A journey through aviation data

Xavier Olive Junzi Sun
Enrico Spinielli Manuel Waltert
David Gianazza

Table of contents

1.

This is the website for the book "A journey through aviation data", a project started by a team of **four aviation enthusiasts**, working in the field of aviation and sharing a common objective to share open knowledge about all what is available to analyse aviation data.

The purpose of this book is to

- recall **background knowledge** required to work with aviation data;
- present the most common **data sources**, API and formats;
- introduce computational frameworks that make it possible to **easily handle aviation related data**, with a focus on the Python, R and Observable languages;
- showcase **common data visualization frameworks** on usual applications;
- recommend **good practices to share new data, code and results**.

Read more about the motivation of the project in the **preface**.

Start reading Download PDF Download ePub

The book is **free of access and editable by the community**. Read more about how to contribute.

Preface

About a century after the invention of powered flight, aviation has slowly become a vital element of everyday life. While pioneers and flying aces build the collective imaginary around the early days of aviation, technical advances around surveillance systems, the use of radar in civil aviation in the 1950s, the generalisation of GPS for civil applications in the 1980s and the ADS-B mandate emerging in the 2000s make the use of data in aviation an interesting field of research for many disciplines. In particular, such effort has been justified by the historic growth of traffic from the early 2000s, and new challenges such as world-wide crises, pandemics or new unmanned technologies.

Aviation and air transportation are data-rich environments. At the very start of each aircraft, it comes with its own design information and performance data. During flight operations, it can collect several gigabytes of raw data per flight including trajectory data and sensor information. Beyond the aircraft itself, information regarding procedures, flight tables, surveillance states, and weather reports are also constantly being generated and aggregated.

Traditionally, open data has not been a well adopted concept in the aviation industry. The availability and sharing of data on a global scale and with a varied community of researchers and practitioners is limited. Such a lack of transparency hampers the industry as a whole, limiting its efficiency and sustainability.

In recent years, the open data philosophy is gaining ground within the aviation research community, primarily thanks to the wide adoption of Automatic Dependent Surveillance–Broadcast (ADS-B) technology. Data sharing within the aviation industry has also been identified as an enabler for a more rational use of resources. With lower cost of storage devices and more convenient internet access, large open data has become one of the strong foundations for researchers, and a gold mine of information for the passionate.

In such a Eureka moment in open aviation science, four aviation enthusiasts with different backgrounds come together and present this open book. This book presents the ecosystem of common data formats used in aviation. It takes the readers onto a data journey, with a strong focus on open access. With a little bit of programming knowledge and aviation background, this book also presents insights of data mining and visualisation techniques that convey a colorful story of aviation.

Who is this book for?

This book was written for graduate students, academics, scientists and analysts addressing data based aviation research. This includes questions related to aviation data science, aircraft performance, environment impact, economic analysis, and more. A basic set of skills in one programming language commonly used in data science is required: in its current form, the book covers Javascript, Python and R. The book will give the reader a comprehensive overview on common aviation data formats, data sources, and a decent command in the language of her choice to address data parsing, data analysis and data visualisation techniques.

> ! Who is this book not for?
>
> **Do not expect** to find in this book a crash course in Python, R or Javascript.

If you are passionate about aviation, some chapters may be of interest, but you should get proficient in basic programming to enjoy the full content.

How to get a copy of this book?

The book is designed as an online book, edited with TU Delft OPEN Publishing, and is made available online https://aviationbook.netlify.app/ all along the writing process. Stable outstanding versions will be tagged, marked with a DOI and made **freely and openly** available as web versions, printable PDF and ebook documents.

How is this book organised?

Part 1. Background knowledge about aviation

This part brings in the minimal background necessary to comprehend the aviation world, including vocabulary and historical aspects which led to the current situation.

Part 2. The ecosystem of aviation data

This part goes through all the most commonly used data formats in the aviation and ATM data analysis community.

Part 3. Process Data

This part introduces mathematical and programming skills. The tidy paradigm to manipulate data frames is introduced. Challenges associated with geometrical shapes, geographical coordinates, trajectories, projections are presented, before introducing common AI tools for information extraction, prediction and optimisation.

Part 4. Visualise Data

This part turns to the data visualisation aspects. It explains how to choose the most appropriate tool to convey a message with particular focus on geographical information.

Part 5. Share Data

The most overlooked aspect of data analysis probably turns around data sharing. Data curation is often a very time consuming process and enriching data by labelling specific tags or merging several sources of information brings additional value to a dataset. This part deals with the data sharing and publication process. (paper reproducibility?)

Table of contents

If you just found about this project, you may want to read the preface first.

Part I.

Background knowledge about aviation

2. A short history of aviation

Xavier Olive

Aviation refers to operations of aircraft in general. The word was coined in the middle of the 19th century, derived from the Latin word *avis* for “bird”. Historical records mention many legends of human attempting to fly in Greek, Persian, Nordic or Inca mythologies. Around the globe, deities with wings, feathers or other bird attributes appear, and men start to notice that even birds can stay afloat without flapping. In the 16th century, Leonardo da Vinci imagines flying machines in a secret manuscript of thousands of words and hundreds of sketches of an “ornithopter”, at the same period kites are imported from China and become popular in Europe.

This chapter attempts to draw a quick panorama over the history of aviation, focusing on heavier-than-air aircraft, until the digital age when data started to be produced and stored for further analysis. We split this chapter in several sections, matching important milestones in the history of aviations.

2.1. Flying machines

1783–1904

It all began in the late 18th century with the pioneering efforts of the Montgolfier brothers, Joseph-Michel and Jacques-Étienne, who successfully demonstrated the possibility of manned flight using balloons. On June 4, 1783, in Annonay, France, they launched a 9-meter-tall balloon with a fire underneath that heated the air, causing it to rise and lift the balloon off the ground.

Building upon the success of balloons, the concept of dirigibles or airships emerged in the late 19th century. Ferdinand von Zeppelin, a German inventor, took the lead in developing rigid airships. His creations, known as Zeppelins, featured a metal framework covered with fabric and contained multiple gas cells for buoyancy. The first fully controllable Zeppelin took flight on July 2, 1900, near Lake Constance in Friedrichshafen, Germany. This marked a significant milestone in aviation, showcasing the potential for long-distance travel and commercial applications.

Meanwhile, advancements in glider technology were also taking place. Otto Lilienthal, a German aviation pioneer, conducted extensive research and made over 2,000 flights between 1891 and 1896. Lilienthal's experiments with various wing designs and control mechanisms greatly contributed to the understanding of aerodynamics and the principles of flight. His work laid the foundation for future aviators, inspiring them to push the boundaries of flight further.

In France, Clément Ader, an engineer and inventor, made notable contributions to aviation history. On October 9, 1890, he flew the Éole, a steam-powered monoplane, which is considered one of the first attempts at powered flight. While the distance covered was limited, Ader's achievement demonstrated the feasibility of powered aviation and encouraged others to pursue similar endeavors.

The turning point in the history of aviation came with the Wright brothers, Orville and Wilbur. Inspired by Lilienthal's work, the brothers began experimenting with gliders in the late 19th century. Between 1900 and 1902, they built and tested a series of glider prototypes, refining their understanding of lift, drag, and control. They constructed wind tunnels to collect data and developed their innovative three-axis control system, which allowed for precise maneuverability. The lessons learned from these glider experiments provided the Wright brothers with invaluable insights into the principles of flight and set the stage for their next monumental step: in 1903, the Wright brothers achieved their groundbreaking accomplishment. They successfully flew the Wright Flyer, a powered aircraft, for approximately 12 seconds in Kitty Hawk, North Carolina. This historic flight is considered the first controlled and sustained powered flight in history.

2.2. The pioneer era

1904–1914

The period between the Wright Brothers' groundbreaking flight in 1903 and the following decade witnessed remarkable advancements in the history of aviation. While the Wright Brothers continued to refine their aircraft designs, other notable figures emerged.

One such figure was Alberto Santos-Dumont, a Brazilian aviation pioneer who captured the world's attention with his groundbreaking flights in Europe. In 1901, Santos-Dumont designed, built, and flew the first powered airships, winning the Deutsch Prize when he flew around the Eiffel Tower in his airship No. 6. He further solidified his reputation by piloting the 14-bis, a canard biplane, in Paris, France, in 1906. This flight, witnessed by a large crowd, demonstrated the practicality of powered flight and earned him widespread recognition as a pioneer aviator. Santos-Dumont continued to innovate, incorporating ailerons between the wings to improve lateral stability. His final design, the Demoiselle monoplanes (Nos. 19 to 22), first flown in 1907, became the world's first series production aircraft, with the Demoiselle No. 19 being constructed in only 15 days.

Around the same time, Louis Blériot, a French aviator and inventor, left his mark on aviation history. In 1909, Blériot accomplished a monumental feat by becoming the first person to cross the English Channel in an airplane. His successful flight in the Blériot XI monoplane demonstrated the increasing capabilities of aircraft for long-distance travel. Blériot's achievement inspired a wave of enthusiasm for aviation, fueling a spirit of competition among aviators. Aviation races and competitions gained popularity, driving inventors and pilots to push the boundaries of speed, endurance, and innovation.

On September 23, 1913, Roland Garros embarked on an ambitious and historic flight from St Raphael in Southern France to Bizerta, Tunisia, in 1913. This pioneering long-distance journey garnered significant attention at the time. Garros piloted a Morane-Saulnier monoplane, covering a distance of approximately 1,500 kilometers (930 miles) in over 10 hours of flight time. Initially, Garros had intended to make a stop at Cagliari, the capital of Sardinia, to refuel. However, he was progressing so well that he soared past this point at a great height. This journey marked one of the earliest long-distance flights across the Mediterranean.

The military potential of airplanes was quickly recognized, leading to their use in warfare. Italy became the first country to employ aircraft for military purposes during the Italian-Turkish war in 1911–1912, using them for reconnaissance, bombing, and artillery correction flights in Libya. Bulgaria followed suit, using airplanes to attack and reconnoiter Ottoman positions in the First Balkan War of 1912–1913. However, it was during World War I that airplanes saw significant utilization in offensive, defensive, and reconnaissance capacities by both the Allies and the Central Powers. The war became the first conflict to witness widespread and intensive use of airplanes and airships, showcasing their strategic importance and paving the way for further military aviation development.

2.3. World War I

1914–1918

World War I witnessed the emergence of aerial combat, giving birth to the era of fighter pilots. The skies transformed into battlegrounds as airplanes took on crucial roles for reconnaissance, bombing, and engaging enemy aircraft. France, Britain, Germany, and Italy emerged as leading manufacturers of fighter planes that saw action during the war, with notable contributions from German aviation technologist Hugo Junkers, who pioneered the use of all-metal aircraft starting in late 1915.

Among the notable figures of the era, Roland Garros, a French aviator, made significant advancements by pioneering the concept of shooting through a propeller. Garros equipped his aircraft with deflector plates, allowing him to fire a machine gun through the propeller's arc. His innovations provided a substantial advantage in aerial combat. Garros met his untimely demise on October 5, 1918, when he was shot down and killed during aerial combat over France. Another prominent figure was Manfred von

Richthofen, known as the Red Baron, who became one of the most renowned and successful pilots of the war, tallying 80 confirmed kills before his death in 1918. Georges Guynemer, a French fighter pilot, also made a significant impact before his untimely death in 1917, embodying heroism and bolstering French morale.

The advancements in aircraft technology during the war led to the development of specialized fighter planes. Aerial photography became a vital component of intelligence gathering, with reconnaissance aircraft capturing images of enemy positions and fortifications, providing crucial information for military planning and strategy. The war underscored the importance of air superiority, leading to the deployment of anti-aircraft guns and fighter planes by both sides to counter enemy aircraft. This, in turn, spurred advancements in anti-aircraft technology and tactics.

World War I acted as a catalyst for the rapid advancement of aviation, leaving a lasting impact on both military and civilian aviation. The experiences and lessons learned during the conflict laid a solid foundation for future developments, driving the industry towards new heights of innovation and progress. It highlighted the immense potential of aircraft as strategic tools and propelled aviation into a new era. Amidst this transformative period, there were notable figures, such as Santos-Dumont, who voiced their opposition to the warlike use of airplanes.

2.4. The Golden Age

1919–1939

One notable development after World War 1 was the establishment of Aeropostale, also known as Compagnie Générale Aéropostale, a French airmail company that played a crucial role in the expansion of aviation networks and the development of international air travel. Founded in 1918, Aeropostale, under the leadership of Pierre-Georges Latécoère, expanded its operations and established a network of airmail routes. These routes extended from Toulouse Montaudran airfield in France to destinations such as Casablanca in Morocco, Dakar in Senegal, Buenos Aires in Argentina, and Rio de Janeiro in Brazil. Aeropostale's flights covered vast distances over challenging terrains, including the Sahara Desert and the Andes Mountains.

Aeropostale's pilots and aircraft faced numerous challenges, including harsh weather conditions, navigational difficulties, and technical limitations. Despite these obstacles, Aeropostale successfully maintained regular airmail services. Aeropostale's impact extended beyond its operational lifespan. It captured the imagination of the public and inspired a sense of adventure and exploration. The pilots of Aeropostale, such as Antoine de Saint-Exupéry, who later became famous for writing *The Little Prince*, Jean Mermoz, famous for his 1930 South Atlantic crossing, and Henri Guillaumet, known for his remarkable survival after a crash landing in the Andes Mountains, became symbols of courage and the romanticism associated with early aviation.

During the interwar period, commercial airlines offering scheduled passenger services began to emerge. One noteworthy example was Aeromarine Airways, which operated in the United States from 1920 to 1923. Using seaplanes, Aeromarine Airways provided flights between cities such as New York, Boston, and Atlantic City. In Europe, KLM Royal Dutch Airlines was established in 1919 and holds the distinction of being the oldest operating airline in the world. KLM pioneered international scheduled services by initially connecting Amsterdam with London. Its success served as inspiration for the creation of other European airlines, including British Airways in 1919 and Air France in 1933. Air France was formed through a merger involving Aeropostale, along with two other airlines founded in 1919 and 1920, dedicated to domestic and international routes.

In the United States, the Air Mail Act of 1925 and the Air Commerce Act of 1926 contributied to the establishment of major U.S. airlines, including United Airlines, American Airlines, and Delta Air Lines. Pan American World Airways, commonly known as Pan Am, holds a prominent and influential position in the history of aviation. Founded in 1927, Pan Am launched its first international passenger route in 1928, connecting Key West, Florida, and Havana, Cuba. Pan Am became an iconic symbol of the golden age of aviation, capturing the imagination of the public.

The first successful non-stop flight over the Atlantic Ocean took place in May 1927. American aviator Charles Lindbergh accomplished this feat by flying solo in a custom-built, single-engine monoplane named the *Spirit of St. Louis*. Lindbergh departed from Roosevelt Field in New York and landed in Le Bourget Field near Paris, France. In June 1928, Amelia Earhart made history by becoming the first woman to fly across the Atlantic, albeit as a passenger rather than as the pilot. The flight took place from Newfoundland, Canada, to Wales, and Earhart gained significant recognition for her participation in this groundbreaking journey. In May 1932, she became the first woman to fly solo non-stop across the Atlantic Ocean. Amelia Earhart disappeared in 1937, during an attempt to circumnavigate the globe. She and her navigator were en route over the Pacific Ocean when communication with them was lost. Despite extensive search efforts, they were never found, and their fate remains a mystery.

Technological advancements in aviation were profound during this time. The development of jet engines by Hans von Ohain and Sir Frank Whittle revolutionized aviation, leading to faster and more efficient aircraft. In the 1920s, Jimmy Doolittle became interested in instrument flying, which involved using cockpit instruments to navigate and control an aircraft instead of relying solely on visual cues. One of his notable accomplishments was the invention of the artificial horizon and directional gyroscope, which provided pilots with crucial information about the aircraft's attitude and heading. Doolittle advocated for the integration of instrument flying into pilot training and aviation practices. His efforts led to the establishment of instrument flight rules (IFR) and the implementation of instrument training programs in aviation.

As the world moved closer to World War II, rapid advancements in aircraft design, such as the introduction of monoplane fighters and strategic bombers, transformed aerial warfare. Notable aircraft of the era included the Supermarine Spitfire and the Messerschmitt Bf 109, which would become iconic symbols of aerial combat during the war.

2.5. World War II

1939–1945

As nations engaged in fierce battles, the development of aircraft and radar systems played a crucial role in gaining strategic advantages. Sir Robert Watson-Watt was a Scottish physicist who played a pivotal role in the development of radar. His research and efforts led to the creation of the Chain Home radar system in the United Kingdom. This early warning radar system provided crucial information about incoming enemy aircraft, enabling the British Royal Air Force (RAF) to effectively intercept and defend against German air attacks.

The use of radar technology during World War II was a game-changer in aerial combat. Radar allowed for early detection of enemy aircraft, facilitating effective defense and counterattacks. Alongside Watson-Watt's Chain Home system, the introduction of airborne radar, such as the H2S radar in British bombers, provided unprecedented navigational capabilities and target identification for aircraft flying in low visibility conditions.

In addition to radar, the development of jet engines revolutionized aviation during World War II. German engineer Hans von Ohain and British inventor Frank Whittle independently worked on jet propulsion technology, leading to the creation of the world's first operational jet engines. The German Messerschmitt Me 262 and the British Gloster Meteor became the first jet-powered combat aircraft, showcasing the incredible speed and maneuverability that jet technology offered.

2.6. The post-war era

1945–1979

After World War II, civil aviation experienced significant growth and development. The post-war era witnessed a surge in air travel, leading to the expansion of commercial airlines and the establishment of new routes around the world. The introduction of jet engines revolutionized civil aviation, providing faster and more efficient means of transportation. The de Havilland Comet, the world's first commercial jet airliner, made its maiden flight in 1949, ushering in a new era of high-speed air travel.

The development of jet engines continued to evolve in the post-war period. Rolls-Royce, General Electric, and Pratt & Whitney were among the key players in advancing jet engine technology. Their efforts led to the creation of more powerful and fuel-efficient engines, enabling aircraft to fly faster and cover longer distances. The Boeing 707, introduced in the late 1950s, became a symbol of the jet age, marking a significant milestone in commercial aviation and paving the way for larger and more capable jetliners.

As air traffic increased, the need for efficient air traffic management became apparent. To ensure safe and organized movement of aircraft, air traffic control systems were established. The implementation of radar-based air traffic control systems played a crucial role in enhancing airspace management. Secondary surveillance radar (SSR) technology allowed for the identification and tracking of aircraft by transmitting unique codes known as transponder signals.

The post-war era also witnessed the emergence of supersonic flight. The iconic Concorde, a joint project between British Aircraft Corporation and Aérospatiale, made its first flight in 1969. This revolutionary aircraft had the capability to fly at supersonic speeds, transforming long-haul travel by drastically reducing flight times between continents. The Concorde became an icon of technological achievement and luxurious air travel. However, despite its initial success, factors such as high operational costs, a fatal accident at Paris airport in 2000, and growing environmental concerns led to the eventual phasing out of supersonic commercial flights.

2.7. The digital age

1980 and later

The last quarter of the 20th century saw a change of emphasis, with no significant revolutionary progress being made in flight speeds, distances, and materials technology.

One notable development during this period was the widespread adoption of digital flight management systems (FMS) in commercial aircraft. The Boeing 767 was the first to introduce these computer-based systems, which replaced traditional analog instruments. FMS allowed for more precise navigation, automated flight planning, and improved aircraft performance. The integration of FMS into cockpits paved the way for increased safety, efficiency, and reliability in aviation operations.

The use of GPS (*Global Positioning System*) also played a crucial role in transforming aviation. Following the incident of Korean Air Flight 007 in 1983, where the aircraft from New York to Seoul via Anchorage was shot down after deviating from its intended route, there was a renewed emphasis on enhancing navigation and surveillance capabilities. GPS technology provided a highly accurate and reliable means of determining an aircraft's position, velocity, and time. Its widespread adoption in the 1980s and 1990s greatly improved aircraft navigation, enabling precise route planning, automated guidance systems, and enhanced situational awareness for pilots.

Additionally, this period saw the emergence of more advanced air traffic management systems. New technologies were implemented, allowing for better monitoring and management of air traffic based on radar and data processing capabilities. These systems facilitated more efficient routing, reduced congestion, and enhanced safety in busy airspace. The digitalization of air traffic management systems played a key role in accommodating the increasing volume of air traffic and ensuring smooth operations in the rapidly evolving aviation landscape.

This book delves into the details of these technologies and explains how to make the most of collected data in aviation and air traffic management.

