

REFERENCE COURSE - FOR ANY ADULT

What ADS-B is and how it works

Twelve chapters. No prior knowledge of aviation or radio is assumed; secondary-school mathematics is enough for the worked examples, and they can be skipped without losing the thread. Reading time about 50 minutes.

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CHAPTER 1

The problem: a sky full of aircraft that nobody can see

On an ordinary weekday, around 30 000 flights cross European airspace. An airliner at cruise moves at roughly 250 metres per second, or 900 km/h; two aircraft heading towards each other close at half a kilometre every second. A pilot looking out of the window sees almost nothing of this: at 10 000 metres, other aircraft are specks, and cloud hides most of them anyway. The sky is a three-dimensional road network with no roads painted on it, and the traffic on it is both fast and invisible.

Air traffic control exists to keep that traffic apart. The rules are simple in principle: in controlled airspace, aircraft are kept at least 1 000 feet (about 300 metres) apart vertically, or a set horizontal distance apart, typically 5 nautical miles (9.3 km) near radar coverage and far more over the oceans. To apply the rules, a controller needs to know, continuously and reliably, the position of every aircraft in the sector: not where it was a minute ago, but where it is now, how high it is, and which way it is going. The whole subject of this course is how that knowledge is obtained. The technical word for it is **surveillance**.

A number to keep in mind

At 900 km/h, an aircraft travels 15 km in a minute and 250 m in a second. Any surveillance method that updates slowly, or with a large error, leaves the controller guessing over exactly the distances that matter.

CHAPTER 2

Before ADS-B: finding aircraft with radar

The first answer, developed in the late 1930s and matured during the Second World War, was **primary radar**. A large rotating antenna sends out a short, very powerful pulse of radio energy. When the pulse strikes an aircraft, a tiny fraction of it is reflected back. The radar measures the time between the pulse leaving and the echo returning; since radio travels at the speed of light, 300 000 km/s, the time gives the distance. The direction the antenna was pointing gives the bearing. Primary radar is wonderfully independent: the aircraft needs no equipment at all, which is why it is still used by the military. But it has real weaknesses. The echo from a distant aircraft is extraordinarily faint, so the transmitter must be enormous. The echo says nothing about who the aircraft is or how high it is. And the antenna takes several seconds to complete a rotation, so each aircraft is seen only once every 4 to 12 seconds, during which it has moved up to 3 km.

The second answer, **secondary surveillance radar** (SSR), turned the aircraft into a participant. A ground station transmits a question, an *interrogation*, on 1030 MHz. A small radio on board, the **transponder**, hears the question and answers on 1090 MHz with a strong signal of its own. Because the reply is transmitted rather than reflected, it is millions of times stronger than a radar echo, and because it is generated by a computer, it can carry information. In the oldest form (Mode A) the reply contains a four-digit identity code assigned by the controller; in Mode C it also contains the aircraft's altitude. In the 1980s came **Mode S** ("S" for selective), in which every transponder has a unique 24-bit address, can be interrogated individually, and can answer with 56- or 112-bit data messages. Keep that number, 1090 MHz, and that word, Mode S, in mind: ADS-B is built directly on both.

Secondary radar was a great improvement, but it still shares two limitations with its predecessor. The aircraft speaks only when asked, so the ground still needs an interrogating station within range, which rules out oceans, deserts and mountain ranges. And the station still needs a rotating antenna to know which direction the reply came from, so each aircraft is still seen only once per rotation, and the controller's screen still shows a dot that jumps every few seconds rather than a smoothly moving aircraft. To improve on that, something fundamentally different was needed: a way for the aircraft to report its position without being asked, and without the ground having to measure anything at all.

CHAPTER 3

The idea: let the aircraft tell us

By the 1990s, two technologies had matured that made a different approach possible. Satellite navigation gave every suitably equipped aircraft an accurate knowledge of its own position, far better than any radar could measure from the ground. And the Mode S transponder already provided a radio that could send data messages on 1090 MHz. Put the two together and the logic is irresistible: instead of the ground struggling to measure where the aircraft is, let the aircraft, which already knows, simply say so, at regular intervals, to everyone. That is ADS-B, and the four words of its name are a precise description.

