Module 4

AIR NAVIGATION SYSTEM AND ENVIRONMENTAL SYSTEMS

- The Air Navigation Services (ANS) are an essential part of the entire Air Transport System (ATS) where airport, airline and air navigation service provider (ANSP) are working close together as major stakeholders with different objectives and interests.
- The ANS is one substructure of the Air Traffic Services.
- The key responsibility of ANSP is to ensure seamless, safe and cost-efficient air transport flow of all aircraft on the airport and in the airspace.
- Communication, Navigation and Surveillance (CNS) are key technologies, which enable an efficient Air Traffic Management (ATM) among the stakeholders.
- However, only if the information about aircraft actual and predicted position is rationally processed and quickly distributed and shared among ANSP, airport and airline, better efficiency in terms of higher punctuality and infrastructural utilization as well as environmental indicators in terms of less emissions and lower noise impact can be achieved.

4.1 Principles of Operation — The Role of the Air Navigation Services

- The ANSP is the main stakeholder for ATM. It has to organize, monitor and control the air traffic in order to ensure safe and efficient flying.
- As public services they are governmental institutions, which are sometimes managed according to private law (e.g. German DFS, Swiss Sky Guide).
- Looking at Fig. 9.1 acquisition and information handling in form of management can be identified as key driving technologies, which influence the future progress in ATM.
- Three technology areas are of crucial relevance:
    - Management and organization of information flow
    - Networked communication systems which allow worldwide exchange of information between aircraft and ground stations as well as among aircraft only

- Systems to determine the position of aircraft either by onboard measurement or surveillance.

- For this purpose the ANSP as the air traffic control entity (ATC) has to control the air traffic flow and to manage the use of the airspace as shown in Fig. 9.2.
- Summarizing all these activities ATM is defined as the dynamic, integrated management of air traffic and air space, including air traffic services, air space management and air traffic flow management.
- ATM is intended to provide all necessary to inform (ATS), organize and coordinate (ASM) and control (ATFM) the aircraft before and during their flight through the airspace.

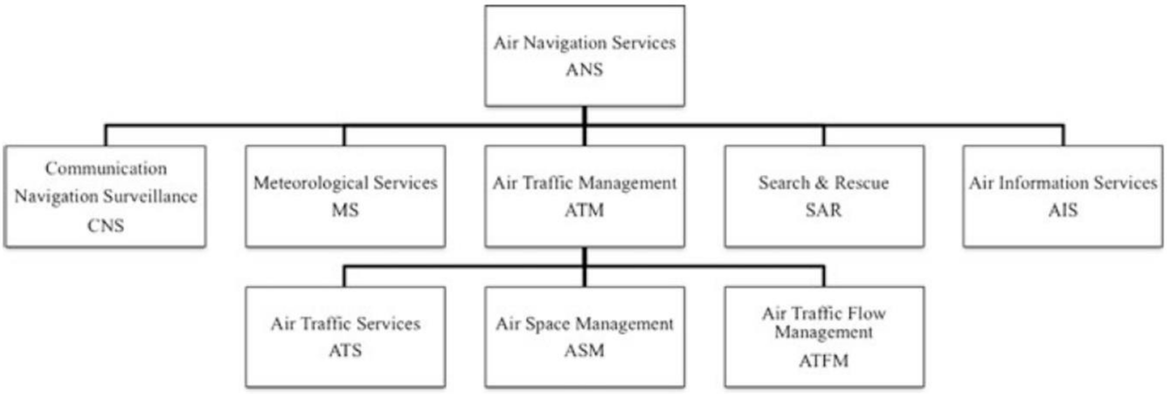


Fig. 9.1 Air navigation services

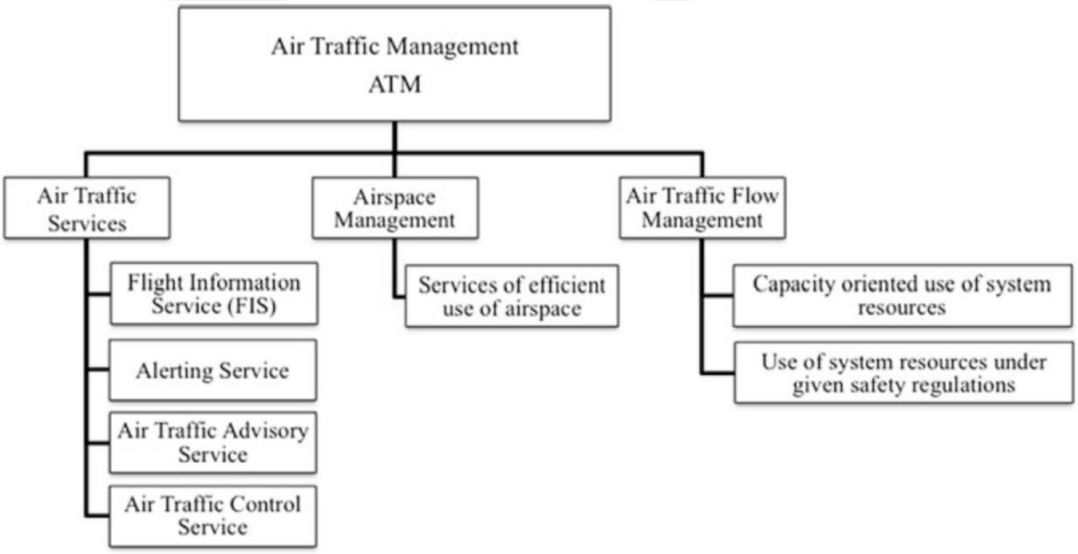


Fig. 9.2 Definition and structure of air traffic management, [2]

- the provision of flight plan information and approval before and during flight is one of the main tasks of the ANSP.

- Proposed flight plans are sent to the Central Flow Management Unit (CFMU) of Eurocontrol, which approves these proposals or gives advice for adaptions based on their global knowledge about the actual aircraft flow conditions in Europe.
- Before flight, for example weather information as well as the availability of air routes, sectors and airspaces is provided by ANSP as part of Air traffic services and Flight Information Services (FIS).
- Further, during flight the air traffic controller organize and guide the aircraft when they are passing various air space sectors. Here also the capacity-driven allocation of routes and aircraft through sectors is done.
- In order to ensure flight safety the ANSP defines and controls horizontal and vertical as well as timely minimum separation between controlled aircraft.
- The absolute distances between the aircraft are depending on the principle flight rules to be applied, which are distinguished between Visual Flight Rules (VFR) and Instrument Flight Rules (IFR).
- For visual flight the principle “see and avoid” applies. While for VFR minimum horizontal and vertical line of sight are required as well as minimum lowest cloud levels, IFR is performed assuming no visual orientation is given, but only cockpit navigation aids are given.
- Flying according to IFR therefore requires special additional equipment like the artificial horizon and radio communication aids, which in addition need to provide a high reliability.
- At controlled airports ATC is responsible for giving take-off and landing allowances as well as it controls the airfield movements of the aircraft.
- To fulfil all these tasks various regulations are set up by ICAO, which require to be transferred to the national level by the national air transport authorities.
- The ICAO document 4444 “Rules of the air and air traffic services” provides the set of regulations about structures, procedures and required systems to establish the ATM worldwide in a harmonized and very similar way.

4.2 Airspace Structures

- The airspace around the world is structured in a very similar way and normally
    - The horizontal extension is oriented along the geographical country borders.
    - Vertically there is no upper limitation.

- However for air navigation service purposes the airspace is vertically organized in an upper and lower airspace. The limits are defined on national level, e.g. in Germany the upper airspace begins at 24.500ft, also called flight level FL 245, while the lower airspace is below 24.500ft down to the ground (GND).
- In both airspace sections Flight Information Regions (FIR) are defined, which are characterized by special rules. For the lower airspace the regions are called FIR, while Upper Information Regions (UIR) are the corresponding definitions for the upper airspace.
- As shown in Fig. 9.3 the upper limits of various airspaces are varying and decreasing the closer the airspace is to the Terminal Control Area (TMA).

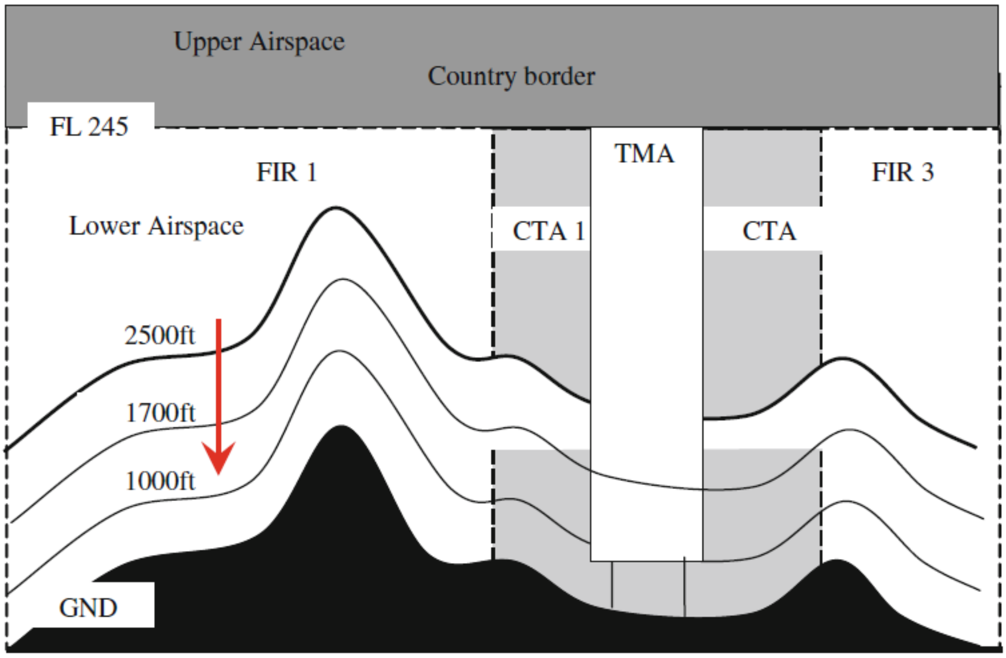


Fig. 9.3 Principle vertical airspace structure setup

- The principle set up of airspace structures in a horizontal representation is shown in the Fig. 9.4, where the German flight information regions (FIR, left) and European sectors (right) are presented.
- While the lower airspace has clear lower and upper boundaries, the upper airspace has only a limit for the controlled regions, which are established in Germany up to flight level FL 660. Above this flight level no controlled airspace and associated rules are established. However, this upper level may be different for various countries.
- The Control Area (CTA), which is a vertical and horizontal definition of a supervised area, and is segmented into radar sector responsibilities, which are supervised by an air traffic controller team of the ANSP.

