Operational and Technological Background on Air Traffic Management

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The technology associated with air traffic management (ATM) is complex and advancing rapidly. This chapter describes how ATM "works" and the issues involved in introducing new technology. A nontechnical description of the operational and technological characteristics of ATM is provided in a form that is suitable for a reader who is not familiar with the ATM industry. The scope of this chapter reflects the concepts relevant to understanding the economics, regulation, and governance of ATM.

The operational functions associated with ATM, its organization, and the characteristics of the communication, navigation, and surveillance (CNS) infrastructure that support ATM are described in the first part of this chapter. A brief description of the major new satellite-based technological systems currently being used, such as ADS-B, then follows. Investment in new technology can increase safety and the capacity of airspace as well as generating fuel savings and environmental benefits. An overview of the significant challenges involved in adopting new technology to support ATM, including coordinating changes in technology at an international level, is provided. The Single European Sky ATM Research (SESAR) joint undertaking and the US Next Generation Air Transport system (NextGen) are major technological development programs.

This chapter is abstracted from specific air navigation service providers (ANSPs) and other institutions. General terminology is used and the use of acronyms is reduced as much as possible.

Introduction to Air Traffic Management

ATM is an air navigation service that coordinates air traffic in airspace primarily through air traffic control (ATC), air traffic flow management (ATFM), and airspace management. ANSPs are the institutions that provide ATM and other air navigation services related to ATM. The management of air traffic by ANSPs is directed to safe and efficient operation of aircraft in airspace and on the ground. (The main services that comprise air navigation services are described in Chapter 1.)

A main function of ATM is ATC, the process of separation of aircraft in the sky as they fly and at airports where they land and take-off. ATFM involves sequencing aircraft along air routes and at airports. To provide ATM services, ANSPs acquire and maintain air navigation equipment for CNS infrastructure and develop and disseminate procedures and data for safe and efficient navigation of the airspace.

Air Traffic Management. https://doi.org/10.1016/B978-0-12-811118-5.00002-3

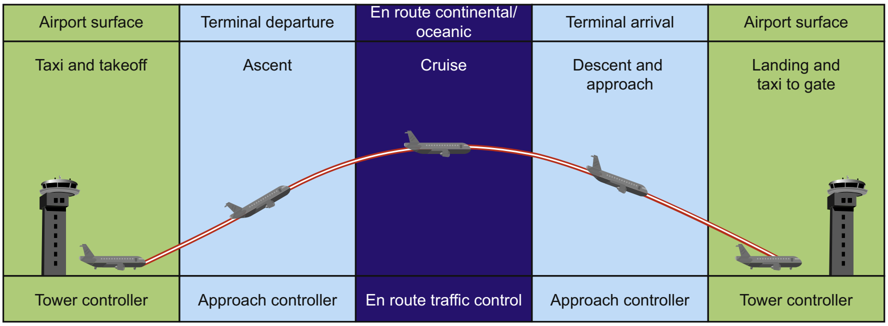

Figure 2.1 Phases of a flight requiring different types of air traffic control.

Air Traffic Control

ATC services are provided by licensed air traffic control operators (ATCOs) for the purpose of preventing aircraft collisions in the air and on the ground at airports, and expediting and maintaining an orderly flow of air traffic. The types of ATC services provided ATCOs depend on the category of airspace and the stage of a flight.

Stages of a Flight

Aircraft travel from one airport through space to another airport. ATC is divided into various service areas defined by the different demands for controlling the individual phases of a flight. The main stages of a flight are aircraft maneuvering on the ground, take-off and landing, terminal navigation associated with departure and arrival to or from an airport (approach services), and en route cruising between airports. The typical stages of a flight requiring different types of ATC are depicted in Fig. 2.1.

The main responsibilities of air traffic controllers associated with the three main stages of a flight are described in Box 2.1.

The Safe Separation of Aircraft

Safe separation of aircraft is undertaken by ATCOs located in airport control towers and area control centers (ACCs). Air traffic controllers manage the flow of aircraft so that they are vertically and horizontally separated at prescribed and safe distances from other aircraft, from the ground and from protected airspace. This includes arranging aircraft in an order for landing and take-off along organized flight paths.

A fundamental distinction in the way separation is achieved is between flights under visual flight rules (VFRs) and instrument flight rules (IFRs), classifications that involve internationally agreed rules for flying under the different conditions. Box 2.2 describes the difference between the two types of flight rules.

There are international standards on minimum separations between aircraft. Differences from the international standards can exist in a jurisdiction and are published in Aeronautical Information Publications (AIPs).[1]

[1] AIPs are publications issued by or with the authority of a State and containing aeronautical information essential to air navigation.

Box 2.1 General Types of Air Traffic Control

Tower controllers are responsible for all aircraft and vehicle movements on taxiways and runways and in the immediate vicinity of the airport. They are located in an airport's control tower and are generally responsible for separating aircraft on the maneuvering areas (runways and taxiways) as well as in the air and within close proximity to the airport. Control towers separate aircraft visually but use a range of technology to assist with this.

Approach (terminal) controllers use surveillance technology, such as radar, to manage the flow of aircraft arriving and departing from major airports. Control services are generally provided for an extended area, such as a radius of 50 km around major airports. They are located in a control center that may or may not be located at the particular airport where the landing or take-off is expected. Once an aircraft is airborne from an airport, the aircraft's movement is managed by terminal (or approach) controllers to ensure separation between airborne aircraft within the airport terminal area. Similarly, terminal controllers sequence aircraft on their descent to an airport but before landing.

En route controllers are located at area control centers and manage aircraft movements in upper airspace including continental and oceanic routes. En route air traffic controllers manage air navigation systems that govern aircraft movements once a flight has reached cruising altitude or the flight level assigned by air traffic control in the flight information region (FIR) for the country of departure. (FIRs are discussed in Chapter 3.) Within an FIR there may be separate air traffic sectors (working sectors) managing different parts of the airspace to accommodate the effects of large geographical areas and the density of aircraft traffic operating in the approach or en route phase of flight.

Skyguide, 2007. Air Navigation Services. Booklet. https://www.skyguide.ch/wp-content/uploads/fileadmin/user_upload/publications/others/skyguide_ANS_e.pdf.

Vertical separation is the vertical spacing required between two aircraft as they proceed, either along the same route or to cross the routes of each other if they are in close proximity. Vertical separation is usually expressed relative to specific altitudes in hundreds of feet (a Flight Level number[2]). For example, in many situations the international standard for vertical separation requires that there must never be less than a minimum of 1000 ft vertically between aircraft, if they are flying below 29,000 ft (FL290) and 2000 ft if they are flying above 29,000 ft. In some geographic areas and circumstances, the vertical minimum separation is reduced, which allows aircraft to fly safely at more optimum profiles, increasing fuel efficiency and airspace capacity.

Lateral (or longitudinal) separation between aircraft is applied to aircraft, moving in the same direction, one behind the other, along the same line or route, and flying at the same level. Lateral separation standards can be in time (minutes) or in nautical

[2] For example, 25,000 ft is expressed as Flight Level 250.

Box 2.2 Flight Rules—Visual Flight Rules (VFR) and Instrument Flight Rules (IFR)

Visual Flight Rules

Procedural methods of separation are based on pilot reports to estimate the aircraft position. In airspace not monitored by radar or satellite-based navigation services, aircraft separation is achieved by the use of various procedural rules including time and estimated position.