It is **automatic**: nothing triggers a transmission. The transponder sends on its own schedule, about twice a second, whether or not any ground station is within range and whether or not the pilot does anything; indeed the pilot cannot stop it in flight short of switching the transponder off, which is forbidden. It is

dependent: every item in the message comes from the aircraft's own equipment, the position from its satellite receiver and the altitude from its pressure altimeter, and the ground measures nothing; it trusts what it is told. It is **surveillance:** its purpose is to let others know where the aircraft is, for air traffic control and for nearby aircraft, as distinct from navigation, which is the aircraft knowing where it is itself, and from communication, which is talking to the pilot. And it is a **broadcast:** the message has no addressee, no acknowledgement and no encryption, and anyone with a receiver within range hears exactly the same thing, whether they are a control centre, another airliner, or a school.

"Dependent" is the word that worries engineers and the one that most repays explanation. Radar makes an independent measurement: if the aircraft's instruments are wrong, the radar does not care. ADS-B inherits every error of the aircraft's own navigation system, and if that system is deceived or fails, the broadcast position is wrong with the same confidence. This is why every ADS-B message carries, alongside the position, a statement of how much the aircraft trusts its own position (the integrity and accuracy categories we meet in chapter 5), and why radar has not been switched off.

"Broadcast" is the word that makes this course possible. Because the messages are sent in the clear to everyone, they are heard not only by air traffic control but by any receiver tuned to 1090 MHz, including the one you might put on a school roof. The same property is the source of the system's main limitation, discussed in chapter 11: a message anyone can read is also a message anyone can forge.

CHAPTER 4

How the aircraft knows where it is

Everything in ADS-B rests on the aircraft knowing its own position, so this chapter is about satellite navigation. The generic term is **GNSS**, Global Navigation Satellite System; the American GPS is the best known, and Europe's Galileo, Russia's GLONASS and China's BeiDou work on the same principle. Each system is a constellation of around 24 to 30 satellites orbiting at roughly 20 000 km altitude, far above the aircraft, each carrying an atomic clock accurate to a few billionths of a second. Each satellite continuously transmits a radio signal that says, in effect, "this is satellite number N, my position is such-and-such, and the time at which I sent this is exactly T".

The receiver on the aircraft hears that signal a little later, because radio takes time to travel: at 300 000 km/s, the 20 000 km from the satellite takes about 67 thousandths of a second. The receiver compares the time stamped in the message with the time of arrival. The difference, multiplied by the speed of light, is the distance to that satellite. One distance places the receiver somewhere on a sphere around that satellite. Two spheres intersect in a circle; three spheres in two points, one of which is usually absurd (deep underground or far out in space) and is discarded. So three satellites would be enough, if the receiver had a perfect clock.

It does not. An atomic clock costs tens of thousands of euros and would not fit; the receiver has a cheap quartz clock that may be wrong by far more than the timing precision required. Here is the elegant part. The receiver treats its own clock error as a fourth unknown, next to its three position coordinates, and listens to a fourth satellite. Four equations, four unknowns: the receiver solves for its position and, as a by-product, corrects its own clock to within a few tens of nanoseconds. This is why a satellite receiver needs at least four satellites in view, and why every GNSS receiver is also, incidentally, one of the most accurate clocks in the building.

It is worth dwelling on the magnitudes, because they explain why satellite navigation is really an exercise in timekeeping with the geometry as an afterthought. Light travels 30 centimetres in a nanosecond and 300 metres in a microsecond, so a timing error of one millionth of a second becomes a position error of 300 metres, and the few-metre accuracy of a modern receiver corresponds to timing at the level of about ten nanoseconds. Take a concrete case. A satellite stamps a signal with the time 12:00:00.000 000 000; the aircraft's receiver hears it at 12:00:00.070 000 000. The travel time is 0.070 s, so the distance is $0.070 \times 300\,000 \text{ km/s} = 21\,000 \text{ km}$. Had the receiver's own clock been fast by a single microsecond, it would have computed 21 000.3 km, 300 metres too far, and the same error would have crept into every other satellite's distance too. That shared error is precisely what the fourth satellite exposes and removes.

Two altitudes, not one

Satellites give a height above the Earth's mathematical surface, a *geometric* altitude. Yet the altitude an aircraft broadcasts for air traffic purposes is not that one. It is the **barometric altitude**, derived from the air pressure outside the aircraft, measured by a small opening in the fuselage called the static port. Air pressure falls with height in a known way (roughly 1 hPa per 8 metres near the ground, more slowly higher up), and every altimeter in the world converts pressure to height using the same standard atmosphere, referenced to 1013.25 hPa at sea level. On a day of unusual pressure, every aircraft's barometric altitude is wrong by the same amount, which is exactly the point: what matters for separation is not the true height above the sea but that two aircraft which both read "flight level 350" are truly 300 metres apart from one reading "flight level 340". ADS-B broadcasts the barometric altitude in its position messages, in steps of 25 feet (7.6 m), and separately broadcasts the difference between that and the satellite height, so that a receiver can recover both.