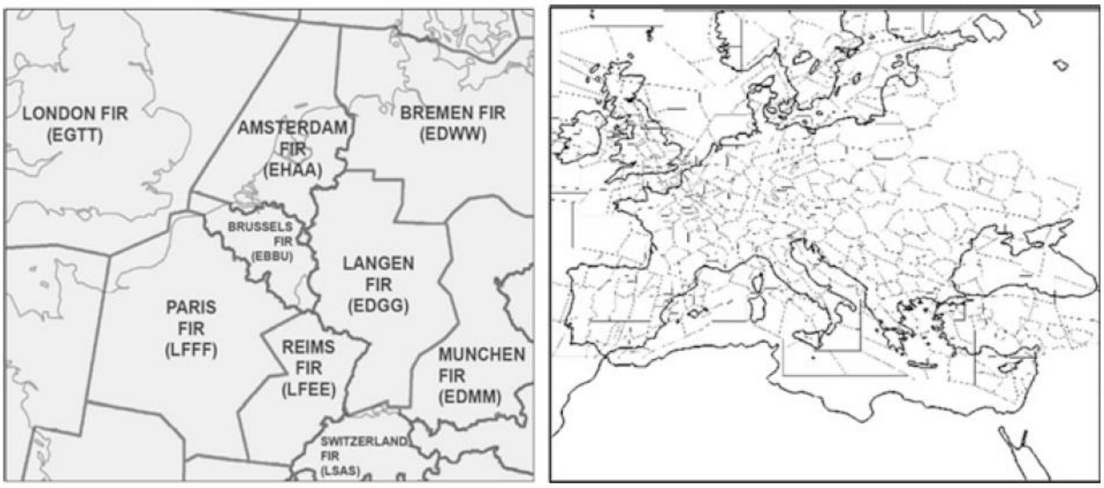


Fig. 9.4 Flight information regions in Germany and European sectors

- A special area within the FIR around controlled airports is called Control Zone (CTR), which is oriented along the runway directions, and TMAs.
- In order to ensure safe operation in such high traffic density areas the maximum speed is limited to 250 kts, in airspace category C for VFR flights below 10000ft and in category D also for IFR flights further the minimum visual sight is to be 5 km for Visual Meteorological Conditions (VMC). To enter such a controlled area, an explicit allowance from ATC is requested.

4.3 Airspace and Airport Capacity

- Capacity in air transport is the capability of a subsystem, e.g. an airport runway system, to handle a certain amount of aircraft in a given time window.
- Taking this principle into account, establishing a requested amount of people´s mobility in terms of passenger-kilo meter (Pkm) will lead to transport systems of either high frequency low payload vehicle operations or low frequency high payload vehicles.
- While the first provides more individuality and flexibility the later can offer more efficiency regarding energy effort and environmental compatibility, because for the same energy effort more people can be moved.
- For the development of future transport systems a tradeoff is to be made between this two fundamental approaches, which never exist solely but emphasis has to be given to more global objectives people want.
- Runway capacity is therefore depending on various influences like
    - Number of runways

- Runway dependency
- Amount and position of taxi ways
- Weather conditions
- Aircraft mix

- Based on these characteristics the maximum capacity of an airport or airspace is variable. Capacity is related to the demand of aircraft movements. This is different from the passenger demand for transport capacity on certain lags or flows. This passenger demand can be fulfilled by a certain amount of aircraft with a particular seat capacity. But also the frequency of flights is a measure to increase the transport capacity.
- In ATM the demand describes the request of airlines to operate a certain amount of aircraft on given routes at selected airports at certain time windows.
- For example in the early morning phase between 6:30 and 9:00 h there is typically a high demand for flights to bring people to business locations. A similar situation is given in the afternoon between 16:00 and 19:00 h when many people travel back. In between there might be a much lower request for air travel opportunities at a given airport. Therefore spare capacity is available.
- Capacity of an airport is mainly related to the throughput of airport runways. It is defined as the maximum amount of aircraft, which can take-off and land within an hour.
- When the demand for flights is higher than the defined service capacity, unacceptable delay rates arise.
- In order to make air transport as attractive as possible it is required to reduce the delay to a minimum but not necessarily to zero. As long as a delay can be forecasted it can be managed in either way. Therefore in the last years the term "planned delay" derived from railway transport has been proposed also for aviation.
- Airspace capacity covers any individual or aggregated volume of airspace. It relates to the throughput of that volume per unit of time for a given safety level.
- Network capacity is concerned with the overall network throughput taking into account the network effect of the airspace and airport capacity as a function of traffic demand patterns.
- The required average total capacity C_{tot} of a subsystem in the air transport infrastructures should fulfil the demand and provide some spare capacity to

compensate a limited amount of unexpected events within the considered time window:

$$C_{\text{tot}} = C_{\text{Demand}} + C_{\text{Spare}}$$

- It is very difficult to provide fixed values for the required spare capacity, because it is a tradeoff between the economical effort and the achievement of fluency of air transportation. As a rule of thumb C_{Spare} should be calculated as 5–10 % of C_{Demand}.

4.4 Aircraft Separation

- In order to ensure safe flight operation, there are binding rules for separating aircraft from each other, horizontal evasion rules are defined, which are very similar to those known from maritime sailing and car driving.
- Vertical separation also called altitude separation is based on flight levels, which are defined by barometric pressure height according to the ICAO standard atmosphere.
- Because the barometric pressure varies depending on local weather conditions two different procedures apply. For en route flight above a determined transition height of 5000ft every barometric altimeter of an aircraft is set to the 1013.25 hPa reference pressure.
- Although the use of relative pressure altitudes referencing to this more theoretical value implies significant absolute failures compared to the actual local barometric pressure, the procedure is quite robust and safe, because all aircraft in a local region have the same failure in its altitude measurement, but the relative failure and uncertainty among the aircraft altitude measurement is very small.
- If the real absolute pressure altitude would be constantly used, aircraft might reduce their altitude relatively to the ground, which may cause flight into the ground or collision with aircraft at different altitudes above ground, Fig. 9.8.

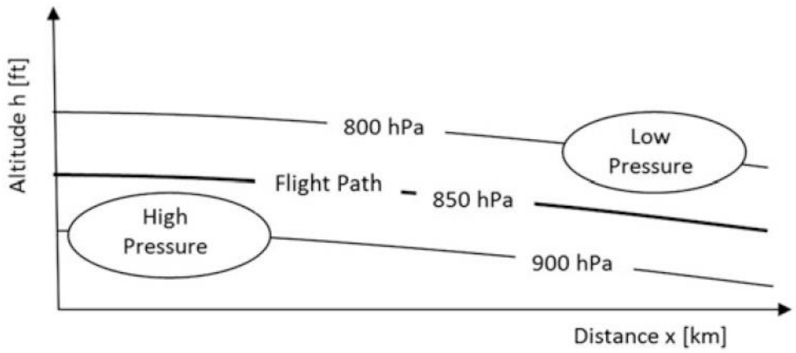


Fig. 9.8 Absolute altitude variation depending on continuous pressure level flight

- In general a vertical separation of 1000ft shall be kept. Exceptions are allowed to apply smaller separations of 500ft with the introduction of Reduced Vertical Separation Minima (RVSM). This is possible, if highly accurate position navigation and surveillance aids are used, like integrated navigation onboard systems.
- For the landing phase at a transition level of typically 5000ft ± 500ft between last flight level and the transition altitude the reference pressure is set to local airfield pressure to ensure, that the aircraft will not fly at a pressure -driven sink rate as shown in Fig. 9.8.
- Flying at constant pressure altitude would drive the aircraft to the ground, which causes severe safety risks, especially if a flight is going from high to low pressure areas and airport field elevation is above SL.
- Due to the introduction of Required Vertical Separation Minima (RVSM) in any case the vertical separation of 1000ft has still to be kept at altitudes above 5000ft.
- If no more precise Required Navigation Performance (RNP) of the navigation systems is given or RVSM operations are applied, 2000ft vertical separation has to be kept in the upper air space above 29000ft.
- In the case of horizontal separation two different situations must be considered.
  - First, generally aircraft shall follow each other in a time or range depending distance of at least 5 min or 20 nm if no radar surveillance is available.
  - Second, for wake vortex situations especially at ground proximity during approach and departure operations the aircraft mass is becoming the driving factor. Due to the pressure distribution on the wing at the aircraft wing tips wake vortices are induced containing much energy and cause heavy turbulences for subsequent aircraft.

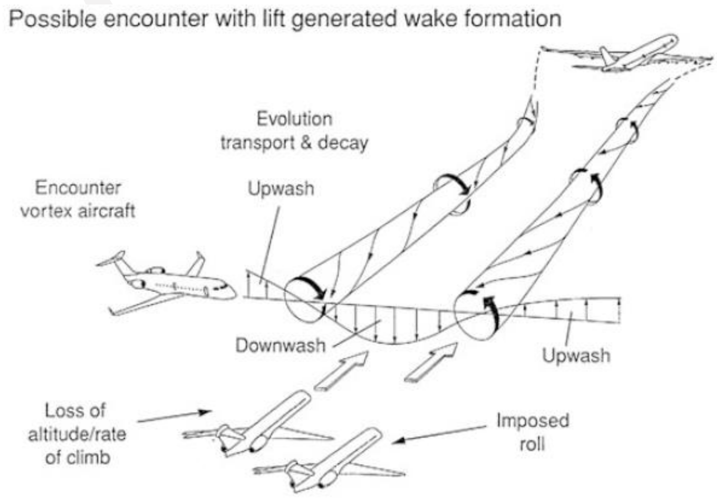


Fig. 9.9 Possible encounter with lift generated wake formation [7]

- Figure 9.9 shows the principle effect of wake vortex situations. The aircraft approaching nearly perpendicular from the left will experience a significant pitch down at the first wake and counter rotating pitch up at the right wake. A lighter aircraft flying directly behind a bigger one, will be pressed down or rotated by the departing wakes.
- In order to ensure safe flight operation, there are binding rules for separating aircraft from each other, “Area Control Services”.
- Additionally also horizontal evasion rules are defined, which are very similar to those known from maritime sailing and car driving.
- Vertical separation also called altitude separation is based on flight levels, which are defined by barometric pressure height according to the ICAO standard atmosphere. Because the barometric pressure varies depending on local weather conditions two different procedures apply.