When flying under VFR, precisely defined minimum distances for visibility and proximity to clouds must be maintained. VFR pilots orient themselves mainly by prominent landmarks, with the natural horizon as their reference point. In this category, the "see and avoid" principle is applied. Each VFR pilot is solely responsible for avoiding collisions and near-misses. However, air traffic control does assist VFR pilots in their task with precise traffic information from a flight information center. VFR generally applies to small planes operating in less congested airspace and at low altitudes where pilots are responsible for separation from other aircraft (not controllers) (Poole, 2014).

Instrument Flight Rules

In contrast to VFR movements, IFR flights can operate in all weather conditions. As a consequence, there are normally no regulations laid down in relation to the visibility required to maneuver. Aircraft flying under IFR are equipped with instruments and navigation devices that, in conjunction with ground installations and satellite navigation aids, allow nonvisual orientation. For these flights, air traffic control is responsible for preventing collisions.

All large passenger aircraft have instrument landing systems (ILS) capability (Skyguide, 2007). An ILS is comprised of two transmitters—the localizer and glide slope—which are used to ensure that an aircraft is within the lateral and vertical parameters for the runway being used. An ILS comprises a landing course transmitter, the localizer, a glide-path transmitter, and distance measuring equipment. During the final stages of approach, from about 15 km, a display instrument provides IFR pilots with precise data on the aircraft's position in relation to the ideal approach axis, the optimum glide-path, and the distance to the threshold of the runway.

Conventional ILS is being replaced by a satellite-based landing system called ground based augmentation system (GBAS). GBAS can guide multiple highly precise and smooth approaches simultaneously (Airservices Australia, 2016a).

miles. Again, the required degree of separation depends on the circumstances, including whether aircraft are climbing or descending through altitude as they approach or leave airports, cruising at level, the method of separation used by ATC (e.g., procedures or radar), and other factors.

Separation standards (distances) have to take into account the diversity of the aviation community, ranging from general aviation through to long-haul international aviation and the mix of aircraft and CNS capability.[3] As an illustration, separation standards take into account whether aircraft are approaching or taking off from the same runway or closely spaced runways and whether following aircraft could be effected by wake turbulence (Skybrary, 2016).

Air traffic controllers apply and monitor minimum separation. Monitoring compliance with minimum separation distances becomes more complex in heavy traffic and hazardous weather conditions.[4] Switzerland provides an example in Europe where the airspace is complex for ATC because of the high proportion of flights descending to or climbing from airports in and around Switzerland (Skyguide, 2016). Singapore is an example of complex airspace in Asia.

The methods used to achieve separation are varied and complex and depend on the phase of a flight, the relative trajectories of the aircraft involved, the technology in use, and local terrain conditions. Historically, separation of aircraft has been primarily based on prescriptive flight procedures and specified equipment in aircraft. Technical systems and procedures are used by air traffic controllers, including systems that process location and flight plan data.

Area Control Centers

ACCs undertake ATC for precisely defined areas of responsibility in terms of stages of a flight, which cover terminal and/or en route ATC, and a geographic area, which may not coincide with national borders. Air traffic controllers are in constant radio contact with the pilots in their area, except that over the ocean the primary communication may be by a data link.[5]

The procedures for the handover of aircraft from one ACC to another are regulated by international bilateral agreements. Information about a flight, including its call sign, altitude, and type of aircraft, is transmitted along data transmission lines to the next ACC before a handover process. Every flight is coordinated and passed from one ACC to the next between its departure airport and the control tower at its destination airport.

Pilots are required to submit Flight Plans[6] to ANSPs before take-off. These plans contain all the data relating to planned flights and allow air traffic controllers to plan

[3] In some circumstances time-based minimum separations of aircraft can be used for aircraft making their final approach to land instead of minimum distances that are fixed whatever the wind conditions. Time-based approaches enable adaptation to weather conditions. For example, in strong headwinds distance-based separations lead to longer gaps of time developing between aircraft. This means fewer flights landing per hour, leading to delays and increased holding at busy times, which result in increased fuel burn and reduced airport capacity. Time-based separation has been implemented at Heathrow Airport (SESAR, 2015).

[4] The complexity of an airspace depends on traffic density, horizontal crossings, and the vertical flight profiles of the controlled flights.

[5] Data link or controller-pilot data link communication is a means of communication between controller and pilot using the data link (text messages) for ATC communication instead of voice radio communication.

[6] For IFR flights, there is a requirement for all aircraft from airlines to business aircraft using ATC to lodge a flight plan with an ANSP before a flight. A flight plan describes how the aircraft is going to fly from a point of departure to a point of arrival. Traditionally, routes have been specified as a sequence of waypoints and altitudes. New technology is allowing greater flexibility in route specification.

traffic movements in advance. The flight plan data, and collaboration between all the control centers involved in the flight, forms the basis for controlling flights.

Operating procedures used by air traffic controllers are highly formalized and consistent with regulations and procedures developed by the International Civil Aviation Organisation (ICAO), a United Nations agency with a primary role in the governance of international civil aviation (Chapter 3). Air traffic controllers and pilots can only use languages recognized by international agreement. English is the commonly used language for aviation internationally. Aviation English, known as "voice," is a precisely defined, greatly simplified form of English using internationally valid, clearly understandable traffic terminology.

Categories of Airspace

Airspace is classified into categories that determine the level of ATM service provided. The categories are set by ICAO. A primary distinction is between controlled and uncontrolled airspace.

Controlled airspace is the airspace that is actively monitored by air traffic controllers and is broken up into different classes, subclasses, or classifications. An aircraft pilot must first gain a clearance from ATC to enter controlled airspace. Air traffic controllers monitor and enforce separations between aircraft in controlled airspace. An aircraft will pass through different classes of airspace, in which different rules will apply to it depending on how far and how high the aircraft flies.

Uncontrolled airspace is the airspace where air traffic controllers do not provide aircraft separation services. Aircraft *may* not be visible to ATC in uncontrolled airspace. Uncontrolled airspace may be located underneath or adjacent to controlled airspace.[7] In Australia the large majority of light aircraft and helicopters operate in uncontrolled airspace. Aircraft separation is governed by ATM procedures in uncontrolled airspace. Different categories of airspace reflect different restrictions on the use of the airspace and the provision of different types of ATC services. Broad categories of airspace are described in Box 2.3.

Box 2.4 describes the ICAO classes of airspace that represent the type of air traffic service that is expected within that particular area of airspace. Individual States apply the ICAO classifications that suit their airspace environment. Fig. 2.2 gives a general depiction of how the classes of airspace work.

Organization of Air Traffic Control Into Sectors

The airspace that is attributed to ACCs is composed of blocks of airspace, referred to as "sectors" or volumes. The traffic safety in a sector is the responsibility of specifically qualified air traffic controllers who have qualifications that are specific to their

[7] ANSPs may provide an "alerting service" in some parts of uncontrolled airspace. For example, Airways New Zealand provides an Alerting Service to aircraft receiving an Aerodrome Control Service or an Aerodrome Flight Information Service when the aircraft is known by Air Traffic Services to be in need of assistance or known, or believed, to be the subject of unlawful interference. Airways New Zealand (2012). https://www.airways.co.nz/assets/Documents/Airways-Service-Framework.pdf.

Box 2.3 Categories of Airspace

Lower airspace—A part of controlled airspace below a vertical limit, such as below 19,500 or 24,000 ft and outside the terminal or airport airspace.