CHAPTER 5

Anatomy of a message

The ADS-B message used by airliners worldwide is a Mode S transmission called the **extended squitter**; "squitter" is old radar slang for a transmission sent spontaneously rather than in reply, and "extended" because at 112 bits it is twice the length of the original Mode S reply. Engineers write "1090ES" for "1090 MHz extended squitter". Each transmission lasts 120 microseconds in total: an 8-microsecond *preamble*, a fixed pattern of four pulses that lets a receiver recognise the start of a message and synchronise its clock, followed by 112 data bits at one bit per microsecond.

How a bit is sent: pulse position modulation

Each one-microsecond bit slot is split into two halves. A pulse of radio energy in the first half and silence in the second means 1; silence then a pulse means 0. There is therefore exactly one pulse per bit, whatever the data, and the receiver only has to decide which half of each slot was louder. This scheme, pulse position modulation, is robust against the kinds of noise and fading a signal suffers on its way from a transponder to a distant antenna, and it is cheap to decode.

Four bits in pulse position modulation: 1, 0, 1, 1



The 112 bits

DF	CA	ICAO address	ME - the payload	PI
5 bits downlink format	3 bits capability	24 bits unique aircraft identity	56 bits position, altitude, velocity, call sign or status, depending on the type code in its first 5 bits	24 bits error check (CRC)

The first five bits, the downlink format, say what kind of Mode S message this is; the value 17 means "ADS-B from a Mode S transponder". The 24-bit **ICAO address** is the aircraft's permanent identity, assigned when it is registered: there are 2 to the power 24, or 16 777 216, possible addresses, allocated in blocks to states by ICAO, the UN's civil aviation body. Belgian aircraft, for instance, carry addresses from 448000 to 44FFFF in hexadecimal. Unlike the four-digit code of old Mode A, this address never changes and is never shared, so a receiver can be sure which aircraft it is hearing from the very first message.

The 56-bit **ME** field is the actual content, and its first five bits, the *type code*, say what the rest means. Type codes 1 to 4 carry the aircraft's call sign, such as BEL1234 or RYR7KL, as eight six-bit characters. Codes 9 to 18 carry an airborne position with barometric altitude; 20 to 22 the same with satellite altitude. Code 19 carries velocity: the ground speed decomposed into east-west and north-south components, the vertical rate, and the difference between barometric and satellite altitude. Codes 28, 29 and 31 carry status: emergency codes, selected altitude, and the integrity and accuracy categories that say how far the broadcast position can be trusted (an "NIC" of 8, say, promises the true position is within 185 m of the reported one, with high probability).

The last 24 bits are a **cyclic redundancy check**, a number computed from the preceding 88 bits by a fixed polynomial division. The receiver repeats the computation on the bits it decoded; if the result does not match, at least one bit was corrupted in flight and the message is discarded. Since a one-microsecond pulse can easily be lost to noise or to an overlapping message from another aircraft, this check is what keeps garbled positions off the controller's screen. A real message, as a receiver would log it, looks like this:

8D 4840D6 202CC371C32CE0 576098

8D: downlink format 17, capability 5. 4840D6: ICAO address, a Dutch aircraft. 20...: type code 4, an identification message, which decodes to the call sign KLM1023. 576098: the error check.

Fitting the Earth into 34 bits

A position message has only 17 bits for latitude and 17 for longitude. That is 131 072 steps around the whole globe, about 300 m each at the equator: not nearly good enough. ADS-B solves this with **compact position reporting**. The Earth is divided into zones; the 17 bits give a very precise position (to about 5 m) within a zone, but not which zone. The aircraft alternates between two slightly different zone grids, "even" and "odd" messages, and a receiver that has heard one of each can work out the zone unambiguously. Once it has, a single message is enough to follow the aircraft, since it can hardly have jumped to another zone in half a second. It is a neat trick that doubles the useful precision at no cost in bits.