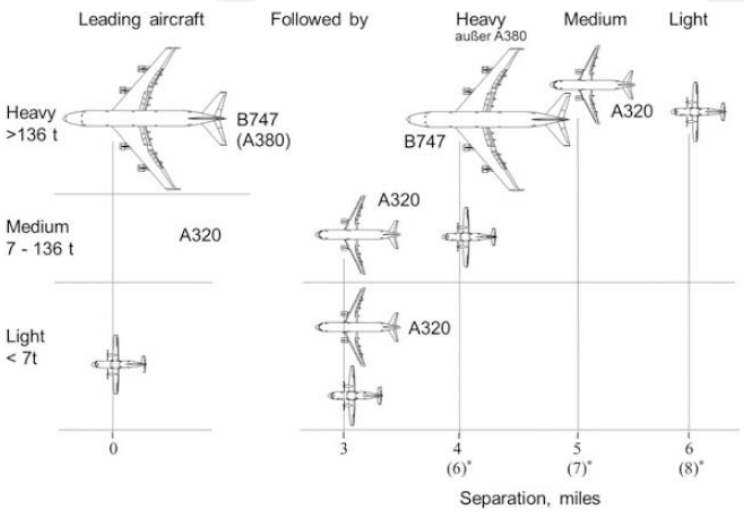


Fig. 9.10 Wake vortex separation minima between fixed wing aircraft [12]

4.5 Flight Guidance Systems

- Communication Navigation and Surveillance (CNS) systems are required to handle traffic flows safe and efficient.
- Relevant KPIs are defined in ACARE, e.g. increased punctuality, capacity and security but also reduced emissions. Only regarding CO2 emissions ATM is expected to provide the potential of 8–12 % CO2 emissions reduction.
- Here navigation systems can provide some improvements like
    - Shorter tracks due to higher accurate navigation performance
    - Increased onboard en route and approach accuracy independent from ground systems

  - Stable landing performance with more robust and reliable ground systems regarding maintainability/calibration and electronic perturbations.
  - Assured integrity and availability
  - High resistance to interferences and perturbations.
- Space-Based Augmentation Systems (SBAS) and Micro Electro Mechanical Systems (MEMS) are technology trends in communication and navigation, which provide significant potentials to achieve the objectives mentioned before. Especially, these technologies are also appropriate to use available and finally limited capacities in air space and at airports at its best.

4.5.1 Navigation Systems

- According to DIN 13312 navigation is every measure (observation, measurement and analysis) which determines a geographic location and/or the movement of an object or vehicle.
- Aside from fundamental visual navigation, in aviation navigation systems can be distinguished between
  - Radio navigation,
  - Inertial navigation,
  - Satellite navigation and
  - Integrated navigation systems.
- The following table gives an overview about the related systems from functional point of view (Table 9.2):

Table 9.2 Various navigation system types [2, 15]

Navigation principle	Navigation aid	Abbreviation
Radio navigation	Non-directional beacon, automated direction indicator	NDB/ADF
	VHF omnidirectional (radio) range	VOR
	Distance measurement equipment	DME
	Instrument landing system	ILS
Inertial navigation	Inertial navigation system (stabilized gyroscopic inertial platform)	INS
	Inertial reference system (captivated "Strapdown" platforms	IRS
Satellite navigation	Global navigation satellite system (GPS, GALILEO, GLONASS etc.)	GNSS
Integrated navigation	Flight management system	FMS
	Area navigation (integrated radio-and satellite-based navigation)	RNAV
	Precision navigation	PRNav

4.5.1.1 Radio Navigation Systems

Radio navigation systems are subsystems in the ANS substructure of the ATS. The most relevant systems are introduced with its main features in the following sections.

Distance Measurement Equipment:

- The Distance Measurement Equipment (DME) is used since the early 1950s of the twentieth century, standardized by ICAO.
- It provides the information about the transverse distance between the aircraft and the radio ground station.
- Its physical principle is based on runtime measurement, where the relative slope distance between the DME ground station and the aircraft is calculated,

$$R = c \cdot \frac{t}{2}$$

- Where c = 299.792.458 m/s is the speed of light and t is the runtime between sending out the signal from the aircraft and receiving the response from the DME ground station. In practice there is a system specific time shift of 50 µs introduced to the runtime signal.
- The transmitter unit on board of the aircraft, called interrogator, sends out the measurement signal, which is received and processed by the ground station (transponder). At the end the slope distance is measured, which implies some error concerning the intended horizontal distance measurement.

$$d = \sqrt{R^2 - h^2}$$

- The more the aircraft approaches to the DME ground station, the more the measurement error increases, i.e. when the aircraft is directly above the station, the measurement provides the height above the station, Fig. 9.11.

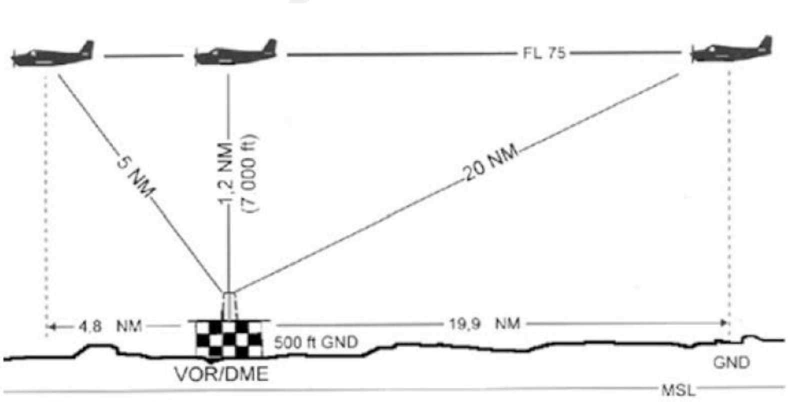


Fig. 9.11 DME distance and height error relation [2]

- Consequently, the error in distance measurement increases from 0.047 % at 360 km to nearly 20 % at 20 km.
- The accuracy of the DME is therefore limited by the combination of flight level and relative distance. Further the accuracy of the radio measurement is in the range of ±450 m related to target ranges of 200 nm. Due to the interrogation and respond principle of the system the maximum capacity of a single DME station is limited to 360 aircraft theoretically. In practice a lower amount of about 250 aircraft can use the station.
- DME stations are very often combined with VOR stations, which provide the corresponding relative bearing or directional information. Providing both type of information the precise aircraft position can be determined.

Very High Frequency Omnidirectional Radio Range:

- The Very High Frequency Omnidirectional Radio Range (VOR) provides a relative bearing information to the aircraft.
- Typically VOR stations are positioned along major traffic routs, and offer a measurement range of about 130 nm.
- Like DME stations also VOR stations are identified by an individual code, which is associated to the radio frequency of the station. The pilot has to set this code or frequency in the cockpit, when he wants to use the VOR station.
- VOR stations are also placed within the vicinity or directly on the site of airports, where their range is limited to approximately 25 nm. The accuracy of the system is about ±5.2° with conventional technologies. Using a Doppler-VOR the accuracy can be improved to 1°.
- Setting a fixed phase difference corresponding to the requested track allows course tracking to a VOR station, Fig. 9.12.

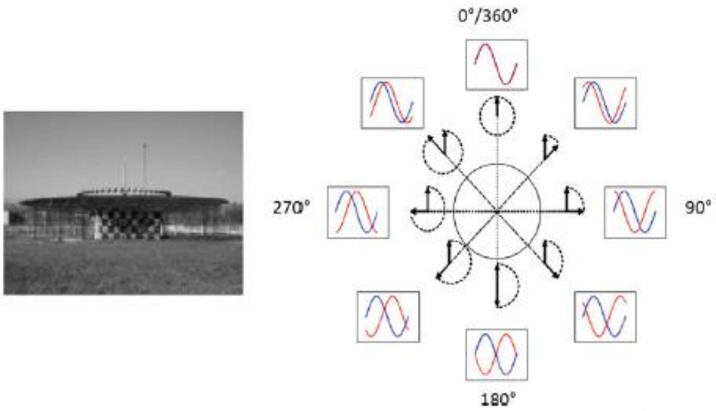


Fig. 9.12 VOR phase difference measurement for relative bearing and VOR antenna [2]

- In the cockpit specific displayed information either in an integrated display or in a separate device Course Deviation Indicator (CDI) like below is provided, Fig. 9.13.

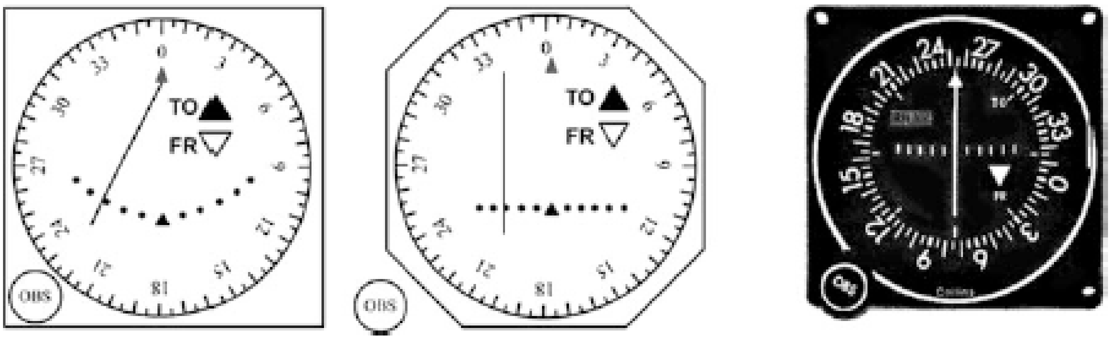


Fig. 9.13 VOR cockpit indication and course deviation indication (CDI) [2]

- The CDI also indicates, whether the aircraft flies To (TO) or From (FR) the VOR station. Very close to the VOR station also this radio navigation device has an error cone, which is called "cone of silence". Right above the station the onboard receiver does not get any signal information.

Non-Directional Beacon (NDB):

- A third radio navigation aid to be introduced is the Non-Directional Beacon (NDB), which is widely used since the 1930s of the last century.
- In combination with the onboard device called "Automatic Direction Finder" (ADF) this system also provides directional information.
- The operational range of the ground station is between 25–150 nm.
- NDBs are often used in the vicinity of airports, where they are widely used by airliners for cross-check or as "locators" for pre-visual clearance to an airport. Since
- NDB provides only horizontal directional information it is used as a Non-Precision-Approach device. Because it is not providing the direction, which the aircraft is approaching to and it is sensitive to interferences, the NDB cannot be used as a primary navigation device.
- Only in conjunction with the ADF installed on aircraft accurate directional information can be determined.

