be carried out with pilot and automation only or with pilot flanked by ground figure. It is also recommended that a system of video and audio time-event markers, called “time hacks,” be included in future eye tracking/flight simulator studies.
Research consists to evaluate the relationship between pilot’s mental workload and operational performance by eye tracking during GAT flight operations in a virtual reality of flight simulator. This study could provide guidelines for future training design to reduce pilots mental workload and improve situational awareness for enhancing flight safety.
Eye movement measurement offers deep insights into human-machine interaction and the mental processes of pilots. Measurements based on different aspects of ocular behavior, such as the number of fixations, dwell time, and the dilation of pupil, have been used to reveal the status of mental workload. There was evidence that increasing in workload could increases dwell time and the frequency of long fixations (Van Orden, Limbert, Makeig, & Jung, 2001).
In summarize, the eye movements are useful to reveal the diagnostic information that enables the development of appropriate strategies which efficiently target a particular feature of the performance of a task.

This exploratory study of military single pilot workload management and automation use will must be conducted to answer the following questions:

- How do single pilots manage their workload?
- Where do they have problems managing their workload and what might be some reasons why?
- Are there any workload management approaches that might be characterized as “best practices” and why?
- How do automation and advanced technologies help or hinder single pilots in their workload management and what might be some reasons why.

In single pilot operations all of the workload must be managed alone. Cockpit automation is a substantial help to the single pilot in accomplishing many flight tasks but one that comes with a cost. Pilots must first tell the automation what to do, through programming, and then carefully monitor it to make sure it does what the pilot intended (Roscoe, 1992).
It is important to understand the varying roles that advanced automation can play: first, it can act as a substitute, replacing a function the human operator would normally perform. Such is the case when an autopilot controls pitch and roll and flies a holding pattern, and when

automation calculates descent points, rates, and speeds, assists with fuel management, and performs wind corrections (Casner, 2003; Hinton & Shaugnessy, 1984). Second, it can play the role of an augmenter by providing active assistance to the pilot's actions in the form of envelope protection. Third, automation can aid pilots by collecting, integrating, and presenting information about aircraft systems, airspace, traffic, and weather. For a successful flight, pilots must be able to delegate tasks to automation to reduce their own workload so that they may free up time and cognitive resources to focus on tasks that require higher-level thinking and decision making (Palmer, Rogers, Press, Latorella & Abbot, 1994).
It is also crucial that pilots constantly monitor the automation to ensure it is doing what is intended. In addition, pilots need to know what to do if the system is not performing as desired.

Although automated systems are able to assist in flying the aircraft, pilot workload has not decreased but it has simply changed in nature. For example, the pilot's task has shifted from total active controller of the aircraft to supervisory controller over the automated systems, which requires that the pilot know how the automated system operates in order to be able to understand, predict, and manipulate its behavior.
Furthermore, although automated systems are able to perform procedural and predictable tasks, it is the human operator who is ultimately responsible for tasks requiring inference, judgment, and decision making.

An essential part of military pilot workload in busy civil airspace is attending to background communications on the radio, in part to monitor for a call from ATC but also to be alert to surrounding aircraft activity in case there might be some effect upon one's own flight.
So, maintaining and balancing an optimal level of workload is essential for completing the task productively. Fighter aircraft is one such example, where the pilot is loaded heavily both physically (due to G manoeuvering) and cognitively (handling multiple sensors, perceiving, processing and multi-tasking including communications and handling weapons) to fulfill the combat mission requirements. This cognitive demand needs to be analysed to understand the workload of fighter pilot not only in mission scenarios.
To understand the military pilot's task and performance at each civil flying phase could assist pilot's training schedule in optimal way on simulators as well as in actual flight conditions.

To support high workload situations, the categories A, D and E (see Figure 5.2) have a possible applicability to fighters. In GA the transition from "Two Pilots" to "Single Pilot" represents a potentially critical situation, unlike for fighters because military pilot is trained to act individually in critical situations and times. So the transition to civil navigation would not cause any particular difficulties, however the on-board implementation would represent a substantial help in the management of tasks and timescales.
Also, the implementation of several concepts have already been proposed such as a **Ground Operator** or a **Harbor Pilot**. These figures are borrowed from the proposals introduced for the civil SPO.

Actors refocusing

Captain. The captain (unless incapacitated) serves as the Pilot-In-Command (PIC), making all decisions pertaining to command of the flight. As such, he/she bears the ultimate responsibility for safe and efficient operation of the flight. The captain is the final decision-maker regarding the flight mission, and (according to procedures) calls on automation and ground operator assets to accomplish this mission.

The captain's main tasks are to manage risk and resources (both human and automation). Under SPO, the fundamental command/leadership role of the captain will not change, but he will likely take on some of the conventional Pilot Flying (PF) and Pilot Monitoring (PM) duties, while other PF and PM duties are allocated to the automation or the ground operators.
High workload situations will be analysed to establish information priorities and automate tasks.

Ground Operators. In current operations, flights receive ground support services from their Airline Operations Center (AOC). There are various AOC teams that provide specialized services, e.g., dispatch, ATC coordination, crew scheduling, maintenance operations, customer service, and weather operations. It is anticipated that SPO would primarily affect the functions of the dispatch operations, with limited impact on other AOC services. In SPO, certified dispatchers become ground operators who perform the following three core functions:

- Conventional Dispatch of multiple aircraft;
- Distributed Piloting support of multiple nominal aircraft. This function would be applicable only to nominal aircraft, corresponding to Taxonomy Condition 1 defined in Figure 5.3;
- Dedicated Piloting support of a single off-nominal aircraft.

This function corresponds to sustained one-on-one piloting support requested by the captain under high-workload or challenging off-nominal operating conditions or where the ground operator has to take command of an aircraft whose captain has become incapacitated. The tasks associated with this function may include flying the aircraft, e.g., remote manipulation of the aircraft's Flight Management System (FMS) for route amendments, or remote manipulation of the aircraft's Mode Control Panel (MCP) for sending speed/altitude/heading commands to the autopilot. The Dedicated Piloting function would be applicable to Taxonomy Conditions 2, 3, and 4 defined in Figure 5.3. The skills and training required to perform the dedicated piloting support function are essentially the same as those of a conventional pilot.
The ground operator tool set may also include next generation dispatcher tools to reduce workload. Additionally, SPO will require a secure and reliable airground link for voice and data communications. These requirements are similar to those currently being considered for Unmanned Aircraft Systems (UAS) operations in the national airspace system.
There are many possible structures for organizing ground operators to perform the three core functions described above that have been selected by NASA, based on subject matter expert opinion, for evaluation in an upcoming human-in-the-loop evaluation.

- **Hybrid Ground Operator Unit (HGO).** Each HGO is trained and certified to perform all three core functions and generally serves multiple flights from pre-flight planning to gate arrival. However, if/when one of these flights encounters an off-nominal condition that requires dedicated support, the other aircraft are handed off to other HGOs under the direction of the unit's supervisor.

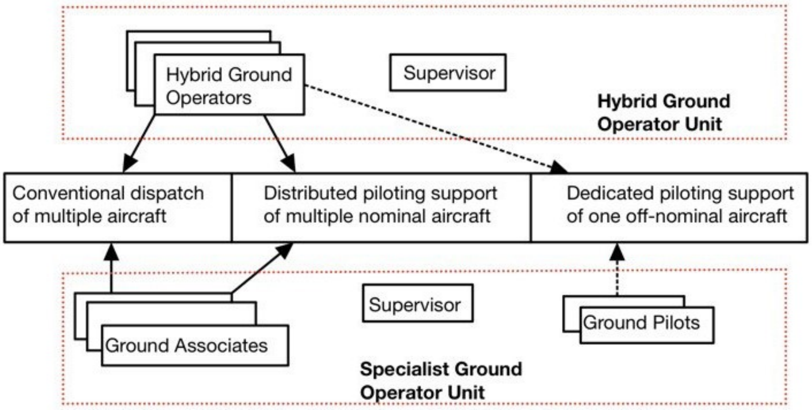


Figure 5.5: Examples of ground operator unit structures

- **Specialist Ground Operator Unit.** There are two types of members: **Associates (GAs)** are trained and certified to perform tasks associated with Conventional Dispatch and Distributed Piloting support for nominal aircraft and **Ground Pilots (GPs)** who trained and certified to perform tasks associated with Dedicated Piloting support for off-nominal aircraft.

- **Harbor Pilot.** Ground operator serving as a member of a hybrid unit or a specialist unit. The function of a harbor pilot is similar to current practice in maritime operations. Each harbor pilot provides distributed piloting support to individual nominal aircraft as they climb and descend through a complex terminal area airspace. This could reduce the workload of other positions in the ground operator units, enabling each position to support more aircraft.

5.4 Human Machine Interface (HMI)

In the context of technologically advanced aircraft, within the man-machine relation, it has been shown that the main limitation is the man: human limitations during flight are much more visible. The pilot must perform his mission with the highest possible success rate to assure the continuity of the action.

Military pilots more than being the masters of their aircraft, they are the system managers: they have to manage internal and external subsystems to optimize the aircraft functions, control the automatic flight control systems, overseeing sensors and other mechanical components rather than exerting direct control, and communicate with air traffic control, ground-based commanders, etc. Pilots remain after all more versatile than machines. Currently, both pilots and machines are therefore required to compensate for each other's weaknesses, and optimize system performance as a whole.

As technology develops, the relationship between man and machine changes. Focus of skill sets are shifting from motoric skills towards cognitive skills. Military pilots must be able to manage different systems, detect and analyse essential elements, and make right decisions at a quick pace. Human-machine cooperation determines what kind of results are achieved.

5.4.1 Navigation Instruments

It is suggested to use PFD (Primary Flight Dispaly) shows 3D course indications (see Figure 5.6), called a Highway-In-The-Sky (HITS) display that provides both lateral and vertical guidance along the planned flight path and presenting a 3D picture of the surrounding terrain. Keeping the symbolic aircraft within the green boxes on the display ensures that the flight remains within the selected GPS route and altitude.

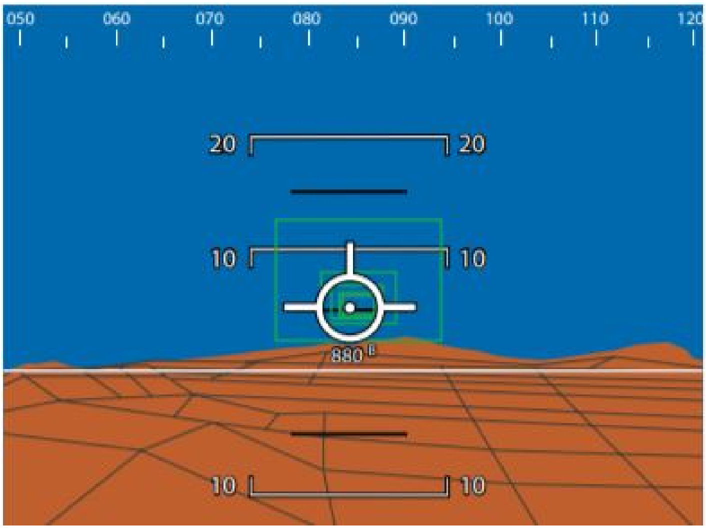


Figure 5.6: An attitude indicator with HITS display symbology

This function could be introduced directly on the pilot's augmented reality helmets. Also, integrated system that uses the PFD to provide controls and a display for the FMS could be integrated, as shown in Figure 5.7.