How often

A transponder in flight sends a position message twice a second, a velocity message twice a second, and its call sign every five seconds, plus status messages at longer intervals, so around four to five extended squitters per second in all. Each lasts 120 microseconds; the transponder is actually transmitting ADS-B for well under a thousandth of the time. The rest of the second it is listening for, and replying to, radar interrogations on 1030 MHz and the collision-avoidance queries of other aircraft.

CHAPTER 6 - PHYSICS

The wave: radio as invisible light

The message leaves the aircraft as a **radio wave**, and the single most useful idea in this course is that a radio wave and a ray of light are the same thing. Both are electromagnetic waves: a pattern of electric and magnetic fields oscillating together and travelling through space at the speed of light, c , which is 299 792 458 metres per second, or near enough 300 000 km/s. What distinguishes a radio wave from green light, from the X-rays in a hospital or from the microwaves in a kitchen oven is only how fast the fields oscillate: the **frequency**, f , measured in hertz (oscillations per second).

Because the wave travels at a fixed speed, the frequency fixes the distance between one crest and the next, the **wavelength**, λ . In one second the wave travels c metres and completes f oscillations, so each oscillation occupies c / f metres:

$$c = f \times \lambda$$

For ADS-B: $\lambda = 300\,000\,000 / 1\,090\,000\,000 = 0.275$ m. The wave between the aircraft and your antenna has crests 27.5 cm apart, roughly the length of a school ruler.

Wave	Frequency	Wavelength	Note
FM broadcast radio	100 MHz	3 m	Car aerials are a fraction of this
ADS-B / Mode S	1 090 MHz	27.5 cm	Also used by radar transponder replies
Mobile phone (4G band)	1 800 MHz	17 cm	A close neighbour in the spectrum
Wi-Fi, microwave oven	2 450 MHz	12 cm	Same frequency, vastly different power
Visible green light	560 000 000 MHz	0.000 54 mm	Half a million times higher in frequency

Two consequences matter for everything that follows. First, since the wave is light, it travels in straight lines unless something bends or blocks it, and it does not go through the Earth. That sets the range of the system, the subject of chapter 7. Second, since its wavelength is 27.5 cm, the metal structures that interact with it most strongly, antennas, are of that order of size, the subject of chapter 8.

Why radio is not sound

The most common confusion, in adults as much as children, is between radio and sound, probably because a "radio" is a box that produces sound. They are unrelated phenomena. Sound is a pressure wave in air, a chain of molecules pushing on their neighbours; it needs a material to travel through, it moves at 340 m/s, and it cannot cross a vacuum. Radio needs nothing: it crosses the vacuum between a satellite and the aircraft, and it moves nearly a million times faster. The aircraft's engine noise and its ADS-B message leave it at the same moment; the message arrives at a receiver 20 km away in 67 microseconds, the sound a full minute later.

Why 1090 MHz

The frequency is an inheritance. International agreements in the 1950s reserved the band from 960 to 1215 MHz for aeronautical radionavigation, and 1090 MHz became the reply frequency of secondary radar transponders. When ADS-B was designed, reusing the transponder already fitted to every airliner was far cheaper than installing a new radio, so ADS-B simply became another thing the Mode S transponder says on 1090 MHz. In the United States, smaller aircraft flying below about 5 500 m may use a second system instead, UAT on 978 MHz, which is why receivers there often listen on both.

CHAPTER 7 - PHYSICS

Range: the curve of the Earth and the fading of the signal

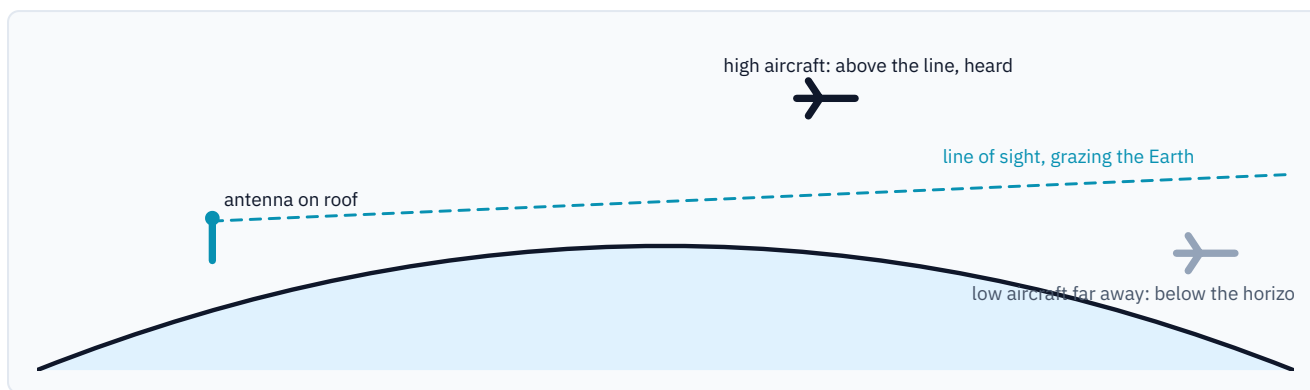
A transponder transmits with a peak power of a few hundred watts. How far away can such a signal be heard? Two quite different things limit it, and it is worth keeping them apart: geometry, which sets a hard edge, and power, which sets a soft one.