4.5.1.2 Satellite-Based Navigation

- In the 1970s, the American military services developed a satellite-based navigation system called Global Navigation Satellite System (GNSS) of Global Positioning System (GPS). This system became fully operational with 24 satellites in the 1990s.

- Similar systems have been established in Russia, called GLONASS and China, where it is named COMPASS. In Europe the GALILEO system is under development, which is intended to enter into service around 2015. All systems follow the same setup consisting of
    - a space segment, representing the satellites
    - a ground segment, used for controlling and supervising the satellites as well as for data transmission
    - a user segment, which is represented by different kind of civil and military users.
- Four satellites each are operating on at least six nearly circular trajectories at about 20200 km altitude. The resulting 24 satellites are required to ensure a worldwide coverage over 24 h, Fig. 9.14.
- Also four different satellites are required to provide the necessary runtime information to calculate the position parameters latitude, longitude, altitude and time.
- The fundamental satellite navigation formula is used to calculate the Pseudo Range. The term Pseudo Range describes the fact that the measured distances between the aircraft and the satellites differ from the true distances by a constant factor. This constant deviation is to be determined and corrected to calculate the true distance.

Fig. 9.14 General GPS satellite arrangement and pseudo range measurement

- If a high precision ground reference position is available, for example through a ground station close to an airport runway the accuracy can be improved significantly. Because of the accurately known position of the station, this information can be used to reduce the satellite runtime signal error.

- This method, also known as Ground-Based Augmentation System (GBAS) or Differential Global Positioning System (DGPS) has been used several times to improve the position calculation, when the less accurate civil GPS signal is used. GBAS is today the most promising way to achieve a level of accuracy and integrity to replace Instrumental Landing Systems (ILS).
- In a similar way, so-called Airborne-Based Augmentation System (ABAS) have been developed using Receiver Autonomous Integrity Monitoring (RAIM) or Aircraft Integrity Monitoring (AIM). RAIM uses internal monitoring algorithms to supervise the GPS receiver onboard of an aircraft. Those algorithms check regularly the correct functioning of the receiver components. The AIM uses onboard sensors like inertial sensors or radio navigation systems, to compare the GPS signals and to check the correctness and accuracy as major characteristics for the integrity of GPS.
- Space-Based Augmentation Systems (SBAS) represent a third type of supplementary systems, which have been installed by the United States (Wide Area Augmentation System, WAAS), Japan (Multifunctional Satellite Augmentation System, MSAS), **India (GPS Aided Geo Augmented Navigation, GAGAN**) and Europe (European Geostationary Navigation Overlay System, EGNOS).

4.5.1.3 Inertial Navigation

- Onboard navigation subsystems are to provide two main functions.
    - First, they have to deliver the critical control parameter like air data, attitudes, angular rates and acceleration.
    - Second, the aircraft positioning information like position, time reference and speed is needed to allow more accurate and safer aircraft guidance.
- Gyroscopes and accelerometers are known as inertial sensors because they are representing the property to resist a change in momentum. This principle is used to sense angular and linear motion.
- Due to this principle gyroscopes and accelerometers are essential as well for automatic flight control systems (FCS) as for spatial reference in navigation.

Gyroscopes:

- While formerly gyroscopes were mainly built as angular momentum gyros to date most of the gyroscopes are ring laser gyros (RLG). But also the Fibre Optical Gyro (FOG) has reached a high level of accuracy, so that this principle is often used for

AHRS due to cost reasons and less mechanical complexity. Both concepts use the time measurement principle to sense angular rates.

- Splitting a light beam the light running clockwise and counter clockwise through a path needs different time if the optical wire of the gyro is rotating due to external excitation.
- This principle is called “Sagnac Effect”. Because this effect is very low for low rates of rotation some kind of amplification is needed, to sense and measure also small rotations accurately.
- Compared to the FOG a RLG has the advantage of a very high reliability of 60.000 h MTBF (Mean Time Between Failures) and a very low drift. The weight of such an optical gyro is in the order of 450 g requiring 7.5 W.

Accelerometers:

- The translational movement of a vehicle is measured using the Newton’s principle by accelerometers.
- Over the year’s different types beginning with typical mass-spring devices and ending up with solid state accelerometers nowadays have been developed.
- Like for the gyro systems the tradeoff between required accuracy on the one hand and low manufacturing cost has to be made. Here simple spring-mass devices provide low cost but also low accuracy.

Table 9.5 Comparison of various navigation aids [18]

Navigation aid	NDB/ADF	VOR	DME	GNSS	INS	Doppler
Information	Direction to ground station	Direction to ground station	Slope distance to ground station	3D-position	3D-position	2D-position
				3D speed	3D speed	3D speed
					A/C state	
Range [NM/km]	200/370.4	200/370.4	200/370.4	10.799/ 20.000	n.a.	n.a
Max. user	Unlimited	Unlimited	200	Unlimited	Unlimited	Unlimited
Precision	1…5°	2°	0.1NM	100-300 m	1.5–2NM	0.5–1 % of flightpath
Reliability	Good	Very good	Very good	Very good	Fair to good	Fair
Basis	On ground	On ground	On ground	On ground	Aircraft	aircraft

4.5.2 Air Transport Surveillance

- In order to ensure a maximum level of air safety, which is one of the major ANSP tasks, Radar (Radio Detecting And Ranging) systems are used to control the airspace.
- For this reason, worldwide radar stations are distributed to observe the airspace and to control the air traffic flow.
- Nevertheless radar surveillance is limited to over ground areas as well as coast areas, due to the limited radar system tracking range.
- There are two different principles of RADAR systems used,
  - the autonomous or non-cooperative Primary Surveillance Radar (PSR) and
  - the cooperative Secondary Surveillance Radar system (SSR), which is based on a bidirectional communication between a ground station and the air vehicle.
- Both systems are used in parallel and the provided information is merged and displayed at the air traffic controller station. Here the aircraft position and additional objects like navigation stations, runways of sector boundaries are presented to provide best situation awareness to the controller.
- In the background of such an ATC controller display modern Radar Data Processing Systems (RDPS) are operated to process all incoming information. They calculate the forecasted aircraft position and place the symbol at the most probably expected position.
- In this context, the RDPS calculates on the one hand the measured aircraft trajectory, which is called "plot" and adds to this past time information the expected next position, which is called "track".
- In Fig. 9.17 the different information is presented, which is associated to the relevant aircraft.

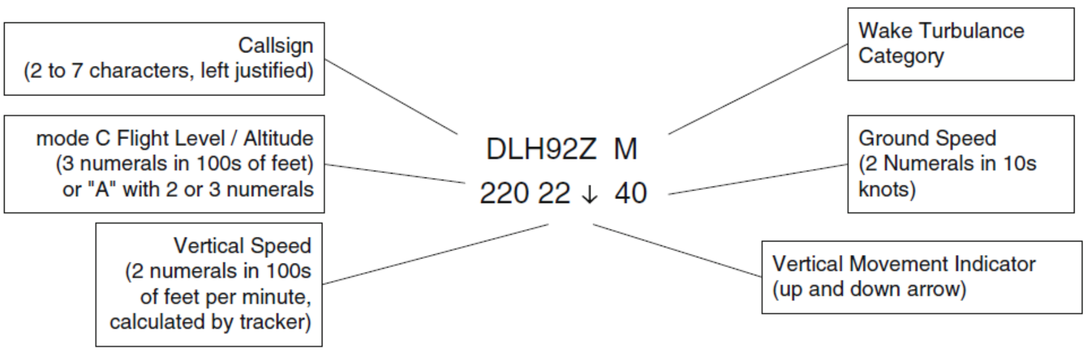


Fig. 9.17 Typical aircraft label on a radar display [20]

- Tacking the SSR-code data for the calculation of the aircraft track this information is correlated with the Flight Data Processing System (FDPS), which contains the flight plans of aircraft. The entire information is covered by the so-called aircraft label.

4.5.2.1 Physical Characteristics of Radar Systems

- Radar operates in a similar manner as the DME measuring the runtime of an emitted signal. While the DME only analyses the runtime itself, radar systems also use the reflected energy content of the signal. The reflection characteristics of objects can be used not only for detection but also for classification and identification of objects.
- This capability makes radar systems attractive for surveillance and identification applications on ground as well as onboard of aircraft. The following Table 9.6 provides typical reflection area characteristics of selected objects.

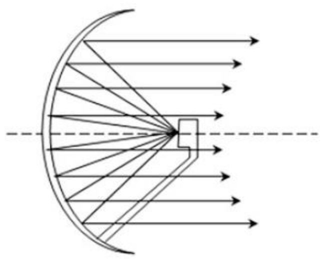
Table 9.6 Radar reflection characteristics of different aircraft [2]

Object	Max. cross section σ [m^2]	Min. cross section σ [m^2]
General aviation aircraft	10	5
Business jet	20	10
Transport aircraft	100	20
Fighter aircraft	5	0.3

σ = radar cross section, A = Area, λ = wave length, a = diameter

- By its nature the radar cross section σ describes the relation between the electromagnetic power reflected by the target to the power received by the target.
- For flat metal plates the radar cross section is not only depending on the area A but also on the wave length λ.
- The active reflective radar cross section is depending on the geometric size and form of the respective object and its material and surface characteristics.
- Due to the physical refraction of the radio waves from thinner upper atmospheric layers to the thicker ones, radio waves follow roughly the curvature of the earth.
- As a consequence the maximum detection range of radar systems is much longer than the detection range of optical systems, which allows the so-called “over the horizon targeting”.

Fig. 9.18 Collimation principle of radar beams



- Additionally also the ionosphere at 80–400 km has good reflection characteristics, which allows to extend the detection and transmission range of radar systems significantly.

4.5.2.2 Primary Surveillance Radar

- Primary radar systems (PSR) are active unidirectional surveillance systems, which send out electromagnetic signals, which are passively reflected by moving and fixed objects, Fig. 9.19.