Upper airspace—Part of controlled airspace above a vertical limit, such as 19,500 or 24,000 ft[28] usually used by jet aircraft in the cruise phase of flight.

Oceanic airspace—Long stretches of airspace over thousands of miles of ocean.

Restricted airspace—Requires aircraft operators to obtain certain specified permissions to enter the airspace. Restricted airspace includes airspace around military installations, high-density flying operations, such as at an air show or other large public event, or for safety and security reasons in the vicinity of bushfires or major crime scenes.

No-fly zones—Similar to restricted airspace but are imposed and enforced by the military, usually established around military exercises or State meetings.

[28] In Europe, the Upper Information Region (UIR) is defined as airspace above a division level (generally FL195). The level for UIR can vary in different countries (Eurocontrol, 2016b).

area of control. The number of flights that can be handled simultaneously by controllers varies according to traffic complexity and the technology being used. The size of a sector, in terms of the area of airspace that is covered, reflects the demands that the air traffic places on controllers, which vary with traffic density, the stage of the flight, and other factors.

Each sector has a control unit (generally a team of two or three air traffic controllers). ACCs manage a number of sectors. During low-traffic hours, sectors may be regrouped so that the number of sectors (and controllers) is reduced, with individual sectors managing larger portions of airspace. Conversely, when airspace is congested, such as in peak periods, sectors may be divided into smaller portions to increase the airspace capacity.

Dividing airspace into more sectors leads to a less-than-proportionate increase in airspace capacity (Dumez and Jeunemaître, 2001). The number of air traffic controllers generally increases in proportion to the number of sectors opened. However, the increased use of sectors leads to increased coordination between sectors, and dealing with potential conflicts in flight movements becomes more complex. After a certain point, increasing the capacity by division of airspace into more sectors is no longer workable.

Air Traffic Flow Management

ATFM is an overarching control of airspace to coordinate and ensure safety of flights. Safety considerations and congestion at airports limit the number of flights that air

Box 2.4 Classes of Airspace

Annex 11 of the International Convention on Civil Aviation sets out ICAO classifications of airspace:

Class A. Only instrument flight rule (IFR) flights are permitted; all flights are provided with air traffic control service and are separated from each other.

Class B. IFR and visual flight rule (VFR) flights are permitted; all flights are provided with air traffic control service and are separated from each other.

Class C. IFR and VFR flights are permitted; all flights are provided with air traffic control service and IFR flights are separated from other IFR flights and from VFR flights. VFR flights are separated from IFR flights and receive traffic information with respect to other VFR flights.

Class D. IFR and VFR flights are permitted and all flights are provided with air traffic control service; IFR flights are separated from other IFR flights and receive traffic information with respect to VFR flights; VFR flights receive traffic information with respect to all other flights.

Class E. IFR and VFR flights are permitted; IFR flights are provided with air traffic control service and are separated from other IFR flights. All flights receive traffic information as far as it is practical.

Class F. IFR and VFR flights are permitted; all participating IFR flights receive an air traffic advisory service and all flights receive flight information service if requested.

ICAO (2016c). Annex 11 to the International Convention on Civil Aviation, Air Traffic Services, fourteenth ed. July, Section 2.6.

traffic controllers can handle.[8] ATFM is used to regulate traffic demand according to available airspace capacity while minimizing delays and avoiding safety risks associated with overloaded ATC sectors (Jaffe, 2015). The objective is an optimum balance between airspace capacity and the volumes of flights handled to achieve safe and efficient air traffic movement. ATFM can be referred to as air traffic flow and capacity management.

Approaches to Air Traffic Flow Management

The traditional approach used in managing air traffic was based on the principles of “first come, first served” and “equitable access to airspace” (ICAO, 2014). Holding patterns, involving aircraft approaching an airport circling while waiting to land at an airport, are an inefficient and costly way of delaying aircraft arrivals at an airport that has reached its capacity. The management of air traffic has evolved so that air traffic is

[8] Overloading air traffic controllers is stressful and detrimental to safety.

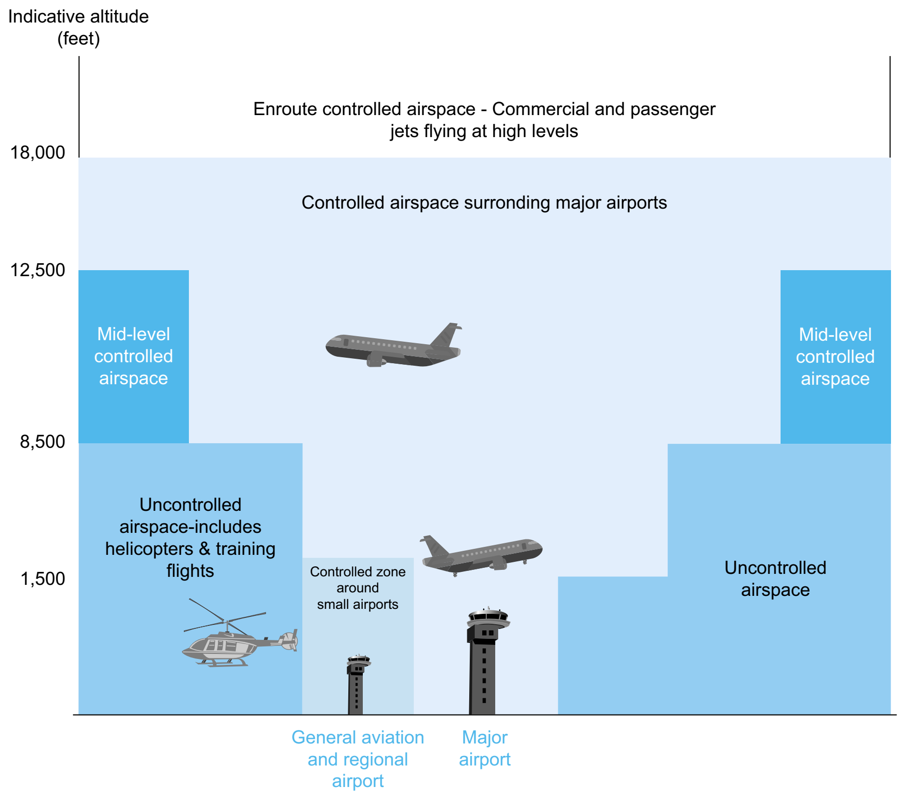

Figure 2.2 Illustration of the application of categories of airspace.

managed to achieve overall system efficiency, improved environmental impacts, and reduced operating costs.

Flight plans are the basis of ATFM. Flight movements into, out of, and around a region subject to ATFM can be analyzed and planned to optimize traffic flow (ICAO, 2014). A strategic ATFM plan is designed to resolve anticipated congestion in problematic areas to facilitate traffic flows, generally several months to 1 week before the flight operation dates.[9] Daily traffic plans are developed, usually 1 day before the planned flight operations, involving adaptations and adjustments to the strategic plans that have already been developed. On the day of flight, real-time optimization of air traffic flow is undertaken to mitigate any disturbances that occur in the case of an unforeseen event with major impact on traffic.

ATFM involves a number of techniques and includes systems that can be simple or complex. One tool commonly used to manage air traffic flow is the use of ground delay programs where aircraft departures are delayed. ATFM planning is not universally used. In some regions it may only apply when there are constraints, such as

[9] During this phase operational scenarios can be developed to take into account anticipated specific events, which may cause congestion, such as sporting events, Christmas, skiing or summer holiday traffic.