3. Earth models

This chapter provides a few notions of geodesy that are useful to the computation of aircraft trajectories. For a more complete documentation, the reader may refer to the first chapters of the book of Michel Capderou [1] on satellites, and also to the book of Dominic J. Diston [2].

There are several possible models of the Earth's surface, among which the geoid, the ellipsoid of revolution and the sphere. The geoid is defined as the equipotential surface of the gravity field, conforming to the shape defined by the actual mean sea level. This equipotential surface is not easy to compute and is often approximated by a simpler model: the ellipsoïd of revolution, where the Earth is considered as a sphere flattened at the poles. In an ellipsoid of revolution, each section in a meridian plane is an ellipse of parameters a for the major axis (lying in the equatorial plane), and b for the minor axis (between the South and North poles). The parameters a and b of the ellipse are constant, whatever the meridian. For some applications or computations, an even simple model can be used: a spherical Earth model.

Let us briefly describe the spherical model and the ellipsoid of revolution in the rest of this chapter, starting with the sphere for simplicity's sake.

3.1. The Spherical Earth Model

3.1.1. The Earth-Centered, Earth-Fixed (ECEF) Coordinate System

The Earth is modeled here as a sphere of radius R_T. Let us define a reference frame fixed to the Earth and for which the axis z_e passes through the poles and is oriented from the South pole to the North pole. The x_e axis is chosen in the equatorial plane and passes through the center of the Earth and through the Greenwich meridian (an arbitrarily chosen meridian). The y_e completes this system and is chosen so as to form a direct orthonormal coordinate system centered on O, the Earth's center.

In the following, we shall denote $(\vec{\imath}_e, \vec{\jmath}_e, \vec{k}_e)$ the orthonormal vectors of the ECEF reference frame $Ox_e y_e z_e$.

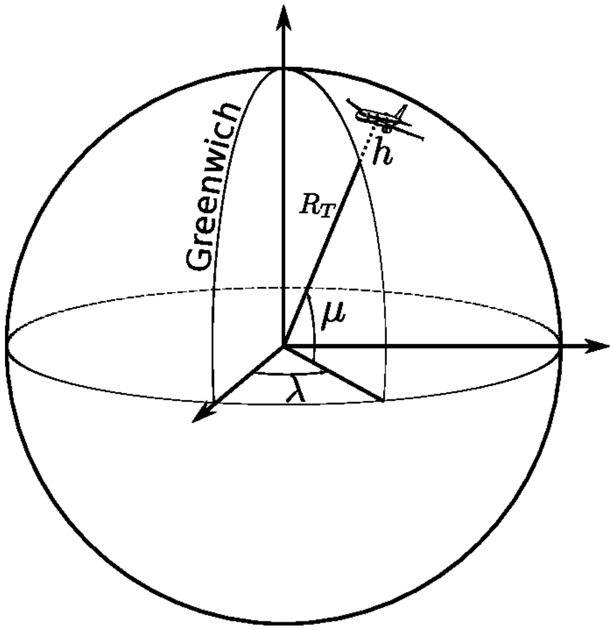


Figure 3.1.: Spherical Earth model

In this coordinate system, the position of a point P is given by its latitude, longitude, and distance from the center of Earth, or more simply its altitude h above the surface of the globe, as illustrated in Figure 3.1. The latitude, denoted μ in the following, is the angle between the equatorial plane $x_e O y_e$ and $\overrightarrow{OP}$. The longitude, denoted λ, is the angle between the Greenwich meridian plane $x_e O z_e$ and the meridian plane containing $\overrightarrow{OP}$.

3.1.2. The North-East-Down (NED) reference frame

For given point P, located on or at proximity of the Earth's surface, let us define another system of axes, called the NED (North, East, Down) system, or the local horizontal reference frame centered on point P. In this NED frame, the x_h axis is in the local horizontal plane and passes through P, pointing to the North. The y_h axis is also in the horizotal plane and passes through P, but it points to the East. Finally, the vertical axis z_h passes through P and points downward, toward the center of the Earth. The axes system $Ox_hy_hz_h$ is represented on Figure 3.2.

An orthonormal basis of vectors $(\vec{i}_h, \vec{j}_h, \vec{k}_h)$ is associated to this system.

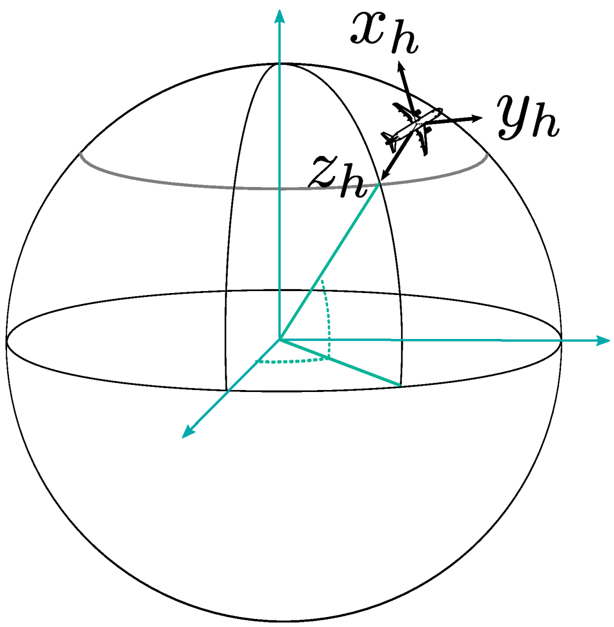


Figure 3.2.: North, East, Down (NED) reference frame, on a spherical earth

3.1.3. Coordinates of a Point on the Sphere

The Cartesian coordinates – in the ECEF (Earth-Centered, Earth-Fixed) system – of a point P at altitude h are given by Equation 3.1:

$$\{\overrightarrow{OP}\}_{ECEF} \left| \begin{array}{l} x_e = (R_T + h)\cos\mu\cos\lambda \\ y_e = (R_T + h)\cos\mu\sin\lambda \\ z_e = (R_T + h)\sin\mu \end{array} \right. \tag{3.1}$$

In the NED (North, East, Down) system where the unit vector $\vec{k}_h$ points downward from P, the position vector can be expressed very simply by Equation 3.2, and the coordinates by Equation 3.3.

$$\overrightarrow{OP} = -(R_T + h)\vec{k}_h \tag{3.2}$$

$$\{\overrightarrow{OP}\}_{NED} \left| \begin{array}{l} x_h = 0 \\ y_h = 0 \\ z_h = -(R_T + h) \end{array} \right. \tag{3.3}$$

3.1.4. Velocity of a Point with Respect to the ECEF Frame

Let $Ox_my_mz_e$ be the orthonormed direct system such that x_mOz_e is the meridian plane containing P, the position of the mobile agent. This referential is obtained simply by rotating the ECEF axes $Ox_ey_ez_e$ of an angle λ around the axis of the poles z_e. Let $(\vec{\imath}_m, \vec{\jmath}_m, \vec{k}_e)$ be the orthonormal basis associated with the reference frame fixed too the meridian plane passing through P.

The velocity with respect to the ECEF reference frame, considered as fixed, is given in Equation 3.4, taking into account the angular speed $\vec{\Omega}_{Ox_my_mz_e/ECEF} = \dot{\lambda}\vec{k}_e$ of the $Ox_my_mz_e$ system around the axis Oz_e:

$$\left.\frac{d\overrightarrow{OP}}{dt}\right|_{/ECEF} = \left.\frac{d\overrightarrow{OP}}{dt}\right|_{/Ox_my_mz_e} + \vec{\Omega}_{Ox_my_mz_e/ECEF} \wedge \overrightarrow{OP} \tag{3.4}$$

The derivative $\left.\frac{d\overrightarrow{OP}}{dt}\right|_{/Ox_my_mz_e}$ is obtained simply by deriving Equation 3.2 assuming $Ox_my_mz_e$ is fixed. With this assumption, we place ourselves in the meridian plane and only take into account the rotational motion of $\vec{k}_h$ in this plane when expressing its derivative :

$$\left.\frac{d\overrightarrow{OP}}{dt}\right|_{/Ox_my_mz_e} = -(R_T + h)\frac{d\mu}{dt}\frac{d\vec{k}_h}{d\mu} - \dot{h}\vec{k}_h = \dot{\mu}(R_T + h)\vec{\imath}_h - \dot{h}\vec{k}_h \tag{3.5}$$

By combining Equation 3.5 and Equation 3.4, the velocity with respect to the ECEF reference frame is then expressed (see Equation 3.6) in a simple form in the basis of vectors $(\vec{\imath}_h, \vec{\jmath}_h, \vec{k}_h)$ associated with the local horizontal frame NED.

$$\begin{aligned}\frac{d\overrightarrow{OP}}{dt}_{/ECEF} &= \dot{\mu}(R_T+h)\vec{\imath}_h - \dot{h}\vec{k}_h + \left(\dot{\lambda}\vec{k}_e\right) \wedge \left(-(R_T+h)\vec{k}_h\right) \\ &= \dot{\mu}(R_T+h)\vec{\imath}_h + \dot{\lambda}(R_T+h)\cos\mu\vec{\jmath}_h - \dot{h}\vec{k}_h\end{aligned} \tag{3.6}$$

Adopting the slightly unwieldy but explicit notation convention where "*/ECEF*" means *"with respect to the Earth's reference frame"* and $\{.\}_{NED}$ means *"in the NED (North, East, Down) coordinate system"*, the coordinates of the velocity with respect to the Earth are given by Equation 3.7.

$$\left\{\frac{d\overrightarrow{OP}}{dt}_{/ECEF}\right\}_{NED} = \begin{pmatrix} \dot{\mu}(R_T+h) \\ \dot{\lambda}(R_T+h)\cos\mu \\ -\dot{h} \end{pmatrix} \tag{3.7}$$

3.2. The Ellipsoid of Revolution

A more accurate approximation than the sphere of the Earth's surface is the ellipsoid of revolution. In the ellipsoid model, each section in a meridian plane is an ellipse of major axis a and minor axis b. The parameters a and b of the ellipse are the same in all meridian planes. The approximate surface of the Earth is thus determined by a single ellipse, which is rotated around its minor axis, which is coincident with the polar axis.

In the following, we will denote e the eccentricity of the ellipse, which verifies the following equation Equation 3.8:

$$e^2 = 1 - \frac{b^2}{a^2} \tag{3.8}$$

The equation of the ellipse is recalled in Equation 3.9, where z is the minor axis (the polar axis), and x is the major axis of the ellipse:

$$\frac{x^2}{a^2} + \frac{z^2}{b^2} = 1 \tag{3.9}$$

3.2.1. Several Definitions of Latitude

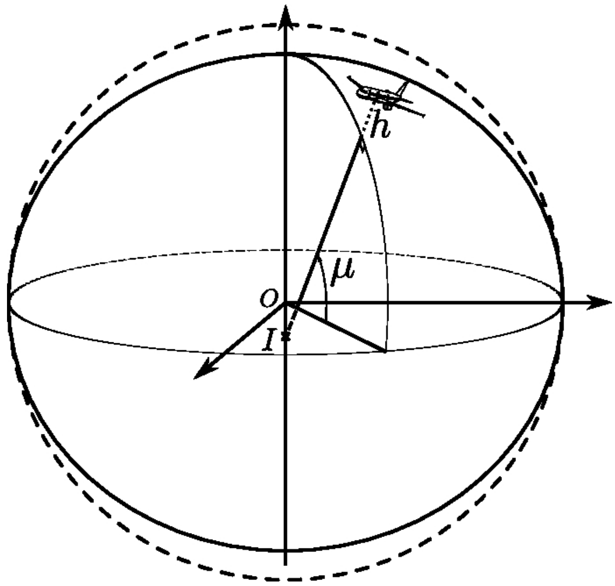


Figure 3.3.: Geodetic latitude (μ) and geodetic altitude (h) on an ellipsoid of revolution

Historically, latitude was calculated by measuring angles between the local horizontal plane and the direction of reference stars (the North Star for example). The horizontal plane is determined as being perpendicular to the direction of the plumb line. This direction is therefore the normal to the equipotential surface represented by the local geoid. This latitude measured "on the ground" is called the "astronomical latitude".

The *geodetic latitude* is defined as the angle between the equatorial plane and the line perpendicular, at the considered point N, to the surface of the ellipsoid of revolution (see Figure 3.3). Note that this perpendicular line does not pass through the center O, but intersects the polar axis at a point I. The distance IN is sometimes called the "great normal" and is denoted $\mathcal{N}$.

The *geocentric latitude* is the angle between the equatorial plane and the axis going from the center of the Earth O to the point N considered. Finally, the *parametric latitude* or *reduced latitude* is used for calculation purposes and corresponds to the geocentric latitude of a point N' (see Figure 3.4) on a circle with center O and radius a. This point

N' is obtained by following the parallel to the axis Oz passing through the point N. The geocentric and parametric latitudes are illustrated in Figure 3.4.

In the rest of this chapter, μ will denote the geodetic latitude, χ the geocentric latitude, and u the parametric latitude.

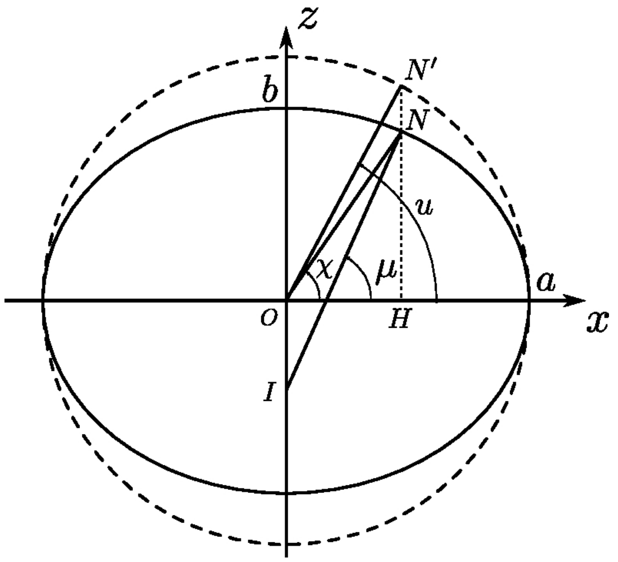


Figure 3.4.: Geocentric (χ), geodetic (μ), and parametric (u) latitudes

3.2.2. Some Useful Characteristics of the Ellipse

3.2.2.1. Relations between geodetic, geocentric, and parametric latitudes

Let us remind that the ellipse is an affine transformation, of axis Ox of direction Oz and of ratio $\frac{b}{a}$, of the circle of center O and radius a. In other words, the points of the ellipse are obtained from the circle of center O and radius a by applying a multiplicative factor $\frac{b}{a}$ to the coordinate z.

Therefore, in Figure 3.4, we observe that $\frac{HN}{OH} = \frac{b}{a}\frac{HN'}{OH}$. We immediately deduce the relation Equation 3.10 between the geocentric latitude χ and the parameterized latitude u.

$$\tan\chi = \frac{b}{a}\tan u \tag{3.10}$$

Moreover, by differentiating Equation 3.9, we obtain the slope of the tangent to the ellipse at point N, expressed in Equation 3.11:

$$\frac{dz}{dx} = -\frac{b^2}{a^2}\frac{x}{z} \tag{3.11}$$

The direction of the normal is then given by Equation 3.12:

$$\tan\mu = \frac{a^2}{b^2}\frac{z}{x} \tag{3.12}$$

From the definition of geocentric latitude, we can also see that:

$$\tan\chi = \frac{z}{x} \tag{3.13}$$

From Equation 3.12 and Equation 3.13 we deduce the relation between the geocentric latitude χ and the geodetic latitude μ :

$$\boxed{\tan\chi = \frac{b^2}{a^2}\tan\mu} \tag{3.14}$$

By combining Equation 3.10 and Equation 3.14, we can easily deduce the relation Equation 3.15 between the parametric latitude u and the geodetic latitude μ:

$$\tan u = \frac{b}{a}\tan\mu \tag{3.15}$$

3.2.2.2. Coordinates of a point on the ellipse

The point N' of Figure 3.4 is on a circle of radius a. Its coordinates are simply expressed as a function of the parameterized latitude, as follows:

$$\{\overrightarrow{ON'}\}_{Oxz} \left| \begin{array}{l} x = a\cos u \\ z = a\sin u \end{array} \right.$$

The point N on the ellipse is obtained by an affine transformation of the point N', of ratio $\frac{b}{a}$. The z-coordinate of N is therefore simply $\frac{b}{a}(a \sin u)$. The coordinates of N are given by Equation 3.16:

$$\{\overrightarrow{ON}\}_{Oxz} \left| \begin{array}{l} x = a \cos u \\ z = b \sin u \end{array} \right. \tag{3.16}$$

Furthermore, considering the geodetic latitude μ and the great normal $\mathcal{N} = IN$, we observe that $x = \mathcal{N} \cos \mu$. Taking into account this expression and Equation 3.15, the coordinate z is rewritten as a function of the geodetic latitude as follows:

$$z = b \sin u = \frac{b}{a} \tan u (a \cos u) = \frac{b^2}{a^2} \tan \mu (\mathcal{N} \cos \mu) = \mathcal{N} \frac{b^2}{a^2} \sin \mu$$

By introducing the eccentricity Equation 3.8, we finally obtain the coordinates of N as a function of the geodetic latitude μ, expressed in the following equation Equation 3.17:

$$\{\overrightarrow{ON}\}_{Oxz} \left| \begin{array}{l} x = \mathcal{N} \cos \mu \\ z = \mathcal{N}(1 - e^2) \sin \mu \end{array} \right. \tag{3.17}$$

3.2.2.3. Expression of the great normal $\mathcal{N}$

The expression of the great normal $\mathcal{N}$ is simply found from Equation 3.17 and the equation of the ellipse Equation 3.9:

$$\begin{aligned} & \frac{x^2}{a^2} + \frac{z^2}{b^2} = 1 \\ \Leftrightarrow \quad & \frac{\mathcal{N}^2 \cos^2 \mu}{a^2} + \frac{\mathcal{N}^2 (1 - e^2)^2 \sin^2 \mu}{b^2} = 1 \\ \Leftrightarrow \quad & \mathcal{N}^2 \left[1 - \sin^2 \mu + \frac{a^2}{b^2} (1 - e^2)^2 \sin^2 \mu \right] = a^2 \\ \Leftrightarrow \quad & \mathcal{N}^2 \left[1 - \sin^2 \mu + (1 - e^2) \sin^2 \mu \right] = a^2 \\ \Leftrightarrow \quad & \mathcal{N}^2 \left(1 - e^2 \sin^2 \mu \right) = a^2 \end{aligned}$$

The great normal can be expressed as follows:

$$\boxed{\mathcal{N} = \frac{a}{\sqrt{1 - e^2 \sin^2 \mu}}} \tag{3.18}$$

3.2.3. The ECEF and Other Reference Frames for the Ellipsoid of Revolution

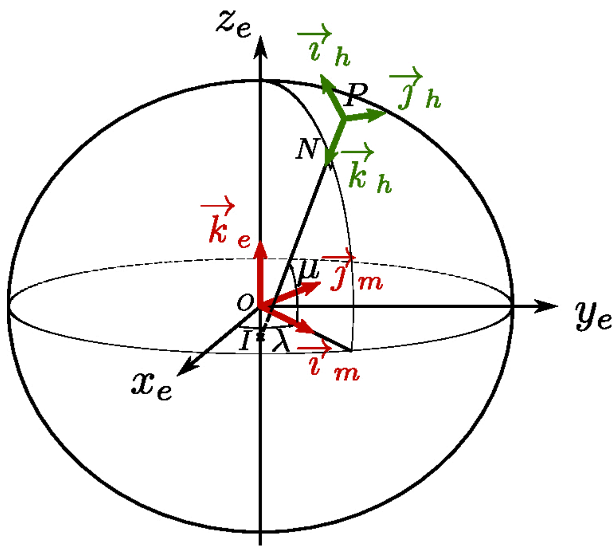


Figure 3.5.: Earth-Centered, Earth-Fixed (ECEF) and mobile reference frames, on the ellipsoid of revolution

In the case of the ellipsoid of revolution, we use an ECEF (Earth-Centered, Earth-Fixed) reference frame similar to the spherical model. Its system of axes is noted here $Ox_ey_ez_e$, with a base of orthonormal vectors $(\vec{\imath}_e, \vec{\jmath}_e, \vec{k}_e)$. For calculation purposes, we will also use an orthonormal reference frame $(\vec{\imath}_m, \vec{\jmath}_m, \vec{k}_e)$ obtained by a rotation of angle λ around the polar axis z_e. The vectors $\vec{\imath}_m$ and $\vec{k}_e$ are thus in the meridian plane passing through N (and P). We will denote $Ox_my_mz_e$ the associated axis system.