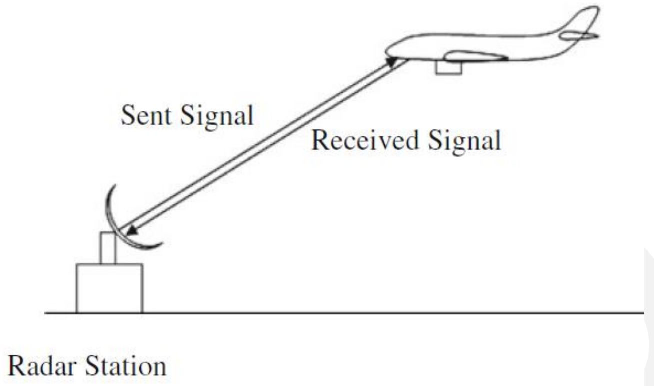


Fig. 9.19 Runtime measurement principle of primary radar systems

- Due to the passive reaction of the objects only their position is identified by signal runtime measurements.

$$R = c \cdot \frac{\Delta t}{2}$$

- Considering the speed of light of c = 2.99792458 × 108 [m/s] for signal transmission, the angular distance R between the radar ground station and the object can be easily calculated by measuring the runtime of signal towards and backwards to the object:
- Primary radar systems, working in a pulse mode instead of a continuous wave mode, are designed and used for different applications in air traffic surveillance. Depending on the required range and associated transmission power the following PSR systems are applied:
- **Airport Surface Movement Detection Equipment (ASDE)** used for airfield and runway surveillance at the airport with a range of about 2 nautical miles and 50 kilowatt pulse power typically at wave length 0.9–2 cm (K-Band).
- **Route Surveillance Radar (RSR)** is usually used for observation of air traffic control areas, which are at altitudes of about 50000–70000ft. Due to a typical range

of 120–150 NM, its transmission power is much higher at 1–5 MW using wave length of 23 cm (L-Band).

- **Precision Approach Radar (PAR)** running in the X-Band is used for supervising the precision approaches and landings on the glide path. Sometimes it is also used for so-called "Ground Controlled Approaches, GCA", where the controller gives verbal commands to the pilot to stay on the right glide path.

4.5.2.3 Secondary Surveillance Radar

- Secondary radar systems (SRS) which are also called Air Traffic Control Radar Beacon Systems (ATCRBS) are cooperative surveillance systems, where the aircraft transponder actively responds to interrogator signals of the ground station.
- Consequently this system works only if the aircraft is equipped with such a transponder. While the primary radar system provides the track information (direction and relative distance to the PSR ground station) of the air vehicle the SRS delivers encrypted the identity of the air vehicle, which is called Mode A and its barometric flight level information (Mode C) in 100 feet resolution.
- These are important information for the air traffic controller to guide the aircraft en route as well especially during approach and landing.
- Compared to the PSR system the SRS shows some differences:
  - The SRS can only be used with onboard transponders. If an air vehicle is not equipped, e.g. many general aviation aircraft or sailing planes, no information is available.
  - Due to the active reply of the onboard transponder no clutter, i.e. mal information is possible
  - Additionally the active reply reduces the signal energy loss to $1/R^2$ compared to the 2 ways $1/R^4$ energy decrease of the PSR.

4.5.3 Communication Systems

- Oral radio communication has played a paramount role in aviation over decades.
- Also to date it is an elementary communication media, which is now supported by data communication or so-called data link systems.

4.5.3.1 Voice Radio Communication

- Pilots and air traffic controller traditionally use radio communication systems in High Frequency (HF) and Very High Frequency (VHF).

- Due to an increasing lag of frequency resources the bandwidth of usable frequencies is more and more limited.
- Additionally the wave length of the VHF is limited in its range to about 150–200 nm, because a line of sight is required between transponder and receiver.
- For a rough estimation there is a relation between the range of the radio R in [nm] and the related flight level of the aircraft h [ft]:

$$R = 1.225 \cdot \sqrt{h} \qquad [\mathrm{m}]$$

- For a 10000 ft flight level, the achievable communication range is about 122.5 nm as an example.
- Another advantage of VHF radios is their ability to be used for direction finding, which is an additional safety feature.
- The controller can use the radio communication to identify a certain aircraft by voice and direction.
- Due to the range limitation of VHF radio systems also HF radio systems are used especially for oversea cruise.
- Like the radar systems HF radios allow the so-called "over the horizon" ranging, because they take advantage of the ionospheric reflection. This physical advantage is useful for communication over oceans or sparsely populated regions.

4.5.3.2 Data Link Communication

- There are various data link systems, which have been developed up to date. They use the VHF and HF radio transmission for operation.
- High Frequency Data Link (HFDL) uses HF radio communication for data transmission. It is appropriate for aircraft as a long range data link, which are not equipped with SatCom.
- Additionally HFDL is valuable redundancy for SatCom around polar regions, where SatCom has reduced coverage and performance.
- VHF data link (VDL) has been defined in four modes using VHF radio communication frequencies for data transmission. The modes define whether data and voice are transmitted point to point or broadcast.
- SatCom is a further data link subnet for ground—onboard communication. The key benefit is the worldwide coverage and accessibility. Based on different satellite systems it will become the backbone for the future integrated ATM System.

- Mode-S previously introduced as secondary radar and identification system is also used as a data link. Using four different modes up- and downlink communication and also point to point communication between aircraft is supported.
- Data links also provide service functions like transmission of maintenance information to speed up turn around or ground time or transmission of passenger check-in or rebooking data. They will become a valuable functional feature of future aircraft.

4.6 Integrated Air Traffic Management and Control Systems

- In order to extend air transport capacities and to improve efficiency in terms of punctuality and energy effort the ANSP and related industries develop integrated CNS-systems, which combine the performances of the individual systems.
- The Aeronautical Telecommunication Network (ATN) specified by ICAO integrates several data link technologies into a comprehensive network to combine the air-to-ground (Downlink), ground-to-air (Uplink) and air-to air communications.
- Since the 1990s of the last century mainly driven by military applications digital data links using the features of VHF and HF transmission have been developed to improve communication between aircraft and ATC.
- In civil aviation the Aircraft Communication Addressing and Reporting System (ACARS) has been developed. Due to the line of sight restriction a ground-based receiver/transmitter network is used to exchange all data. Thus ACARS can be used only over land mainly.

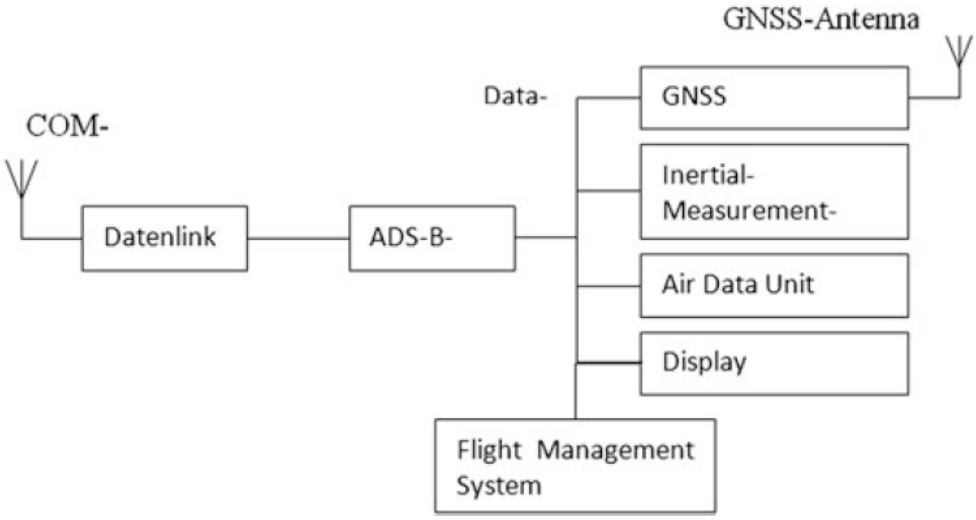


Fig. 9.20 System architecture of automatic dependent surveillance—broadcast, ADS-B

- The development of satellite-based navigation and communication systems has brought out the Automatic Dependent Surveillance-Broadcast (ADS-B) as a non-commercial successor of ACARS. It is a general purpose data-link-system using satellites as relay stations, which provide a worldwide coverage.
- Radar, navigation and data link systems are merged and integrated to ATM/C systems with the major objective to make data and information available to any air transport participant and any time. This is the main progress in ATM, guidance, navigation and control systems. For this purpose the concept of ATN has been developed.

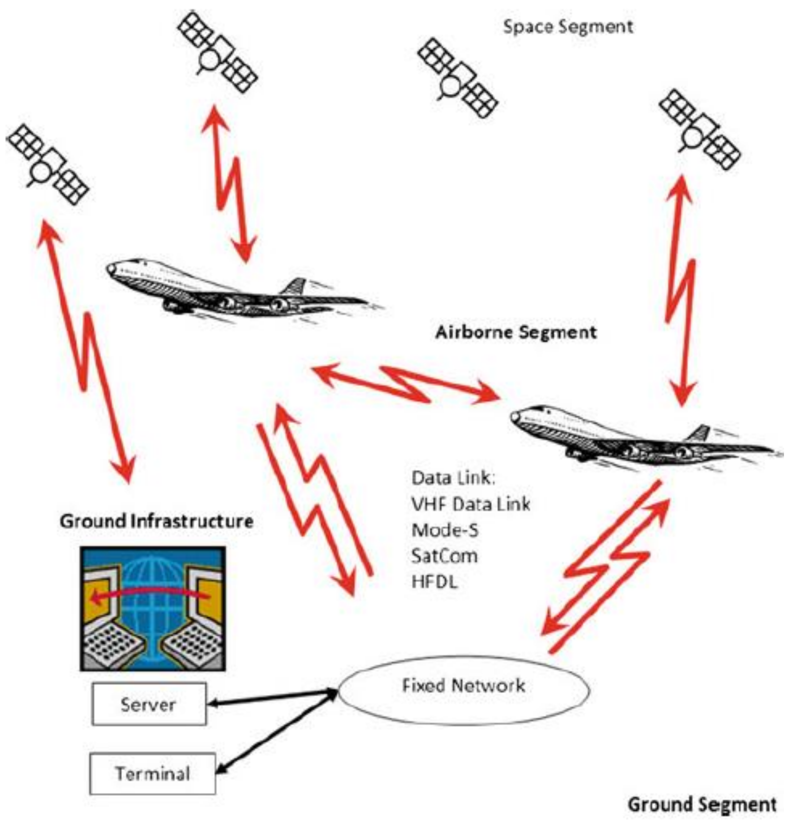


Fig. 9.21 Principle concept for Aeronautical Telecommunication Network (ATN)

- ATN will be installed to provide various services:
  - Next generation collision avoidance system based on ADS-B (Automatic Dependent Surveillance—Broadcast)
  - Controller—Pilot data link communications (CPDLC) replacing standard information communication by automatic data transfer to relieve VHF oral communication
  - Traffic Information Service—Broadcast (TIS-B) providing uplink air traffic situation information Flight Information Services—Broadcast (FIS-B) providing weather, departure and arrival information

- Ground-Based Augmentation System to improve satellite navigation-based position identification by providing ground correction data.