Figure 5.7: An integrated avionics system

Instrument System Failure

The pilot must able to recognize failure indications when they appear on the PFD: manufacturers typically use a bold red "X" over, or in place of, the inoperative instruments and provide messages about failed systems. For example, in Figure 5.8(a), the inoperative airspeed, altitude, and vertical speed indicators indicate the failure of the air data computer or in Figure 5.8(b), the inoperative attitude indicator indicates the failure of the Attitude and Heading Reference System (AHRS).

(a) A PFD indicating a failed air data computer

(b) A PFD indicating a failed AHRS

Figure 5.8: Failures and the Primary Flight Display

Mode Awareness

Mode awareness refers to the pilot's ability to keep track of how an advanced avionics cockpit system is configured at all times. One strategy is to include "mode checks" as part checklist or callout procedures. For example, after programming a route it must be verified that the navigation indicator shows course guidance from the desired source, and that the indication agrees with estimate of the correct direction and distance of flight.
Also, to help military pilot stay in touch with the progress of the flight while the avionic performs the navigation task, it is a good practice to announce arrival (mentally, single pilot; or orally, to the flight crew or to Ground Operators) at each waypoint in the programmed route. For example, when arriving at SUNOL intersection, you might announce, "Arriving at SUNOL. TRACY is next. The course is 051 degrees, and the ETE is 10 minutes."

En Route Sensitivity

Usually in GA, when operating en route, the FMS maintains a sensitivity of 5 nautical miles (NM): a Course Deviation Indicator (CDI) displaying course indications from the FMS deflects full-scale when the aircraft drifts 5 NM to either side of the desired track to the active waypoint. An aircraft is considered to be en route when it is more than 30 NM from the origin and destination airports programmed into the flight plan. There are and have been some units that use different values.

En Route Modifications

ATC may issue instructions to a point defined by a VOR radial and DME value. If the unit's memory is very limited, the pilot should also be adept at removing the waypoint or use a support component, such as electronic flight bag to complete mission. One of the most useful features of an support avionics is its ability to provide you with immediate access to a large navigation database.

5.4.2 Information Systems

Commercial aircrafts have information systems available in the advanced avionics cockpit that allow to follow flight progress, and in avoiding terrain, traffic, and weather hazards en route. Information systems are used to enhance situational awareness and increase the safety margin: for example, moving map continuously displays the aircraft's position and helps pilot maintain the situational awareness as your flight progresses, while Terrain Awareness and Warning System (TAWS) color codes surrounding terrain to make it easily apparent when terrain poses a threat.

Terrain Display

A terrain display usually relies on a GPS location signal to compare the position and altitude of the aircraft against the terrain found in an internal topographical database. As seen in Figure 5.9, the position of the aircraft and surrounding terrain are displayed on an MFD where are used a simple color-coding convention to portray the difference between the present altitude of the aircraft and the height of the surrounding terrain:

- Terrain more than 1,000 feet below the aircraft is coded black;
- Terrain less than 1,000 feet but more than 100 feet below the aircraft is coded yellow;
- Terrain less than 100 feet below the aircraft is coded red (man-made obstacles generally do not appear in a topographical database).

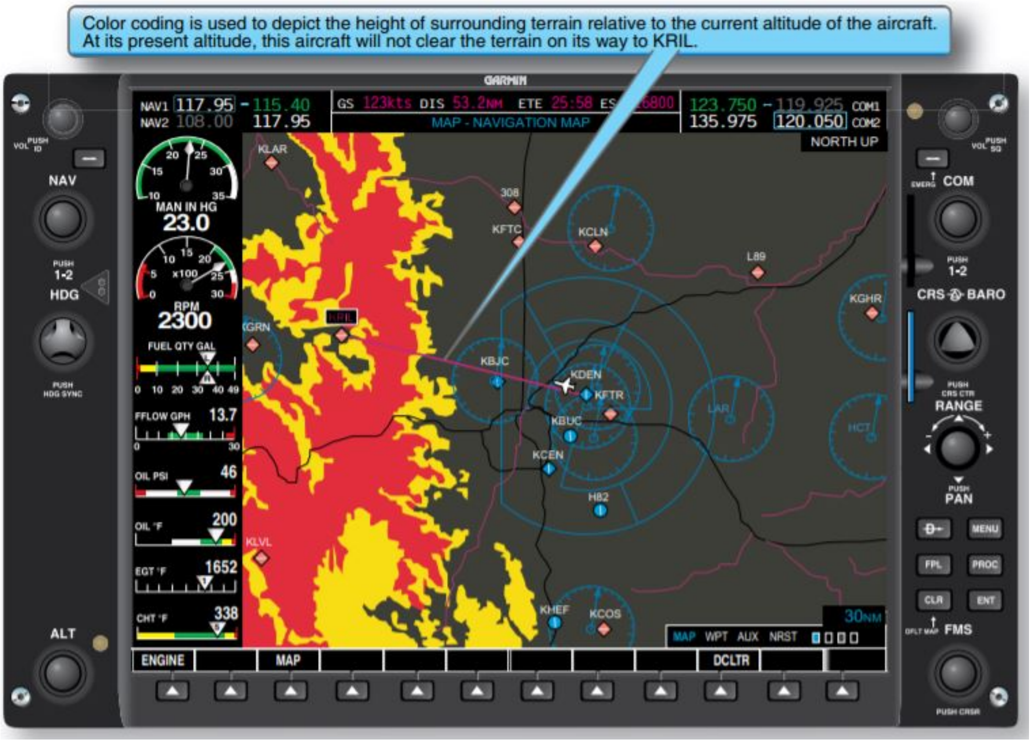


Figure 5.9: Terrain depicted on an MFD

One of the risks involved in proceeding directly to a waypoint is that you may be yet unaware of any significant terrain between the present position and the waypoint.

Terrain Awareness and Warning Systems (TAWS)

TAWS put togheter the features of a terrain display along with a warning system that alerts to potential threats posed by surrounding terrain.
There are presently two classes of certified TAWS that differ in the capabilities they provide to the pilot: TAWS A and TAWS B.
TAWS A provides indications for the following potentially hazardous situations:

- 1. Excessive rate of descent;
- 2. Excessive closure rate to terrain;
- 3. Altitude loss after takeoff;
- 4. Negative climb rate;
- 5. Flight into terrain when not in landing configuration;
- 6. Excessive downward deviation from glideslope;
- 7. Premature descent;
- 8. Terrain along future portions of the intended flight route.

TAWS B provides indications of imminent contact with the ground in three potentially hazardous situations:

- 1. Excessive rate of descent;
- 2. Excessive closure rate to terrain (per Advisory Circular (AC) 23-18, to 500 feet above terrain);
- 3. Negative climb rate or altitude loss after takeoff.

TAWS Aural Alerts

Using a predictive "look ahead" function based on the aircraft's ground speed, the terrain system alerts pilot to upcoming terrain: at a closure time of approximately 1 minute "Caution! Terrain!" alert is issued and at closure time reaches 30 seconds "Terrain! Terrain!" alert.
A second type of aural alert warns about excessive descent rates sensed by the system ("Sink Rate!") or inadvertent loss of altitude after takeoff ("Don't Sink!").

All aircraft would be safer with TAWS (certified under Technical Standards Order (TSO)-C151) and crews trained to use the technology.
An important issue is the lack of training program outside the military that teaches anyone to fly based on the TAWS display.

5.4.3 Traffic Data Systems

All traffic data systems provide aural alerts when the aircraft comes within a certain distance of any other detected aircraft: aural alert instructs the pilot to perform a vertical avoidance maneuver, for example aural alerts are: "Climb! Climb!" and "Descend! Descend!".
TCAS and traffic advisory systems use similar symbology to present traffic information, shown

in Figure 5.10 (the colors used to display traffic symbols vary with the capabilities of the display).

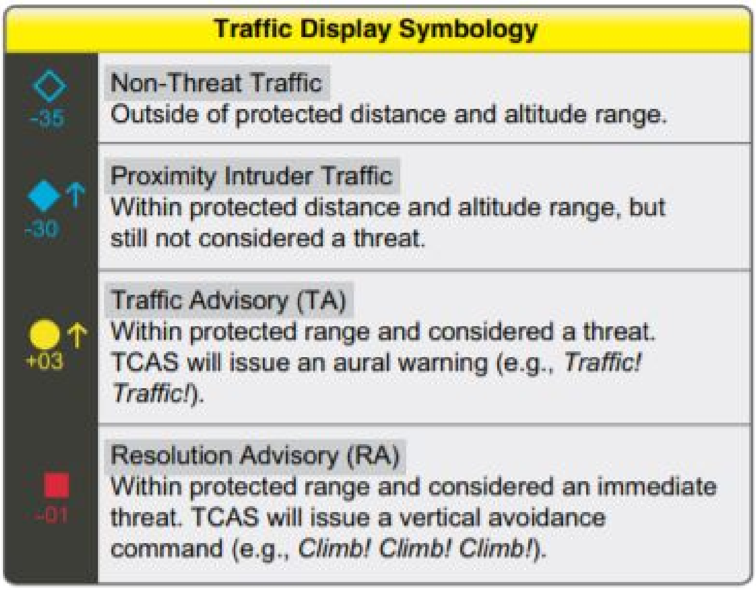


Figure 5.10: Traffic display symbology

5.4.4 Electronic Checklists

In commercial aircrafts, some systems are capable of presenting checklists that appear in the aircraft operating manual on the MFD, that's why in military fighters, checklist could be introduced to augmented reality helmet. It is important to note that electronic checklists are only available when the aircraft's electrical system is powered up. In almost all instances, the aircraft must have emergency checklists in paper (or plastic) form in the event of power or electrical failure.

5.4.5 Electronic Charts

In military aircraft terminal and approach procedure charts could be presented on pilots augmented reality helmets, where the position of the aircraft could be superimposed on the instrument approach chart.
Electronic charts are also useful when taxiing, as they can help improve navigation on the airport surface and reduce runway and taxiway incursions.

5.4.6 FMS/RNAV Pages on the MFD

In GA, some advanced avionics systems are able to draw information from the FMS/RNAV and present it on the MFD, in a larger format. This function could be introduced also in military fighters.

Chapter 6

Obsolescence Management

Obsolescence, "no longer functional" defined by dictionary, strikes at all levels, from the smallest (electronic) component to a complete system. If a component becomes obsolete, does the (sub)system of which it forms a part, but equally a system can become obsolete while each of its constituents remains current. If components and their interaction no longer provide the performance required, and it is not simple to change or replace, then the system is obsolete. Figure 6.1 summarises the facets of the obsolescence problem.