Table 2.1 Examples of techniques used for optimizing air traffic flow depending on the circumstances

Technique	Description
Airspace flow program	Computer programs identify constraints in the en route system and develop flight schedules (through the use of aircraft Flight Plans) to enter the constrained area. From this a plan is developed to distribute expected departure clearance times to adjust the air traffic demand to the area.[29]
Miles (or minutes) in trail	The number of miles required between aircraft departing an airport, over a fix, at an altitude, through a sector, or on a specific route. Minutes-in-trail describe the minutes needed between successive aircraft.
Sequencing programs	Arriving or departing aircraft can be assigned specific times to cross a designated point. En route aircraft can also be assigned specific departure times.
Use of altitude	Traffic flow managers can increase capacity by requiring aircraft to remain at a lower altitude than they would otherwise operate at, and by directing arriving aircraft to descend earlier than otherwise required.
Ground delay program	Aircraft bound for a particular destination are required to hold at the departure gate to facilitate traffic flow to a given airport.
Severe weather avoidance plan	Alternative predesignated routes are made available in the event of severe weather, such as thunderstorms.

Based on information on Traffic Flow Management in the National Airspace System, 2009 contained in Jaffe (2015) as well as other sources.

periods of excess demand associated with thunderstorm activity and wind turbulence. Table 2.1 above provides some examples of the techniques used in ATFM.

To achieve optimum air traffic for the system as a whole, ATFM takes into account the performance capability of aircraft; as a result the "first come, first served" rule may be overridden. Although the ATFM system results in "winners" and "losers" on an hour-to-hour and day-to-day basis, overall air traffic involved in the system operates more efficiently, increasing the total flow of traffic. This means that it is very important that the system is properly managed so that everyone accepts his/her share of the pain for the betterment of the system (Jaffe, 2015). Coordination between aviation stakeholders is a key consideration to successful implementation of an effective ATFM system (ICAO, 2014). Airport and airspace capacity need to be carefully defined and balanced with the demands for capacity. Additionally, the information provided by the various stakeholders needs to be accurate. Equitable access over the long term needs to be taken into account in the ATFM plans.

[29] Characteristics of the US system operated by the FAA (FAA, 2008).

Examples of Air Traffic Flow Management Programs

Both the United States and Europe have established system-wide, centralized traffic management facilities to ensure that traffic flows do not exceed what can be safely handled by ATC units and to try to optimize the use of available capacity (Eurocontrol and FAA, 2016). China initiated a Multi-Airport Collaborative Departure Clearance System in 2012 between Beijing, Shanghai Pudong, and Guangzhou airports to alleviate the pressure of growth of commercial aviation on the country's ATC infrastructure (Jaffe, 2015).

Potential congestion is managed for westbound aircraft operating from South and Southeast Asia to Europe during the busy nighttime through a system known as the Bay of Bengal Cooperative Air Traffic Flow Management System. A secure web-based computer system is used to manage aircraft transit when Afghanistan airspace has limited capacity for air traffic (AEROTHAI, 2016).

Aeronautical Information Services

ANSPs compile and distribute aeronautical information necessary for airspace users, including information on safety, navigation, technical issues, administrative procedures, and legal issues. Aeronautical information service functions cover preparation, processing, and handling of dynamic data (weather and other conditions that impact flight planning and operations) and static data (covering the location and character of navigation aids, the physical characteristics of airports, and geography) (Eurocontrol, 2016a). Maps show air routes and the areas that air traffic control centres (ATCCs) are responsible for.

Communication, Navigation, and Surveillance, and Other Infrastructure

CNS systems are the main infrastructure used to provide ATM. They are the "technical backbone" of ATM. The planning, installation, and maintenance of these technical systems is typically undertaken by ANSPs.

Communications systems allow data and instructions to be passed between air traffic controllers and pilots and between ATC units and other relevant stakeholders.

Navigation systems assist pilots in planning and controlling aircraft movements between locations involving a constant awareness of an aircraft's position. Navigation equipment transmits radio signals that assist aircraft to determine their location in space regardless of the weather conditions. Navigation equipment is critical, especially for Instrument Landing Systems that enable aircraft to land based solely on transmitted signals.

Surveillance systems provide air traffic controllers with a visual display on a screen of the aircraft flying in the airspace under their control allowing them to monitor and provide separation instructions to aircraft.

The type of CNS systems used affects the performance of ATM, i.e., the level of safety, airspace capacity, and aircraft flight times and fuel burn. CNS systems also depend on avionics[10] in the aircraft. As aircraft fly across the networks of different ANSPs, CNS infrastructure must be interoperable between the connecting systems.

Traditional Approaches Used for Communication, Navigation, and Surveillance

The traditional approaches used for CNS services relied on ground-based radar technology, such as primary and secondary radar systems. First developed in the 1930s, ground-based infrastructure was progressively built up over the 20th century to provide a worldwide navigation system. These systems were the primary support for air navigation and surveillance until the 21st century. Under ground-based technology, aircraft navigation has been based on using a set of coordinates, or waypoints, defined by sensor-specific, fixed ground-based beacons. These beacons provide signals to guide aircraft along published routes. Under ground-based radar technology, pilots are required to follow the existing network of rigid waypoints and airways. Jet routes formed into linear fixed patterns, "jetways," effectively connected the dots, or the ground-based navigation aids (navaids)[11] along a route (Jaffe, 2015).

Ground-based radar systems have a number of limitations (Oster and Strong, 2007):

Slow speed and reduced accuracy—Radar is slow compared with the speed of the aircraft, resulting in delays/lags in the information received by controllers. The accuracy of navigation by ground-based navigation aids decreases significantly with increasing distance from the aid.

Limited coverage—Coverage from ground-based systems is not available in all parts of world and not available over large stretches of ocean.

High maintenance costs—Ground-based navigational aids require a maintenance infrastructure to keep them operational. In some developing countries, an adequate maintenance structure may not be in place, which could compromise the reliability of the system.

Rigid flight routes—Systems that rely on flying over ground-based navigation aids preclude flying more direct routes.

The majority of airspace across oceans does not have radar coverage because of high costs or infeasibility (Jaffe, 2015). Flights across oceans are subject to procedural separation, requiring large separation distances between aircraft. For example, the in-trail separation standard is around 80°miles in oceanic areas, compared with standard separation under radar coverage of 3–5°miles.

[10] Avionics are the electronic systems that operate in aircraft cockpits. Modern aircraft have hundreds of electronic systems, including systems for communication, navigation, and a variety of early warning systems.

[11] Navaids (navigation aids) are devices or a (radar-based) system that provide pilots with navigational data. Navaids provide relative navigation or point-to-point tracking using equipment such as nondirectional beacons, VHF omni-directional ranges, and distance measuring equipment.

Major New Technologies

Modern satellite-based technologies are now being used for CNS and began replacing ground-based radar systems in the 1990s. Air navigation systems are shifting to systems that use global navigation satellite systems (GNSS)[12] and computerized on-board systems. Satellite systems provide continuous real-time information on aircraft positions. Through the use of global positioning satellite (GPS) precision navigation systems are fully integrated into an aircraft's flight management system.