The local horizontal reference frame NED (North, East, Down), with orthonormal base $(\vec{\imath}_h, \vec{\jmath}_h, \vec{k}_h)$, is similar to the one of the spherical model, except that the vertical direction determined by vector $\vec{k}_h$ does not pass through the center of the Earth but is defined as the normal to the surface of the ellipsoid. The vector $\vec{\imath}_h$ points to the North, and $\vec{\jmath}_h$ to the East. These different reference points and axis systems are described in Figure 3.5.

3.2.4. Coordinates of a Point on the Ellipsoid

The position of a point P located at an altitude h above the surface of the ellipsoid of revolution can be broken down as follows (see Figure 3.5), where the point N (nadir) is the point on the surface of the ellipsoid located at the vertical of the point P:

$$\overrightarrow{OP} = \overrightarrow{ON} + \overrightarrow{NP}$$

3.2.4.1. Coordinate of the Nadir Point N

$$\{\overrightarrow{ON}\}_{Ox_m y_m z_e} \left| \begin{array}{l} x_m = \mathcal{N} \cos\mu \\ y_m = 0 \\ z_e = \mathcal{N}(1-e^2)\sin\mu \end{array} \right. \tag{3.19}$$

$$\{\overrightarrow{ON}\}_{ECEF} \left| \begin{array}{l} x_e = \mathcal{N} \cos\mu \cos\lambda \\ y_e = \mathcal{N} \cos\mu \sin\lambda \\ z_e = \mathcal{N}(1-e^2)\sin\mu \end{array} \right. \tag{3.20}$$

In these equations, $\mathcal{N}$ is the “great normal” at point N, given by Equation 3.18.

3.2.4.2. Coordinates of point P at altitude h

$$\{\overrightarrow{OP}\}_{Ox_m y_m z_e} \left| \begin{array}{l} x_m = (\mathcal{N}+h) \cos\mu \\ y_m = 0 \\ z_e = \left[\mathcal{N}(1-e^2)+h\right]\sin\mu \end{array} \right. \tag{3.21}$$

$$\{\overrightarrow{OP}\}_{ECEF} \left| \begin{array}{l} x_e = (\mathcal{N}+h) \cos\mu \cos\lambda \\ y_e = (\mathcal{N}+h) \cos\mu \sin\lambda \\ z_e = \left[\mathcal{N}(1-e^2)+h\right]\sin\mu \end{array} \right. \tag{3.22}$$

3.2.5. Velocity of a Point with Respect to the ECEF Frame

$$\left.\frac{d\overrightarrow{ON}}{dt}\right|_{/Ox_my_mz_e} = \dot{\mu}\left(\frac{d\mathcal{N}}{d\mu}\cos\mu - \mathcal{N}\sin\mu\right)\vec{\imath}_m + (1-e^2)\dot{\mu}\left(\frac{d\mathcal{N}}{d\mu}\sin\mu + \mathcal{N}\cos\mu \ldots\right.$$

$$\text{with} \quad \frac{d\mathcal{N}}{d\mu} = ae^2\sin\mu\cos\mu\left(1-e^2\sin^2\mu\right)^{-\frac{3}{2}}$$

$$\begin{aligned}
\left.\frac{d\overrightarrow{ON}}{dt}\right|_{/Ox_my_mz_e} =& \dot{\mu}\left[ae^2\sin\mu\cos^2\mu\left(1-e^2\sin^2\mu\right)^{-\frac{3}{2}} - a\left(1-e^2\sin^2\mu\right)^{-\frac{1}{2}} \sin \ldots\right. \\
& + \dot{\mu}(1-e^2)\left[ae^2\sin^2\mu\cos\mu\left(1-e^2\sin^2\mu\right)^{-\frac{3}{2}} + a\left(1-e^2 \sin \ldots\right.\right. \\
=& \dot{\mu}\frac{a}{\left(1-e^2\sin^2\mu\right)^{\frac{3}{2}}}\sin\mu\left[e^2\cos^2\mu - (1-e^2\sin^2\mu)\right]\vec{\imath}_m \\
& + \dot{\mu}\frac{a(1-e^2)}{\left(1-e^2\sin^2\mu\right)^{\frac{3}{2}}}\cos\mu\left[e^2\sin^2\mu + 1 - e^2\sin^2\mu\right]\vec{k}_e \\
=& \dot{\mu}\frac{a(1-e^2)}{\left(1-e^2\sin^2\mu\right)^{\frac{3}{2}}}\left[-\sin\mu\vec{\imath}_m + \cos\mu\vec{k}_e\right] \\
=& \dot{\mu}\frac{a(1-e^2)}{\left(1-e^2\sin^2\mu\right)^{\frac{3}{2}}}\vec{\imath}_h
\end{aligned}$$

$$\left.\frac{d\overrightarrow{ON}}{dt}\right|_{/Ox_my_mz_e} = \dot{\mu}R_M\vec{\imath}_h \tag{3.23}$$

where R_M is the meridian radius of curvature (see Figure 3.6):

$$\boxed{R_M = \frac{a(1-e^2)}{\left(1-e^2\sin^2\mu\right)^{\frac{3}{2}}}} \tag{3.24}$$

In addition, we have:

$$\begin{aligned}
\left.\frac{d\overrightarrow{NP}}{dt}\right|_{/Ox_my_mz_e} &= -\dot{h}\vec{k}_h - h\frac{d\vec{k}_h}{dt} = -\dot{h}\vec{k}_h - h\dot{\mu}\frac{d\vec{k}_h}{d\mu} \\
&= h\dot{\mu}\vec{\imath}_h - \dot{h}\vec{k}_h
\end{aligned}$$

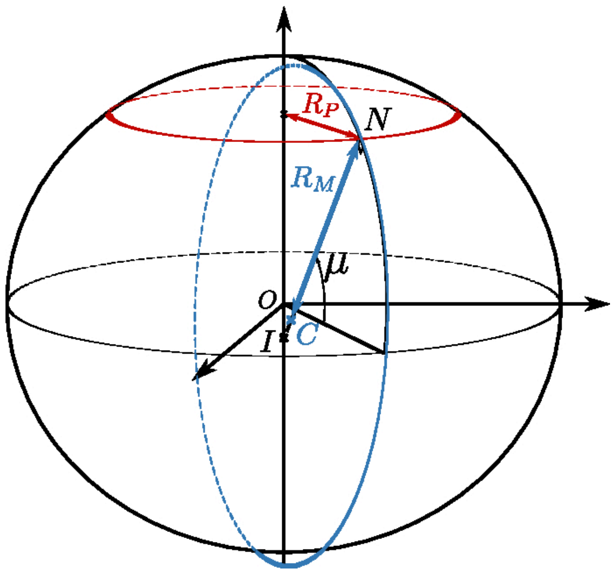


Figure 3.6.: Meridian radius of curvature R_M, in blue, and radius of curvature R_P in the local plane of latitude μ, in red

We deduce that:

$$\left.\frac{d\overrightarrow{OP}}{dt}\right|_{/Ox_my_mz_e} = \dot{\mu}(R_M + h)\vec{\imath}_h - \dot{h}\vec{k}_h$$

Taking into account the rotation $\vec{\Omega}_{Ox_my_mz_e/ECEF} = \dot{\lambda}\vec{k}_e$ of the reference frame $Ox_my_mz_e$ around the axis Oz_e, we obtain:

$$\begin{aligned}\left.\frac{d\overrightarrow{OP}}{dt}\right|_{/ECEF} &= \left.\frac{d\overrightarrow{OP}}{dt}\right|_{/Ox_my_mz_e} + \vec{\Omega}_{Ox_my_mz_e/ECEF} \wedge \overrightarrow{OP} \\ &= \dot{\mu}(R_M + h)\vec{\imath}_h - \dot{h}\vec{k}_h + \dot{\lambda}\vec{k}_e \wedge (\overrightarrow{ON} + \overrightarrow{NP}) \\ &= \dot{\mu}(R_M + h)\vec{\imath}_h + \dot{\lambda}(\mathcal{N} + h)\cos\mu\vec{\jmath}_h - \dot{h}\vec{k}_h\end{aligned}$$

By introducing $R_P = \mathcal{N}\cos\mu$, the radius of the parallel passing through the point N (see Figure 3.6), we finally obtain the expression Equation 3.25

$$\boxed{\left\{\left.\frac{d\overrightarrow{OP}}{dt}\right|_{/ECEF}\right\}_{NED} = \begin{pmatrix}\dot{\mu}(R_M + h) \\ \dot{\lambda}(\mathcal{N} + h)\cos\mu) \\ -\dot{h}\end{pmatrix} = \begin{pmatrix}\dot{\mu}(R_M + h) \\ \dot{\lambda}(R_P + h\cos\mu) \\ -\dot{h}\end{pmatrix}} \tag{3.25}$$

In this equation, the meridian radius of curvature R_M is given by Equation 3.24, and the radius R_P of the parallel circle is given by the following equation Equation 3.26:

$$\boxed{R_P = \mathcal{N} \cos \mu = \frac{a \cos \mu}{\sqrt{1 - e^2 \sin^2 \mu}}} \tag{3.26}$$

4. Atmosphere models for aircraft altimetry

The elements presented in this section are mainly taken from the ICAO (International Civil Aviation Organization) Standard Atmosphere Manual, and the revised atmosphere model **ATMORev?** used in the Eurocontrol BADA (Base of Aircraft Data) performance model.

4.1. The International Standard Atmosphere (ISA)

4.1.1. The Hydrostatic Equation

$$-dp = \rho g dh \tag{4.1}$$

where ρ is the air density.

4.1.2. The Ideal Gaz Law

$$p = \rho R T \tag{4.2}$$

In this equation, R is the specific constant for dry air ($R = 287.05287 \quad m^2/K.s^2$), and T is the air temperature.

4.1.3. The Geopotential Altitude

In Equation 4.1, the acceleration $g = g(h)$ due to the combined effects of Earth gravitation and rotation varies with the altitude h. Depending on the chosen Earth model, the expression of $g(h)$ can be more or less complex.

To simplify the expression of the atmospheric model equations, we introduce a new quantity, the geopotential altitude

H, defined by Equation 4.3, where $g_0 = 9.80665 \quad m/s^2$ is the reference value for the gravity of Earth, taken at the mean sea level at a reference latitude.

$$gdh = g_0 dH \tag{4.3}$$

4.1.4. Characteristics of the Standard Atmosphere at Mean Sea Level

The main characteristics of the ISA atmosphere at mean sea level are shown in Table 4.1.

Table 4.1.: Reference parameter values for the standard atmosphere, at mean sea level

Earth gravity	$g_0 = 9,80665$	[m/s^2]
Atmospheric pressure	$p_0 = 101325$	[Pa]
Temperature	$T_0 = 288,15$	[K]
Air density	$\rho_0 = 1,225$	[kg/m^3]
Speed of sound	$a_0 = 340,294$	[m/s]

4.1.5. Temperature as a Function of Geopotential Altitude

The temperature is a piecewise linear function of the geopotential altitude.

$$T = T_b + \beta_b(H - H_b) \tag{4.4}$$

The different atmospheric layers, with the values of the temperature gradient up to the altitude of 80 km, are described in Table 4.2. Note that Equation 4.4 can be used for negative altitudes, with the parameters of the layer 0.

Table 4.2.: Profil de température, jusqu'à la mésopause (80 km).

N° couche	Altitude géopotentielle	Limite inf.	Gradient	Nom
b	H_p, [km]	T_b, [K]	β_b, [K/km]	
0	0	288.15	-6.5	troposphèr

1	11	216.65	0	stratosphère
2	20	216.65	+1.0	stratosphère
3	32	228.65	+2.8	stratosphère
4	47	270.65	0	stratosphère
5	51	270.65	-2.8	mésosphère
6	71	214.65	-2.0	mésosphère

Commercial aviation is concerned by the first two layers, in the troposphere and the beginning of the stratosphere. The troposphere and the stratosphere are separated by an isobaric surface, the tropopause, at 11 km altitude.

4.1.6. Atmospheric pressure

Equation 4.2 gives us an expression for the air density $\rho = \frac{p}{RT}$ which can be replaced in Equation 4.1, by introducing the geopotential altitude (see Equation 4.3).

$$dp = -\rho g dh = -\rho g_0 dH = -\frac{g_0}{RT} p dH$$

Taking into account the expression of Equation 4.4 in the altitude layer (numbered b) where we are located, we obtain:

$$\frac{dp}{p} = -\frac{g_0}{RT} dH = -\left(\frac{g_0}{R}\right) \frac{dH}{T_b + \beta_b (H - H_b)}$$

This leads to two possible expressions of the pressure as a function of the geopotential altitude, depending on the value of the temperature gradient:

$$\begin{aligned} \beta_b \neq 0 \qquad & \ln \frac{p}{p_b} = -\frac{g_0}{R\beta_b} \ln \left(\frac{T_b + \beta_b (H - H_b)}{T_b} \right) \\ \beta_b = 0 \qquad & \ln \frac{p}{p_b} = -\frac{g_0}{RT_b} (H - H_b) \end{aligned} \tag{4.5}$$

$$\begin{aligned} \beta_b \neq 0 \qquad & p = p_b \left[\frac{T_b + \beta_b (H - H_b)}{T_b} \right]^{-\frac{g_0}{R\beta_b}} \\ \beta_b = 0 \qquad & p = p_b \exp \left[-\frac{g_0}{RT_b} (H - H_b) \right] \end{aligned} \tag{4.6}$$

4.1.7. Geopotential Altitude as a Function of Atmospheric Pressure

Conversely, starting from Equation 4.5, we can easily express the geopotential altitude H as a function of the atmospheric pressure.

$$\begin{aligned} \beta_b \neq 0 \qquad & H = H_b + \frac{T_b}{\beta_b}\left[\left(\frac{p}{p_b}\right)^{-\frac{R\beta_b}{g_0}} - 1\right] \\ \beta_b = 0 \qquad & H = H_b - \frac{RT_b}{g_0}\ln\left(\frac{p}{p_b}\right) \end{aligned} \tag{4.7}$$

4.1.8. Air Density as a Function of Geopotential Altitude

The density of air is simply expressed from Equation 4.2.

$$\rho = \frac{p}{RT} \tag{4.8}$$

It is expressed as a function of geopotential altitude by replacing pressure and temperature by their expressions from Equation 4.6 and Equation 4.4. We then find Equation 4.9, where $\rho_b = \frac{p_b}{RT_b}$ is the air density at the base of the considered altitude layer.

$$\begin{aligned} \beta_b \neq 0 \qquad & \rho = \rho_b \left[\frac{T_b + \beta_b(H - H_b)}{T_b}\right]^{-\frac{g_0}{R\beta_b}-1} \\ \beta_b = 0 \qquad & \rho = \rho_b \exp\left[-\frac{g_0}{RT_b}(H - H_b)\right] \end{aligned} \tag{4.9}$$

4.1.9. Speed of Sound

The speed of sound in air is given by the following equation, where $\kappa = 1.4$ for air :

$$a = \sqrt{\kappa RT} \tag{4.10}$$

4.2. Non-ISA atmospheres for Altimetry

In general, the real atmosphere does not satisfy the assumptions of the International Standard Atmosphere (ISA). An atmosphere can be non-ISA in many different ways. First of all, it is not always composed of dry air only. Also, the temperature and pressure conditions at sea level and/or the temperature gradient may be different from those defined by the standard atmosphere.

For the measurement of aircraft altitude, however, relatively simple assumptions about the atmosphere are made, using the notion of pressure altitude, which we will detail in the rest of this section.

4.2.1. Concept of Pressure Altitude

Let p be the pressure at geopotential altitude H, in the non-ISA atmosphere modeled in this section. The *geopotential pressure altitude* (or simply *pressure altitude*) is defined as the geopotential altitude at which the pressure p would be measured if the atmosphere were standard.

The pressure altitude is denoted H_P. Note that, by definition, the isobar $p = p_0 = 1013.25$ it hPa corresponds to a zero pressure altitude ($H_p = 0$).

4.2.2. Hydrostatic Equilibrium, Law of Perfect Gases, Humidity

For altimetry purposes, the non-ISA atmosphere modeled in this section is assumed to be at hydrostatic equilibrium, and to follow the law of perfect gases. The humidity of the air is not taken into account, as in the ISA model. Equation 4.1 and Equation 4.2 which were made for the ISA model remain valid, with the same specific constant R for air.

4.2.3. Assumptions on Temperature Gradient

The following assumptions are made about the temperature profile, with respect to the altimetry requirements:

- the layers of atmosphere are defined in pressure altitude H_p, and not in geopotential altitude H[1]. For aviation purposes, we only consider the two lowest layers : the troposphere, and the stratosphere, separated by the tropopause located at the pressure altitude given by Equation 4.11:

$$H_{p,\text{trop}} = 11000 \quad m \tag{4.11}$$

- the temperature depends linearly on *pressure altitude* (i.e. the altitude that would be observed if the atmosphere were ISA), with the following gradient:

$$\begin{aligned} \frac{dT}{dH_p} = & -6.5 \quad \text{K/km} \qquad \text{for} \quad H_p < H_{p,\text{trop}} \\ & 0 \quad \text{K/km} \qquad \text{for} \quad H_p \geq H_{p,\text{trop}} \end{aligned} \tag{4.12}$$

In the following, we will denote β the numerical constant of the temperature gradient in the troposphere:

$$\beta = -6.5 \quad \text{K/m} \tag{4.13}$$

4.2.4. Temperature and “ISA Temperature”

Let T be the temperature at a given point in the atmosphere located at a pressure altitude H_p. We will denote T_{ISA} the temperature that we would have observed at the same pressure altitude (and thus at the same pressure) if the atmosphere had been standard.

According to the assumptions made in this section, in each layer of the atmosphere, the temperature is a linear function of the pressure altitude, with an identical temperature gradient for T and T_{ISA}. Consequently, the difference between T and T_{ISA} remains constant whatever the pressure altitude H_p, at the vertical of a given geographical point. We will denote ΔT this difference.