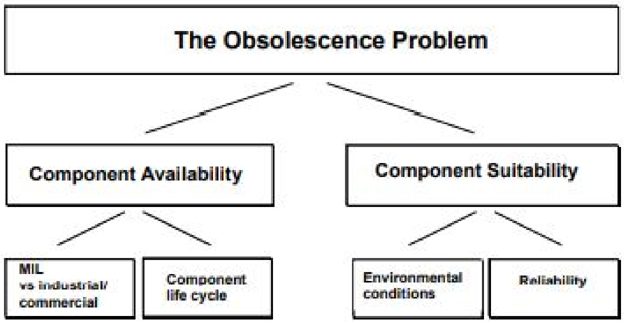


Figure 6.1: Obsolescence Problem Tree

Obsolescence management is an ever-increasing topic in the DoD, infact “It has been estimated that the obsolescence problem has cost the military services $27 billion over the 10-year period beginning in 1982” [1].

The obsolescence problems faced in today’s military environment do not stem only from aging systems but also from rapid changes in commercial technology: currently, technology updates every 18 months to 3 years, typical life cycle of electronic part lasts from 4 to 7 years, etc. As a result, new military systems are finding increasing electronics obsolescence problems. Part obsolescence does not mean that the part is no longer required but refers to a component or part that the commercial market considers no longer economically feasible to manufacture.

The military services no longer control most of the electronics industry and therefore have little influence on electronics manufacturers and technology upgrade cycles.

Several automated tools are designed to predict future obsolete parts at the beginning of the system’s life cycle. It is important to understand the steps to resolve an obsolescence problem:

[1] Virginia Day and Zachary F. Lansdowne, *“Impact of Electronics Obsolescence on the Life Cycle Costs of Military Systems”*, Air Force Journal of Logistics, 17, no. 3 (Summer 1993): 29.

- First, an item is identified as a possible obsolete item or a manufacturer sends notification (to all users) of intent to discontinue production of the item;
- In the second step, the potential obsolescence problem would be verified while determining the extent of the problem;
- Once the problem has been verified, analysis is performed to determine the best alternative for resolution of obsolescence;
- Finally, the most cost-effective resolution option is implemented.
  In performing the cost-benefit analysis, many factors and variables that are unknown or not easily identifiable can make the decision a very difficult one.

Many experts point out that the main question is not how to solve obsolescence, but how to manage the problems economically in the best interest of the program, selecting the most cost-effective solution.
Also, the technical risk associated with redesigning the component or system must be analyzed. First, the solution identified should be the most cost-effective solution for the life of the system to minimize future impacts to the system. Second, the solution should be consistent with mission requirements in terms of performance.

Members of the MITRE Corporation developed a life cycle cost model with six questions that should be considered as criteria for evaluating the cost-benefit analysis model:

- How many years must the solution last?
- How well does the system, board, or box function in terms of both operations and reliability?
- How many other integrated circuits in the board, box, or system are also obsolete, or will become obsolete during the remaining service life of the system?
- How many of the obsolete integrated circuits are likely to be needed?
- What options are available, and what are their relative costs?
- What is the impact of the chosen replacement strategy on operations and maintenance costs?[2]

6.1 Strategies to Mitigate Obsolescence using Commercial Components

Many programs such as the F22 stealth fighter, AWACS, Tornado and Eurofighter are suffering from obsolescence.
With the rapid movement towards Commercial Off The Shelf (COTS) solutions within the US DoD, associated benefits and drawbacks must be reviewed.
Commercial Of The Shelf (COTS) technology in military systems was initiated by the US Federal Acquisition Reform Act as early as 1994 and the use of COTS in Defence Systems goes from detailed environmental considerations of fast jet use to ground systems implementations

[2]Virginia Day and Zachary F. Lansdowne, *"Impact of Electronics Obsolescence on the Life Cycle Costs of Military Systems"*, Air Force Journal of Logistics, vol. 17 no. 3 (Summer 1993): 30.

using COTS systems and software.
Diminishing Manufacturing Sources (DMS) result in an inability to procure military components for long term product support. Therefore the use of COTS parts in military systems has become a necessity. But, it was argued that the use of COTS to mitigate obsolescence is a contradiction in itself, because COTS provide an additional challenge to obsolescence management. COTS software items too can become obsolete (and this is related to hardware obsolescence) in the same sort of way, although failure is less likely.
One of the major impediments to use of COTS devices in military avionics is the incompatibility of environmental requirements specified for the parts and for the equipment.
When constrained by financial and timescale limits, innovative COTS based solutions could be provided to update an obsolete system and may be a valid strategy for providing a swift and low cost upgrade to obsolete ground sector equipment in the short to medium term.

COTS can be used as a solution for obsolescence, however solely short term, since they are subject to even shorter lifetimes than military parts. The Figure 6.2 shows the comparison between traditional and COTS-based system acquisition lifecycles.

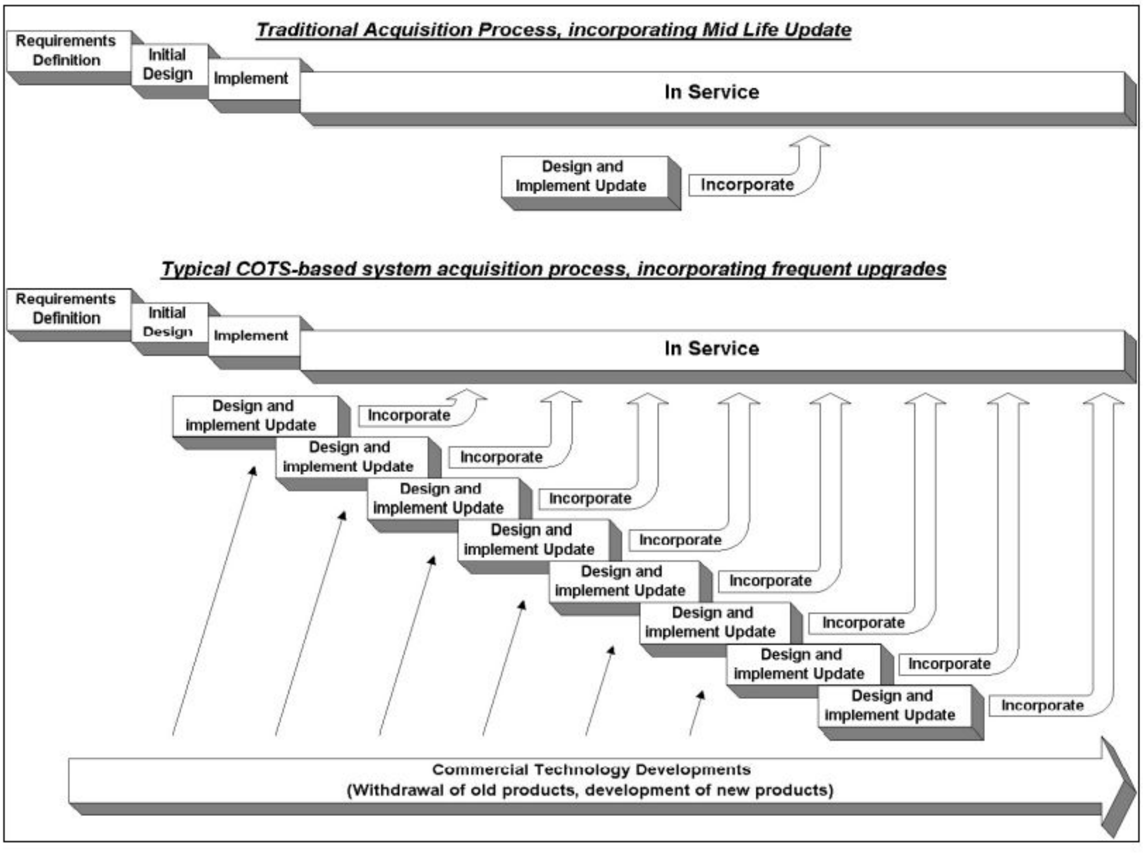


Figure 6.2: Comparison of traditional and COTS-based system acquisition lifecycles

Figure 6.3 shows the expected life cycles for chosen weapon systems and that high tech equipment developed today, introduced into service in 3 to 4 years time or even later depending on the weapon system, will soon become unsustainable.

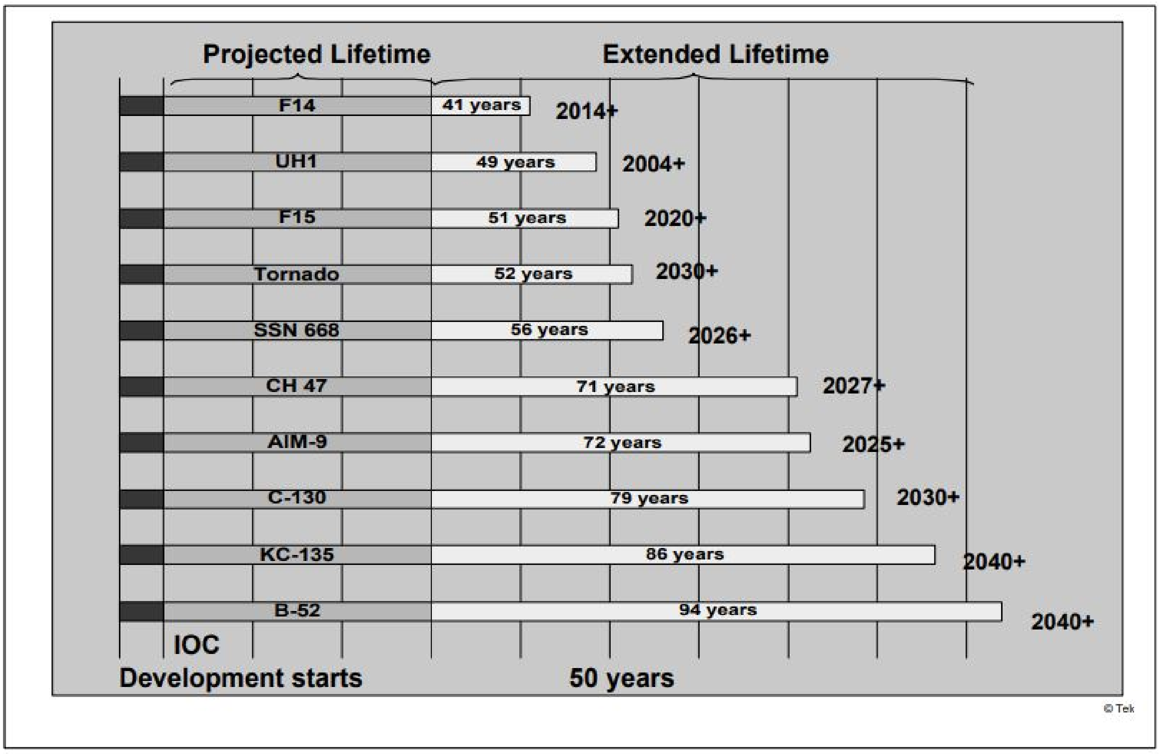


Figure 6.3: Weapon System Life Cycles

The use of commercial components in military equipment could create problems as:

- Short life cycles;
- No disciplined obsolescence notification process;
- Environmental Conditions;
- Temperature / Altitude / Humidity;
- Nuclear hardening;
- Vibration;
- Shock;
- EMC;
- Shrinking parameter margins;
- Shrinking structure width;
- Electromigration;
- Dielectric breakdown.