Advanced air navigation systems comprise a number of subsystems that are integrated into a new system referred to as the future air navigation system (FANS). FANS is a system of systems, comprising components of ground, air, and space technologies, and is expected to drive a more efficient ATM system, with more efficient flight trajectories and reduced fuel burn (Jaffe, 2015). FANS uses the GNSS, the concept of performance-based navigation (PBN) and the use of Automatic Dependent Surveillance—Broadcast (ADS-B). These and other systems are integral to future ATM.

Global Navigation Satellite System

GNSS navigation allows an aircraft to determine its position at any time and navigate along an arbitrary but preplanned path. The precision of the continuous position and tracking guidance provided by GNSS area navigation increases safety and efficiency. The use of GNSS has also allowed the introduction of long range wind optimized flight paths and more direct routes.

Performance-Based Navigation

PBN is a global set of navigation standards, based on generic performance requirements for aircraft navigation. The aircraft navigation requirements are defined in terms of standards for the accuracy, integrity, continuity, and functionality required for a particular airspace or airport (CANSO, 2015, 2017). Under the PBN framework, aircraft must comply with specified operational navigation performance requirements along a route, during a procedure, or in the airspace. Area navigation performance specifications vary for aircraft navigating departure, arrival, approach, or en route segments of a flight. PBN procedures are commonly built to be flown by aircraft equipped with GNSS capability.[13]

The PBN system provides *absolute navigation* in that the aircraft operates by first determining its present position in terms of latitude and longitude and then where this

[12] The GNSS is a satellite navigation system for aircraft, akin to GPS for automobiles. Modern satellite systems incorporate glass LCD displays with moving color base-maps that are generally more pilot-friendly and accurate than navigation with reference to ground-based navigation aids. Aircraft positions derived from GNSS have a high level of accuracy that remains precise and constant with distance from the source of the signal, i.e., everywhere.

[13] Aircraft with alternative types of equipment, such as ground-based distance measuring equipment, may also use PBN. There is a choice of navigation sensors and equipment that can be used to meet the performance requirements.

position is in relation to the intended flight path. In comparison, conventional ground-based radar provides *relative navigation* where the aircraft position is identified relative to navigation aids. As the aircraft can determine its current position under a PBN system, it can operate anywhere that the positioning system will operate. This gives PBN a major advantage of flexibility compared with traditional navigation. In these systems the emphasis is on three-dimensional (3D) and four-dimensional (4D) flight trajectories.[14]

PBN encompasses two types of navigation specifications: required navigation performance (RNP) and required area navigation performance (RNAV).[15] RNP requires on-board performance monitoring and alerting capability that enables aircraft to remain within the acceptable navigational parameters and notifies flight crew if a deviation occurs (Jaffe, 2015).[16] RNAV is similar to RNP but without added monitoring and alerting capabilities. Area navigation systems often integrate several sources of navigation information to provide highly accurate navigation solutions. The monitoring and alerting capabilities of RNP allows aircraft to fly more precise flight paths than RNAV.

PBN allows an aircraft operator greater freedom to plan the route of a flight from entry to exit point within a given airspace region without regard to the fixed airway system or other constraints (Jaffe, 2015).

Automatic Dependent Surveillance—Broadcast

ADS-B is a surveillance system for monitoring and transmitting an aircraft's identification, position, altitude, airspeed, and intent (whether the aircraft is turning, climbing, or descending) to air traffic controllers and to other aircraft.[17] The system uses GPSs to determine aircraft position, and either ground stations or satellites (space-based ADS-B) to transmit this information to ATCCs or other aircraft (Maris and Weigel, 2006). ADS-B requires aircraft to be fitted with an ADS-B capable transponder. ADS-B enables aircraft tracking by air traffic controllers and in-flight by pilots, without the need for conventional radars.

The ADS-B system is based on the ability of the aircraft to periodically and automatically broadcast a set of data. The new communications technology makes more use of satellite data link communications instead of very high frequency (VHF) and high

[14] Three-dimensional (3D) trajectories involve latitude, longitude, and altitude, whereas four-dimensional (4D) trajectories include the additional dimension of time.

[15] The specification of standards associated with RNP and RNAV refers to the tolerances for system error and varies with the phase of flight. For example, RNAV1 requires a total system error of not more than 1 nautical mile for 95% of the total flight time. RNAV1 is typically used in the terminal environment. RNAV2 requires a total system error of not more than 2 nm for 95% of the total time. RANV2 is typically used in the en route environment. RNP specification values also refer to 95% accuracy values.

[16] In an aircraft utilizing a stand-alone GNSS, RNP is achieved through the use of Receiver Autonomous Integrity Monitoring.

[17] There are two broad types of ADS-B equipment for aircraft; they are ADS-B Out and ADS-B In. ADS-B Out uses on-board avionics to broadcast an aircraft's position, altitude, and velocity to nearby aircraft equipped to receive the data via ADS-B In and to a network of ground stations, which relays the information to ATC displays. ADS-B In–equipped aircraft allows pilots to receive traffic information directly to the cockpit. Real-time weather and other aeronautical information can also be received if aircraft have the equipment (such as a Universal Access Transceiver) (US FAA, 2016).

frequency voice-based radio communication systems. Its principle is to send as many reports as possible to receptors[18] able to capture the signal (Rodrigues et al., 2012).

Aircraft equipped with ADS-B have greatly improved situational awareness and increased safety. ADS-B allows pilots to see other aircraft around them, avoid bad weather and terrain, and receive flight information, such as temporary flight restrictions. Transitions to more fuel-efficient flight levels are easier and faster.

The introduction of an ADS-B system does not produce major benefits until all aircraft, or a large percentage, in an operational area are equipped with ADS-B avionics (Rodrigues et al., 2012). Aircraft traffic in signal range, but not equipped with ADS-B equipment, will not be able to receive and process broadcast data and potentially not be able to avoid collisions unless alternative technology is also in use. ADS-B is currently used across continental Australia and is being progressively introduced in many other countries.

Space-Based Automatic Dependent Surveillance—Broadcast

Space-based ADS-B is a system of (ADS-B)[19] on a satellite constellation, which is expected to be available from 2018. Spaced-based ADS-B uses space-grade receivers on a second-generation satellite constellation (Aireon, 2017). Space-based ADS-B will provide ADS-B surveillance from a single, global system. ADS-B coverage can be extended over oceans, mountains, remote areas, and polar regions to provide real-time visibility of ADS-B equipped aircraft anywhere in the world. The system is being developed by Aireon a partnership involving a group of ANSP and Iridium Communications. It will use the Iridium NEXT satellite constellation.

The adoption of space-based ADS-B is expected to involve a step change in improvement to aircraft safety for oceanic operations (Flight Safety Foundation, 2016; Robyn and Neels, 2017). ANSPs who adopt the system will be able to provide surveillance in areas where currently no surveillance exists, augmented surveillance (filling in gaps or providing an additional layer of surveillance) for existing ADS-B, or radar surveillance systems and contingency surveillance for ground systems.

In addition to the ANSPs already involved in the Aieron partnership (Nav Canada, ENAV, the Irish Aviation Authority, and Navair), Malaysian Airlines, Isavia[20] (Iceland), and the Civil Aviation Authority of Singapore[21] have signed agreements to provide space-based ADS-B surveillance-broadcast services when it becomes available. Malaysian Airlines plans to move away from radar by adopting the Aireon space-based ADS-B system when it becomes available enabling the airline to have seamless

[18] There are a relatively greater number of signals than from radar-based systems.