[1]Special VFR (SVFR) flights are only allowed in controlled airspace, in which (i) the minimum visibility must be at least 1500m, (ii) ground must be visible at all times, and (iii) aircraft must be clear of clouds. Aircraft operating SVFR flights must be equipped as if they conducted an IFR flight.

$$T = T_{ISA} + \Delta T \tag{4.14}$$

Taking the isobar $p = p_0$ as the troposphere base, the temperature profiles for T and T_{ISA} are expressed as follows in Equation 4.15, where the pressure altitude of the tropopause is given by Equation 4.11.

$$\begin{aligned} T &= T_0 + \Delta T + \beta H_p && \text{for} \quad H_p < H_{p,trop} \\ T_{trop} &= T_0 + \Delta T + \beta H_{p,trop} && \text{à la tropopause} \\ T &= T_{trop} && \text{for} \quad H_p \geq H_{p,trop} \end{aligned} \tag{4.15}$$

$$\begin{aligned} T_{ISA} &= T_0 + \beta H_p && \text{for} \quad H_p < H_{p,trop} \\ T_{ISA,trop} &= T_0 + \beta H_{p,trop} = 216,65 \quad K && \text{à la tropopause} \\ T_{ISA} &= T_{ISA,trop} && \text{for} \quad H_p \geq H_{p,trop} \end{aligned} \tag{4.16}$$

4.2.5. Reference Altitudes and Levels in Altimetry

4.2.5.1. The isobar $p = p_0 = 1013.25$ it hPa (StdRef)

By definition of pressure altitude, the isobar *StdRef* is at pressure altitude $H_p = 0$. Its temperature (at a given geographical point) can differ from the ISA conditions by a ΔT difference.

$$\begin{aligned} p_{StdRef} &= p_0 \\ T_{StdRef} &= T_0 + \Delta T \\ T_{ISA,StdRef} &= T_0 \\ H_{p,StdRef} &= 0 \end{aligned}$$

4.2.5.2. Mean Sea Level (MSL).

By definition, mean sea level is at geopotential altitude $H = 0$, and at geodetic altitude $h = 0$. The pressure differs from the pressure p_0 under ISA conditions at sea level by a difference Δp. The pressure altitude at mean sea level $H_{p,MSL}$

is obtained simply by replacing the geopotential altitude H by the pressure altitude H_p in the first expression of Equation 4.7 valid for the ISA atmosphere, and applying it to the troposphere by taking as a base the isobaric $p = p_0$.

$$\begin{aligned}
&p_{MSL} = p_0 + \Delta p \\
&T_{MSL} = T_0 + \Delta T + \beta H_{p,MSL} = T_{ISA,MSL} + \Delta T \\
&T_{ISA,MSL} = T_0 + \beta H_{p,MSL} \\
&H_{p,MSL} = \frac{T_0}{\beta}\left[\left(\frac{p_{MSL}}{p_0}\right)^{\frac{g_0}{\beta R}} - 1\right] \\
&H_{MSL} = 0
\end{aligned}$$

4.2.6. Relation between Geopotential and Pressure Altitudes

Combining Equation 4.1 and Equation 4.2, we see that a variation in pressure dp in the non-ISA atmosphere corresponds to a variation in geopotential altitude dH, according to the following Equation 4.17.

$$dp = -\frac{p}{RT} g_0 dH \tag{4.17}$$

The same variation of pressure in an ISA atmosphere would correspond to a variation of pressure altitude dH_p, satisfying Equation 4.18.

$$dp = -\frac{p}{RT_{ISA}} g_0 dH_P \tag{4.18}$$

Dividing the expression Equation 4.17 by Equation 4.18, we obtain the relation between geopotential altitude variation and pressure altitude variation, given by the following Equation 4.19.

$$\frac{dH}{dH_p} = \frac{T}{T_{ISA}} \tag{4.19}$$

The relation Equation 4.20 between H and H_p is obtained by integrating Equation 4.19 taking into account Equation 4.15

and Equation 4.16 for the expression of the temperatures T and T_{ISA}.

$$
\begin{aligned}
H &= H_p - H_{p,MSL} + \frac{\Delta T}{\beta} \ln\left(\frac{T_0 + \beta H_p}{T_{ISA,MSL}}\right) && \text{for} \quad H_p < H_{p,trop} \\
H_{\text{trop}} &= H_{p,trop} - H_{p,MSL} + \frac{\Delta T}{\beta} \ln\left(\frac{T_{ISA,trop}}{T_{ISA,MSL}}\right) \\
H &= H_{\text{trop}} + \frac{T_{ISA,trop}}{T_{ISA,MSL}}(H_p - H_{p,trop}) && \text{for} \quad H_p \geq H_{p,trop}
\end{aligned}
\tag{4.20}
$$

where

$$
\begin{aligned}
H_{p,MSL} &= \frac{T_0}{\beta}\left[\left(\frac{p_{MSL}}{p_0}\right)^{\frac{g_0}{\beta R}} - 1\right] \\
H_{p,trop} &= 11000 \quad \text{m} \\
T_{ISA,MSL} &= T_0 + \beta H_{p,MSL} \\
T_{ISA,trop} &= T_0 + \beta H_{p,trop}
\end{aligned}
$$

4.2.7. Pressure p as a Function of Pressure Altitude H_p

Equation 4.6 can be transposed directly to the non-ISA case, replacing H by H_p and T by T_{ISA}. For the troposphere and stratosphere, we then obtain the expressions given in Equation 4.21:

$$
\begin{aligned}
p &= p_0 \left[\frac{T_0 + \beta H_p}{T_0}\right]^{-\frac{g_0}{R\beta}} && \text{for} \quad H_p < H_{p,\text{trop}} \\
p_{\text{trop}} &= p_{ISA,trop} = p_0 \left[\frac{T_0 + \beta H_{p,\text{trop}}}{T_0}\right]^{-\frac{g_0}{R\beta}} \\
p &= p_{ISA,trop} \exp\left[-\frac{g_0}{RT_{ISA,trop}}(H_p - H_{p,\text{trop}})\right] && \text{for} \quad H_p \geq H_{p,\text{trop}}
\end{aligned}
\tag{4.21}
$$

4.2.8. Pressure Altitude H_p as a Function of Pressure p

$$
\begin{aligned}
H_p &= \frac{T_0}{\beta}\left[\left(\frac{p}{p_0}\right)^{-\frac{R\beta}{g_0}} - 1\right] && \text{for} \quad p \geq p_{ISA,trop} \\
H_p &= H_{p,\mathrm{trop}} - \frac{RT_{ISA,trop}}{g_0}\ln\left(\frac{p}{p_{ISA,trop}}\right) && \text{for} \quad p < p_{ISA,trop}
\end{aligned}
\tag{4.22}
$$

with

$$
p_{ISA,trop} = p_0\left[\frac{T_{ISA,trop}}{T_0}\right]^{-\frac{g_0}{R\beta}} = p_0\left[\frac{T_0 + \beta H_{p,\mathrm{trop}}}{T_0}\right]^{-\frac{g_0}{R\beta}}
$$

4.2.9. Air Density ρ as a Function of Pressure Altitude H_p

$$
\begin{aligned}
\rho &= \frac{p_0}{T_0 + \Delta T + \beta H_p}\left[\frac{T_0 + \beta H}{T_0}\right]^{-\frac{g_0}{R\beta}} && \text{for} \quad H_p < H_{p,\mathrm{t}} \\
\rho_{\mathrm{trop}} &= \frac{p_{ISA,trop}}{R(T_{ISA,trop} + \Delta T)} \\
\rho &= \frac{p_{ISA,trop}}{R(T_{ISA,trop} + \Delta T)}\exp\left[-\frac{g_0}{RT_{ISA,trop}}(H_p - H_{p,\mathrm{trop}})\right] && \text{for} \quad H_p \geq H_{p,\mathrm{t}}
\end{aligned}
\tag{4.23}
$$

4.2.10. Speed of Sound

The speed of sound in the non-ISA atmosphere is given by $a = \sqrt{\kappa RT}$ (Equation 4.10), the temperature T being given by Equation 4.15.

5. Anatomy of an aircraft

5.1. Anatomy of an aircraft

APU, bleed, winglet etc.

Recognise an Airbus from a Boeing

5.2. Flight mechanics

Various speeds

Various angles, track, heading, bearing, etc.

thrust, drag, lift

- ACAS/TCAS

6. A taxonomy of airspaces

- Definition of the term ‘airspace’
- Airspace classes (A, B, C, D, E, F, G), controlled vs. uncontrolled airspace
- Airspace around airports (TMAs, CTRs)

7. Aerodromes and airports

In ICAO Annex 14, the term **aerodrome** is defined as *"a defined area on land or water (including any buildings, installations and equipment) intended to be used either wholly or in part for the arrival, departure and surface movement of aircraft."* The reference to a *defined area* suggests that aerodromes are systems, designed and operated for the purpose of both facilitating the efficient handling of departing and arrving aircraft as well as providing all the processes required by aircraft between take-off and landing. As such, aerodromes do not only have to be land-based. Rather, water-based as well as floating structures, such as oil rigs or ships, can be considered as aerodromes. Consequently, aerodromes are not solely designed for fixed-wing aircraft, but also for rotary-wing vehicles.

Since aerodromes have such a diverse range of applications, a distinction is made between different types of aerodromes. This typification often varies from country to country or region to region and (unfortunately) is not internationally standardised. For instance, an aerodrome designed for use of rotary-wing aircraft, i.e., helicopters, is called a **heliport**. A facility specifically designed for seaplanes and/or amphibian vehicles, which are aircraft able to land both on land and on water, is referred to as a **water aerodrome**. An aerodrome designed for the usage of small, often propeller-driven, general aviation aircraft, is called an **airstrip**, an **airfield**, or **small aerodrome**. Quite frequently, these type of aerodromes are equipped with a grass runway. An aerodrome used exclusively for military air operations is called a **military air base**. Finally, **civil airports** refer to facilities which are mainly available to commercial air transport. This refers to flight movements in which passengers (or cargo) are transported by an airline for a fee. For the remainder of this section, the focus is primarily on land-based **civil airports** designed for use by fixed-wing aircraft.

According to European Regulation (EU) 2018/1139, all aerodromes in the European Union which

i. are open to public use;

ii. serve commercial air transport; and

iii. have a paved instrument runway of 800 metres or more, or exclusively serve helicopters using instrument approach or departure procedures;

fall under the scope of the *Basic Regulation* (BR) of the **European Union Aviation Safety Agency** and its *Implementing Rules* (IR). These aerodromes are therefore subject to legally binding requirements that define how they must be designed, maintained, and operated. Aerodromes which handle no more than 10'000 commercial air transport passengers per year and no more than 850 movements related to cargo operations per year can be excempted from an applicablility of Regulation (EU) 2018/1139. For this reason, EASA publishes on its website a list of aerodromes specifying for which Regulation (EU) 2018/1139 is applicable and which aerodromes are exempted.

Aerodromes falling under the scope of the *basic regulation* must be certified. In simple terms, in this certification procedure an aerodrome must show how and in what way the *certification specifications* of EASA are complied with or, if they cannot be complied with, what measures are/were taken to ensure an equivalent level of safety. The demonstration of an equivalent level of safety is particularly important for aerodromes that have grown over many decades and can only make certain changes to the facilities to ensure specifications under great financial constraints or not at all, e.g., due to topographical reasons.

Certification specifications are stipulated by the EASA in the **CS-ADR** document for aerodromes and the **CS-HPT** document for heliports. These certification specifications define to a great detail, how large parts of an aerodrome and a heliport have to be designed and built. For example, CS-ADR defines how runways, taxiways, or aprons of an aerdrome must be designed, sized, or marked.

7.1. Anatomy of an aerodrome

An aerodrome can be divided into two distinct parts: the **airside** and the **landside**. Although there are different definitions for these two terms both in the literature and in the industry, we use the following definitions in this document:

- The **airside** of an aerodrome covers all areas which can be used by aircraft. This includes both the maneouvring area as well as the apron(s) of an aerodrome.
- The **landside** of an aerodrome covers all areas which are not accessible for aircraft. This includes the terminals, docks, the baggage handling system (BHS), ground access infrastructure, etc.

In the following, aerodrome infrastructure and components associated to the airside and the landside are introducted and described in more detail.

7.1.1. Airside components of an aerodrome

The airside of an aerodrome consists of the maneouvring area and the apron(s). In CS ADR-DSN.A.002, the **manevouvring area** is defined as the *"part of an aerodrome to be used for the take-off, landing and taxiing of aircraft, excluding aprons"*. Consequently, the maneouvring area consists of both runway(s) and taxiway(s). As such, CS ADR-DSN.A.002 defines a **runway** as a *"rectangular area on a land aerodrome prepared for the landing and take-off of aircraft"*, while a **taxiway** is a *"defined path on a land aerodrome established for the taxiing of aircraft and intended to provide a link between one part of the aerodrome and another"*. Finally, the **apron(s)** of an aerodrome are according to CS ADR-DSN.A.002 defined as an *"area intended to accommodate aircraft for purposes of loading or unloading passengers, mail or cargo, fuelling, parking, or maintenance"*.

> **Note**
>
> Facilities on the airside of an aerodrome are designed and sized for a **critical aircraft**, which is either a real-world of fictitious aircraft. Consequently, aircraft that

put higher requirements to the facilities than the critical aircraft, e.g., greater weight, longer wingspan, etc., cannot use the airport or parts of the airport. To prevent each aerodrome from having to describe individually which critical aircraft was used, an **aerodrome reference code** (ARC) which describes certain characteristics of the critical aircraft applied is used instead. As such, the ARC consists of two components: an aerodrome code number and a code letter. The **aerodrome code number** describes the reference field length of the critical aircraft in four categories:

Table 7.1.: Aerodrome code number (CS ADR-DSN.A.005)

Aerodrome code number	Reference field length
1	< 800 m
2	≥ 800 m and < 1200 m
3	≥ 1200 m and < 1800 m
4	≥ 1800 m

The **aerodrome code letter** describes in six categories the maximum wingspan of the critical aircraft:

Table 7.2.: Aerodrome code letter (CS ADR-DSN.A.005)

Aerodrome code letter	Maximum wingspan
A	< 15 m
B	> 15 m and ≤ 24 m
C	> 24 m and ≤ 36 m
D	> 36 m and ≤ 52 m
E	> 52 m and ≤ 65 m
F	> 65 m and ≤ 80 m

For example, an aerodrome with an ARC of "4F" can be used by aircraft with a reference field length of more than 1800m and a wingspan of up to 80m, whereas on an aerodrome with an ARC of "4E" the wingspan is limited to 65m.

7.1.1.1. Runways

Runways facilitate the landing and taking-off of aircraft. In terms of their geometric properties, a runway can be described in terms of its width, slope(s), length, and orientation.

The **width** of a runway is defined in CS ADR-DSN.B.045 and is usually measured from at outside edges of the runway. As such, the width of the runway depends both on the Aerodrome Code Letter (see Table Table 7.1) and the Outer Main Gear Wheel Span (OMGWS) of the critical aircraft as indicated in Table Table 7.3. Thereby, the OMWGS describes the distance between the outside edges of the main gear wheels of the critical aircraft.

Table 7.3.: Runway width (CS ADR-DSN.B.045)

Aerodrome Code number	4.5m ≤ OMGWS	4.5m ≤ OMGWS < 6m	6m ≤ OMGWS < 9m	9m ≤ OMGWS < 15m
1	18m	18m	23m	-
2	23m	23m	30m	-
3	30m	30m	30m	45m
4	-	-	45m	45m

The **slope** of a runway is specified both longitudinally and transversely. The **longitudinal slope** refers to the slope of the runway along its longitudinal axis. The average longitudinal slope of a runway is determined "by dividing the difference between the maximum and minimum elevation along the runway centre line by the runway length" (CS ADR-DSN.B.060). Additionally, CS ADR-DSN.B.060 specifies the maximum longitudinal slope which must not been exceeded in any portion of the runway. Finally, airport designers must ensure that the change in slope between two consecutive portions of the runway is below a certain value. The applicable values for the average longitudinal slope, maximum longitudinal slope, and the maximum longitudinal slope change, which all depend on the aerodrome code number (see Table Table 7.1), are summarized in Table **?@tbl-rwy-lgnt-slope**

Table 7.4.: Longitudinal slope of runways (CS ADR-DSN.B.060 & ADR-DSN.B.060)

Aerodrome Code number	Average longitudinal slope	Maximum longitudinal slope	Maximum longitudinal slope change
1	2%	2%	2%
2	2%	2%	2%
3	1%	1.5%	1.5%
4	1%	1.25%	1.5%

The **transverse slope** describes how a runway is sloped along its width to allow efficient drainage of rainwater. In practice, two different profile types of transverse slopes are used. *Chambered* profiles have their highest point at the centre of the runway, allowing water to drain to both sides of the runway, while the *single crossfall* profiles have thei highest elevation at one edge of the runway, allowing water to drain in the direction of the other edge. On runways of airports with an aerodrome code letter of A and B, see Table Table 7.2, the transverse slope must be between 1% and 2% according to CS ADR-DSN.B.080, on airports with an aerodrome code letter of C to F the transverse slope must be between 1% and 1.5%.

According to CS ADR-DSN.B.035, the **length** of a runway is to be sized in such a way that the operational requirements of the critical aeroplane for which the runway is designed can be met. In this context, the operational requirements are described by means of the following *declared distances*:

- **Take-off run available** (TORA):
- **Take-off distance available** (TODA):
- **Accelerate-stop distance available** (ASDA):
- **Landing distance available** (LDA):

The **orientation** of a runway describes its magnetic direction along its length. For example, a runway running in a north-south direction has an orientation of 360° or 180°, while a runway running in a west-east direction has an orientation of 090° or 270°. To enable pilots and air traffic controllers to identify runways unambiguously, each runway is given a

designator. To this end, two-digit numbers are used as designators, e.g. 27, 07, 15, etc., which designate the nearest one-tenth of magnetic direction of a runway when viewed from the direction of approach. Example: If a pilot taxis onto runway 15 and aligns the aircraft so that its nose points in the direction of the other end of the runway, the aircraft's magnetic compass will indicate a value of 150° +/-5°. At airports with two parallel runways, the designator is supplemented with the letter "L" for "left" and "R" for "right". At airports with three parallel runways, the designator of the runway in the middle is supplemented with the letter "C" for "centre".

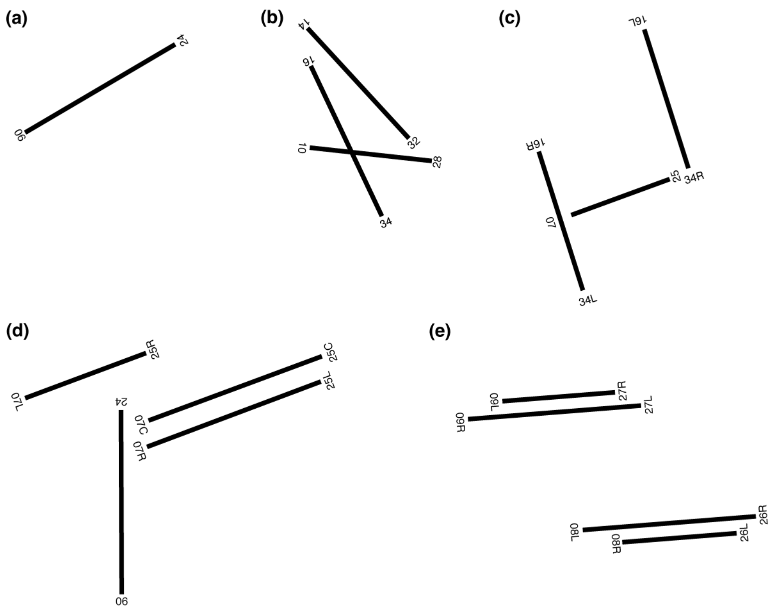


Figure 7.1.: Runway designations.

The orientation of runways depends on a number of factors such as prevailing wind conditions, topographical conditions, etc. Flight crews are encouraged to take off and land into the wind whenever possible. For each aircraft type, there are clear guidelines that specify how strong the so-called crosswind component may be during a landing. For this reason, airport planners take into account long-term weather records on the strength and direction of the wind at an airport in order to orient the runway(s) in such a way that the crosswind componente (i.e. the amount of wind perpendicular to the runway) can be minimised. For this task, the so-called *us-*

ability factor is used, which measures the percentage of time during which the operation of a runway is not restricted due to crosswind. According to GM1 ADR-DSN.B.015, a runway is considered optimally oriented if a usability factor of greater than or equal to 95% can be achieved. In addition to considering the wind direction, airport planners must also ensure that the runway can be operated safely. In this respect, topographical conditions (mountains, valleys, etc.) are of great importance. Furthermore, runways are often aligned in such a way that sensitive areas such as residential areas, hospitals, etc. are not strongly affected by the emissions of air traffic. In places where several airports are located in a relatively small area (e.g. London, New York, Los Angeles, etc.), care is also taken when choosing the runway orientation that these airports do not influence each other's operations.

There is no requirement as to the **number** of runways an aerodrome must offer. Basically, the more runways an aerodrome is equipped, the greater its maximum capacity. At the same time, however, the provision of runways is associated with high investments and operating costs, which suggests that aerodrome should build as few runways as possible.

The **layout** of an aerodrome runway system depends on how many runways are available at a site as well as how they are arranged and oriented in relation to each other. While in practice the runway systems of most aerodromes are unique, in theory a distinction is made between the following generic aerodrome layout types:

- **Single runway**: As the name suggests, aerodromes with a single runway layout have a single runway, as is the case, for example, for the airports of London Gatwick (EGKK), Geneva (LSGG), Luxembourg (ELLX), or San Diego International (KSAN). Thanks to the existence of a single runway, the single runway layout is the moste simple one, as no dependencies between runways exist. Consequently, the one runway can be optimally utilised by air traffic control, which in practice leads to single runway aerodromes having a remarkably high capacity. Indeed, depending on the aircraft mix at the aerodrome (i.e., the percentage of large aircraft vs. smaller aircraft utilising the aerodrome), single runway aerodromes can handle up to 98 aircraft movements per hour under visual flight conditions according to FAA Advisory Circular 150/5060-5. Under instrument flight conditions, up to 59 aircraft movements per hour are realistic. However, single runway layouts also comes with certain disadvantages. For instance, taxi distances can be long at single runway aerodromes, as the terminal(s), dock(s) and thus also the stands for the aircraft are often located at one of the two runway ends (e.g. at London Gatwick). Moreover, aircraft operations at single runway aerodromes can also be affected by weather conditions resulting in crosswind situations. In such cases, no other, differently oriented runways are available on which lower crosswind components would result. Finally, an incident or even an emergency on the runway of a single runway airport leads to the entire flight operation having to be suspended. The same can also happen if certain maintenance work has to be carried out on the single runway.