The supplier industry will be forced to make more and more use of commercial components simply because of the continual erosion of the supply base of military components.

The impact of COTS based-acquisition can be seen in Table 6.1 that compares the "traditional" approach, in which the customer (say, NATO) fully specified all system components, to a COTS-based procurement.

TRADITIONAL	COTS-BASED
NATO able to plan and control system development	COTS components change asynchronously and rapidly
NATO able to define functionality	COTS supplier defines functionality to suit larger market. NATO spec may preclude use of COTS if too rigid.
NATO able to control/view development process to support its responsibilities for certification, etc	COTS item is "black box" and alternative approaches to certification, etc may be needed
NATO able to control interfaces and interoperability	Interoperability may be enhanced if same COTS component in both systems, but otherwise may be very difficult because COTS interfaces not fully defined/maintained
NATO able to exploit expertise, standards, etc for component engineering	Key activity now becomes systems integration – more of a "black art"
NATO able to control functionality	COTS supplier may define upgrade package (e.g. operating system plus applications)
NATO able to co-ordinate change to component with change to whole system	COTS component change driven purely by commercial factors, not synchronised with system constraints (e.g. refits). May lead to many variants of equipment fit across fleet of platforms.
NATO able to procure changes/fix problems, especially in emergency, perhaps in the field	COTS component changed if and when supplier sees market advantage; NATO not a significant customer
NATO able to assume component will remain available (especially components that wear out)	COTS component may simply cease to be available (not just be unsupported) if commercial market moves away from it

Table 6.1: Traditional vs COTS-Based Acquisition

6.1.1 Example of COTS Integration in a Modern Avionics Architecture

The purpose of this section is to provide a general overview of COTS integration through several examples taken by the MB-339CD avionics system[3].
The latest version of the MB-339 twin seat jet powered advanced trainer employs a modern state-of-the-art avionics architecture based on standard bus interface (i.e., MIL-STD-1553 and ARINC 429), capable to integrate COTS equipment.
The system presents a COTS solutions that are applied at hardware level in computer processing, interface and memory devices, providing state-of-the-art high performance solutions.
Radio navigation equipment, air data computer and an embedded inertial-GPS platform are employed as proven, off-the-shelf and fully qualified military equipment.

To shorten development cycle and reduce recurring costs, several Commercial-Off-The-Shelf

[3]R. Sabatini, M. Massari, *MB-339CD Aircraft Development COTS Integration in a Modern Avionics Architecture*. Paper presented at the RTO SCI Symposium on "Strategies to Mitigate Obsolescence in Defense Systems Using Commercial Components", held in Budapest, Hungary, 23-25 October 2000, and published in RTO MP-072

(COTS) solutions were investigated and adopted at three development levels: avionics system design, equipment selection and components employment.

Avionics System Design

In the MB-339CD avionics (Figure 6.4) architecture the transfer of information is completely digital.
An essential feature for COTS integration in the MB339CD aircraft was the adopted of a several types of standards:

- MIL-STD-1553B is applicable to the main avionics data bus;
- ARINC-429 is used to interface several navigation equipment like VOR/ILS and ADF;
- EIA Standard RS-422 allows the point-to-point data transfer from SAU to CSMU;
- EIA Standard RS-485 is used to multiplexing the information between control panels, transceivers/transponder and remote display units.

Specific functions, which in the past required dedicated hardware resources, were implemented via software, for examples:

- "the Flight Director, that was originally a stand-alone analog computer, was replaced by a software module running in the Mission Processor;
- navigation sources and modes selection, which previously requested dedicated cockpit control panels, were provided by the MFD's softkeys through format dependent labels;
- weapon selection and monitoring, originally implemented through a dedicated armament control panel, was provided by the SMS format in the Multifunction Display;
- specific devices like altitude/airspeed switches or dedicated engine throttle position microswitches were replaced by software controlled functions using shared information".

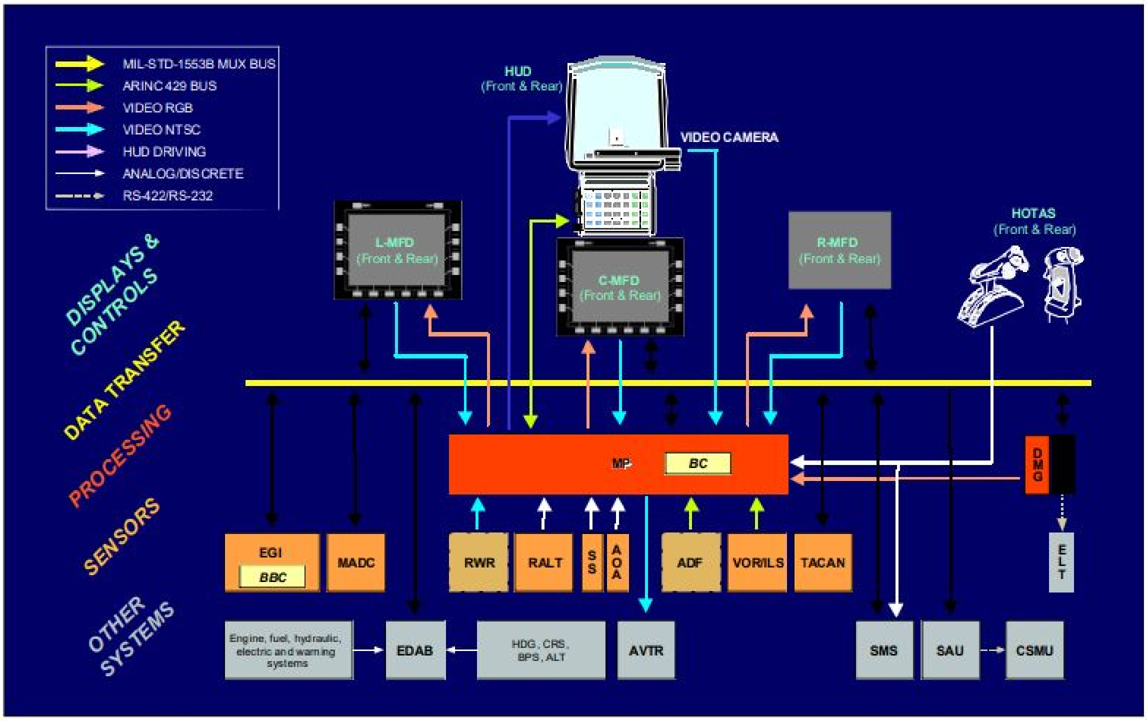


Figure 6.4: MB-339CD Avionics Architecture

Equipment

One of the driving criteria in the selection of the equipment integrated in the aircraft was the use of COTS units and, when this aim did not allow to comply with the operational requirements or military environmental constraints, the reuse of existing military off-the-shelf equipment.
Examples of COTS equipment included the VOR/ILS/MB navigation receiver and the ADF: they were general aviation units that were integrated using ARINC-429 interface in the Mission Processor.
While the reuse of existing units have been applied in:

- "Navigation sensors like TACAN, Air Data Computer and Radar Altimeter;
- Central processing equipment as the Mission Processor and the Data Transfer System/Digital Map Generator;
- Recording units like Video Recorder;
- Cockpit displays, including HUD and MFD".

Components

At hardware level, the implemented avionics showed that the most important goals of a military aircraft development program (i.e., growth potential of computing resources and reduction of size, weight and power), are achieved by employing electronic components derived by commercial and industrial applications. COTS components were selected on technical suitability, such as temperature range, power and voltage rating.
COTS applications adopted for avionics system are described below:

- "all the equipment connected to the MIL-STD-1553 data bus used the same off-the-shelf bus transceiver chip in a configuration capable to cover both Remote Terminal and Bus Controller functions;
- all the CPUs embedded in the avionics units were COTS components with extended temperature range; no MIL-STD-1750 CPU was employed while a wide range of industrial CPU were used including: Motorola microcontroller 68332, Intel microprocessors 80960, 80C186, 80C196 and 80C51, Texas Instrument digital signal processor TMS 320C3X;
- the removable cartridge of the DTS included COTS solid state Flash memory with PCMCIA interface;
- the active matrix colour liquid crystal display of the MFD was a COTS component exhibiting full compliance with military requirements thanks to the ruggedized design process;
- the incremental Gray encoders used for the rotary cockpit controls were COTS components selected on the basis of resolution, power supply and reliability requirements compliance".

Test and Evaluation

COTS technology was applied not only to the on-board systems but also to the test, verification and evaluation tools including laboratory test equipment, avionics Rig and Flight Test Instrumentation.
The avionics Rig was used not only for testing and verification purposes, but also for pre-flight

evaluation: test pilots and engineers could evaluate the various functions of the avionics system and man-machine interfaces, minimising costs by reducing the number of flight test sorties required.
Flight test activity, conducted on the prototype aircraft (equipped with COTS acquisition and recording systems, such as Differential GPS, Magnetic Recorders and Telemetry Data Link) was carried out by both company and Air Force test pilots to demonstrate the expected performances, functionalities and man-machine interfaces under real flight conditions.

Certification and Logistics Support

The certification process did not address individual COTS components, modules or subassemblies, but equipment certification was gained by establishing that the various components were selected on the basis of proven technical suitability for the intended application (e.g., component temperature range, power or voltage rating, quality control procedures of the component manufacturer and COTS availability/implementation in similar applications). Furthermore, COTS did not require additional custom engineering, because the commercial equipment manufacturers provided continuous assistance in solving obsolescence of electronic devices and circuits.

The approach applied in the avionics development here presented, has yielded a solution where COTS components have provided cost benefits reducing obsolesccence risk and improving logistics supportability.
This includes a strictly modular software and hardware architecture and the use of "state of practice" standards.

It is evident that the problem of obsolescence with consequent use of COTS products is a point that can be used to support the introduction of fighters using commercial products into GAT and reduce the future gap between military and commercial manufacturers.

Chapter 7

Adaptation of Military Pilot Training

The primary aim of the military pilots training system is to pick out to provide qualitative training, both for their academics and in terms of their specialization as aviation personnel.
Air Force pilot training is in the midst of a revolution, because the current training system was designed for the demands of the 1950s and revolved around two basic needs:

- the first was the need to focus on basic flying skills from the beginning and continue to practice these throughout a professional pilot's career;
- the second was the need to enhance training programmes to account for added demands on pilots brought about by increased automation, emerging technology, high-density airspace, and globalization.

Up to now, each branch of the military has its own requirements and specific training programs for what it takes to be a pilot for them. It must be considered that some programs may offer you the option to obtain a civilian license, but military pilots mainly attend both officer training and flight training inside of military sector rather than relying on third parties.