4.6.1 Multilateration (MLAT)

- Multilateration is a well-known method for position measurement, which has been used for long time with long range navigation systems like LORAN or OMEGA.
- Today the principle of multilateration, which is based on the so-called "time difference of arrival" (TDOA) is using data link signals like those of VDL, HFDL, Mode-S, or ADS-B. At least three ground-based reference stations are required, which calculate the time differences of the arriving data link signals.
- As a result 2 or 3D positioning is achieved, using existing onboard equipment in a different way.

4.6.2 Airborne Collision Avoidance Systems

- In order to install provisions to avoid "Mid Air Collisions" the ICAO has established regulations for Airborne Collision Avoidance Systems (ACAS).
- Technical solutions for those ACAS are realized as "Traffic Alert and Collision Avoidance Systems, TCAS".
- Two systems have been introduced and all aircraft with more than 5.7 t to takeoff mass or 19 passengers have to provide a TCAS II system, which not only gives warnings about aircraft in the vicinity ("Traffic Advisory") but it also provides recommendations for vertical evasion maneuvers ("Resolution Advisory").
- Technically those systems are based on the Mode-S transponder functions, where the course and altitude information of the responding aircraft are used by the TCAS system to track aircraft in the vicinity.

4.6.3 Terrain Awareness and Warning System

- Like ACAS mainly enforced by FAA a Terrain Awareness and Warning System (TAWS) has been defined to prevent aircraft from Controlled Flight Into Terrain (CFIT), which is one of the major causes for aircraft accidents.
- Those systems use onboard information like radar and pressure altitude, vertical and horizontal speed, as well as glide path deviation of an ILS and landing gear and flapping settings.

- Up to seven different modes are available to create warning, e.g. about exceeded sink rates, glide path deviation and also shear winds.

4.6.4 Interfaces between ATM and Aircraft

- In order to demonstrate the interfaces between all this elements Fig. 9.22 provides an overview about the principle architecture of these elements.

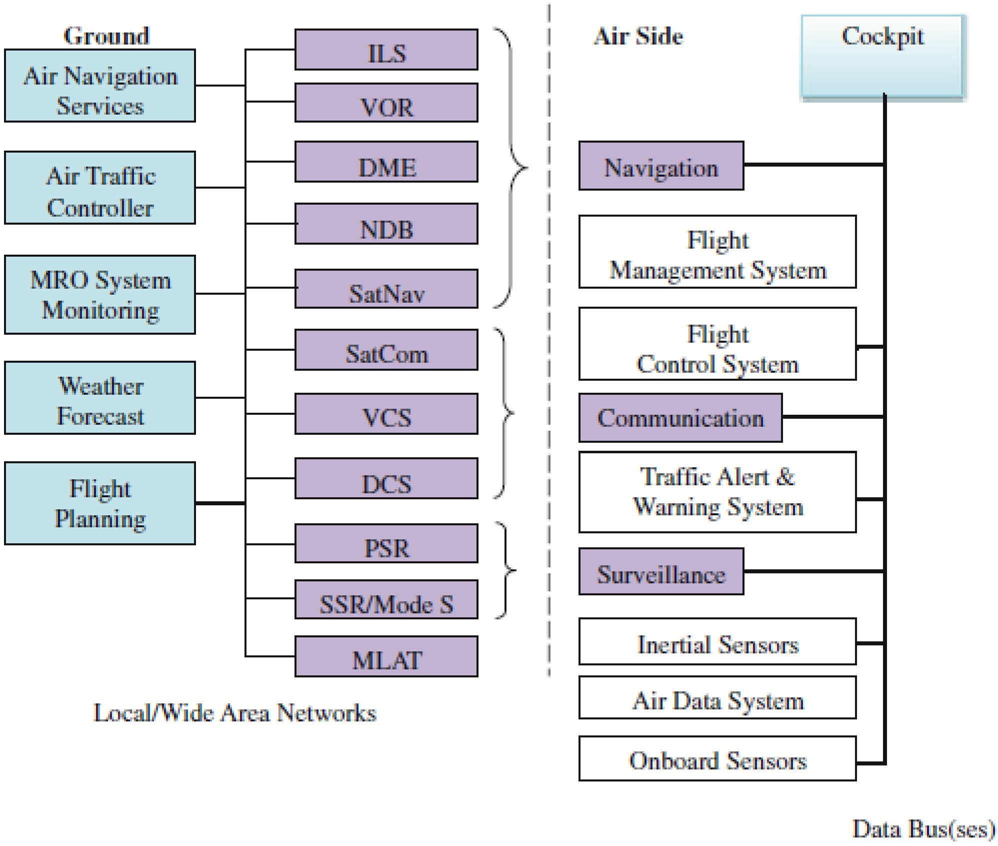


Fig. 9.22 Integration and interfacing air traffic management ground and air side

- Ground and air side of ATM cooperate through the provision, receipt and exchange of information provided by the various ground-based communication and navigation systems. Air Navigation Services provide and operate the different navigation systems like ILS, VOR and DME. They also provide radio communication systems like VHF and HF.
- The Air Traffic Controller and the cockpit crew use this information including weather forecast to coordinate and update the flight plan including the arrival and departure procedures.
- Maintenance Repair Overhaul (MRO) services based on data links are used by airlines and MRO companies.

- Navigation information is mainly used by the flight management system (FMS) to calculate the flight path and the related aircraft performance. This information is further used to feed the FCS, which automatically controls the rudder and flaps of the aircraft. For this purpose also the onboard inertial and air data sensors are used.
- The traffic alert and warning system (TAWS) uses this information as well and includes also the information of the cooperative secondary radar to calculate potential midair collision situations.
- The integration and interfacing of the ground and air side of the ATM infrastructures and processes is based on the cooperative principle, Fig. 9.22. This principle worked well during the last decades for civil aviation.
- During the early years of the twenty-first century unmanned air vehicles or systems called UAV or UAS became more and more relevant for military missions but also for aviation in general.
- The integration of those systems regarding coordinated navigation, communication and surveillance is a major challenge of research and development for the next decades.
- UAV/S are typically used for reconnaissance and surveillance missions. Especially military and industrial reconnaissance missions are intended, not to be detected and therefore are non-cooperative.

4.7 Environmental aspects – emission, noise and sound

- The airport's contribution to sustainable air transport covers a much wider range of aspects, starting with the energy effort for its buildings regarding heating, air conditioning and lighting.
- But also ground handling services, airfield lighting are issues to be addressed for sustainable air transport contribution.
- Also land use, herbicides and pesticides, which are used on airports to clear the airfield are elements of the environmental impact.
- But also the use of low pollutant deicing liquids as well as low emissions and noise during taxiing is important from airport's and airline's point of view.
- Guiding the aircraft safely through the airspace the air navigation service provider can support sustainable air transport especially with respect to noise abating approaches and departures but also by realizing shortest flight regimes.

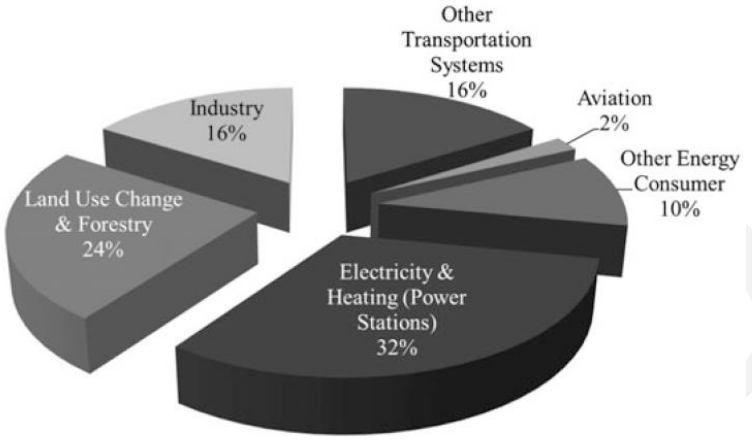
- During operational life maintenance and service activities like deicing or engine washing create pollutants too.
- At the end of the life cycle of an aircraft or any other technical system in air transport recycling becomes more and more a relevant issue.
- When technical systems reach their end of life, dismounting, separation and sustainable reuse of materials have to be considered.

Fig. 10.1 Environmental aspects of aviation

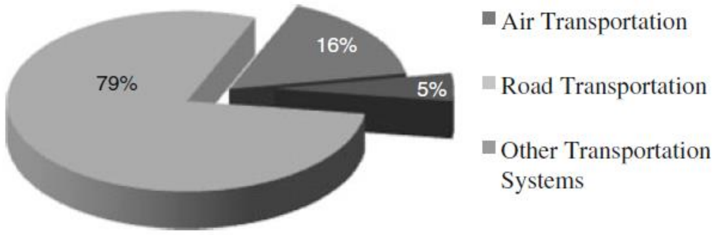
4.7.1 Air Transport Emissions Impact on the Climate

- The impact of anthropogenic emissions is a sensitive matter with many uncertainties and also a lot of political interests. There is no doubt that man-made emissions contribute to climate change.
- Since the 1990s of the last century, the Intergovernmental Panel on Climate Change (IPCC), which is the United Nations climate panel, reports continuously about the scientific knowledge on man-made climate impact.
- It has been observed, that the global average temperature raised about 0.8 °C during the last 150 years and due to the significant amount of especially CO2 emissions the IPCC prognoses further 2 °C increase during the next 50 years. Further climate sciences have recently discovered and documented in the latest IPCC report that aviation contrails may have a more relevant impact than CO2.

- There are also other investigations which relate the man-made emissions during the last 150 years since industrialization to the very long lasting climate behavior.
- As a conclusion those analyses conclude that man-made emission contribute less, than stated by the IPCC and the direct and indirect effects of the sun, take a larger share of the actual temperature increase.
- Due to the very complex mechanisms of the climate system, it is very difficult to come to a final assessment. It is therefore strongly recommended to look carefully at different perspectives and analysis.