[19] ADS-B involves the following components: Automatic—the system transmits information without pilot and ATC input; Dependent—the position and velocity information transmitted is reliant on the global positioning system (GPS); Surveillance—it provides a method for determining various aspects of the aircraft's position and intent; and Broadcast—the transmitted information is available to anyone with suitable receiving equipment.

[20] See Isavia Signs Agreement to Deploy Space-based ADS-B, January 18, 2017. https://aireon.com/2017/01/18/isavia-signs-agreement-deploy-space-based-ads-b/.

[21] See Carey, B., 2017. Singapore, Aireon Sign Agreement for Space-based ADS-B, http://www.ainonline.com/aviation-news/air-transport/2016-02-17/singapore-aireon-sign-agreement-space-based-ads-b.

real-time global tracking of its aircraft including in areas where regional ANSPs do not have full surveillance (ETB Travel News, 2017; Grossman, 2017). This would be a significant improvement in flight safety although there is no guarantee that the system would have helped in the case of Flight 370.[22]

Traffic Collision Avoidance Systems

Traffic Collision Avoidance Systems involve equipment fitted to an aircraft that warns a pilot if the aircraft is at risk of a collision with another aircraft and provides advice on the resolution necessary for the pilot to avoid a collision (Australian Government CASA, 2016).

Continuous Climb Operations and Continuous Descent Operations

Departure and arrival routes at airports based on conventional navigation require intermediate level-offs or "step-down" approaches. This navigation method together with the spacing required between routes is a source of inefficiency. The level segments increase fuel burn since they generally take place at suboptimal altitudes.[23]

New procedures based on PBN allow the number of level segments to be reduced or for continuous climbs and descents to be implemented. The procedures require advanced synchronization and separation of air traffic and depend on traffic densities in terminal airspace (Eurocontrol and FAA, 2016).

Continuous descent operations is an operation in which an arriving aircraft descends continuously to the greatest possible extent, by employing minimum engine thrust before the final approach fix (Eurocontrol, 2016c). Continuous climb operations (CCO) is where an aircraft is able to climb to its optimal cruising height without having to stop at various levels in-between (UK CAA, 2013). The extended arrival management operations (XMAN) system involves the establishment of the arrival sequence much earlier than conventional approaches, leading to speed adjustments 150–250 nm away from the arrival airport (Jaffe, 2015). The use of XMAN facilitates continuous descent approaches at major airports improving flight efficiency and reducing fuel emissions.

These arrival and departure systems enable minimum thrust settings reducing fuel emissions and increase airport accessibility (Jaffe, p. 69). Flight departures, arrivals, and approach paths can also be optimized using satellite systems, so that aircraft noise can be minimized and there is some flexibility in the placement and spread of residual noise.

The United Kingdom has introduced the possibility of a continuous climb from departure to cruising altitude at some airports[24] (UK CAA, 2013). The complexity of the airspace design, including the close proximity of other airports, is a factor that can require the need for aircraft to level off. Additionally, the need to deconflict with another aircraft trajectory and the need to avoid airborne holding stacks are factors that limit the use of CCO.

[22] Flight 370 disappeared in March 2014 when it flew out of satellite range and the plane's location transmitter went dead—with a chance it was intentionally shut off (Grossman, 2017).

[23] During descent the impact on fuel efficiency is generally higher because additional thrust has to be applied to fly level (Eurocontrol, 2016d).

[24] This is dependent on the aircraft's own configuration and performance capability and being cleared to do so by an air traffic controller.

Information Management and Collaborative Decision-Making

Programs are being developed to improve data management between ANSPs and to achieve greater integration of ATM, airports, meteorological services, and airline operations through information and data sharing.

System wide information management (SWIM) is an information management concept for sharing data between ANSPs automatically through a common information model. The program aims to provide more cost-effective and flexible communications to facilitate ATM decision-making and increase system performance (ICAO, 2016b). Through centralized data provision, data available to one ANSP, such as airport operational data, the position and speed of an aircraft, and weather information, would become available system-wide immediately to ANSPs participating in the system, instead of with the time-delays associated with the tradtional systems.

Information programs between ANSPs require strict governance arrangements for management and security of the data. For example, compulsory rules are needed to ensure stability and security of the system, traceability of the information, sanctions for infringements, and, in addition, a third-party liability regime.

Collaborative decision making (CDM) is a concept that involves information and data sharing between airport operators, aircraft operators, ground handlers, and ANSPs with the aim of improving operational performance of the separate participants involved in a flight process from one airport to another. The aim of Airport Collaborative Decision Making (A-CDM) is to improve the operational efficiency at airports by reducing delay, improving the predictability of events during the progress of a flight, and optimizing the utilization of resources and infrastructure (Airservices Australia, 2016b).

Remote Virtual Tower Services

Remote virtual tower technology allows air traffic services to be remotely provided through direct visual capture and visual reproduction. Remote towers use a range of advanced technologies, including high-definition, infrared, and pan-tilt-zoom cameras to provide visual surveillance augmented by available radar and flight data to deliver additional information in real time (Guillermet, 2017). The service is remote in the sense that the ATC service is provided by air traffic controllers located in an operational facility that is remote or separate from where the airport is located or not in a direct line of sight of airport runways. The new technology provides the level of detail and accuracy required for controllers to provide safe real-time ATC services to VFR and IFR traffic from outside a control tower with an out-of-the-window view of an airport runway.

Remote tower services can reduce the cost of providing air traffic services to small or local airports in regional and remote areas that have high running costs compared with the number of flights they handle. They are suitable for places where it is too expensive to build, maintain, and staff conventional tower facilities and services, or at airports where new services are being provided.[25]

Remote tower services are also useful for busier airports that are not geographically remote (SESAR, 2015). In some places such as in London, there is a need for contingency towers for any outages of the services provided by the tower. As remote tower

[25] See Air Traffic Management (2016).

technology incorporates advanced features, such as object tracking, motion-based alerting, infrared vision, digital image magnification, and hotspot monitoring, it has the capacity to provide operational resilience and safety assurance, should the primary tower be compromised. Additionally remote towers can address issues, including accessibility, training, and security, to deliver more resilience and a higher efficiency in degraded and other situations.

The world's first remote tower service was opened in Sundsvall, Norway, in 2014 providing service for Örnsköldsvik airport over 150 km away (SESAR, 2015). The IAA, Ireland's ANSP, has conducted trials in a live air traffic environment for remote tower operations for Cork and Shannon airports, to be provided from a remote tower center in Dublin (Kearney, 2017).

The "Sectorless" (Flight-Centered) Air Traffic Management Concept

The "sectorless" ATM concept envisages en route ATC without conventional sectors (German Aerospace Center, 2017). Under the concept one controller would be assigned to several aircraft regardless of their location and will guide these aircraft during their entire flight in upper airspace from entry to exit. A controller may give instructions only to the pilots of assigned aircraft. The aircraft-centered approach provides more flexibility and fewer handovers and enables user-preferred routes (German Aerospace Center, 2017).

Trials by the German Aerospace Centre have shown that the sectorless ATM concept is operationally feasible. However, its introduction is likely to be gradual and coexist with conventional ATM concepts before being applied to an entire airspace over a country or a continent (Birkmeier and Korn, 2014). Although the sectorless ATM concept is only in development phase, it is one of the building blocks for shifting to trajectory-based operations (Blondiau and Delhaye, 2017).