Potential hazard, if training method are not effective, is the lack of in-flight situational awareness, decision-making, and inadequate risk management.
As the skills required of pilots change, training must also be renewed.

In order to introduction military fighters in GA and boost the increasing use of COTS components, it might be suggested to:

- standardise the obtaining of civil licences so that all military pilots are familiar with them and the avionics used, and
- allow training on the civil side to be carried out by personnel from within the civil sector.

7.1 New technologies for fighter pilot training

The aviation industry is an innovator and early adopter of training technologies, being quick to embrace technologies that may lead to enhancements: it was the first sector to adopt computer-based training.
Nowadays, new digital applications are rapidly shaping fighter pilot training.
To monitor the stress level and cognitive load of pilot trainees during exercise, both in simulator use and aircraft training, Operator Performance Analytics System (OPAS) software are developed by Patria and test in Finnish Air Force.

The system provides the instructor with information on the pilot's cognitive workload, and based on this information, the level of complexity of the ongoing exercise can be increased or lowered. The OPAS system could also be used for assessing and analyse capabilities and monitoring the development of pilot acquisition of GA procedures.

7.1.1 Wearable technology

Portable devices attached to the human body that collecting data and delivering information can be used in a range of applications:

- augmented reality helmets where digital information is over on what people view (also a digital presentation of the air traffic controller's paper flight);
- wearable smart-clothing that senses health data (respiration, heart rate, body temperature, etc.);
- fitness bands track movement, calories, sleep quality and quantity;
- eye-tracking devices that sense stress levels associated with cognitive load.

7.1.2 Big Data in aviation training

Applications of big data are already being used in aviation training:

- safety management programmes use cluster analysis on routine operational data from Flight Data Recorders to identify anomalies at specific airports and assign training content;
- machine-driven learning algorithms that analyze data from simulated operation scenarios to understand individual training needs;

The quality of findings from big data is reliant on the quality of information it receives.

7.1.3 Adaptive eLearning

Beyond the use of big data, data can also be tapped into on an individual basis to drive the pilot's training. With the technology improvements, the training is designed to adapt to the needs learning using artificial intelligence to guide the structure of the training program. Also, new research is incorporating emotion-sensing technology using computer webcams.
This technology, more expensive than traditional static eLearning, should be regarded as an extension of classroom, simulator and teaching practices.

7.2 Fatigue Education and Training

Fatigue is characterized by a general lack of alertness and degradation in mental and physical performance. Fatigue manifests in the aviation context with events that includes procedural errors, unstable approaches, lining up with the wrong runway, and landing without clearances. There are three types of fatigue:

- **Transient fatigue** is acute fatigue brought on by extreme sleep restriction or extended hours awake within 1 or 2 days;

- **Cumulative fatigue** is fatigue brought on by repeated mild sleep restriction or extended hours awake across a series of days;
- **Circadian fatigue** refers to the reduced performance during nighttime hours, particularly during an individual's WOCL (typically between 2:00 a.m. and 6:00 a.m.).

Fatigue threatens aviation safety because it increases the risk of pilot error that could lead to an accident. This risk is heightened in passenger operations because of the additional number of potentially impacted individuals. The rule provides different requirements based on the time of day, whether an individual is acclimated to a new time zone, and the likelihood of being able to sleep under different circumstances.
The existing distinctions between domestic, supplemental and flag passenger operations have removed because the factors leading to fatigue are universal and addressing the risk to the flying public should be consistent across the different types of operations.

The FAA has adopted a system approach, whereby both the carrier and the pilot accept responsibility for mitigating fatigue. The carrier provides an environment that permits sufficient sleep and recovery periods, and the crew members take advantage of that environment.
The natural circadian rhythms experienced by most people that causes them to be naturally more tired at night than during the day is recognised. So, flight crew members will be able to work longer hours during the day than during the night. Significant changes in time zones, a situation unique to aviation, are accounted for to reduce the risk to the flying public posed by "jet lag".
Part 121 air carriers are currently statutorily-required to annually provide, as part of their Fatigue Risk Management Plan, fatigue-related education and training to increase awareness of:

- fatigue;
- "the effects of fatigue on pilots;"
- "fatigue countermeasures."

One of the regulatory concepts introducec is the restriction on flight-crew members' maximum Flight Duty Period (FDP). In creating a maximum FDP limit, the FAA attempted to address three concerns. First, flight-crew members' circadian rhythms needed to be addressed because studies have shown that flight-crew members who fly during their Window Of Circadian Low (WOCL) can experience severe performance degradation. Second, the amount of time spent at work needed to be taken into consideration because longer shifts increase fatigue. Third, the number of flight segments in a duty period needed to be taken into account because flying more segments requires more takeoffs and landings, which are both the most task-intensive and the most safety-critical stages of flight.
Actual time at the controls (flight time) is limited to 8 or 9 hours, depending on the time of day that the FDP commences.

Split duty rest must be at least 3 hours long and must be scheduled in advance. The rationale for this is that flight-crew members must, at the beginning of their FDP, evaluate their ability to safely complete their entire assigned FDP. In order to do so, they must not only know the length of the FDP, but any scheduled split duty rest breaks that they will receive during the FDP.

The FAA considers *Emergency and Government Sponsored Operations* to be the only types of operations that merit separate consideration because of the special operational circumstances that otherwise limit a certificate holder's flexibility to deal with unusual circumstances.

7.3 Pilot Automation Dependency

The use of both automated and autonomous systems is essential. For automated systems, there is an assumption that the pilot initiates the automated sequence of actions and needs to take over once again at the end of the automated task sequence.

Autonomous systems are capable of performing defined operations within certain parameters without human input or guidance. Unlike automated systems, autonomous systems have a set of adaptive, artificially-intelligence based capabilities that allow responses within particular boundaries that were not pre-programmed or anticipated in the design. Although there are numerous safety benefits provided by automation, an over-reliance can introduce new hazards and risks: because automated systems have become very reliable, the risk exists that pilots may become complacent and rely too much on the automation. Most flights in GAT are routine, so the work can become very procedural.

It is critical that each State, that are responsible for military pilot training programs, has the ability to identify whether an over-reliance on automation is a risk factor, and determine how to mitigate this risk through pilot training program and other safety oversight means.

The warning here is that the automation and/or autonomy should be built around tasks that require long periods of vigilance, mental fatigue, mental overload.

Modern flight training must address this issue and teach avionics mastery combined with judgment. It is necessary understood where pilot's attention goes in the cockpit, because he could drown in information, and remind that technology is just a tool: the pilot should always have a good situational awareness.

Chapter 8

Economic Impact Considerations

Business case exercises related with the adoption of ATM requirements, including a cost-benefit analysis (CBA), specifically focusing on the military community normally reach the conclusion that it is very difficult to obtain reliable information due to the fact that costs associated with State aircraft are subject to a great deal of uncertainty due to the huge number of aircraft types and variants. One area of uncertainty relates to the non-recurring costs, such as design authority and contract administration costs, which may vary enormously depending on the particular procurement policy being applied in different States.
When civil ATM improvements are introduced, a larger part of benefits go to civil stakeholders and military airspace users are severely impacted in financial terms whereas the benefit for military operations is very limited. This imbalance should ideally trigger compensatory incentives that should be considered in the near future.
This subject needs to be further expanded in the context of PBN IR impact assessment.

8.1 Metrics to Compare Aircraft O&S costs in the DoD

Reference is made to the report emanates from a RAND project[1] titled "Developing a Consistent Definition of Cost per Flying Hour for Use Throughout the Department of Defense (DoD)" to issues associated with the Cost Per Flying Hour (CPFH) metric.
CPFH is a metric widely used by the military services for different purposes, such as for Flying Hour Programs (FHP), for flying-hour reimbursable billing rates, and to compare Operating and Support (O&S) costs of different aircraft programs.
The key difference between CPFH used for FHP and the CPFH used to compare O&S costs of different aircraft programs is that cross-system O&S comparisons intentionally include some categories that are fixed (i.e., do not vary with flying hours). Cost-per-aircraft metric (where Primary Aircraft Inventory [PAI] is used for the number of aircraft) is as an alternative metric for comparing the O&S costs of aircraft.
Comparisons of CPFH are most appropriate when the intention is to compare costs that vary closely with flying hours, such as fuel, depot-level reparables, or perhaps engine-related costs. While, O&S costs include elements that are fixed or insensitive to changes in flying hours, such as unit-level personnel, sustaining support, or modifications.
The DoD's Cost Assessment and Program Evaluation (CAPE) office defines a standard O&S cost-element structure that comprises six major elements of:

- (1) unit personnel,

[1]Michael Boito, Edward G. Keating, John Wallace, Bradley DeBlois, Ilana Blum, *Metrics to Compare Aircraft Operating and Support Costs in the Department of Defense*, RAND Corporation, Santa Monica, Calif.

- (2) unit operations,
- (3) maintenance,
- (4) sustaining support,
- (5) continuing system improvements,
- (6) indirect support.

A metric that is an alternative to CPFH as a way to compare O&S costs of different aircraft is annual O&S cost per aircraft, that has characteristic of changing in the same direction that flying hours and total O&S costs for a fleet change. Efforts to reduce total program O&S costs, for example the streamlining the flying-hour program and making more use of simulators rather than flying for training could be considered.
Let's not forget that the unique value of a military aircraft is its readiness and availability for tasking, regardless of how much it is flown. So, annual O&S cost per aircraft more intuitively expresses the cost of available aircraft and Primary Aircraft Inventory (PAI) is the measure of the number of aircraft. PAI is the number of aircraft assigned to perform the mission and includes combat, combat support, training, and test aircraft.

This study is conducted in order to learn about what definition of operating and support (O&S) Cost Per Flying Hour (CPFH) is best suited to compare the O&S costs of military aircraft (actual and probable if fighter will introduce in GAT), to make decisions regarding development of new aircraft (with civil avionics or PE compliance) or retention of existing aircraft.
This comparison which is difficult to perform especially when comparing new aircraft programs to their antecedent, must to account for differences in actual costs versus estimated costs. Actual flying hours and costs are typically constrained by available resources, while estimated flying hours and costs are typically based on the premise of full funding needed to achieve crew proficiency.

As the name suggests, CPFH is calculated as an aircraft fleet's costs divided by its flying hours:

$$CPFH = \frac{TotalO\&SCost}{TotalFlyingHours} \tag{8.1}$$

A related difficulty with the CPFH metric is that the denominator of flying hours for a given fleet tends to change over time due to contingency flying and budget availability. Flying hours are therefore unstable over time and make the CPFH metric volatile.
There is ambiguity as to which elements of O&S cost to include in the numerator as well as whether to use only peacetime flying hours in the denominator or whether to also include contingency or operational flying hours. Obviously, the more cost categories that are included in the numerator and the fewer flying hours that are included in the denominator, the greater the estimated CPFH will be.