Share of man-made CO_2 emissions [11]



Share of air transport NO_x emissions

- Transport and aviation together provide 18 % CO2, where aviation shares about 2 %. Therefore, transport or mobility as a major driver for prosperity and welfare is also a significant contributor to CO2 emissions.
- Although the portion of aviation seems to be fairly small, it needs to be considered carefully, because these emissions are occurring in unique form at high altitudes during cruise conditions at 10,000–12,000 m approximately.
- A similar situation is given for the contribution of air transport to the overall NOx emissions of transport. Also for NOx emissions, a share of about 5 % for air transport seems to be fairly small.
- But also in case of NOx emissions, the occurrence at high altitudes makes the effects on the atmosphere unique.

- For the understanding of the atmospheric impact of emissions, their dynamic geographic and time-depending behavior is of paramount importance.
- CO2 emissions cause a slow but long-term increase of temperature. The maximum temperature raise caused by CO2 is achieved later than 35 years after the pulse emission, while all other increases are reduced by more than 50 % at this point. This is what makes the impact of CO2 unique.
- While ozone, contrails and water lead to a short-term increase of temperature, ozone in the primary mode and hydrocarbons cause a mid-term decrease of the temperature, which turns to zero change after about 100 years approximately.

Table 10.1 Life time of emissions in the atmosphere [12]

Emission	Life time
Carbon dioxide (CO_2)	50–200 years
Methane (CH_4)	8–10 years
Ozone (O_3)	Some months
Water steam (H_2O)	Some weeks
Nitrogen oxide (NO_x)	Some weeks
Cirrus, contrails	Up to some weeks

- Road transport clearly dominates CO2 and Ozone creation, while aviation is the unique contributor to the creation of contrails and cirrus clouds.

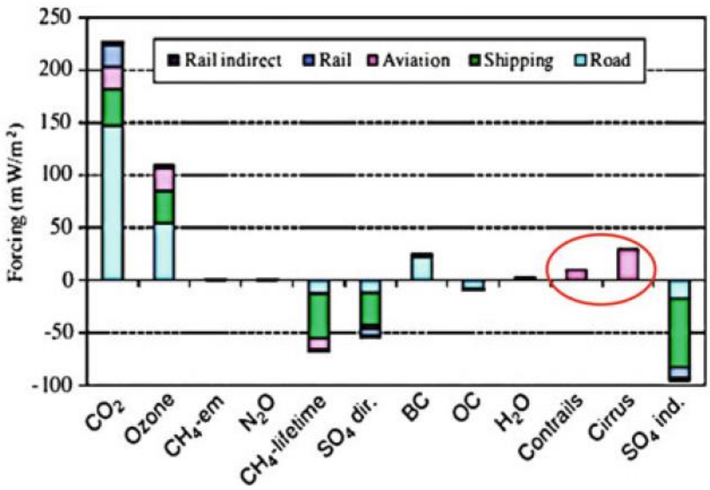
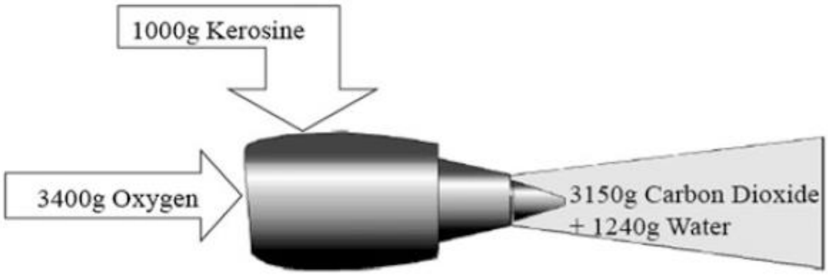


Fig. 10.4 Stakeholder relevance on the environmental impact of air transport [13]

Aircraft Emissions:

- Aircraft emissions are generated by engines. Nevertheless, the required thrust to be delivered by the engines is directly depending on the aircraft weight and the aerodynamic drag.
- Today, turbine engines dominate the world aircraft fleet as turbo-propeller or turbo-fan engines. Piston engines are used in general aviation aircraft and play only a minor role. For aircraft cruise conditions, Fig. 10.5 presents the principle combustion process and products of a turbine engine.



Further combustion products:

6-20 g	Nitrogen oxides (NO_x)	0,1g	Lubrication oil
1,5-10g	Carbon monoxide (CO)	0,03g	OH
0,2-3g	Unburned (UHC/HC)	0,01-0,03g	Sood (C)
0,8—1,0g	Sulfid (SO_2)	0,01g	Micronutrients
0,15g	Nitrous Oxide (N_2O)	0,0001g	Methane (CH_4)

Fig. 10.5 Principle chemical engine process and its products in aircraft cruise condition

- The chemical combustion process of a turbine engine in cruise condition based on 1000 g of kerosene and 3400 g of oxygen results in 1240 g water steam and 3150 g carbon dioxide mainly. Both components have a major impact on the radiative forcing (RF).
- Although constituting minor share nitrogen oxides, carbon monoxide, unburned HC, sulphides and sood are further combustion products, which need to be considered.

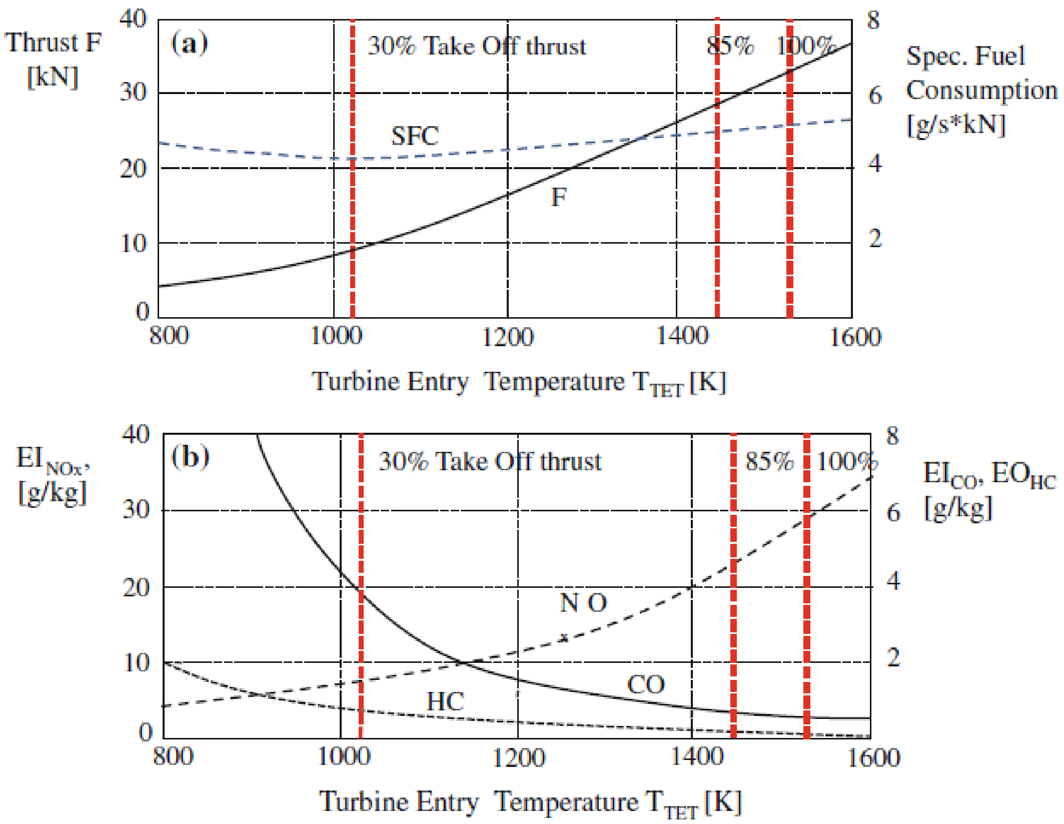


Fig. 10.6 Turbine entry turbine impact on engine thrust (a) and emissions (b)

- Looking at Fig. 10.6, the engine thrust and the resulting emissions depending on the turbine entry temperature are presented. Considering the Turbine Entry Temperature (TET) as an indicator for the engine power setting, one can see in the upper figure that the resulting thrust is following quadratic or nearly proportional behavior in a first approximation. Further the specific fuel consumption shows a minimum over a wider range of TET while it is increasing at lower and higher TET.
- Looking at the lower Fig. 10.6b, the more thrust is required, e.g. during takeoff, the higher the turbine entry temperature needs to be, the higher the nitrogen oxide generation will be in the combustion chamber, while HC and carbon monoxide decrease. In this context, emphasis should be put to the fact, that the absolute values for the emission indices (EI) for NOx are five times the value for CO and HC.
- Figure 10.7 provides an overview about the portion of different emissions in major flight phases.

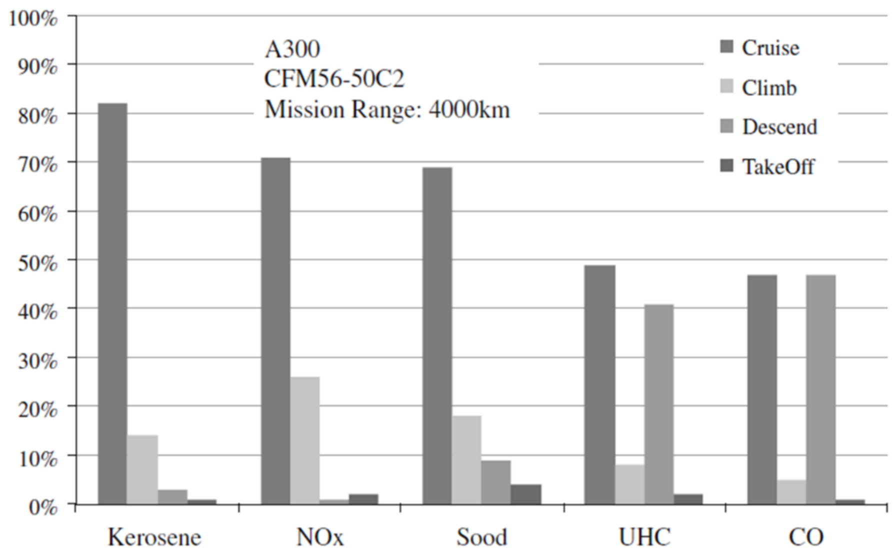


Fig. 10.7 Flight phase depending emissions [14]

Measures for Emission Reductions:

- In principle, three areas of measures are available to mitigate the emission impact. The first area addresses the overall air transport performance in terms of aircraft movements. In order to ensure people’s mobility, aviation is needed to connect the world on a global basis. However, people´s mobility can be realized by frequently operated smaller aircraft or bigger aircraft flying not that often.
- To avoid the so-called “Rebound Effect”, which describes, that saved energy, fuel or emissions of a given transport performance is used for increasing performance it is mandatory to limit the amount of aircraft movements worldwide, but to increase

the capacity of aircraft. Second, there are some technical measures to improve the individual climate impact performance.