- **Open-V** or **open-L runways**: Airports that have an open-V or open-L runway layout have more than one runway, which have different alignments and do not cross at any point. In open-L layouts, the runways are perpendicular to each other, while in open-V layouts the angle between the runways is less or more than 90°. An example of an open-L layout can be found in Rome Fiumicino (LIRF), while Dublin Airport (EIDW) has an open-V layout. One of the advantages of open-V and open-L layouts is the circumstance that the capacity of the aerodrome can be substantially higher than with a single runway layout. According to FAA Advisory Circular 150/5060-5, aerodromes with an open-L or open-V layout can carry out up to 150 aircraft movements per hour under visual flight conditions and 59 movements under instrument flight conditions. Besides that, the aerodrome is less restricted with regard to crosswinds and, thanks to the availability of a second runway, incidents, accidents or maintenance on one runway do not lead to the complete closure of the airport. However, since the runways do not have the same orientation, aerodromes with an open-V or open-L layout have a greater land consumption. Furthermore, the expansion of the apron, terminals and docks may be limited by the runways. Moreover, incidents in the apex between the runways of airports with an open-V and open-L layout can lead to a strong impact on flight operations.

- **Intersecting** or **crossing runways**: At aerodromes with an intersecting or crossing runway layout, the runways physically intersect. A good example of an airport where the intersecting runways are arranged at 90° to each other is New York LaGuardia (KLGA), while the intersecting runways at Hamburg (EDDH) or Basel-Mulhouse (LFSB) airports, for example, have an angle not equal to 90°. At airports with intersecting runways, they can never be operated independently, which increases the complexity for air traffic control. Likewise, the capacity of the aerodromes depends on which pister to land on, which runway to take off on and where the intersection between the runways is located. To illustrate this, consider two runway configurations for New York LaGuardia Airport as shown in Figure Figure 7.2. In configuration (a), the aircraft land on runway 13 and take off on runway 22. Consequently, both a taking-off and a landing aircraft have "quickly" passed the intersection point between the two runways, which means that after a take-off or landing clearance has been granted on one runway, the other runway can be used again by other aircraft relatively quickly. In configuration (b), on the other hand, in which aircraft land on runway 04 and take off on runway 31, the intersection point is relatively far away. In this configuration, once a take-off or landing clearance is given on one runway, air traffic control has to wait a "long time" until the other runway can be used again. Consequently, the capacity of the airport is higher under configuration (a) than under configuration (b). In addition to these effects of crossing runways on airport capacity, there is the further complication that incidents and accidents at the crossing point can lead to the suspension of all flight operations at the airport.

- **Parallel runways** and **multiple parallel runways** are characterised by runways which are parallel to each other. If an airport has two parallel runways, it is called a parallel runway system. However, if more than two runways are parallel, it is called a multiple parallel runway system. For the operation

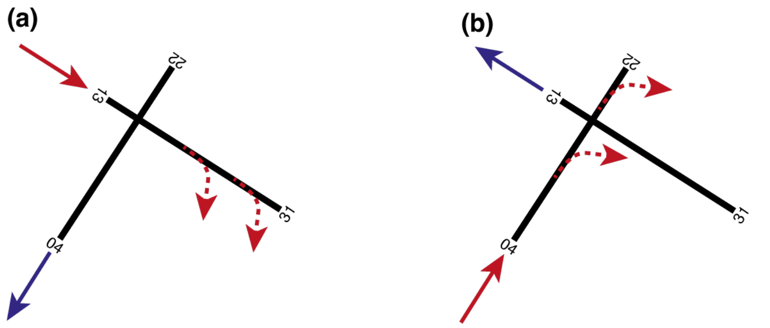
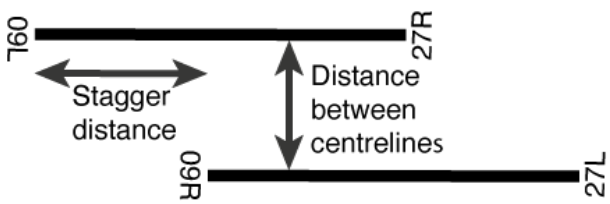


Figure 7.2.: Influence of runway configuration on capacity of aerodromes with crossing runway layout.

of parallel runways, two geometric properties illustrated in figure **?@fig-distances-parallel-runway** are important, namely (i) the separation distance between two parallel runways and (ii) the stagger between parallel runways. The separation distance describes how far apart the centrelines are between two parallel runways, while the stagger distance describes how far apart the thresholds of the parallel runways are in the direction of the longitudinal runway axis.



First, let us look at how the separation distance affects the operation of parallel instrument runways, which are runways that allow for operations under instrument flight conditions. According to CS ADR-DSN.B.055, the minimum separation distances between parallel runways defined in table Table 7.5 must be maintained so that the modes of operation illustrated in Figure 7.3 can be performed.

Table 7.5.: Minimum required separation distance between parallel instrument runways according to CS ADR-DSN.B.055.

Mode of operation	Minimum required separation distance
Indepedent parallel approaches	1035m
Dependent parallel approaches	915m
Independent parallel departures	760m
Segregated parallel operations	760m

Mode of operation *independent parallel approaches* refers to an operational concept in which air traffic control can operate parallel runways independently of each other for approaching traffic. This means that landings on one runway do not lead to operational restrictions for arriving aircraft on the other runway, and vice versa. For independent parallel approaches to be possible, the centrelines of the parallel runways must be at least 1035m apart, which is the case at Munich Airport (EDDM) or London Heathrow (EGLL), for example. Because the runways can be operated independently of each other, such airports have capacities of up to 120 aircraft movements per hour under instrument flight conditions according to FAA Advisory Circular 150/5060-5. At airports where parallel instrument runways are at least 915m apart, *dependent parallel approaches* can be flown. This refers to simultaneous approaches on two parallel runways where air traffic control must ensure certain radar separation minima between the approaching aircraft. Since in this case the operation on one runway affects the operation on the other runway (and vice versa), the theoretically possible capacity of such runway systems is approximately 75 movements per hour. Consequently, the maximum capacity of aerodromes were only dependent parallel approaches can be flown is significantly lower than at airports with independent parallel runway systems. Parallel runway systems separated by at 760m allow for *independent parallel departures* and *segregated parallel operations*. While the former allows air traffic controllers to consider the runways independent from each other for departing traffic, the latter allows for the operation of one runway solely for arrivals and the other one exclusively for departures.

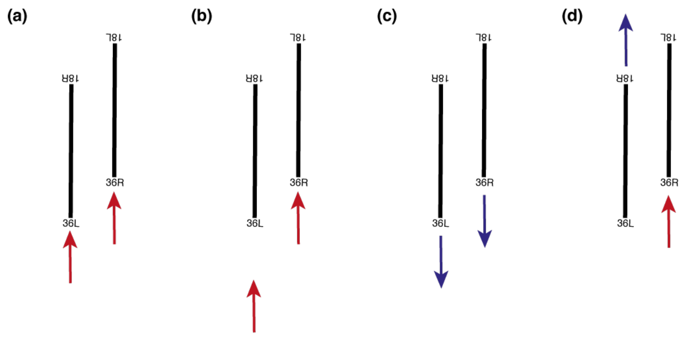


Figure 7.3.: Mode of operation of a parallel runway system: (a) Indepedent parallel approaches, (b) dependent parallel approaches, (c) independent parallel departures, and (d) segregated parallel operations.

At some aerodromes with independent parallel runways, the thresholds are displaced, as can be seen in Figure 7.4. In technical jargon, this is referred to as staggered runways. Staggered runways can have a positive impact on airport operations by allowing shorter taxiing distances for aircraft and additional vertical separation of approaching aircraft. The influence of staggered parallel runways on taxi distances can be illustrated using the example of Athens Airport, as shown in Figure 7.4 (a). If aircraft land on runway 03R (red dashed line) or take off on runway 03L (blue dashed line), the average taxiing distance is shorter than if runway 03R were used for take-offs and 03L for landings. The effect of the stagger on the vertical separation of approaching aircraft is illustrated in Figure 7.4 (b) and (c): If the glide path angles of the approaches to the parallel runways are identical, two simultaneously approaching aircraft are not at the same altitude since the thresholds of the runways are displaced.

7.1.1.2. Adjacent areas

To increase the level of safety of flight operations, airports have to install a number of so-called *adjacent areas* around

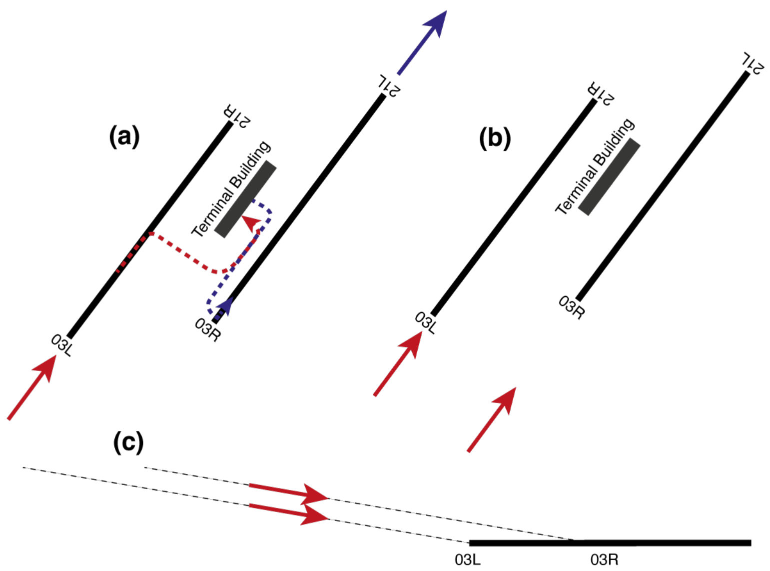


Figure 7.4.: Staggered parallel runways using the example of Athens Eleftherios Venizelos International Airport (LGAV): (a) Reduced taxi times due to staggered parallel runways, (b) additional vertical separation between two approaching aircraft due to staggered parallel runways, (c) longitudinal view of parallel approaches on staggered runways.

runways. In particular, a distinction is made between the following adjacent areas for runways: (i) runway shoulder, (ii) runway strip, and (iii) runway end safety area (RESA):

- runway shoulder,
- runway strip,
- runway end safety area (RESA)

Some adjacent areas can be provided

- clearway
- stopway

7.1.1.3. Runway markings

7.1.1.4. Runway lights

7.1.1.5. Obstacle limitation surfaces (OLS) and obstacle free zones (OFZ)

7.1.1.6. Taxiways

- Taxiway dimensioning
- Taxiway marking, lighting, signage

Types of taxiways: * “Normal” taxiways * Apron stand taxilane * Apron taxiway * Rapid exit taxiway

7.1.1.7. Aprons

- Aprons
- Stands

7.1.2. Landside components of an aerodrome

8. Air navigation services

Merriam-Webster defines the term **airspace** as “the space lying above the earth or above a certain area of land or water”. According to the Chicago Convention on International Civil Aviation of 1944, every state “has complete and exclusive sovereignty over the airspace above its territory”. Horizontally, a state’s airspace extends over its entire territoriy, which also include territorial waters. According to the United Nations Convention on the Law of the Sea, territorial waters extend up to 12 nautical miles (22.2 km) from a state’s coastline. Vertically, a state’s airspace begins at the earth’s surface and ends at an altitude of 100 km above mean sea level, which is also known as the Kármán-Line.

In order to manage an airspace, a state usually commissions a so-called **air navigation service provider** (ANSP), which is a public or private entity that offers so-called **air navigation services**. These air navigation services comprise of the following five components:

- Aeronautical Information Management (AIM)
- Air Traffic Management (ATM)
- Meteorological Services (MET)
- Communication, Navigation, Surveillance (CNS)
- Search and Rescue (SAR)

For the remainder of this section, the components of air navigation services are described in more detail.

8.1. Aeronautical Information Management

Aeronautical Information Management (AIM) is considered with the collection, assembly, publication, exchange, and dissemination of quality-assured, timely and digital aeronautical data in collaboration with all relevant stakeholders. Aeronautical data includes aeronautical information publications

(AIP), notice to airmen (NOTAM), preflight information bulletins (PIB), and aeronautical information circulars (AIC).

Aeronautical Information Publications (AIP), which contain "aeronautical information of a lasting character essential to air navigation", see ICAO Annex 15, are issued by a state or by an authority of the state, such as an ANSP. Since their structure is standardized by ICAO Annex 15, AIP usually consist of three distinctive parts:

- *GEN - General information*: As the name implies, GEN contains general information, such as the authority responsible for the AIP, locally applied units of measure, abbreviations used in the AIP, locally applicable time zones and daylight saving time regulations, airspace charges regulations, etc.
- *ENR - Information referring to en-route*: ENR contains information that is of importance during the flight, i.e., while aircraft are *en-route*. ENR is divided into the following 6 parts: (i) information on general rules and procedures for visual flight (VFR) and instrument flight (IFR) or the airspace classes applied, (ii) description of the vertical and horizontal spread of airspaces, (iii) description of airways, (iv) description of radio navigation systems and infrastructures, (v) navigation warnings such as military airspaces, known aviation obstacles, danger areas, etc., and (vi) en-route chart material.
- *AD - Information referring to aerodromes*: AD includes information on both aerodromes and heliports and is divided into 3 parts. The first part contains an index of all aerodromes and helipads of a state as well as a description of the classification system of aerodromes applied in the state. Parts 2 and 3 of AD include detailed information on individual aerodromes or heliports, such as opening times, aerodrome operators, available service facilities, dimensions and alignment of runways, runway and approach lights, relevant aeronautical obstructions, etc. detailed maps are also provided, which contain information on ground-based infrastructure, i.e., aprons, taxiway, runways, etc., as well as flight procedures, i.e., standard instrument departures, standard terminal arrival routes, approach procedures.

To keep AIPs up to date, they are revised in an internationally standardized cylce, which is known as the **AIRAC cycle**. This AIRAC cycle follows a fixed 28-day rhythm, which is internationally standardised. The publication dates are known years in advance and are published, for example, by Eurocontrol.

Notice to airmen (NOTAM) A NOTAM contains information that is of importance to personnel involved in flight operations. While AIPs tend to contain static information that is valid over long periods of time and is known well in advance, NOTAMs include information that is dynamic in nature as it is not known far enough in advance to be published in any other way. Indeed, according to ICAO Annex 15, NOTAMs contain "information concerning the establishment, condition or change in any aeronautical facility, service, procedure or hazard…".

Prefilght information bulletins (PIB) A PIB consists of a compilation of a number of NOTAMs which are important for the execution of a flight. Consequently, a PIB contains NOTAMs for the origin, destination and alternate airports, as well as NOTAMs for the airspace that the flight is likely to use.

Aeronautical information circulars (AIC) ICAO Annex 15 defines an AIC as "a notice containing information that does not qualify for the origination of a NOTAM of for inclusion in the AIP, but which relates to flight safety , air navigation, technical, administrative or legislative matters." For example, AICs are issued to communicate a strategy in which a state explains how it aims to modernise its ground-based navigational aids, or how a certain new procedure will be implemented in the future.

8.2. Air Traffic Management

The term *air traffic management* (ATM) is defined in ICAO Document 4444 as "the aggregation of the airborne functions and ground-based functions […] required to ensure the safe and efficient movement of aircraft during all phases of operations", which, in practice, is enabled in practice by the following services: (i) air traffic services, (ii) airspace management, and (iii) air traffic flow management.

8.2.1. Air Traffic Services

Air Traffic Services (ATS) is concerned with the control, regulation, and assistance of aircraft and flight crews in real time. To this end, ATS has the following four main objectives:

- The avoidance of collisions between aircraft.
- The provision of advice for the safe and efficient conduction of flights.
- The conduction and maintainance of an orderly flow of air traffic.
- The notification and assistance of concerned organisations in case of search and rescue operations.

To achieve these main objectives, ATS provides the following main services: (i) air traffic control (ATC), (ii) air traffic advisory services, (iii) flight information services, and (iv) alerting services.

Air Traffic Control (ATC): According to ICAO Annex 11, ATC is a service, which aims at the prevention of collisions between aircraft being airborne as well as between obstructions and aircraft being on the maneouvring area of an aerodrome. Besides that, ATC ensures the expedition and maintenance of an orderly flow of air traffic.

To ensure that the airspace is managed efficiently and effectively by ATC, flights are categorized and segmented according to the **flight rules** they are following. Basically, flights are thereby either following so-called *visual flight rules* (VFR) or *instrument flight rules* (IFR). As the name implies, VFR flights follow the principle of “see and avoid”. That is, by looking out of the window, flight crew of VFR flights are responsible for ensuring that they are always sufficiently spatially separated from other flights and obstacles. Therefore, VFR flights can only be conducted when meteorological conditions permit. For instance, VFR flights can only operate in an airspace when the visibility is better than a certain minimum value. Moreover, pilots of VFR flights are prohibited from flying closer than a certain distance to clouds, which implies requirements regarding clouds. In contrast, flight crew operating under IFR are not obliged to look out of their cockpit windows in order to “see and avoid” other flights and obstalce. Rather, IFR flights are separated from other aircraft and obstacles by the ATC. Therefore, meteorological requirements to be met in IFR airspace is less stringent.

Besides differentiating between VFR and IFR flights, the airspace managed by ATC is segmented into a number of smaller sub-segments, so-called airspace blocks as annother means to ensure safe and expeditious flow of air traffic. These airspace blocks are further assigned a specific **airspace class**, which defines (i) which types of flight may use the airspace, (ii) under which circumstances these flights may enter this airspace block, and (iii) which services are offered to aircraft and/or aircraft crews being present in this airspace block. In [ICAO Annex 11][Annex_11, a total of seven distinct airspace classes, called Class A to Class G, are defined. In a first distinction, a distinction can be made between controlled and uncontrolled airspace, which, as indicated in Table XX, refers to Class A to E, and Class F to G, respectively. In this regard, the term *controlled* airspace indicates that ATC offers and provides services to aircraft being present in this airspace block, while no services are provided *uncontrolled* airspace blocks. Besides that, airspace classes differ in they type of flight allowed to enter and operate therein. While IFR flights are allowed to operate in all airspace classes, VFR flights are prohibited from using airspace Class A. Moreover, flights require an **ATC clearance** to enter certain airspace classes. If a clearance is required, pilots must contact ATC and request clearance before entering the airspace. As such, IFR and (if applicable) VFR flights require an ATC clearance for airspace Classes, A, B, C, and D. In airspace Class E, only IFR aircraft require a clearance, while VFR flights are exempt from this obligation. Please note: Aircraft operating as a *special VFR* flight[1], which refers to specially equipped aircraft conducting VFR flights under lower weather minima than those of conventional VFR flights.

[1]Special VFR (SVFR) flights are only allowed in controlled airspace, in which (i) the minimum visibility must be at least 1500m, (ii) ground must be visible at all times, and (iii) aircraft must be clear of clouds. Aircraft operating SVFR flights must be equipped as if they conducted an IFR flight.

Airspace Class	IFR-Flights	VFR-Flights	ATC-Clearance for IFR-Flights	ATC-Clearnace for VFR-Flights
A	Allowed	Prohibited	Required	n/a
B	Allowed	Allowed	Required	Required
C	Allowed	Allowed	Required	Required
D	Allowed	Allowed	Required	Required
E	Allowed	Allowed	Required	Only for SVFR-flights required
F	Allowed	Allowed	Not required	Not required
G	Allowed	Allowed	Not required	Not required

The above mentioned airspace classes are valid in all states that have ratified the Chicago Convention on International Civil Aviation. This does not mean, however, that every airspace class is applied in practice by every State. Rather, each state is free to decide on the structure of its entire airspace and the categorisation of the resulting airspace blocks. For example, Italy applies airspace classes A, C, D, E and G, while Germany, Austria and Switzerland apply airspace classes C, D, E and G.

To prevent collisions between aircraft, ATC uses so-called **separations**. As such, the term separation refers to the vertical and lateral spatial spacing between aircraft. As a target for separations, ATC uses specified minimum separations, which define exactly which vertical and lateral minimum distances must be maintained at all times. In practice, not all aircraft are separated from each other, as separations are only (i) provided in certain airspace classes and (ii) not offered to all flights. With regard to flights, a distinction is made between aircraft operating under Instrument Flight Rules (IFR) and aircraft operating under Visual Flight Rules (VFR). The following table summarises for all airspace classes and types of flight, whether or not separation is provided by ATC. Note, the table must be read as follows: the first column indicates in which airspace class a particular flight is located. The second column indicates whether this flight is operating under IFR or VFR. The third column then indicates which separation services are offered to this flight.