The term CPFH has been used by different analysts to mean different things: Figure 8.1 illustrates this issue, because there are different versions of CPFH in use with different definitions of what is and is not included in the cost numerator. The Air Force Cost Analysis Agency (AFCAA) created Figure 8.1 as part of a discussion of the many ways F-35 CPFH could be defined.

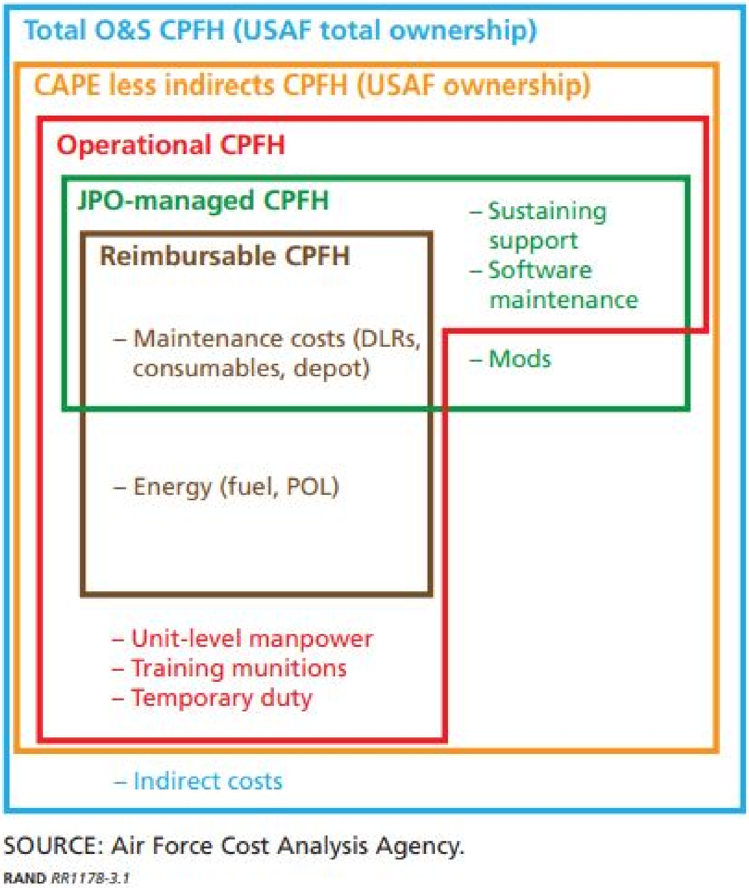


Figure 8.1: Different Cost Elements Used in CPFH Comparisons

The use of CPFH in some contexts is prescribed and defined in DoD policy.

Cost per aircraft, i.e. a fleet's O&S costs divided by the number of aircraft, is a possible alternative metric for comparing O&S costs across aircraft systems. For this metric, the number of total aircraft, not flying hours, serves as the denominator:

$$CostperAircraft = \frac{TotalO\&SCost}{NumberofAircraft} \tag{8.2}$$

But, what is used as the denominator? There are several possible definitions of total aircraft, including PAI which is the number of aircraft assigned to perform the unit's mission and includes combat, combat support, training and test aircraft, thus:

$$CostperAircraft = \frac{TotalO\&SCost}{PAI} \tag{8.3}$$

As is evident, each metric is suited to measure a different purpose and can convey different information about a given aircraft.

Most of the elements shown in Table 8.1 are affected at least somewhat by both flying hours and the number of aircraft. The characterization of elements as either fixed or variable indicates whether that element is predominantly affected by flying hours.
Fixed costs are largely stable over a defined, forecasted range of activity. If that level of activity is increased or decreased significantly, especially over a foreseeable amount of time, fixed costs would no longer be fixed. For example, if flying hours are doubled over a sustained period, it is

highly probable that numbers of maintenance personnel and pilots would have to be increased. Similarly, costs we categorize as variable can include some fixed portion that is unaffected by flying hours.

Category	RAND-Assessed Relationship to Flying Hours
1.0 Unit-Level Manpower	Fixed
1.1 Operations	Fixed
1.2 Unit-level maintenance	Fixed
1.3 Other unit level	Fixed
2.0 Unit Operations	
2.1 Operating material	Variable
2.2 Support services	Fixed
2.3 Temporary duty	Fixed
2.4 Transportation	Fixed
3.0 Maintenance	
3.1 Consumable materials and repair parts	Variable
3.2 Depot-level reparables	Variable
3.3 Intermediate maintenance	Variable
3.4 Depot maintenance	Semi-variable
3.5 Other maintenance	Undefined/Unknown
4.0 Sustaining Support	Fixed
4.1 System-specific training	Fixed
4.2 Support equipment replacement and repair	Fixed
4.3 Sustaining/systems engineering	Fixed
4.4 Program management	Fixed
4.5 Information systems	Fixed
4.6 Data and technical publications	Fixed
4.7 Simulator operations and repair	Fixed
4.8 Other sustaining support	Fixed
5.0 Continuing System Improvements	Fixed
5.1 Hardware modifications	Fixed
5.2 Software maintenance	Fixed
6.0 Indirect Support	Fixed
6.1 Installation support	Fixed
6.2 Personnel support	Fixed
6.3 General training and education	Fixed

Table 8.1: DoD Standard Cost-Element Structure and Relationship of Costs to Flying Hours

8.1.1 Example of Normalization of CPFH

To compare F-35A to F-16C/D CPFH for use in the F-35 selected acquisition reports (SAR), the Air Force Coast Analysis Agency (AFCAA) personnel has selected this following enumeration:

- Normalized flying hours and costs to the same flying hour/primary authorized aircraft (PAA) rate;
- Normalized fuel costs;
- Normalized Total Active Inventory (TAI) to PAA ratio;

- Used the same inflation indexes;
- Normalized F-16C/D mission personnel costs to reflect authorized positions rather than the cost of assigned personnel reported in Air Force Total Ownership Cost (AFTOC);
- Normalized budget-constrained expenditure data from AFTOC to reflect requirements;
- Added weapon-system costs not found in AFTOC for the F-16, e.g., Low Altitude Navigation and Targeting Infrared for Night pods. These additions increased the F-16C/D CPFH by 4 percent. The normalizations increased the F-16C/D CPFH above the raw costs reported in AFTOC by a few thousand dollars per flying hour.

Whenever O&S costs are compared, the elements of O&S cost included should be the same for the aircraft being compared. Indirect costs should usually be excluded from the cost tabulation. Costs should be compared in constant dollars using the same inflation indexes for the systems being compared. We acknowledge that while this is standard advice for comparing costs over different time periods, even when followed it is difficult to achieve the desired intent, especially when estimated future costs are involved.

8.1.2 Cost per Capability

The commercial airline industry uses the metric cost per available seat mile, i.e., the cost to fly one seat one mile. This is a simple cost metric that is widely used and applicable throughout the industry. This metric of cost is possible because the various fleets in the commercial industry are flown for a common purpose that is easily measured.
In contrast, aircraft fleets in DoD fly a variety of missions with different purposes, many of which are complex and multidimensional, that are often not easily measured. Therefore it is far more difficult to find cost-effectiveness measures for aircraft in DoD and specially applicable to all DoD aircraft.
A practical complication with incorporating capability into a metric is that informations on military fighter A/C are often classified, which greatly restricts the use of the metric.

8.2 Estimating the Real Cost of Modern Fighter Aircraft

The most recent cost/price estimates for each aircraft (reported in Table 8.2) are based on cost data published by government auditors, such as the US Government Accountability Office (GAO), Congressional Budget Office (CBO) and Congressional Research Service (CRS), or Britain's National Audit Office (NAO) and divulgate in report by defense-aerospace.com, 2006.

The price figures are provided both in terms of "unit programme cost", i.e. the total cost of a programme divided by the number of aircraft produced, and in terms of "unit procurement cost", i.e. the value of the latest of the most recent production contract divided by the number of aircraft it financed. While these figures are not directly comparable due to different national accounting standards and national budgetary standards, they offer the best public domain available indication of actual aircraft prices.
Unless otherwise indicated, prices refer to complete aircraft (i.e. including engines, flight and mission avionics) without their weapons, except, when fitted, for the fixed gun.

Aircraft Type	Unit Procurement Costs	Program Unit Costs	Comments
Rafale C	(EUR 51.8) $ 62.1	(EUR 113.2) $ 135.8	Air force single-seat (inc VAT)
Rafale M	(EUR 56.6) $ 67.9	(EUR 121.4) $ 145.7	Naval version (inc VAT)
JAS-39C Gripen	(Poland bid) $ 68.9	(SEK 552.9) $ 76.07	Swedish version (inc VAT)
F-18E Super Hornet	$ 78.4	$ 95.3	MYP II contract
Eurofighter (Germany)	(EUR 85.7) $ 102.8	(EUR 118.3) $ 141.9	Tranche 2, Dec. 2003 prices
F-15E Strike Eagle	$ 108.2	Not significant	FY06 order
F-35 Joint Strike Fighter	$ 115.0	$ 112.5	LRIP aircraft (estimates)
Eurofighter Typhoon (UK)	(GBP 64.8) $ 118.6	(GBP 78.6) $ 143.8	Tranche 2, July 2004 prices
Eurofighter (Spain)	Not available	(EUR 105.6) $ 126.7	Tranche 2, mid 2005 prices
F-22A Raptor	$ 177.6	$ 338.8	FY06 contract

Table 8.2: Combat Aircraft Ranked by Unit Production Costs (in millions of currency units)

The ambition is not to fix actual aircraft prices accurately, but rather to provide general estimates.
Table 8.2 points to some interesting conclusions about the economics of combat aircraft production:

- "1. **Aircraft designed by a single country are not necessarily more expensive** than those developed through international cooperation. Gripen and Rafale were both developed by single countries, but end up costing substantially less than Eurofighter, which is produced by a four-nation consortium.

- 2. **Single-nation development does not guarantee lower costs**, as the three US fighters all cost substantially more than the two European "national" fighters, and are comparable to those of Eurofighter, a four-nation cooperative program.
  Conversely, the projected unit cost of the only (partly) cooperative US aircraft, the Joint Strike Fighter, already exceeds that of Gripen and Rafale and of two other US aircraft, F-18E and F-15E, all of which are single-nation designs.

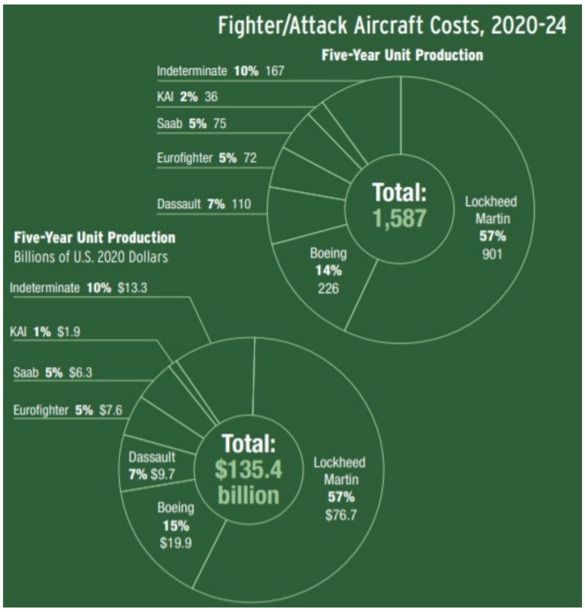
- 3. **Long production runs do not always lead to less expensive aircraft**.
  The F-18E, with a production run of 462 aircraft, costs half as much as the Rafale, which has a much smaller production run of 294 aircraft. JSF will cost twice as much as Rafale, despite having a production run almost ten times as large, and half as much again as the F-18E, whose production run is five times smaller. All three are modern, multirole combat aircraft.