Comparison of Air Traffic Management Using Traditional Technology and More Advanced Satellite-Based Technology

A simplified comparison between ATM using traditional technology with ATM using advanced satellite-based technology is contained in Table 2.2. Although there have been important improvements in technology in recent decades, a considerable component of the global air navigation system is still limited by traditional technologies that developed in the 20th century (ICAO, 2016a).

Summary of the Benefits of Adopting New Satellite-Based Technology

The adoption of new satellite-based technology by ANSPs has a significant influence on the users of airspace. Operational features associated with the new technological systems, such as reduced separation between aircraft and the possibility of using more flexible route structures, generate a range of benefits, including increased airspace capacity, increased aircraft fuel efficiency, and travel time savings. These benefits are enabled because satellite

Table 2.2 **Comparison of air traffic management (ATM) using traditional technology and more advanced technology**

Feature of air traffic control	Traditional approach to ATM	ATM using advanced technology
Communications—Passing data and instructions between pilots and controllers and between control centers	All communications between pilots and controllers are conducted by voice radio. Pilots may have to change radio frequencies as they move along their route from a control center in one sector to another.	Routine communications between pilots and controllers transmitted as text messages—avoids frequency congestion and errors due to mishearing. Controllers' capacity to separate and manage air traffic is increased.
Navigation—Assists pilots to direct their aircraft along safe paths	Navigation is largely based on fixed ground-based beacons guiding aircraft along published routes via waypoints defined by sensor-specific beacons. Flight routes have to fly over ground-based navaids. This type of navigation is "relative navigation" since aircraft's position is always operating relative to the navaids.	Most flights can be "direct" based on a user's preferred altitude and routing without predefined airways. Routine separation between aircraft is automated. Air navigation infrastructure does not need to be placed directly beneath the area of sky aircraft fly through.
Surveillance—Confirming the location of aircraft	Primary radar tracks the movement of planes within a given block of airspace; secondary radar provides more specific information about each aircraft. Signals are received by the geographically closest radar and transmitted to the nearest air traffic control center, processed by mainframe computers, and displayed on controllers' screens.	Widely available global positioning satellite signals can keep track of aircraft locations with greater precision for terminal and en route navigation. Greater precision in the signals from satellites allows for reduced buffer zones separating planes in flight, increasing airspace capacity. Large-scale use of real-time information, facilitated by high-speed data networks, allows the possibility of remote ATM.
Air traffic flow management	Traffic flows to airports are based on "first come, first served." Congested airspace leads to midair holding patterns, reducing airspace capacity and increasing fuel burn.	Traffic flows can be managed at multiple airports through ground delays and other measures, increasing airspace capacity and reducing fuel burn.
Overall	ATM system is largely procedural—every movement requires specific permission from a controller.	Flights can operate to a greater extent on user-preferred routings, optimized for user preferences, such as minimized fuel consumption or shortest overall time.

Compiled by author based on information in ICAO, 2016a. Safety, Performance Based Navigation. http://www.icao.int/safety/pbn/Pages/Overview.aspx, Poole, R. Jr., January 2014. Organization and Innovation in Air Traffic Control, Reason Foundation, Policy Study 431. http://reason.org/files/air_traffic_control_organization_innovation.pdf, Poole, R. Jr., February 10, 2016. Review of ATC Reform Proposals, Testimony to House Committee on Transportation & Infrastructure. House Committee on Transportation and Infrastructure, United States Government Publishing Office, pp. 85–92. https://www.gpo.gov/fdsys/pkg/CHRG-114hhrg98580/pdf/CHRG-114hhrg98580.pdf, and other sources.

systems provide aircraft with the means of precisely determining their current position and can operate anywhere that the positioning system operates (UK CAA, 2016).

The replacement of ground-based technology with satellite-based technology implies that the need for fixed routes has diminished. The use of more flexible route structures in comparison with a rigid en route flight structure enables more efficient flight paths. Fuel burn and emissions can be reduced and flights can be synchronized to minimize or remove delays and optimize the overall flow of air traffic.

The adoption of new technology has different implications for different stakeholders and can result in significant imbalances in the distribution of costs and benefits across stakeholders and over time. Implementation of new technology involves an investment from the service provider (airport and/or ANSP), but it is the airspace user that often receives the largest benefits (CANSO, 2015). Major potential benefits that can be achieved by various stakeholders from the introduction of PBN are summarized in Table 2.3.

The Challenges of Adopting New Technology

There are significant challenges in adopting new technologies in ATM. The introduction of PBN, for instance, is a huge task involving input from a wide range of stakeholders (including ANSPs, airlines, airports, and safety regulators) as well as technological complexities (CANSO, 2015). In addition, new technology needs to be interoperable and a continuous air navigation service provided during the implementation phase.

A high degree of planning and coordination with industry stakeholders is involved in the adoption of new technology, in addition to securing the necessary financial resources for investment in new technology and acquiring regulatory approvals.

Planning and Coordination Required for the Adoption of New Technology

Interoperability

As air traffic is international, the adoption of new technology needs to take into account the ability of aircraft to transition from one country to another. It is essential that ATM systems can communicate effectively on a worldwide basis. Although aviation is an international industry, individual ANSPs are typically tied to a particular State. Interoperability between different technologies adopted by different ANSPs in different States implies that if the ATM technology is upgraded in one country, then it must still be able to communicate with legacy technology in other countries.

Continuity

ATM services cannot be interrupted; they must be continuous. A smooth transition from old technology to new must be assured so that the system operates continuously with extreme accuracy and reliability. If adoption of new technology requires new avionics in aircraft, then either all aircraft will have to use both the old and the new equipment, or the two systems will have to be operated together until all the aircraft have been reequipped.

Table 2.3 **Major economic benefits achieved from adopting new satellite-based technology (performance-based navigation [PBN] and ADS-B) for different stakeholder groups**

Stakeholder group	Major economic benefits derived from improved operational features
Air navigation service providers	• The ability of air traffic controllers to space aircraft more closely allows increased airspace capacity for a given airspace • The new technology generally involves lower levels of investment and is significantly cheaper to maintain than traditional ground-based radar
Airlines	• Improved operating efficiency through reduced fuel wastage from shorter flight tracks, optimized flight profile descents/ascents to/from runways, and from fewer diversions • More consistent access to airports at higher on-time rates reduces flight time variance • Improved safety due to more precise and reliable systems
General aviation	• Improved safety through weather and traffic information services for aircraft equipped with ADS-B technology
Airports	• Enhanced access to airports through PBN departure and arrival systems, including greater reliability of airport access under lower visibility restrictions • Reduced airspace conflicts between adjacent airports and prohibited or special use airspace
Passengers and air freight	• Enhanced safety • Shorter and more reliable flight times • Safer access to terrain and weather challenged destinations
Communities	• Reduced CO_2 emissions due to more direct and flexible routes and the use of lower thrust levels for arrivals and departures • Reduced noise because consistent, precise flight paths can be routed to avoid noise sensitive areas and optimized profile descents/ascents involve lower thrust levels • Increased safety through precise and reliable systems

Table derived from information contained in ICAO website. Safety – Performance based navigation ICAO (2016a) and Jaffe (2015).

Integration With Existing Systems

New technologies need to be integrated with existing systems within the technological systems architecture.

Resistance to Change

Organizational culture is an important factor affecting the ability of an organization to manage and adapt to change. ATC is closely governed by procedures, rules, and regulations, which do not promote a climate conducive to change.