Airspace Class	Flight Rules	Separation provided to this flight
A	Only IFR flights allowed	Between all IFR flights
B	IFR, VFR	Between all other flights
C	IFR	Between all other flights
C	VFR	Between other IFR flights
D	IFR	Between other IFR flights
D	VFR	No separations
E	IFR	Between other IFR flights
E	VFR	No separations
F	IFR	Between other IFR flights, as far as practicable
F	VFR	No separations
G	IFR, VFR	No separations

Advisory services

Flight Information Services

Alerting services

8.2.2. Airspace Management

tbd

8.2.3. Air Traffic Flow Management

tbd

8.3. Meteorological Services (MET)

tbd

8.4. Communication, Navigation, Surveillance (CNS)

To ensure safe and efficient air transportation, Air Traffic Management (ATM) relies on infrastructure, services, and functions in the areas of Communication, Navigation, and Surveillance (CNS). As such, communication enables the exchange of information, be it in spoken or written form, between crews of aircraft and/or air traffic control. Navigation encompasses all services and infrastructures by means of which aircraft crews find their way through space in order to get from one place to another quickly, efficiently, and safely. Finally, surveillance comprises all technical possibilities by means of which air traffic control can determine the position of aircraft. In the following, the most important services, technologies, and processes in the field of CNS are presented.

8.4.1. Communication

8.4.1.1. Voice communications

VHF, HF

8.4.1.2. Data communications

ACARS, Data Link

8.4.2. Navigation

Navigation deals with the question of how aircraft, ships, cars, etc. can move from one place to another in a safe and efficient manner. In this context, the main question navigation is concerned with is how an aircraft, a ship or a car can determine its own position relative to a reference system.

In the past, rather simple and rudimentary methods were used for navigation. Using so-called dead-reckonin, the current position is determined based on a known prior position as well as the current direction and speed of movement. Furthermore, so-called celestial navigation was used, in which the current position is determined based on celestial measurements, i.e. by determining the position of celestial bodies in relation to an observer.

In aviation, the above-mentioned rudimentary methods of navigation can be employed as well. However, over the last century, a number of different, more advanced ways of determining the position of an aircraft have been developed, implemented, and applied. These navigation methods are usually based on infrastructures that are stationed either on land or in space. The most important navigation methods in aviation are described in detail below.

8.4.2.1. Non-Directional Beacon (NDB)

8.4.2.2. VHF Omnidirectional Range (VOR)

https://www.skybrary.aero/articles/vhf-omnidirectional-radio-range-vor https://en.wikipedia.org/wiki/VHF_omnidirectional_range

8.4.2.3. Distance Measuring Equipment (DME)

https://www.skybrary.aero/articles/distance-measuring-equipment-dme https://en.wikipedia.org/wiki/Distance_measuring_equipment

> ⚠ Warning
>
> **TODO**
>
> - add picture of VOR ground station
> - link to decoding with SDR ? (rather easy)

VOR stations were developped in the United States in the 1930s before being deployed after the Second World War. VOR are simple short-ranged ground stations using radio waves to allow any receiver locked on its frequency to determine its bearing with respect to the ground station.

A VOR ground station operates on line of sight (about 200 nautical miles). It uses a phased antenna array to send a strong omnidirectional signal on a determined frequency, serving as a reference for comparison with a highly directional signal rotating clockwise. The phase difference between the reference signal and the directional signal is the bearing from the VOR station to the receiver relative to magnetic north.

VOR stations are often collocated with DME (Distance Measuring Equipments) which measure the distance between an aircraft and a ground station, by timing the propagation delay of radio signals initiated by the airborne interrogator and replicated after a known delay. Again, precise clocks are key to a precise measurement of distances.

Today, VOR stations are being gradually decommissioned as navigation aids move to performance-based navigation.

8.4.2.4. ILS

a word about calibration flights?

8.4.2.5. Global Navigation Satellite System (GNSS)

GPS, Galileo, Baidu, …

https://en.wikipedia.org/wiki/Korean_Air_Lines_Flight_007

8.4.2.6. Recent technologies

- Differential GPS
- LIDAR

8.4.2.7. Airways structure

> ⚠ Warning
>
> **TODO**
>
> - add an excerpt of route map

VOR were traditionally used as intersections along airways. A typical airway will jump in non necessarily straight lines from one navigational point to another. Typical navigational points can be defined as:

- a NDB (Non Directional Beacon, the ancestor of VOR), VOR or DME ground station;
- intersections between two radials from different VOR stations;
- a VOR radial and a DME distance.

Today, more navigational points are defined as simple GPS coordinates.

8.4.3. Surveillance

8.4.3.1. Radars

The fundamental theory of radar started in late 19th century. Since the 1860s, when the electromagnetic theory was discovered by James Clerk Maxwell, the foundation for many science and technology fields was laid out. In the late 19th century, Heinrich Hertz, who proved the existence of electromagnetic waves, also confirmed that metals could reflect radio waves. In the first decades of the 20th century, several systems for using radio waves to provide short-range directional information of objects were developed. German inventor Christian Hülsmeyer is often considered as the first person to use radio waves to detect metal objects in 1904.

However, not until the Second World War, was the concept of RAdio Detection And Ranging (RADAR) developed. The technology was simultaneously researched by both major Allies and Axis countries. However, the United Kingdom led the race in developing a functional radar system.

> ⚠ Warning
>
> **TODO**
>
> - Primary radar
> - Secondary radar
> - Add sub-chapter about ADS-B, mode S?

8.5. Search and Rescue (SAR)

Part II.

The ecosystem of aviation data

9. Flight tracking technologies

Xavier Olive
Martin Strohmeier

A trajectory is a mathematical abstraction used to describe the evolution of a moving object with a finite list of parameters. The most common features in aviation include latitude, longitude, altitude, all indexed by time, with first derivatives such as ground speed, track angle and vertical rate. Depending on the application, some models would expect more features. For example, aircraft performance models could require the pitch, roll and yaw angles, the true air speed, the indicated air speed, the Mach number, etc.

This chapter describes several common formats for trajectories depending on available technology to record them. Associated data sources come with different licensing terms which must be kept in mind when developing or applying computing methods.

Flight data recorders

Obviously, the most comprehensive data source is produced by the aircraft itself, specifically by the *flight data recorder* (FDR) or *quick access recorder* (QAR). Use cases for such data range from flight operational quality assurance (FOQA), post-ops analysis to improve flight safety or operational efficiency, system analysis for predictive or condition-based maintenance. Such data typically contains over 2000 flight parameters and is considered very sensitive by aircraft operators as it may expose some commercial strategies.
It is usually difficult for researchers to get full access to

such data, even under non-disclosure agreement. Also, as aircraft operators own the data, this solution cannot be used for global analyses of all aircraft flying in a designated area.

9.1. Radar tracks

The concept of **primary surveillance radars (PSR)** is fairly simple: it is a rotating radio transponder with an omnidirectional antenna. Commonly, the radar transmits a one-microsecond pulse for every one millisecond and listens to the reflections from the aircraft. The **position of the aircraft** is measured by the distance and angle to the radar. The distance is known as the *slant distance*, which is the line-of-sight distance between an aircraft and the radar. It can be calculated by measuring the time difference between the original signal and the reflection received, since the speed of the radio wave (speed of light) is known. The *azimuth angle* of the aircraft is determined by the rotation angle of the radar.

The slant distance of an aircraft does not always correspond to the horizontal distance to the radar. Since the civil radar usually does not provide elevation information on the target, it is not possible to accurately convert the slant distance to the horizontal distance. Historically, it is sufficient to use primary radar for separating aircraft without considering these altitude differences. However, other systems have been put in place to provide air traffic controllers more accurate altitudes of the aircraft.

! Important

Air navigation service providers (ANSP) own the data produced by the surveillance radar installations they operate.

Radar tracks have a prestigious aura for obvious coverage reasons. However, it is rather unlikely that you gain access to radar trajectories on a systematic basis. Moreover, on international flights, getting a full trajectory would require agreements with ANSPs of all countries aircraft have flown.

In general, trajectories based on radar plots produced by computer systems contain an identifier, timestamps, latitudes, longitudes, altitudes, ground speed, vertical speed and track angle. **Kalman filters** help to smoothen trajectories and compute the derivatives.

9.2. ADS-B

ADS-B stands for **Automatic Dependent Surveillance–Broadcast**. It is probably one of the most well-known source of aircraft trajectories, popularized by famous websites such as Flightradar24 or The OpenSky Network. It is a surveillance technology designed to allow aircraft to broadcast their flight state periodically without the need for interrogation.

The word *automatic* refers to the fact that no inputs from controllers or pilots are required. The word *dependent* indicates this technology depends on information from other onboard systems, such as air data systems and navigation systems.

> **!** Important
>
> Messages do not contain any timestamp information. Timestamps are usually appended by the receiver of the messages, based on the reception time (and not the time of emission by the aircraft).

Information broadcast in ADS-B messages contains, in addition to a unique 24-bit transponder code, named `icao24` in examples below:

- *identification information*: the *callsign* (an 8-character *non-unique* identifier of the mission or the route of the aircraft) and the wake vortex category;
- *positional information*: latitude and longitude in degrees (encoded in CPR format), barometric altitude (converted to ISA equivalent), and GPS altitude in feet;
- *velocity information*: track angle in degrees, ground speed in knots, vertical rate in feet per minute;
- *uncertainty information* around the position and the velocity of the aircraft.

Positional and velocity information is computed by the aircraft based on GNSS and inertial navigation systems of the aircraft.

Warning

There is a common confusion in aviation between three designations for angles:

- the **track angle** represents the direction the aircraft is flying. It is the angle of the speed vector, ranging from 0 (North) to 360 degrees (90° for East, 270° for West);
- the **heading angle** represents the direction the nose the aircraft is pointing at;
- the **bearing angle** usually represents the direction of/to a static object, e.g., the bearing of a runway, or the bearing to a navigational point.

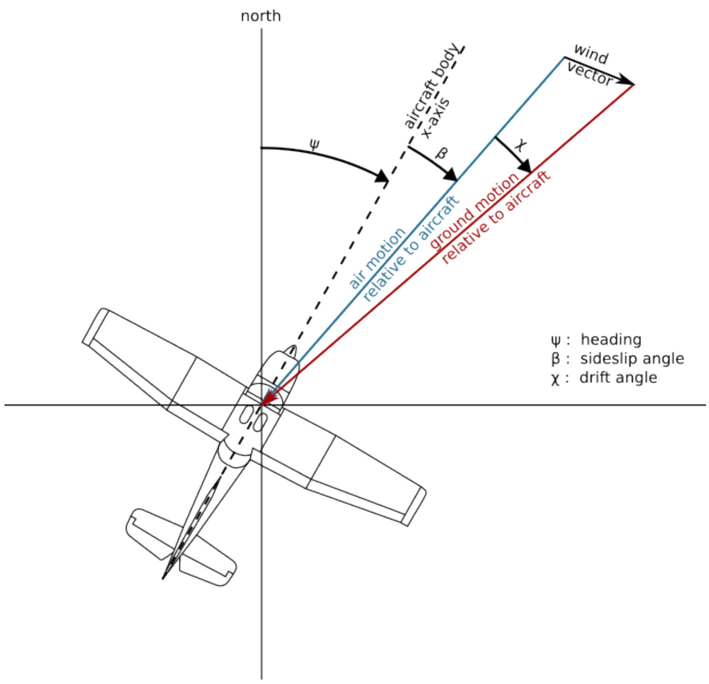


Figure 9.1.: source: https://aviation.stackexchange.com/a/96035

> **ℹ A note about callsign identifiers**
>
> A callsign is an eight-character identifier used for communication with the ATC.
> General aviation commonly uses the aircraft registration (tail number) as a callsign; commercial flights use a (often unique) identifier per route, starting with three letters identifying the airline operator, `BAW` (*pronounce "speedbird"*) for British Airways, `AFR` for Air France, etc.
> Outside commercial aviation, the callsign commonly refers to the mission operated by an aircraft, and this can help distinguish the original intention of an aircraft used for specific purposes.
> For example, aircraft `F-HNAV` uses the `CALIBRA` callsign for flight inspection and VOR/ILS calibration operations, the `JAMMING` callsign during jamming investigation and a more regular `NAK` callsign when commuting between airfields.
> Similarly, test flights operated by Airbus use an `AIB` callsign; Boeing uses a `BOE` callsign; ambulance helicopters often use explicit callsigns: `SAMU` in France (stands for *Urgent Medical Aid Service*) and `LIFE` in many European countries.
> Australian firefighting operations use a specific callsign depending on the role of the aircraft during the operations: `BMBR` for firebombing; `SPTR` for fire spotters; `BDOG`, *bird dog*, for fire attack supervisions (often subcontracted); and `FSCN`, fire scan for remote sensing fire operations.

Even though all information is not available at each timestamp, tabular data (csv) is a common format to represent trajectory data. In this example, the `icao24` code `7c4779` matches a Qantas Boeing B747 registered as `VH-OEJ`.

```
//| echo: false
import { Flight } from "@xoolive/traffic-js"
```

```
//| echo: false
qantas747 = Flight.fromSample("qantas747")
qantas747.table()
```

This tabular information can easily be represented on a map, or as a regular plot for non-geographical features.

```
//| echo: false
{
  const container = yield htl.html`<div style="height: 400px;">
  const map = L.map(container, { scrollWheelZoom: false });
  const layer = L.geoJSON(
    qantas747.resample(d3.timeSecond.every(5)).feature()
  ).addTo(map);
  map.fitBounds(layer.getBounds(), { maxZoom: 7 });
  L.tileLayer(
    "https://{s}.basemaps.cartocdn.com/rastertiles/voyager_labe
    {
      attribution:
        "© <a href=https://www.openstreetmap.org/copyright>Open
    }
  ).addTo(map);
}
```

```
//| echo: false
Plot.plot({
  marks: [
    Plot.line(qantas747.data, {
      x: "timestamp",
      y: "altitude",
      stroke: "steelblue",
    })
  ],
  x: {
    tickFormat: d3.utcFormat("%H:%M"),
    label: "timestamp (UTC)"
  },
  y: {
    label: "altitude (in feet)"
  },
  marginLeft: 50,
  width,
  height: 200,
  grid: true
})
```

What broadcasting means

The letter "B" in ADS-B means *broadcast*: aircraft broadcast messages at the same rate regardless of ground equipments and infrastructure, even if no aircraft or receiver is within range. Aircraft broadcast ADS-B data even over oceans, poles, or deserted areas. Recently, "Space-based ADS-B" has been implemented so that a constellation of low-altitude satellites attempts to receive and decode ADS-B messages from aircraft in the troposphere and forward positional information to ground-based stations. There have been high expectations around this technology which is expected to revolutionize traditional air traffic management over areas such as the North-Atlantic Ocean, controlled by Shannon (Ireland) and Gander (Canada) ACCs.

Tip

A lot of details about the contents of ADS-B messages, Mode S data and their decoding is detailed in a different book, *The 1090 Megahertz Riddle* [3].

9.3. Mode S

The **secondary surveillance radar (SSR)**, also known as the air traffic control radar beacon system (ATCRBS), was designed to provide air traffic controllers more information than what is provided by the primary radar. The secondary radar can be installed separately or installed on top of the primary radar. It uses a different radio frequency to actively interrogate the aircraft and receive information transmitted by the aircraft.

The SSR transmits interrogations using the 1030 MHz radio frequency and the aircraft transponder transmits replies using the 1090 MHz radio frequency. In the early design of SSR, two civilian communication protocols (Mode A and Mode C) were introduced. Mode A and Mode C respectively allow the SSR to continuously interrogate the **identity (squawk code)** and the **altitude** of an aircraft. The **squawk code** in

Mode A is a unique 4-octal digit code given by air traffic controllers to aircraft in their flight information region (FIR) for identification. The altitude in Mode C refers to the barometric altitude obtained from the aircraft's air data system.

> Tip
>
> Some squawk codes are reserved for particular emergency situations:
>
> - 7500 for hijacking situations;
> - 7600 for radio failures;
> - 7700 for general emergencies [4].

Mode S (Mode Select Beacon System) was designed by Lincoln Laboratory at Massachusetts Institute of Technology in the 1970s. Based on different iterations of hardware and software design in the 1980s, the implementation of Mode S in air traffic control began in the 1990s. Since then, Mode S has become one of the main sources for aircraft surveillance.

The main characteristic of Mode S is its **selective interrogation**, which allows the SSR to interrogate different information from different aircraft separately. Unlike the limited number (4096) of unique identification codes in Mode A communication, the Mode S transponder is identified by a 24-bit transponder code, which can support up to 2^{24} = 6,777,216 unique addresses.

> Important
>
> As Mode S consists in selective interrogation, it is strongly dependent on ground infrastructure around. Mode S messages are only sent in reply to an interrogation, therefore **no such data can be expected from an aircraft out of range of an SSR**, over the ocean, poles or deserted areas.

The Mode S uplink signal contains parameters that indicate which information is desired by the air traffic controller. Many downlink formats (DF) are described in the Mode S protocol in order to reply to such information:

- **Altitude and identity replies (DF 4/5)** are rough equivalents to Mode A/C protocols;

- **All-call reply (DF 11)** is the reply sent by Mode S compliant transponders to queries addressed to Mode A/C capable transponders. It contains the 24-bit transponder code, the transponder capabilities [5], and the interrogator identifier;

- **ACAS short and long replies (DF 0/16)**: **Airborne Collision Avoidance System (ACAS)** is a system designed to reduce the risk of mid-air collisions and near mid-air collisions between aircraft. In particular **Resolution Advisories (RA)** generate particular messages (DF16) which can be used to find about past RA alerts [6].
  Details of the protocol are described here.

- **Comm-B, with altitude and identity replies (DF 20/21)**: this protocol supports a large number of different types of messages, defined by **BDS (Comm-B Data Selector)** codes. **Mode S Enhances Surveillance (EHS)** accounts for a handful of BDS codes of particular interests:

  - **BDS 4,0 – Selected vertical intention**, with information about *selected altitude* in the autopilot, barometric pressure setting, and *navigation modes*;
  - **BDS 5,0 – Track and turn report**, with information about the *roll angle*, *true track angle rate* and *true airspeed (TAS)* in addition to ground speed and true track angle information also defined in ADS-B;
  - **BDS 6,0 – Heading and speed report**, with information about *magnetic heading* of the aircraft, *indicated airspeed (IAS)*, *barometric altitude rate* and *inertial vertical velocity* (in feet per minute)

Coupling BDS 5,0 (for the TAS, the true track angle and the ground speed – the two last entries are also present in ADS-B) with BDS 6,0 (for magnetic heading) and can be used to recompute the apparent wind seen by the aircraft.
Magnetic declination must be taken into account.

Tip

ADS-B messages also belong to the Mode S protocol, in the **Extended Squitter (ES)** category (BDS 0,5 through to 0,9). Only Extended Squitter messages (ADS-B) are broadcast, i.e., they are not the result of SSR interrogations.

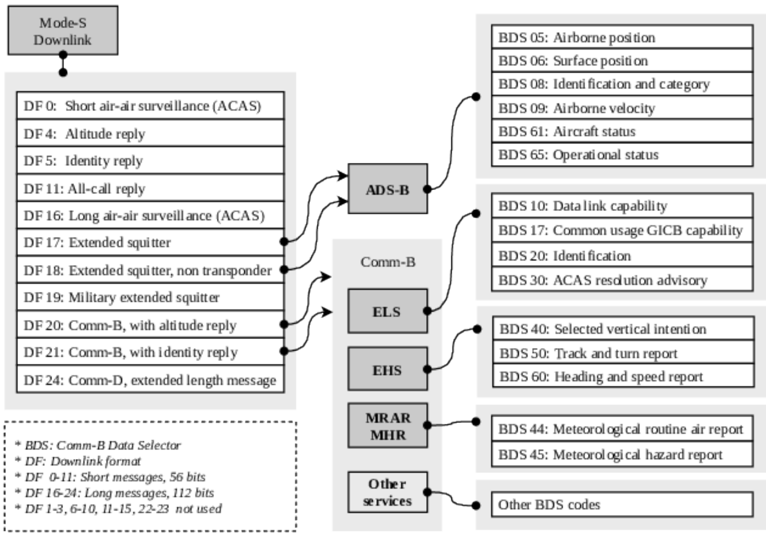


Figure 9.2.: An overview of all Mode S services, excerpt from www.mode-s.org [3]

9.4. ADS-C

Born from the challenges of managing growth in aviation, the International Civil Aviation Organization in 1983 initiated a committee to align emerging technologies with growing air transport needs. By 1987, the committee found issues with the prevailing navigation systems, including communication limitations and the lack of digital links. The answer was satellite technology integration.

This led to the idea of creating a Future Air Navigation System (FANS), comprising several new technologies including the **Automatic Dependent Surveillance–Contract** (ADS-C) system. ADS-C addresses the constraints of High Frequency and Very High Frequency communication through satellite data links, enabling surveillance in remote locations. It also minimizes voice communication by sending automatic position updates digitally. By 1991, manufacturers started adopting FANS technology. Boeing introduced FANS-1, while Airbus presented FANS-A. Both of these were later merged into the widely-used FANS-1/A.