The radio horizon

At 1090 MHz, radio behaves like light: it travels in straight lines and does not bend around the Earth. A ground antenna can therefore hear an aircraft only while there is a straight line between them that does not pass through the ground. For an observer at the surface, the horizon is where that line just grazes the Earth. The higher the aircraft, the further away that grazing point is; the higher the antenna, the further again. The geometry of a tangent to a sphere gives a simple result: the distance to the horizon in kilometres is about 3.57 times the square root of the height in metres. The atmosphere bends radio slightly downward, which stretches the horizon by around 15 percent, so engineers use 4.12 instead:

$$d \text{ (km)} = 4.12 \times (\sqrt{h \text{ aircraft}} + \sqrt{h \text{ antenna}}) \quad \text{heights in metres}$$

Aircraft at 11 000 m, antenna on a 20 m roof: $4.12 \times (104.9 + 4.5) = 451$ km. Aircraft at 1 000 m, same roof: $4.12 \times (31.6 + 4.5) = 149$ km. Aircraft on the ground 15 km away: not heard at all, unless the land between is flat and clear.



This explains the characteristic shape of a receiver's coverage: a circle of 400 km or more for high-flying traffic, shrinking to a few tens of kilometres for aircraft on approach, and almost nothing for aircraft on the ground except at the airport next door. It also explains why receiver height matters far more than receiver quality, and why a hill, a tall building or even the aircraft's own wing, when it banks away from you, can cut a signal off instantly.

The inverse square law

Within the horizon, the signal weakens with distance. A transponder antenna radiates in all horizontal directions, so its power spreads out over an ever larger sphere. The area of a sphere grows with the square of its radius, so the power falling on an antenna of fixed size falls with the square of the distance: twice as far, a quarter of the power; ten times as far, a hundredth. Engineers express this as a *path loss* in decibels, and for 1090 MHz over 400 km it comes to about 145 dB, meaning the received power is about 10 to the power 14.5 times smaller than the transmitted power. A 250-watt pulse arrives as roughly a tenth of a billionth of a milliwatt. A good receiver can detect that, just, which is why the geometric horizon and the power limit happen to coincide at a few hundred kilometres: the system was designed so.

The two limits interact in a way worth understanding. Within the horizon, a strong signal from a nearby aircraft and a weak one from a distant aircraft both decode perfectly, because the pulse position scheme of chapter 5 asks only which half of each bit slot was louder, not how loud. The signal does not fade gradually out of usefulness as the aircraft recedes; it stays decodable until, somewhere near the horizon, either the geometry cuts it off or the noise in the receiver finally drowns it, and the track stops. That is why coverage maps have sharp edges, and why the furthest aircraft a receiver hears are almost always the highest ones.

CHAPTER 8 - PHYSICS

Antennas: catching a 27-centimetre wave

An antenna is a piece of conductor shaped so that a passing electromagnetic wave sets the electrons in it moving in step, producing a tiny alternating current that a receiver can amplify. The reverse happens in the transmitter: an alternating current in the aircraft's antenna launches the wave. The efficiency of this exchange depends on the size of the conductor relative to the wavelength. A straight wire responds most strongly, it *resonates*, when it is half a wavelength long, so that the current sloshing back and forth along it fits the oscillation of the wave exactly, like a child's swing pushed at its natural rhythm. For 1090 MHz, half a wavelength is 13.75 cm.