> *In large rule-governed organizations operating in a high-risk environment such as nuclear power plants and Air Traffic Control Centres (ATCCs), a positive and innovative climate do not evolve easily.*
>
> *Arvidssion et al. (2006), p. 120.*

Furthermore, the fear of job losses and the loss of power of unionized air traffic controllers can be a factor impeding the process of new technology adoption in ATM (Breitenmoser et al., 2013).

Planning

The provision of air navigation services involving new technology requires long-term planning before implementation including coordination between stakeholders and infrastructure providers.

Gaining the most benefit from the introduction of new technology involves synchronization of the introduction of new technology on board aircraft and on the ground (Jaffe, 2015). The adoption of major technological changes to ATM typically means that airlines are expected to invest significant capital to equip their fleets for a future benefit. The network effects and interconnected nature of ATM technologies imply that the level of the benefits from the adoption of new technology will depend on the alignment of ground infrastructure, navigation and communication systems, and the regulatory environment (Oster and Strong, 2007).

Network effects associated with the adoption of ADS-B, for example, imply that the benefits to an airline of having an aircraft equipped with ADS-B are lower if adoption (or equipage) rates by other aircraft are slow. A substantial adoption of the technology is required to achieve financially significant delay reductions (Jaffe, 2015). Furthermore, benefits from the adoption of ADS-B will be limited if there is not a threshold level of ground infrastructure deployment by ANSPs, or if there are delays associated with the necessary ATC procedures and safety certifications. Because of these strong benefit network effects, airlines can face long delays between incurring the costs and receiving the benefits from ADS-B systems.

Testing and Contingencies

ATM planning includes managing the safe deployment of infrastructure. New surveillance techniques and applications need to be tested in simulations and in real scenarios.

In planning the use of satellite-based technologies, ANSPs need to understand GNSS vulnerabilities and put in place commensurate contingency procedures.

Transition Arrangements

There is a potential increase in ATC workloads associated with mixed navigation environments, where a proportion of aircraft operating in the relevant airspace are not able to adopt the new technology, and other aircraft have adopted the technology. This can be a particular issue in dense terminal area operations using differing approach and departure paths (CANSO, 2015). Furthermore, a mixed traffic scenario may lead to a reduction in capacity and so may not be appropriate during periods of airspace congestion. The support of the air traffic controller workforce in implementing major technologically based changes is important in integrating new procedures, such as PBN, with conventional procedures (CANSO, 2015).

Financial Implications of Adopting New Technology

Achieving the potential benefits from new ATM technology requires new investment programs carried out by the ANSPs, aircraft owners, and airports.

Modern avionics and navigation technologies have brought real efficiencies to commercial aviation (Jaffe, 2015). Although the benefits of increased capability (reduced delays and fuel burn) resulting from new technology are relatively easy to ascertain, others benefits (increased safety, noise reduction, etc.) are less tangible and harder to quantify.

There are increased costs associated with the adoption of new technology. Quantified direct costs include aircraft retrofit, redesign of airport airspace, and major airspace redesign. For example, the cost to commercial airlines associated with installation of avionic equipment required by ADS-B systems is an issue in the case of older aircraft that require retrofitting. Although the cost of equipping general aviation aircraft is substantially lower than that for commercial aviation, the costs may still be prohibitively high for many general aviation operators relative to average aircraft value.

Other costs include the necessary training, consultation processes, costs of certification, publication of procedures, and the additional costs associated with mixed-mode operations through the need to maintain the ground infrastructure (navigation aids) in a GNSS environment. Cost savings for ANSPs include savings in maintenance and other costs from retirement of ground-based navigation aids.

Substantial costs are incurred by ANSPs and, in addition, frequently by airlines for the required avionics. Some airline operators will be concerned about upgrade costs. A substantial proportion of the cost of investments in new technology will typically be paid for through air navigation charges to airlines and other users. As airlines bear significant costs associated with investment in new technology, gaining support for investment in new technologies will generally require convincing airline users that the services provided from new technology will provide demonstrable net benefits.

The Availability of Regulatory Resources

A significant part of the process of introducing new technology and procedures for ATM is the certification that they work adequately. Safety regulation and the development of safety standards occur at an international and national level (Chapter 5). Some countries do not have adequate resources for procedural design requirements associated with the technology, the training, the regulatory processes and expertise needed to approve PBN procedures and certify implementation of new technologies.

Major International Programs

New technologies have been implemented in stages around the world. Overall, technological innovation in air navigation services has generally been considered slow (Breitenmoser et al., 2013). Many airlines representatives complain that the current air navigation service technology is behind the current technological capability and modern aircraft have to minimize fuel costs and increase safety (Tomová, 2015).

Modern satellite-based ATM systems are being developed in North America and Europe, as well as in other nations. The two largest programs are the SESAR system and the US NextGen. Both SESAR and NextGen are developing and implementing new technologies that involve the wider application of satellite-based technologies to secure safety, economic, capacity, environmental, and security benefits. The two systems are not identical but are expected to align common equipment standards and to ensure technical interoperability (ICAO, 2009).

The SESAR program is a public/private partnership with principal members comprising the European Community, Eurocontrol, Thales, Airbus, Honeywell, and Alenia Aeronautica (SESAR, 2015). NextGen is coordinated by an Office within the US Federal Aviation Administration (FAA). The vision of these two major projects is to overhaul the existing ground-based navigation and communication systems and replace them with satellite-based four-dimensional infrastructure utilizing digital communication for real-time linkage with ATC, aircraft, and airline operation centers.

In the case of both programs the progress has been described as leading to an "evolutionary" improvement to the ATM operational performance. In Europe the adoption of coordinated approaches to new technology development and implementation is impeded by political and institutional difficulties associated with the large number of countries involved (Chapter 3). In the United States, reports from the Department of Transport, Office of Inspector General,[26] and industry experts[27] have been critical of the rate of progress in meeting the plans to modernize the US national airspace system.

[26] US, Department of Transport, Office of Inspector General, Audit Reports: FAA lacks a clear process for identifying and coordinating NextGen long-term research and development, Report No. AV-2016-094, August 25, 2016; FAA reforms have not achieved expected cost, efficiency, and modernization outcomes, Report No. AV-2016-015, January 15, 2016; FAA has not effectively deployed controller automation tools that optimize benefits of PBN, Report No. AV-2015-081, August 20, 2015.

[27] See National Research Council, A Review of the Next Generation Air Transportation System. Implications and Importance of System Architecture, May 1, 2015; MITRE Corporation, Independent Assessment and Recommendations, October 2014; and Poole (2014, 2016), for example.

Summary and Conclusions

ATM coordinates air traffic in airspace primarily through ATC and aircraft traffic flow management. CNS systems are the main technological infrastructure used to provide ATM. Traditional approaches to ATM have relied on rules and procedures and been supported by CNS systems that have relied on ground-based radar technology, such as primary and secondary radar systems, and voice radio.

Future ATM systems are moving to satellite-based technology and data link communications. New systems provide a wide range of benefits, including increased airspace capacity, increased aircraft fuel efficiency, travel time savings, and environmental benefits.

There are significant challenges in adopting new technologies in ATM. The adoption of new technologies involves different relative costs and benefits to different parties. The introduction of new technologies, such as PBN, is a huge and complex task involving coordination and input from a wide range of stakeholders (including ANSPs, airlines, airports, and regulators). In addition, new technology needs to be interoperable and a continuous air navigation service provided during the implementation phase. The development and implementation of new technology under the large technological programs in Europe and the United States has been slower than expected.

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