- The improvement of engine's overall efficiency offers a potential of about 25 % achieved by reaching the physical limits of thermal and propulsive efficiency.
- Recuperation and intercooling elements improve the thermodynamic efficiency of engines leading to a reduction in the specific fuel consumption (SFC). On the other hand, these new components itself increase the engine weight, which must be compensated by lighter materials and design.

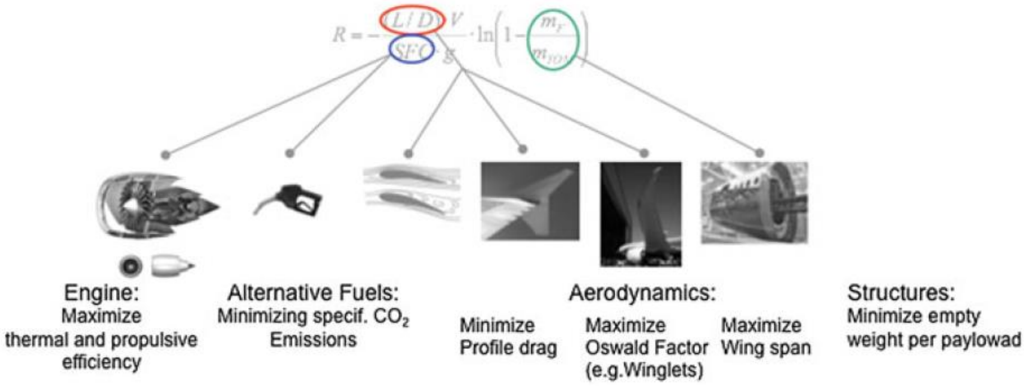


Fig. 10.18 Breguet-Formula showing technical potentials for emission efficiency improvements

- Looking to the current high bypass engines, a decoupling of the fan speed and the core engine shaft speed using an additional gear box improves the efficiency of the engine in terms of fuel consumption and emissions as well.
- Alternative fuels offer a range of 10–20 % of CO2 overall balance reduction, heavily depending on the feedstock used. Aerodynamics in theory can provide indirectly reductions in CO2 emissions of 20–30 % superposing all measures.

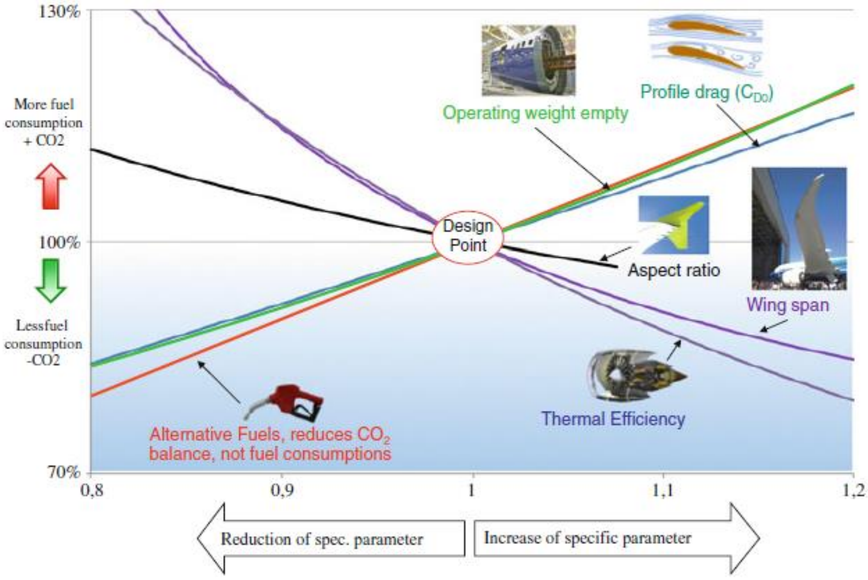


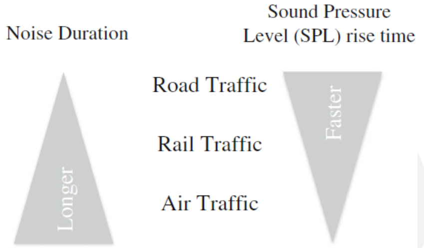
Fig. 10.19 Technology contributions to CO_2 efficiency of aircraft

- The introduction of various emission trading schemes (ETS) in Europe enforces the air transport community to reduce the CO2 emissions and represents an indirect regulatory measure to force the air transport industry to introduce emission reducing technologies. The actually stopped (2013) European ETS approach drives ICAO to develop a global approach to emission trading.

4.7.2 Noise and Sound of Air Transport

- Noise and sound are one of the most sensitive issues in air transport. Because the impression of noise and sound is very subjective, a common assessment is very hard to achieve.

Fig. 10.20 Acoustic properties of different transport systems



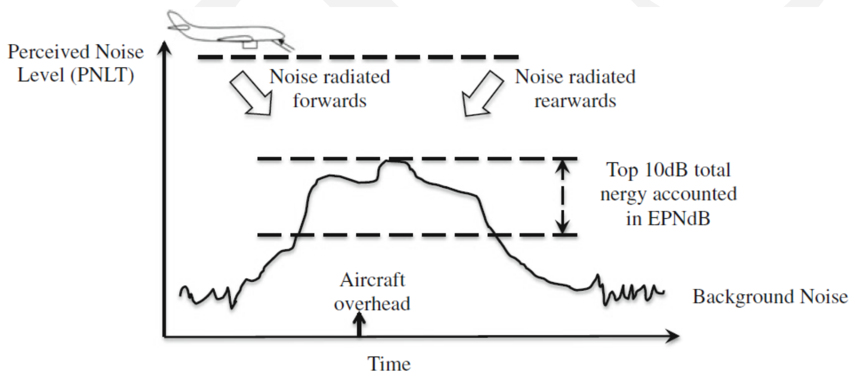


Fig. 10.22 Equivalent perceived noise level

- Looking at an aircraft, various sources of noise are given, which are mainly associated with the engines, the landing gear and the wing flap and slat systems, Fig. 10.28.

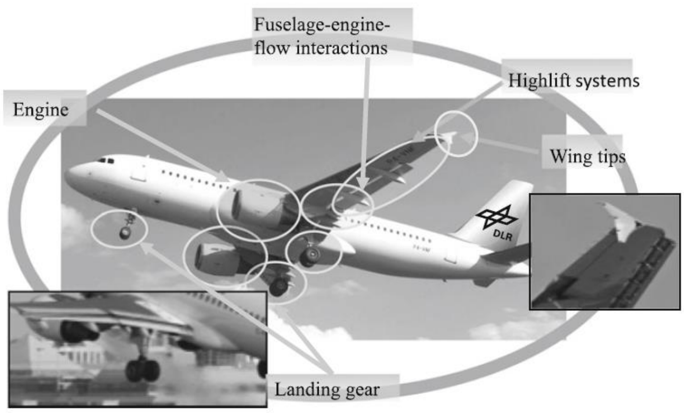


Fig. 10.28 Aircraft noise sources

- When we are talking about technical options for aircraft noise reduction, the source of noise is addressed. Here as previously mentioned, −50 % reduction is achieved, if the SPL at its source is reduced by −3 dB.
- Looking at the aircraft noise sources, the engine noise is predominant during takeoff and landing phases. At takeoff noise is created due to the full power setting by the fan outlet, the combustion and the turbine jet while the airframe contribution is significantly increasing during landing, when the landing gear and the high lift systems become more relevant. The engine is at a low power setting in this phase.
- There are various technical approaches to achieve lower noise creation levels at various sources. Although a single improvement may be not that much, the implementation of several solutions as a package can provide a significant reduction.
- Since the high lift systems, consisting of various flaps and slats is contributing most to the overall SPL, filling cavities and slats can provide remarkable reductions in aircraft noise, Fig. 10.30.

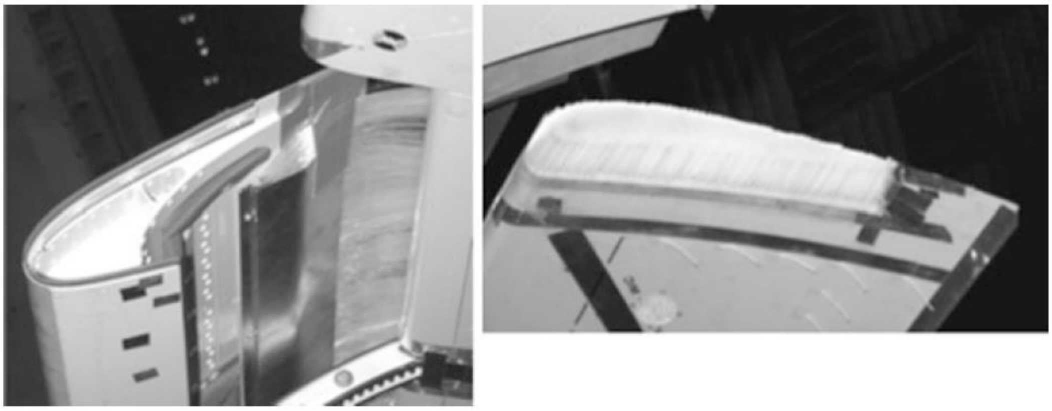


Fig. 10.30 Filling cavities and brushes to reduce noise, DLR [32]

- Research at the German Aerospace Center has shown that those simple measures, which close slots or cavities could reduce the source SPL by 3–5 dB, which means half of the original SPL.
- The principle is quite well known in bionics, where owls have a feathering, which closes slots as much as possible to fly quietly.
- Looking at the landing gear fairings provide the potential for about 3–5 dB noise reduction of the SPL, which means a reduction about 50 % recognized noise level. Here again closing slots and filling cavities creating smooth flow surfaces is the key to reduce the noise level.

- On engine side there are also pragmatic measures to reduce the SPL of the major components, Fig. 10.31.

Fig. 10.31 Engine noise reduction potential