The term **Contract** means that aircraft and ATSUs negotiate agreements to share data. While aircraft can establish concurrent contracts with multiple ATSUs, messages are exclusively exchanged between the aircraft and the ATSU with which a particular contract was established. This differs from ADS-B, where aircraft indiscriminately broadcast messages to everyone.

All surveillance data from the aircraft is sent via contracts. To negotiate such a contract, the ATSU sends a contract request, containing information regarding the surveillance data the ATSU wants to receive, to an aircraft. The aircraft then responds to a contract with a positive acknowledgement and the appropriate report. In case of an error, the aircraft responds with a negative acknowledgement (if the message cannot be parsed), or a non-compliance notification (if the request contains data that is not available to the aircraft).

The type of contract then defines what information the aircraft will return to the ATSU:

- **Periodic contract**: With this contract type, an ATSU can request ADS-C reports at a specified reporting interval with following data: flight ID, predicted route, earth reference, meteorological data, airframe ID, air reference, and aircraft intent.
- **Event contract**: Whenever an event contract is established, the aircraft sends reports in the case a given event occurs. It can be requested in case of the following events: vertical range change, altitude range change, waypoint change, and lateral deviation.
- **Demand contract**: In the case of a demand contract, an aircraft only sends a single report. This can be useful, when a periodic report is not received in time.

Every ADS-C report comprises, at a minimum, a basic report detailing the aircraft's position, accompanied by a timestamp and a figure of merit. The figure of merit denotes the precision of the positional information within the report and the operational status of TCAS. Advanced reports encompass extra data as stipulated in the ADS-C contract.

9.5. UAT

Universal Access Transceiver (UAT) is a technology similar to ADS-B which operates on 978 MHz instead of 1090 MHz for ADS-B Extended Squitter (ES).

The FAA has been encouraging General Aviation aircraft to equip with UAT compliant transponders for slightly cheaper than ES transponders in order to decongestionate the 1090 MHz frequency in the US. The 2020 Mandate allows aircraft to be equipped with UAT transponders if they remain **within the US borders** and **below 18,000 feet**.

As a consequence, UAT messages can only be received by receivers located in the United States or near their borders.

9.6. FLARM

FLARM (a portmanteau of “flight” and “alarm”) is, with TCAS, one of the most widespread technologies for **traffic awareness and collision avoidance**. It is a system used to prevent potential aviation collision and to raise awareness of the pilot, initially tailored for **light aircraft, such as gliders, light aircraft, rotorcraft, and drones**. FLARM obtains its position and altitude readings from an internal GPS (or potentially other GNSS) and a barometric sensor, then broadcasts these together with forecast data about the future 3D flight track, calculated considering its speed, acceleration, track, turn radius, wind and other parameters. This is imperative for smaller lighter (even wind-powered) aircraft.

At the same time, the receiver listens for other FLARM devices within range and processes the information received. Upon receiving such messages, the FLARM system may issue alarms to alert the pilot or show the relative position if other aircraft are within detection range.

The wireless nature of FLARM allows for the reception of signals in a crowdsourced fashion. Although the FLARM radio protocol features message encryption in order to ensure integrity and confidentiality, implementation and encryption keys are available:

- The Open Glider Network (OGN) maintains a tracking platform with the help of many receivers, mostly collocated with flying clubs operating light aircraft at local airfields.
- The OpenSky Network also collects FLARM raw messages, with data accessible to institutional researchers.

FLARM devices are based on the nRF905 chip. Depending on the geographical area they operate in, they transmit in the SRD860 band or in the ISM-band that can be used freely.

- In Europe, Africa and Asia, the two frequencies **868.2 MHz and 868.4 MHz** are used, sending one to two messages per second per frequency. On 868.2MHZ, it transmits from 0.4s to 0.8s; On 868.4MHZ, it transmits from 0.4s to 1.2s.
- In the Americas, Oceania and Israel **another undisclosed frequency hopping scheme** is in place, in order to comply with local regulations.

Information contained in FLARM messages contains:

- the **device address**, a unique identifier, similar to the 24-bit transponder code. *In general,* if the aircraft is also equipped with a transponder, the same identifier is used;
- the **aircraft type**: glider, tow-plane, helicopter, parachute, parachute drop-plane, hangglider, paraglider, UAV, balloon, etc.;
- **positional information**: *latitude* and *longitude* in degrees, *GPS altitude* **in meters**;
- **velocity information**: *horizontal* and *vertical speeds.*

As FLARM is a proprietary product, there is little public information about the exact inner workings of the trajectory prediction algorithm that powers the collision alert function. One version has been developed by ONERA in France and been licensed to FLARM Technology Ltd [7]. At a high level, the documentation [8] describes it as follows: The device calculates its own predicted flight path for about the next 20 seconds. This prognosis is based on immediate past and current vectors, including but not limited to aircraft type, speed, vertical speed, turning radius etc. In addition, it uses a movement model that has been optimized for the respective user.

According to the manual of PowerFLARM Fusion [8], there are three levels of warnings with different types of annunciations: The first warning is issued around 18 seconds before impact, the second warning is issued around 12 seconds before impact and the third warning is issued around 8 seconds before impact. The warning is active as long as the collision risk remains and will change accordingly.

10. Aircraft information

Xavier Olive

A number of flight information is usually not directly accessible from settings recording aircraft trajectories. Metadata usually refers to any additional information enriching a trajectory. Enriching trajectories with relevant information is usually a costly process, and access to such information can be complicated.

10.1. ICAO identifiers

The most common identifier for aircraft in radar based technologies would be the identifier of the transponder: a **six-digit hexadecimal identifier**, i.e. an integer written in its hexadecimal form, which classically identifies an aircraft uniquely. In the remaining of the book, it is commonly referred as the *ICAO identifier*, or `icao24` in data records (24 standing for the number of bits encoding the integer).

Ranges of addresses are reserved per countries, who are free to assign addresses to aircraft registered by their authorities. All US registered aircraft get an address in the `0xa00000` to `0xafffff` range; in Europe, France gets `0x380000` to `0x3bffff`, Germany gets next interval from `0x3c0000` to `0x3fffff`, then the UK gets `0x400000` to `0x43ffff`, etc.

⚠ Are ICAO addresses unique?

Yes and no. In practice, **for most short-term analyses**, we can consider the answer is yes.
However, an aircraft may get a different transponder identifier when she gets a different registration. This

may happen when the aircraft is sold to new owners who want to register their aircraft in a different country. Then, after the aircraft gets a new registration, her old identifier can be reassigned to new aircraft.
Also, most aircraft manufacturers keep a small set of transponders that they reuse across many newborn aircraft for test flights. Those usually correspond to temporary registration numbers.
To sum up, it is safer to keep in mind that:

- the same aircraft can have different ICAO identifiers throughout her life;
- the same identifier can refer to different aircraft depending on the day we get data from her.

10.2. Tail numbers

The tail number is the number usually written on the back side of the aircraft, like the license plate number of cars, but for aircraft. Tail numbers also follow a pattern per country: `F-` for France, `D-` for Germany, `G-` for the UK, with some recognised patterns for specific categories of aircraft. Every country is free to decide how to assign registrations to aircraft within their range, and to give them a tail number accordingly. In some countries, like the US, Japan or Korea, there is a direct correspondence between tail numbers and ICAO identifiers, but that's not the case in every country.

In the US, tail registrations start with the N letter (they are also called N-numbers) and are followed by up to 5 numbers, or up to 4 numbers and 1 letter, or 3 numbers and 2 letters. Letters I and O are excluded. Then there is a *"direct"* correspondence with transponder addresses: `0xa00001` for `N1`, `0xa00002` for `N1A`, `0xa00003` for `N1AA` then `0xa00004` for `N1AB` until `0xadf7c7` fort `N99999`.

What is the PIA program?

To address privacy concerns, FAA has initiated the Privacy ICAO aircraft address (PIA) program to improve the privacy of the eligible US-registered aircraft, ADS-B equipped and flying in the domestic US airspace. Recent research [9] have shown this attempt is vain as it is very easy to break the anonymization and find which PIA address (between N41000 `0xa4d691` and N42 `0xa4f946`) is associated to which aircraft.

Table 10.1 illustrates some examples of patterns in registrations numbers assigned by countries. In the Netherlands, KLM matches the two first letters after the country code to aircraft types.

Table 10.1.: Some countries reserve registration patterns to specific categories of aircraft.

country	range		pattern	category
France	`380000`	`3bffff`	F-	
			F-A	Historic aircraft
			F-C	Gliders
			F-J	Ultralights
			F-W	Test and Delivery
			F-Z	State owned
Switzerland	`4b0000`	`4b7fff`	HB-	
			HB-B	Balloons
			HB-F	Produced in Switzerland
			HB-X or Z	Helicopters
The Netherlands	`480000`	`487ffff`	PH-	
			PH-AO	KLM Airbus A330
			PH-BH	KLM Boeing 787-9
			PH-BK	KLM Boeing 787-10
			PH-BQ	KLM Boeing 777-200

10.3. Aircraft type designators

DOC 8643 - Aircraft Type Designators by ICAO contains designators for aircraft types which are most commonly provided with air traffic service (ATS).

Each designator consists of a 4-letter code associated with a manufacturer and an aircraft type, e.g., `A320` for Airbus A320, `B78X` for Boeing 787-10 or `E190` for Embraer 190. More specific designators can be used for balloons `BALL` or gliders `GLID`.

This designator is often referred as `typecode` in aircraft databases and helps associating an aircraft type to an ICAO identifier.

10.4. Data sources

Maintaining a data base of transponder identifiers, aircraft tail numbers, type designators, owners and/or operators is a very cumbersome process. New aircraft are manufactured every month, which generates new transponder identifiers [10]. Some countries keep a database of their registered aircraft public (e.g. FAA (US), France, Switzerland or The Netherlands), but this is not a systematic practice in every country, and those do not always contain the transponder identifier.

There have also been some crowdsourcing effort to constitute and maintain aircraft databases based on various open records and entries on social networks. Such databases raise some privacy concerns among some aircraft owners, who may be tempted to vandalise those databases [11].

Some public aircraft databases:

- The OpenSky Network aircraft database contains several hundreds of thousands of airframes;
- Flightradar24 give access to an interface to search for individual aircraft;
- The website www.airframes.org, but they are very strict about their terms of use;
- Some Regional Monitoring Agencies (RMA) provide open access to data matching aircraft registered in their area, specifically in Europe or in the Middle-East.

11. Flight plans and trajectories

Enrico Spinielli

EUROCONTROL's Network Manager has devised different flight trajectories formats in order to store and exchange information with the aviation community. Trajectories are recorded as either a sequence of 4D positions (3D plus timestamp) or like a sequence of 4D segments.

In the following sections we will cover the most known formats: M1 (& M2) & M3, ALL_FT+ and SO6.

They are a mix of flight information (ADEP, ADES, callsign, …) and trajectory (4D position, ground speed, …).

11.1. Model 1 (M1 or *FTFM*)

The flight trajectory known as *Model 1*, *M1* or *Filed Tactical Flight Model (FTFM)* is a mathematical model containing a point and airspace volume profile created in ETFMS for a flight. This trajectory is first created when Flight Plan (FPL) details, and any subsequent changes, are received by the Network Operations of EUROCONTROL's Network Manager[1].

[1] Aircraft Operators (AO) willing to fly IFR flights in the Network Manager (NM) area of responsibility are mandated to file the relevant Flight Plan to the Network Manager. The aim of this centralised management of FPL's in Europe is linked to one of the NM mandates, i.e. the ability to detect imbalance between demand (willingness to fly by AO's) and offer (ability to guarantee safety by ATC / airport capacity providing an adequate level of safety). The NM provides the ACC's/airports to monitor the situation and implement measures to resolve the overload (typically via departure delays or rerouting.)

The M1 is a translation of a FPL (especially Field 15) to a point profile, i.e. a sequence of 4D positions (timestamp + longitude, latitude, altitude) plus relevant penetrated airspace ID's, calculated taking into account the aircraft type performance (via BADA) and the environment restrictions as published in the Route Availability Document (RAD).

> **i** Note
>
> **TODO**
>
> 1. add CSV file with sample M1 data in `data/` folder
> 2. Add small sample of data frame for M1
> 3. Plot M1

11.2. Model 2 (M2 or *RTFM*)

An updated version of the M1 when the flight is regulated (i.e. delayed.) This trajectory could be more than a shift in time because of the impact of possibly closed areas or route segments in the new time window of the flight.

11.3. Model 3 (M3 or *CTFM*)

The flight trajectory known as *Model 3*, *M3* or *Current Tactical Flight Model (CTFM)* is an updated version of the M1 model (or eventually M2) where the point/airspace profile is recalculated taking into account surveillance data (*Correlated Position Reports* [CPR][2] or more recently ADS-B position reports) when these show a significant deviation from M1 (or M2.) The deviation considered is of 1 min in time, more than 400 feet in en-route phase, more than 1000 feet in climb/descent phase or more than 10 NM laterally, see 14.3.1 [12].

[2]CPRs are received by NM from ACC's, they consist of surveillance data (callsign longitude, latitude, altitude, timestamp) paired with flight plan info (aircraft type, ICAO 24-bit address)

ℹ Note

TODO

1. add CSV file with sample M3 data in `data/` folder
2. Add small sample of data frame for M3
3. Plot M3 and M1/M3 overlapped to show the differences

11.4. SO6

The SO6 format delivers a flight segment sequence from origin to destination.

#	Field	Type	Size	Comment
1	segment identifier	char		first point name "_" last point name
2	origin of flight	char	4	ICAO code
3	destination of flight	char	4	ICAO code
4	aircraft type	char	4	
5	time begin segment	num	6	HHMMSS
6	time end segment	num	6	HHMMSS
7	FL begin segment	num	1 to 3	
8	FL end segment	num	1 to 3	
9	status	char	1	0=climb, 1=descent, 2=cruise
10	call sign	char		
11	date begin segment	num	6	YYMMDD
12	date end segment	num	6	YYMMDD
13	lat begin segment	float		decimal minute
14	lon begin segment	float		decimal minute

#	Field	Type	Size	Comment
15	lat end segment	float		decimal minute
16	lon end segment	float		decimal minute
17	flight identifier	num		must be unique
18	sequence	num		start at 1 for every new flight
19	segment length	float		nautical miles
20	segment parity	num		0=NO, 1=ODD, 2=EVEN, 3=ODD_LOW, 4=EVEN_LOW), 5=ODD_HIGH, 6=EVEN_HIGH, 7=General Purpose Red , 8=General Purpose Orange , 9=General Purpose Yellow

The parity decides flight level allocation: Odd levels are FL290,310,330… and Even levels are FL280,300,320 …

11.5. ALL_FT+

ALL_FT+ files are available via DDR2 and typically follow a naming convention like `yyyyMMdd.ALL_FT+`, i.e. `20231124.ALL_FT+.7z` for data covering November 24th 2022.

The content of an ALL_FT+ file is quite *massive*, at the time of this writing for version 7 contains 207 columns! ALL_FT+ is clearly an internal NM systems archiving format that has been plainly exchanged.

Documentation and metadata is sparse even from the DDR2 manual or NEST help pages.

> **Note**
>
> TODO this part could help?

Data for a trajectory refer typically to a point profile and can include:

- flight ID / flight number / callsign
- sequence number
- timestamp
- position (longitude, latitude, altitude)
- position ID (i.e. published point ID)
- airspace ID
- (ground / vertical) speed

with timestamp and position as a minimum.

11.6. Flight route

Example: N0441F340 FISTO5B FISTO UY156 PERIG UT210 TUDRA/N0426F280 UT158 AMB AMB9W

11.7. DDR2 `exp2`

The traffic demand file (exp2) can obtained from the EUROCONTROL's Demand Data Repository (DDR2) for a selected period of time (typically one day) and geographic area (e.g. FABEC). The `exp2` includes, for each flight, basic information about the departure time, the origin and destination airports, a unique flight identifier, the callsign, the aircraft ICAO code (e.g. A320) and the requested flight level by the airspace user as submitted in the flight plan.

12. Aeronautical information

> **Tip**
>
> Author: ?

Author's note: This part goes through all the most commonly used data formats in the aviation and ATM data analysis community.

Airspaces & / or aeronautical information in general (AIRAC):

- airport information:
  - ARP
  - runway thresholds
  - parking positions]
- Published Points
- Routes
- SID / STAR
- …

Fatal events both en-route (mid-air collisions) and on the ground (landing or crashes) are at the origin of modern Air Traffic Control. In particular, flight plan filing was devised as a means to let controllers know where an aircraft was supposed to be and eventually be able to deconflict its trajectory with other flights nearby. The flight plan together with latest position reports was (and still is) the best information available to eventually launch search and rescue operations.

In principle, a flight plan could simply be a list of 4D coordinates (3D + time), but it surely was computationally and practically difficult to use it as such by ATC controllers who had to manually follow up airborne flights. So the en-route network was designed to have fixed and limited paths to follow. In doing so the probability of conflicts was increased but at the same time such network improves the efficiency in spotting them.

12.1. Airports, Points and Routes

TODO

- Check nomenclature, i.e. Significant Point, ...
- References:
  - ICAO Doc 4444
  - Rules of the Air https://www.pilot18.com/wp-content/uploads/2017/10/Pilot18.com-ICAO-Annex-2-Rules-of-air.pdf
  - https://skybrary.aero/articles/waypoint
  - https://www.skybrary.aero/articles/ats-route
  - EUROCONTROL HMI:
    1. NVA Navigation Aid
    2. PWP Published Way Point
    3. ICP Internal Point
    4. GEO GEO Point
    5. RFP Reference Point
    6. RAD RADAR Point
    7. TER Terminal Point
    8. BDY Boundary Point
    9. DME Distance Measuring Equipment
    10. VOR VHF Omni-directional radio Range
    11. VOR_DMEco-located VHF Omni-directional radio Range and Distance Measuring Equipment
    12. VOR_DME_NDB co-located VHF Omni-directional radio Range, Distance Measuring Equipment and Non-Directional Beacon
    13. VORTAC co-located VHF Omni-directional radio Range and TACtical Air Navigator
    14. DVOR Doppler VHF Omni-directional radio Range

15. DVOR_DME co-located Doppler VHF Omni-directional radio Range and Distance Measuring Equipment
16. DVOR_DME_NDBco-located Doppler VHF Omni-directional radio Range, Distance Measuring Equipment and Non-Directional Beacon)
17. DVORTAC co-located Doppler VHF Omni-directional radio Range and TACtical Air Navigator
18. ILS Instrument Landing System
19. ILS_DME co-located Instrument Landing System and Distance Measuring Equipment
20. ILS_LLZ co-located Instrument Landing System and Localizer
21. ILS_LLZ_DME co-located Instrument Landing System, Localizer and Distance Measuring Equipment
22. LLZ Localizer
23. LLZ_DME co-located Localizer and Distance Measuring Equipment
24. L Locator
25. LI Inner Locator
26. LM Middle Locator
27. LO Outer Locator
28. L_DME co-located Locator and Distance Measuring Equipment
29. MLS Microwave Landing System
30. NDB Non-Directional Beacon
31. NDB_DME co-located Non-Directional Beacon and Distance Measuring Equipment

The aviation route network is characterized by the definition of geographical points, waypoints, and segments connecting them, route segments.

12.2. Airspaces

TODO

- different types of airspaces
  - from EUROCONTROL CHMI:
    a) SECTOR ES Elementary Airspace Sector
    b) SECTOR CS Collapsed Sector
    c) AUA ATC Unit Airspace
    d) CLUSTER Airspace Cluster
    e) SECTOR CONFIGURATION Sector Configuration
    f) AUAGATC Unit Airspace Group
    g) REGION Region
    h) IR Information Region
    i) NAS National Airspace
    j) AREA Area
    k) ERSA Elementary Restricted Airspace
    l) CRSA Composed Restricted Airspace
    m) AOI Area of Interest
    n) AOP Area of Protection
    o) ERAS Elementary Regulated Airspace
    p) CRAS Composed Regulated Airspace
    q) AIRBLOCK Airblock
  - from Skybrary: https://skybrary.aero/articles/classification-airspace

13. Weather, climate and environment

Tip

Author: Enrico, Junzi, (maybe Esther?)

Note

Author's note: This part goes through all the most commonly used data formats in the aviation and ATM data analysis community.

- METAR
- SIGMET
- Weather, atmosphere
- noise

14. Aircraft performance

Tip

Author: Junzi

Note

Author's note: This part goes through all the most commonly used data formats in the aviation and ATM data analysis community.