- 4. While charges for major program stoppages and restructurings add to program costs, **the increase is not proportional** to the length of the hiatus. Both Eurofighter and Rafale programs were halted and restructured, adding eight or ten years to their development cycle, while F-15E, F18E and Gripen were not, yet this is not demonstrably reflected by the difference in their respective cost.

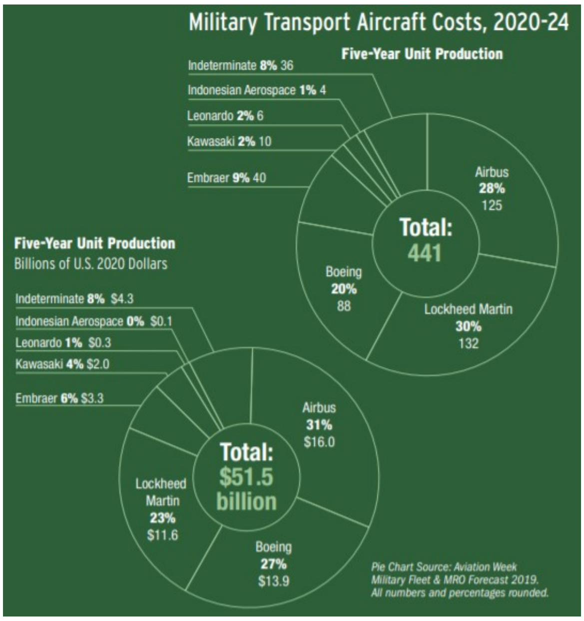
- 5. **Continuity in development is the best way to avoid cost overruns**.
  Gripen and F-18E (the F-15E is not significant in this respect) are the only programs to have avoided lengthy “freezes” and large-scale re-designs, and their production costs are notably lower than competitors’.
  Program unit costs of Rafale, Eurofighter and F-22 exploded after they were “suspended” for several years for major re-designs or funding shortfalls.

- 6. Although these aircraft were all developed beginning in the late 1980s, and for similar missions, there is **no common ratio between R&D and acquisition costs**. Indeed, there seems to be no correlation whatsoever between these costs, reflecting each aircraft’s unique R&D itinerary and development history".

The actual avionics market trends for the years 2020-2024 are shown below in Figure 8.2, where all numbers and percentages are rounded.



(a) Fighter/Attack Aircraft Costs, 2020-2024



(b) Military Transport Aircraft Costs, 2020-2024

Figure 8.2: Data Center

8.3 Cost estimation for the making of proposed product

One of the key elements is to provide an understanding of the investment outlays and potential return (cost and benefits) associated with equipment.
Avionic systems are a case in point and also the most crucial components of commercial and military aircraft systems, as seen in Figure 8.3. Avionics have been on an unaffordable trend due to complexity and cost, particularly in the evolution from hardware-defined systems to modern software-defined systems, where the costs to develop, integrate, and maintain software continues to grow at an unsustainable rate.
The amount of work, money and tests may not cover the operational improvement gained with PE process or COTS’ introduction.

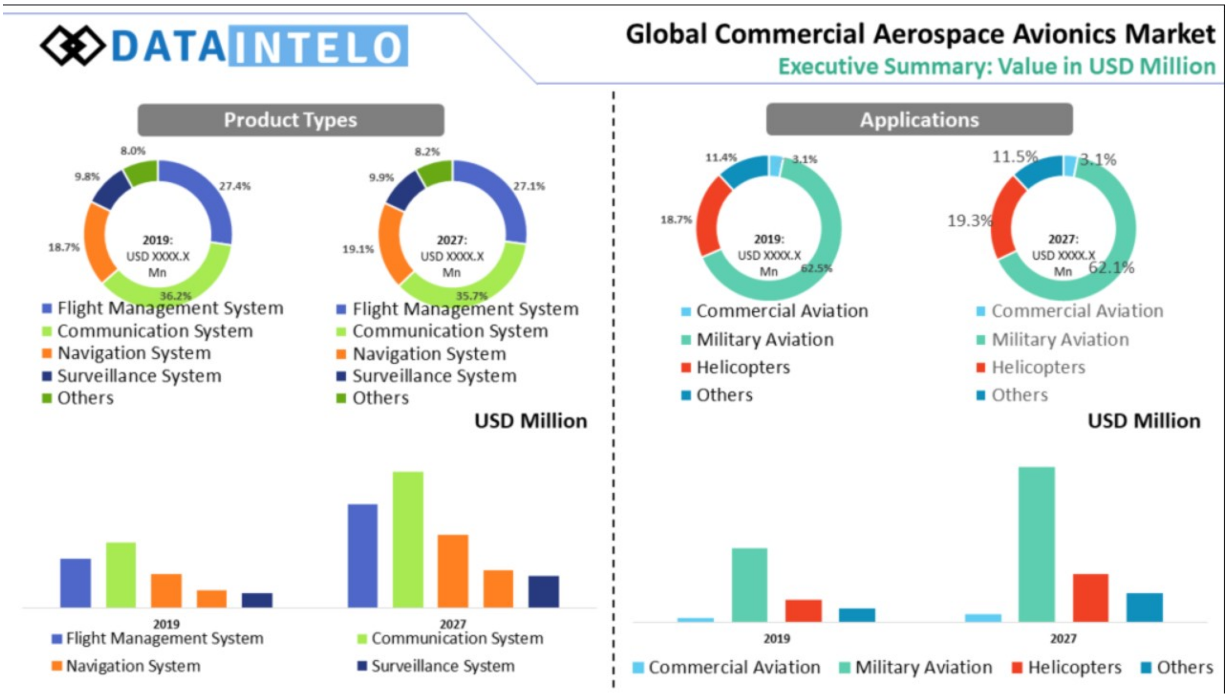


Figure 8.3: Global Commercial Aerospace Avionics Market

The aim of this section is not to contribute to the determination of the information collected, but only to aggregate, de-identify and analyse pricing information provided by the industry and report the results[2].

Average costs across all models:

- PBN (RNP AR) = $50,000
- DataComm = $94,000
- Surveillance = $13,450
- Resiliency = $0

Raw Range of Costs:

- PBN Baseline Item
  - Range = $0 (Basic) - $317,600
- DataComm (FANS 1/A, VDL Mode 2 with push to load)
  - Range = $0 (Basic) - $318,522
- Surveillance (FAA ADS-B out mandate compliant)
  - Range = $0 (Basic) - $88,000
- Resilient NextGen Operations (DME/DME with IRU)
  - Range = $0 (Basic)

[2]NAC Task 19-1 Report to be presented to the NextGen Advisory Committee, 2020

The range of costs data across all models can vary from $0 to $448,000 per aircraft, and the average total cost across all aircraft submitted is $158,000.
To remember: only aircraft forward-fit is considered. In this scenario, costs are amortized over many years through new aircraft payments. This represents a less-painful investment than the retro-fit scenario, but it also lengthens the window of time required to significantly reduce the mixed equipage impediment.

8.3.1 Fighter costs: a complex problem

The greater than 50% unit price increase is consistent with a trend that has seen jet fighter costs increase at an exponential rate over the years since the 1950s (see graph below).

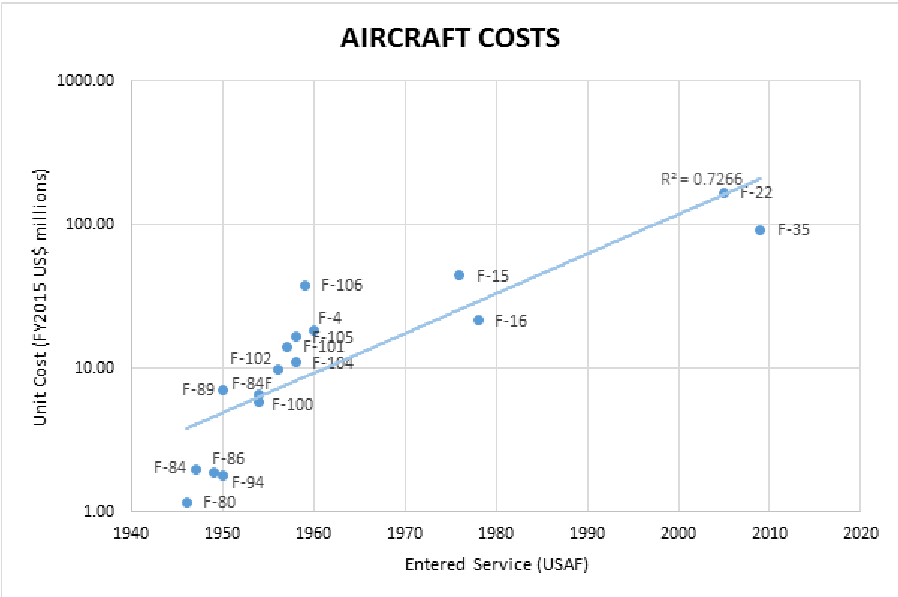
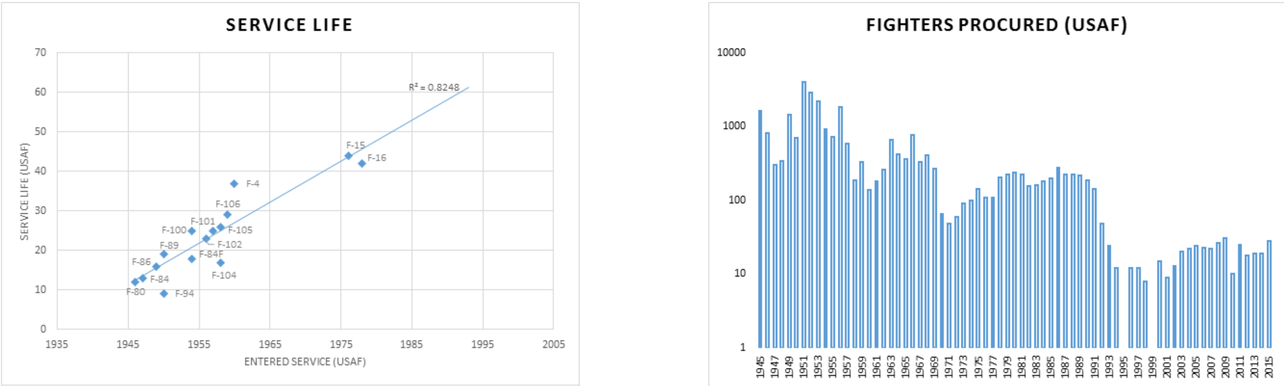


Figure 8.4: Aircraft costs

There are a number of factors that contribute to the increasing cost of fighters, which interact in non-linear ways, but the cost climb has resulted in two main trends:

- the service life of fighter aircraft has steadily increased;
- the number of fighters being procured each year has decreased over time as budgets failed to grow as fast as unit costs.