The commonest practical form is the **quarter-wave monopole**: a vertical rod one quarter of a wavelength long, 6.9 cm, standing on a conducting surface, the *ground plane*. The ground plane acts as a mirror, so the rod and its reflection together behave like a half-wave antenna. This is why the ADS-B antenna on an aircraft is a stubby blade a few centimetres tall on the fuselage, the fuselage being the ground plane, and why a hobbyist's antenna is a short wire on a tin lid. A wire of the wrong length still works, but much less well: the "metal ear" is tuned.

Three further properties of the antenna follow from the physics and each has a visible consequence. The first is **polarisation**. The electric field of an electromagnetic wave oscillates in a definite direction at right angles to its travel, and an antenna responds only to the component of the field along its own length. Aircraft antennas are mounted vertically, so the ADS-B wave arrives vertically polarised, and a receiving antenna must be vertical too; laid on its side it hears almost nothing, as a rope wave shaken up and down is stopped by a horizontal slot. The second is the **radiation pattern**. A vertical antenna is most sensitive towards the horizon and not at all along its own axis, so that its sensitivity in three dimensions has the shape of a ring doughnut with the antenna through the hole. Receivers therefore routinely hear aircraft 300 km away without difficulty and lose one passing directly overhead for a few seconds, a thing worth watching for on any live map. Stacking several resonant elements one above another squeezes the doughnut flatter, concentrating the sensitivity towards the horizon, where the distant aircraft are, at the expense of the overhead; this is what is meant by antenna **gain**, and it is always a redistribution of sensitivity, never a creation of it.

The third concerns what sits between the antenna and the receiver. The antenna picks up not only 1090 MHz but every signal in the neighbourhood, including mobile-phone transmissions a few hundred megahertz away that are vastly stronger, so a filter that passes only the aviation band is placed first. The signal then has to travel down a cable, and at 1090 MHz a coaxial cable loses roughly half the signal every ten metres; the remedy is a low-noise amplifier at the antenna, before the cable, so that the signal is strong enough to survive the journey, rather than at the receiver, where amplifying would amplify the cable's noise along with what remains of the signal. These are details, but they are the details that decide whether a receiver on a school roof hears the aircraft at the horizon or only the ones nearby.

CHAPTER 9

Receiving and decoding

Between the antenna and a dot on a map is a chain of five stages. The antenna turns the passing wave into an alternating current of a few microvolts. A filter and a low-noise amplifier keep the 1090 MHz band, reject everything else, and raise the signal a thousandfold. A software-defined radio tunes to the frequency and samples the signal two million times a second, turning it into a stream of numbers. A decoder searches that stream for the preamble pattern, reads off the 112 bits, checks the parity and decodes the fields. And a tracker gathers the messages from each aircraft into a single, continuously updated record: a position, a track, a label.

The remarkable stage is the third. Until about 2010, decoding 1090 MHz needed purpose-built hardware costing thousands of euros. Then hobbyists discovered that a 20-euro USB television tuner contained a chip that could be told to tune to any frequency and hand the raw signal to a computer. This **software-defined radio** turns the radio problem into a programming problem: a laptop or a Raspberry Pi receives a stream of two million numbers a second describing the signal strength, and free software looks for the

preamble pattern, measures which half of each microsecond slot is louder, assembles 112 bits, computes the CRC, and prints the fields. The receiver project in the secondary kit is exactly this chain, and a school can build it for under 100 euros.

The tracker stage is where the stream of messages becomes knowledge. A single position message, remember, is ambiguous until an even and an odd message have been paired. Velocity arrives separately from position, the call sign separately again, and the tracker stitches them together by ICAO address, discards anything that fails the error check, and holds each aircraft's last known state. If no message arrives for a minute, usually because the aircraft has dropped below the horizon, the track expires.

CHAPTER 10

From one receiver to a map of a continent

One receiver hears a circle of sky a few hundred kilometres across. A map of Europe needs hundreds of them, and the useful ones are not in cities but spread out: on coasts, in valleys, on islands, wherever another receiver's circle does not reach. Each receiver sends its decoded messages, each stamped with the time of arrival, over the internet to a central service. That service *aggregates*: the same message from a high aircraft typically arrives from ten or twenty receivers at once, and the duplicates must be recognised and merged. It also checks: a position that disagrees with every neighbouring receiver's view of the same aircraft is probably a decoding error or a faulty transponder, and is flagged or dropped.