Here are some references for BADA **nuic2010?**, OpenAP [13], [13],

Aircraft performance models are used to study how aircraft fly. They are based on the laws of physics and can be used to predict the aircraft's speed, altitude, thrust, drag, and fuel consumption. There are different categories of performance models, with varying levels of detail. The most detailed, nonlinear six-degree-of-freedom models are commonly used in aircraft control studies. Air traffic management research often assumes a stable aircraft and neglects fast rotational dynamics. This assumption means that a point-mass aircraft performance model is sufficient in most use cases. Such a point-mass model is used throughout this entire dissertation.

There are two different types of point-mass models: kinematic and dynamic. The primary difference is that while a dynamic model focuses on forces and energy, a kinematic model deals only with aircraft motions.

A well-know aircraft performance model, BADA **nuic2010?**, is developed by Eurocontrol. It inlcuded both kinematic and dynamic models. The BADA aircraft performance operation file (OPF) models the dynamic properties of the aircraft, while the airline procedures file (APF) models the kinematic aspects of flights.

Unlike BADA model that relies on strict user license agreement, OpenAP [13], [13], a recent open aircraft model also provide both kinematic and dynamic models for common aircraft types.

14.1. Kinematic model

The kinematic model is a simplified way of describing aircraft motion without considering the forces involved. It is commonly used to analyze the motion of an aircraft during various flight phases, including takeoff, initial climb, climb, cruise, descent, final approach, and landing. For example, the General Aircraft Modelling Environment (GAME) **calders2002?**, a very early model also developed by Eurocontrol, is another example of a kinematic performance model.

The kinematics of aircraft motion varies across different flight phases. Fortunately, we can directly observe essential parameters such as velocity, altitude, acceleration, and range using aircraft surveillance data. By leveraging openly accessible ADS-B data, we can construct accurate models, as demonstrated in the OpenAP kinematic model **sun2019wrap?**.

This approach enables us to gain valuable insights into the behavior and performance of aircraft during each flight phase. Therefore, the use of ADS-B data in constructing kinematic models is a powerful tool for analyzing and improving flight operations.

> **i Note**
>
> OpenAP kinematics table here

> **i Note**
>
> BADA APF

14.2. Dynamic model

When aircraft forces are taken into account, a more complex model is required to accurately describe the aircraft's performance compared to what a kinematic model can provide.

n air traffic management-related studies, the total energy model is commonly used to describe the aircraft's behavior. This model takes into account the conservation of total energy generated by the aircraft's engines to counteract drag and the change of kinetic and potential energy. This model is especially useful for trajectory based studies, like optimization and fuel estimations.

The main components of the dynamic model are thrust, drag, and mass of the aircraft. Thrust represents the force generated by the aircraft's engines, while drag represents the force that opposes the motion of the aircraft through the air. Mass refers to the total weight of the aircraft, including fuel and passengers.

> **Note**
>
> total energy equation + force figure

> **Note**
>
> BADA OPF

> **Note**
>
> OpenAP YAML

14.2.1. Thrust

Thrust is produced by the engines of the aircraft, and modeling aircraft engine performance is a complicated research area. In air traffic management studies, the thrust model is simplified. Instead of trying to model the performance of engines, we are interested in the net force that is produced by the aircraft in different stages of the flight. For example, in BADA v3, thrust is modeled as a polynomial model related to the aircraft altitude.

Aircraft thrust is a parameter that cannot be derived using surveillance data. We have to rely on open models that are created by other researchers. In OpenAP, an empirical model for two-shaft turbofan engine thrust calculation proposed by **bartel2008?**. The model is constructed and evaluated based on real engine performance data. Thus, in this dissertation, thrust is modeled as functions of both altitude and speed, as well as the vertical rate. This offers a more accurate interpolation than the BADA v3 model, in which the thrust is only dependent on aircraft altitude.

14.2.2. Drag

drag polar models, how to estimate them, sample figures from OpenAP

14.2.3. Mass

aircraft mass, why it is hard to find, and how to estimate them

14.3. Other models

ECAC Doc 29 [16]

Piano-X

In-house models [17], [18]

15. An overview of open datasets for aviation

> **Tip**
>
> Author: ?

> **Note**
>
> **Author's note**: This part presents popular frameworks of data analytics and digs into the insides of aviation commonly used data formats, accessible data sources (open or not), together with basic programming literacy for exploring such datasets.

Part III.

Process data

16. The tidy data paradigm

> **Tip**
>
> Author: Enrico, ?

> **Note**
>
> **Author's note**: This part introduces more advanced mathematical and programming skills. The tidy paradigm to manipulate data frames is introduced. Challenges associated with geometrical shapes, geographical coordinates, trajectories, projections are presented, before introducing common AI tools for information extraction, prediction and optimisation.
> Examples in R, Javascript, Python

See [19] and possibly database normalization. See also Chapter 12 of [20].

- concept
- examples in various frameworks
  - R: dplyr, tidyr
  - Python: pandas (?)
  - Javascript: tidy.js, tidy data at Observable

17. Processing geometric and geographical data

> **Tip**
>
> Author: ?

> **Note**
>
> **Author's note**: This part introduces more advanced mathematical and programming skills. The tidy paradigm to manipulate data frames is introduced. Challenges associated with geometrical shapes, geographical coordinates, trajectories, projections are presented, before introducing common AI tools for information extraction, prediction and optimisation.

18. Processing aircraft trajectories

Tip

Author: Xavier

Note

Author's note: This part introduces more advanced mathematical and programming skills. The tidy paradigm to manipulate data frames is introduced. Challenges associated with geometrical shapes, geographical coordinates, trajectories, projections are presented, before introducing common AI tools for information extraction, prediction and optimisation.

19. Information extraction

> **Tip**
>
> Author: Xavier

go around detection

landing and takeoff detection

flight phases

holding pattern, etc.

Part IV.

Visualise Data

20. The art of storytelling

Tip

Author: ?

Note

Author's note: This part turns to the data visualisation aspects. It explains how to choose the most appropriate tool to convey a message with particular focus on geographical information.

21. Grammar of graphics

Tip

Author: ?

Note

Author's note: This part turns to the data visualisation aspects. It explains how to choose the most appropriate tool to convey a message with particular focus on geographical information.

Some references [21] and [22], as well as some implementations in R [23], Python [24] and Javascript [25].

22. Produce meaningful maps

> **Tip**
>
> Author: ?

> **Note**
>
> **Author's note**: This part turns to the data visualisation aspects. It explains how to choose the most appropriate tool to convey a message with particular focus on geographical information.

Part V.

Share Data

23. Reproducible research

Aviation like many other scientific domains suffers for lack of data openness and lack of reproducibility of published research [26]. Many reasons are made up not to disclose data, the main ones being sensitivity and ownership.

24. Produce meaningful maps

Tip

Author: Enrico, ?

Note

Author's note: The most overlooked aspect of data analysis probably turns around data sharing. Data curation is often a very time consuming process and enriching data by labelling specific tags or merging several sources of information brings additional value to a dataset. This part deals with the data sharing and publication process. (paper reproducibility?)

Introduction about reproducible research. This would also include sharing the code beyond the dataset cleaning to producing related summaries, tables/graphics, etc.

1. **Good practices for producing a clean dataset** > #include and use some of the datasets in 'traffic' / Zenodo / > … these could be used in the examples in the book (and it would > be great to explain how to arrive to a clean dataset)
2. **Issues around dataset sharing** > open data, licensing, etc.?

References

[1] M. Capderou, *Handbook of Satellite Orbits: From Kepler to GPS*. Cham: Springer International Publishing, 2014.

[2] D. J. Diston, *Computational modelling and simulation of aircraft and the environment*. Chichester, U.K: Wiley, 2009.

[3] J. Sun, *The 1090 Megahertz Riddle: A Guide to Decoding Mode S and ADS-B Signals*. 2021.

[4] X. Olive *et al.*, "OpenSky Report 2020: Analysing in-flight emergencies using big data," 2020, doi: 10.1109/DASC50938.2020.9256787.

[5] J. Sun, H. Vû, X. Olive, and J. Hoekstra, "Mode S Transponder Comm-B Capabilities in Current Operational Aircraft," Nov. 2020, doi: 10.3390/proceedings2020059004.

[6] M. Schafer, X. Olive, M. Strohmeier, M. Smith, I. Martinovic, and V. Lenders, "OpenSky Report 2019: Analysing TCAS in the Real World using Big Data," Sep. 2019, doi: 10.1109/DASC43569.2019.9081686.

[7] C. Le Tallec and B. Gravier, "Device for improving the security of aircraft in visual flight regime," WO 00/02176, Jan. 2000.

[8] F. Technology, "PowerFLARM Fusion User and Maintenance Manual," 2021. [Online]. Available: https://flarm.com/wp-content/uploads/man/FTD-078-PowerFLARM-Fusion-User-and-Maintenance-Manual.pdf.

[9] G. Michel and M. Strohmeier, "Flying in Private Mode: Understanding and Improving the Privacy ICAO Address Program," *Journal of Aerospace Information Systems*, pp. 1–9, May 2021, doi: 10.2514/1.I010938.

[10] J. Sun, X. Olive, M. Strohmeier, M. Schafer, I. Martinovic, and V. Lenders, “OpenSky Report 2021: Insights on ADS-B Mandate and Fleet Deployment in Times of Crisis,” 2021, doi: 10.1109/DASC52595.2021.9594361.

[11] M. Strohmeier, X. Olive, and J. Sun, “Evading the Public Eye: On Astroturfing in Open Aviation Data,” Nov. 2022, doi: 10.3390/engproc2022028007.

[12] S. Niarchakou and J. Simón Selva, “ATFCM Operations Manual,” Network Manager, EUROCONTROL, 21.0, May 2017. [Online]. Available: http://bit.ly/2zvRCSG.

[13] J. Sun, J. M. Hoekstra, and J. Ellerbroek, “OpenAP: An open-source aircraft performance model for air transportation studies and simulations,” *Aerospace*, vol. 7, no. 8, p. 104, 2020, doi: 10.3390/aerospace7080104.

[14] ECAC/ECEA, *Report on Standard Method of Computing Noise Contours around Civil Airports: Applications Guide*, 4th ed., vol. 1. 2016.

[15] ECAC/ECEA, *Report on Standard Method of Computing Noise Contours around Civil Airports: Technical Guide*, 4th ed., vol. 2. 2016.

[16] ECAC/ECEA, *Report on Standard Method of Computing Noise Contours around Civil Airports: Part 1 - Reference Cases and Verification Framework*, 4th ed., vol. 3. 2016.

[17] D. I. A. Poll and U. Schumann, “An estimation method for the fuel burn and other performance characteristics of civil transport aircraft during cruise: Part 2, determining the aircraft’s characteristic parameters,” *The Aeronautical Journal*, vol. 125, no. 1284, pp. 296–340, 2021, doi: 10.1017/aer.2020.124.

[18] D. I. A. Poll and U. Schumann, “An estimation method for the fuel burn and other performance characteristics of civil transport aircraft in the cruise. Part 1 fundamental quantities and governing relations for a general atmosphere,” *The Aeronautical Journal*, vol. 125, no. 1284, pp. 257–295, 2021, doi: 10.1017/aer.2020.62.

[19] H. Wickham, “Tidy Data,” *Journal of Statistical Software*, vol. 59, no. 10, pp. 23–23, Sep. 2014, [Online]. Available: http://www.jstatsoft.org/v59/i10.

[20] H. Wickham and G. Grolemund, *R for data science*. O'Reilly Media, 2017.

[21] L. Wilkinson, *The Grammar of Graphics*, 2nd ed. Springer-Verlag New York, Inc., 2005.

[22] H. Wickham, "A layered grammar of graphics," *Journal of Computational and Graphical Statistics*, vol. 19, no. 1, pp. 3-28-3-28, 2010, doi: 10.1198/jcgs.2009.07098.

[23] H. Wickham, D. Navarro, and T. L. Pedersen, *Ggplot2: Elegant Graphics for Data Analysis*, Third (under work). Springer-Verlag New York, 2022.

[24] J. VanderPlas *et al.*, "Altair: Interactive statistical visualizations for python," *Journal of Open Source Software*, vol. 3, no. 32, p. 1057, 2018, doi: 10.21105/joss.01057.

[25] A. Satyanarayan, D. Moritz, K. Wongsuphasawat, and J. Heer, "Vega-lite: A grammar of interactive graphics," *IEEE transactions on visualization and computer graphics*, vol. 23, no. 1, pp. 341–350, 2017.

[26] M. Bourgois and M. Sfyroeras, "Open Data for Air Transport Research: Dream or Reality?" in *Proceedings of The International Symposium on Open Collaboration - OpenSym '14*, 2014, pp. 1–7, doi: 10.1145/2641580.2641602.

[27] "Traffic library documentation." [Online]. Available: https://traffic-viz.github.io/.

Authors

Xavier Olive
Toulouse
xo@example.com

Junzi Sun
Delft
js@example.com

Enrico Spinielli
Brussels
es@example.com

Manuel Waltert
Winterthur
mw@example.com

Xavier Olive

Xavier graduated from Supaero, Université de Toulouse, France and holds a PhD from Kyoto University, Japan. He is currently a research scientist, passionate about aviation, maps and data. His research interests include Data Science, Machine Learning and Decision Science applied to aviation, with a particular focus on optimisation, anomaly and pattern detection applied to air traffic management, operations, predictive maintenance, safety analyses and risk assessment. Xavier also teaches artificial intelligence and advanced programming in Python to graduate students.

He is the main author of the open-source traffic [27] Python library, and of the book Programmation Python avancée (in French) with Dunod editions.

Junzi Sun

Scelerisque metus nisi tristique eleifend diam neque dignissim leo dis purus felis a et sollicitudin nulla lobortis eleifend dapibus montes maecenas metus proin ultricies imperdiet litora ultrices pharetra mauris senectus neque potenti potenti duis?

Enrico Spinielli

Tincidunt orci hac accumsan vel odio convallis dictum sodales ac maecenas placerat rhoncus rutrum felis ut id placerat praesent ultrices himenaeos urna dictum pretium convallis erat venenatis tortor inceptos ut suscipit senectus malesuada.

Manuel Waltert

Tincidunt orci hac accumsan vel odio convallis dictum sodales ac maecenas placerat rhoncus rutrum felis ut id placerat praesent ultrices himenaeos urna dictum pretium convallis erat venenatis tortor inceptos ut suscipit senectus malesuada.

A. More information

This will be Appendix A.

A.1. The history of longitude

Knowledge of both latitudes and longitudes are crucial to both cartography and navigation. Latitudes have been relatively easy to determine with a reasonable precision by observing the stars in the sky and measuring their altitudes (angles of elevation). In 3rd century BC, Erathostenes of Cyrene estimated the radius of Earth after he measured a difference of latitudes of 7.2° (the fiftieth part of 360°) between Alexandria and Syene based on the Sun position.

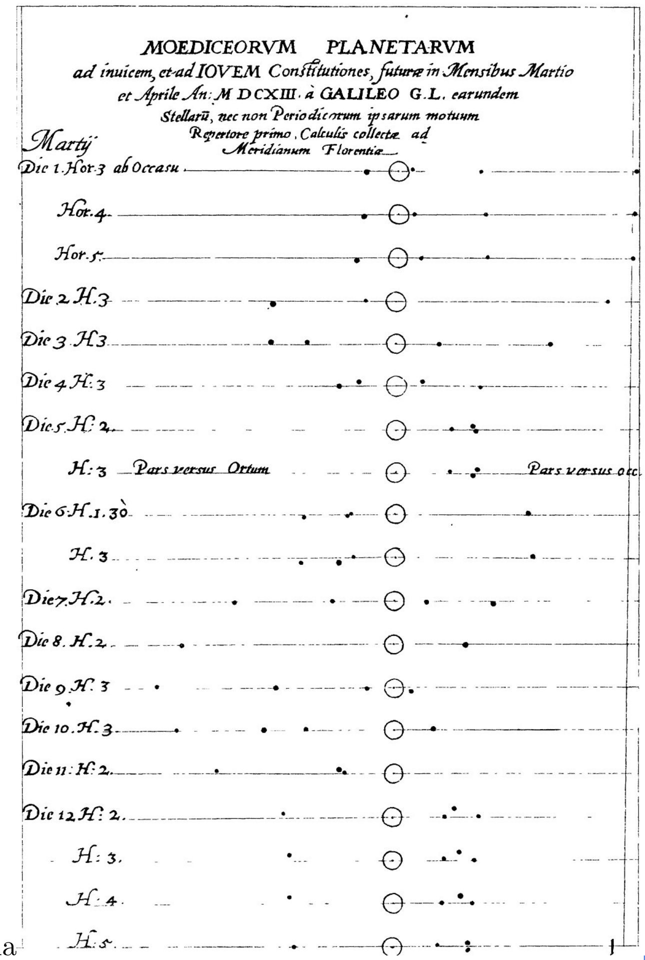
On the other hand, the precise measurement of longitude took centuries of studies, with serious advances coming with the development of telescopes and accurate clocks.

Gemma Frisius, a Dutch mathematician, first suggested travelling with a clock to determine longitudes in the 16th century. The clock would be set to the local time of a starting point whose longitude was known, and the longitude of any other place could be determined by comparing its local time with the clock time. However, this method required precise mechanical clocks which were not available at that time.

In the 17th century, Galileo Galilei is known for his work on orbital periods of Jupiter's four brightest satellites (Io, Europa, Ganymede and Callisto): he determined that sufficiently accurate knowledge of their orbits could be used as a universal clock, making it possible to determine longitudes. However, the method required a telescope, as the moons are not visible to the naked eye.

Note

pick illustration like:

- Sunspots from wikime-


dia
- or more like Tufte *Beautiful Evidence*?

In the 18th century, triangulations were implemented in order to construct more precise maps of the territory, to calculate the radius of Earth and to determine whether the excentricity of our planet made it flattened at the pole (like a tangerine) or at the Equator (like a lemon). Triangulations performed in Laponia and Peru determined in favour of the first option. Precise measures of angles and the law of sines leveraged precise measures of distances between landmarks on the Paris Meridian (see Cassini), leading to precise measurements of geographical coordinates as well.

Warning

TODO

- improve the shitty writing in previous paragraph.

Today, the precision we get with global position systems (GPS) also depends on the precision we can get with clocks, around the nanosecond.

Glossary

Table A.1.: Acronyms

acronym	description
ACC	**A**rea **C**ontrol **C**entre
ADEP	**A**erodrome of **DEP**arture
ADES	**A**erodrome of **DES**tination
AO	**A**ircraft **O**perator
ATC	**A**ir **T**raffic **C**ontrol
CPR	**C**orrelated **P**osition **R**eport
CTFM	**C**urrent **T**actical **F**light **M**odel
DDR2	**D**emand **D**ata **R**epository version **2**
FP	**F**light **P**lan
FTFM	**F**iled **T**actical **F**light **M**odel
ICAO	**I**nternational **C**ivil **A**viation **O**rganization
NM	**N**etwork **M**anager
OSN	**O**pen**s**ky **N**etwork
RAD	**R**oute **A**vailability **D**ocument

Contribute to the project

Minor contributions

Simply click on the "Edit this page" link (to the right of the page) to file a pull request on Github: the website will be automatically updated as soon as the modification is accepted.

Major contributions

We use the Quarto publishing system to build the website and generate the PDF associated to the project. If you want to contribute significantly to the project, by writing a chapter, improving the design or suggesting more changes:

- clone the GitHub project https://github.com/open-aviation/aviationbook/;
- install Quarto for your platform;
- start writing using your favourite text editor. Configuration files for VS Code (`aviationbook.code-workspace`) and RStudio (`aviationbook.Rproj`) are provide and we recommend you to open them.
- keep a terminal open and run the `quarto preview` command. This will open a browser tab with the website running. Every time you save a file, the web page will be reloaded to display changes.
- check the PDF generation does not fail with `quarto render`. You may need to install TinyTeX with `quarto install tinytex`;
- commit and push changes. Use pull requests if you do not have the proper rights on the repository.

Bibliography

We synchronize the bibliography items with a Zotero group: https://www.zotero.org/groups/4370174/aviation-book. Please ask to be part of the group if you want to add new items. The best way to edit the entries is via the Zotero app and automatically export the `bibliography.bib` file using the Better Bibtex extension.
Please install the Better Bibtex extension and manually specify a `Citation Key` for each entry in the `Extra:` field to avoid conflicts between group members.
In the settings:

- When an item has both a DOI and a URL, export: **both**
- Fields to omit from export (comma-separated): `file,keywords,copyright,urldate,issn,abstract,langid`