One major factor in unit cost is the price of labour. Material costs are also a factor, but a linear relationship between cost and material is nearly impossible to establish, because each added step in production requires additional engineering and labour that may or may not be affected by the specific material used.

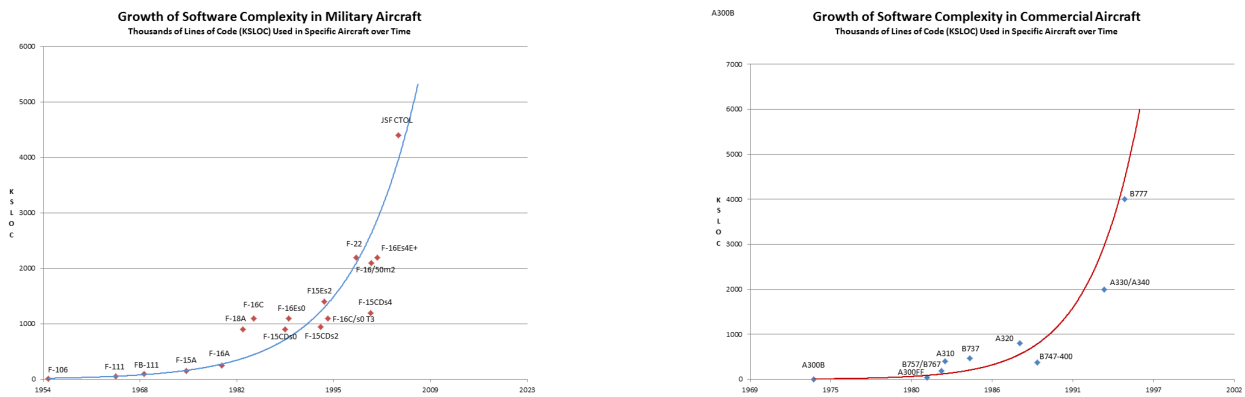


(a) Service Life (b) Fighters procured (USAF)

Figure 8.5: Trends

Fifth-generation jet fighters like the F-35 and F-22 have incredibly complex avionics integrated into their systems, so they require additional computing power to manage and software to operate. The F-35 software supposedly comprises some 20-25 million lines of code (over 10 times more than the F-22). Software contributes zero additional weight to an aircraft, and yet the labour costs for the F-35 software are substantial.

As seen in Figure 8.6, software complexity in aerospace systems is increasing exponentially: Source Lines Of Code (SLOC) in aircraft is doubling about every four years. That trend has been in place for at least five decades and applies to both commercial and to military aircraft.



(a) Military Aircraft (b) Commercial Aircraft

Figure 8.6: Exponential Growth of System Complexity

Since development costs for software systems increase exponentially with SLOC, costs are increasing at an alarming rate. Estimated software development cost increased by a factor of almost 300 over a 32 year period.

This initial assessment of costs has identified preliminary elements to answer the questions of how much equipping will cost. There are many variables in the cost and benefit equation, such as which aircraft are being purchased and where those aircraft will fly or and which avionics improvement are being implemented, which make it impossible to give one set of numbers.

It must also be considered that COTS production volumes, regarding military aircraft, would be amortised over several productions, so the development cost, which for military equipment runs into several millions, would undoubtedly be amortised, as seen in Figure 8.7.

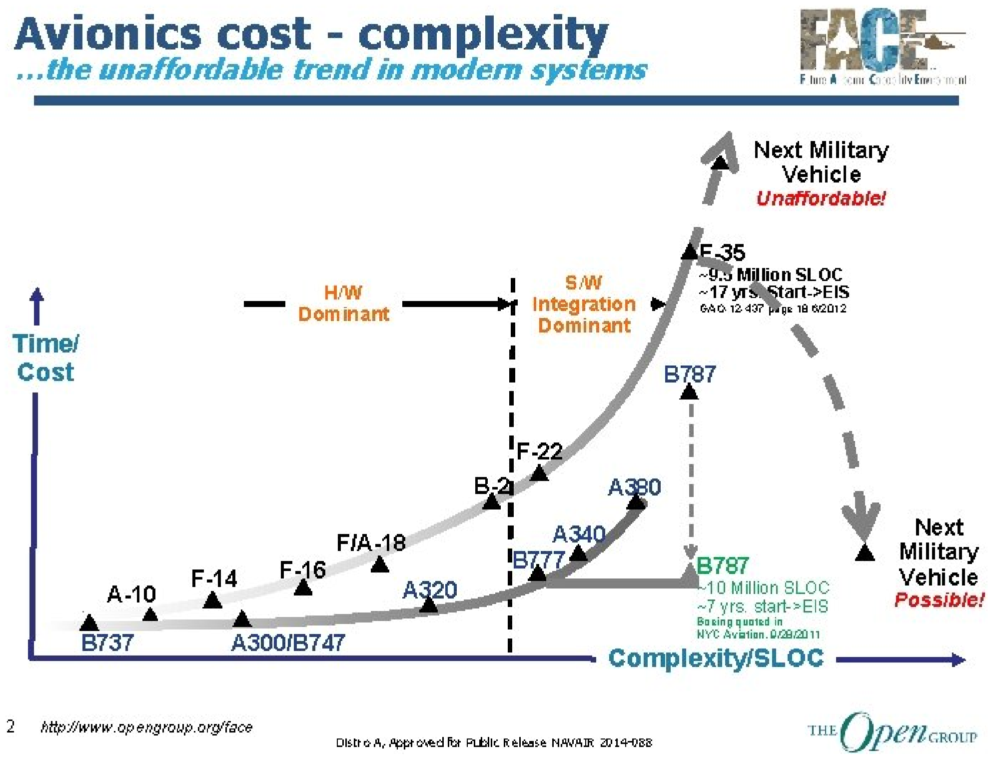


Figure 8.7: The Unaffordable Trend in Modern Systems (© GE Aviation)

Chapter 9

Conclusions

In the coming years, the military avionics supply and demand chain will feature advanced cockpit upgrades, and integration capabilities with civil airspace: as countries move forward on urban air mobility concepts, the use of single global airspace becomes increasingly common.
Focus area for military avionics is mission effectiveness and airspace interoperability: upgrades to RNP/RNAV allows the flexibility to seamlessly plan and execute missions in the most effective manner possible, as opposed to the current requirement for pilots to select between different navigation's systems in some platforms.

A number of benefits from PBN technologies over applications in all phases of flight are identified. These applications include RNAV-RNP arrival and departures, Established on RNP (EoR), Optimum Profile Descents (OPDs), RNAV Q/T/Y routes, LNAV/VNAV approach minima, and instrument approaches where ground based NAVAIDs do not exist.
Expected benefits from PBN include:

- Additional flight efficiency;
- Additional throughput;
- Enhanced safety;
- Fewer Level-offs on arrivals;
- Vertical profiles improved through increased proportion of continuous descent operations, and shorter time and distance in level flight;
- Fuel savings per flight;
- Reduction of military flight time.

Benefit assessments based on actual capability implementation (vs. benefit projections) is a sound approach for establishing expected return on investment. Cost and avionics implementation data and analyses may need to be augmented with other operational assessments to obtain a more complete benefits outlook, specifically for PBN applications. The data in this report could help better understand how to build a business case.

Key challenges for military avionics upgrade, both now and for the foreseeable future, remain in the complexities and differences in closed proprietary architectures commonly found in military aircraft, so the challenge will be promote sharing of civil and military services and convergence of technology.

In the near-term mandates' implementation in fighter A/C will permitted to reduce pilots' workload, improve pilots' situational awareness, and improve the safety and reliability of the aircraft in civil airspace, making use of items that allow the pilots' overlay of flight plans and viewing of nearby points-of-interest, radar, and threat information.

In future studies, it would be informative to evaluate the use of strategies for excessive workload management that are controlled by the pilot (e.g., slowing the aircraft, shedding tasks) as compared to those involving assistance from the outside (i.e., ATC).

Another important innovation was development of open system architecture for on-board computers. Taking into account the availability and logistics issues related to MIL grade components, a decision was taken to use COTS components and ruggedize the on-board computers to meet the severe environmental demands of fighter aircraft. Thanks to this major decision, obsolescence management became easy and on-board equipment will could be upgraded without impacting the core systems and architecture.

The job developed is a departure point that has put in evidence the potentialities of synergetic military and civil resources to be exploited through man-machine co-operation.
The implementation and use of on-board automation are pilot's key elements to have safe flight, situational awareness, and workload management. In Figure 9.1 the relevant features of human-machine cooperation are highlighted.

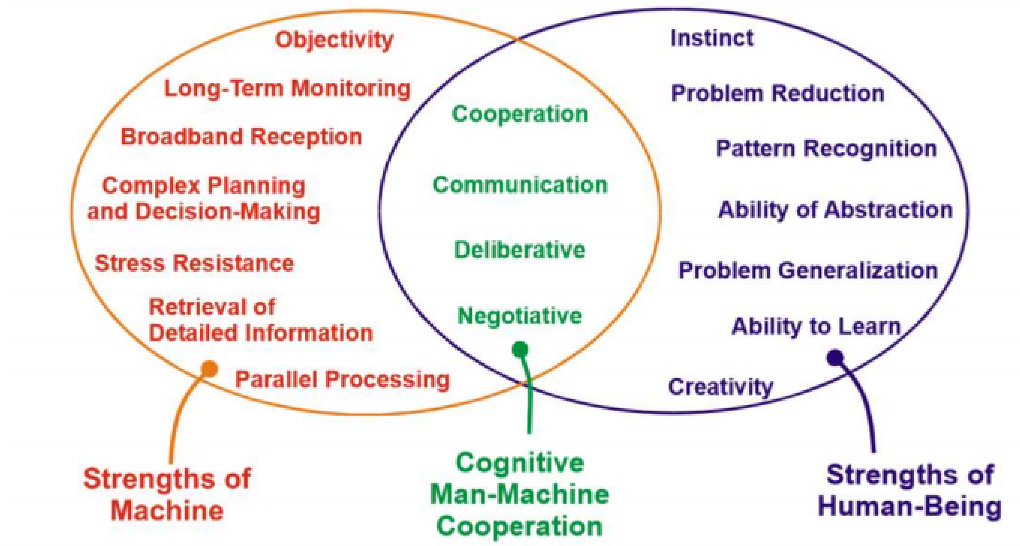


Figure 9.1: Synergetic resources to be exploited through man-machine co-operation

There have been no obvious "show stoppers" for moving toward unique airspace. However, the current state of research is in its initial stages: systems engineers and human factors researchers must continue to be involved in the development of the new tools and technologies to support this purpose.

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