Multilateration: finding aircraft that do not say where they are

Not every aircraft broadcasts a position. Older transponders reply to radar with identity and altitude but have no satellite input; some aircraft deliberately send none. Yet their 1090 MHz transmissions still reach the ground, and a network can locate them by turning satellite navigation inside out. If four receivers with precisely synchronised clocks each record the moment the same transmission arrives, the differences between those moments reveal the differences in distance: a message that reached receiver A one microsecond before receiver B was sent from a point 300 m closer to A than to B. All points with that property lie on a curved surface, a hyperboloid, between A and B. Three such surfaces, from four receivers, intersect at the aircraft. This is **multilateration**, and it demands timing to about a tenth of a microsecond, 30 m, across receivers hundreds of kilometres apart, which the receivers obtain from the same satellites the aircraft uses.

The same idea, twice

Satellite navigation: one receiver, four transmitters whose positions are known, solve for the receiver. Multilateration: one transmitter, four receivers whose positions are known, solve for the transmitter. In both, what is really measured is time, and 1 microsecond is 300 metres.

CHAPTER 11

What it is used for, and where it falls short

Air traffic control is the first customer. Across Europe, controllers now see a fused picture in which ADS-B, with its twice-a-second updates and satellite-grade accuracy, is combined with radar and multilateration; where radar never reached, over the North Atlantic, the Arctic, the Sahara and most oceans, ADS-B messages are picked up by receivers carried on low-orbit communication satellites,

which has allowed aircraft crossing the Atlantic to be spaced far more closely than before. Aircraft are the second customer: an airliner with "ADS-B In" displays nearby traffic to its crew and feeds it into the collision avoidance system. Airports use it to track aircraft and vehicles on the ground in fog. Researchers use the open data to study noise, fuel use, contrails and delays. And a receiver on a school roof is, in a small way, a participant in all of this.

The system's weaknesses follow directly from its design, and each is worth understanding rather than merely listing. Because the messages are broadcast in the clear, neither encrypted nor signed, there is nothing in a message itself that proves it came from an aircraft. A transmitter on the ground could, illegally, broadcast a perfectly formed message describing an aircraft that does not exist, and a receiver would decode it without complaint. What protects the system is not the message but the context around it: a phantom will not appear on radar, will not be found by multilateration, and will not behave like real traffic, and control centres cross-check continuously. A version of the protocol with cryptographic signatures has been discussed for many years; the obstacle is less technical than practical, since every transponder in the world would have to change.

Because the position is dependent on the aircraft's satellite receiver, anything that disturbs satellite navigation disturbs ADS-B. Jamming and spoofing of satellite signals have become common near conflict zones, and an aircraft flying through such an area may be unable to compute a position, or may compute a wrong one. Its messages then carry a degraded integrity category, the controller's system flags them, and radar, the independent measurement that ADS-B was never meant to replace entirely, takes over. The relationship between the two is thus not one of successor and predecessor but of partners with complementary weaknesses.

Because the mandate covers airliners and most larger aircraft but not everything that flies, the map is incomplete by design. Light aircraft outside controlled airspace, gliders, balloons and many military aircraft may carry no ADS-B at all, and some light aircraft use other systems that a 1090 MHz receiver does not hear. And because the broadcast identifies the aircraft, it can identify its owner: following a particular private jet is, in effect, following a particular person, which has led to programmes that mask the registration of aircraft whose owners ask for it, and to a continuing argument about whether information an aircraft broadcasts to the world can also be private. That argument is a good one to put to older students, because the physics gives no answer to it.

CHAPTER 12

A short history

1935 to 1945

Primary radar developed in Britain, Germany and the United States; by the end of the war, "identification friend or foe" transponders answer radar pulses with a coded reply, the ancestor of secondary radar.

1950s to 1960s

Civil secondary radar standardised: 1030 MHz interrogations, 1090 MHz replies, Mode A identity codes and Mode C altitude.

1980s

Mode S, with unique 24-bit addresses and data messages, developed at MIT Lincoln Laboratory and adopted by ICAO. GPS becomes operational for civil users.

1990s to 2000s

ADS-B defined and trialled, notably in Alaska, where radar coverage was impossible and accidents frequent. The 1090 MHz extended squitter is standardised internationally.

2010s

Cheap software-defined radios make reception a hobby; volunteer networks of thousands of receivers appear. Receivers are launched on satellites for oceanic coverage.

2020

ADS-B becomes mandatory for most aircraft in controlled airspace in the United States (January) and the European Union (June, with a transition to the end of the year). The sky starts talking, everywhere, all the time.

Glossary

ADS-B

Automatic Dependent Surveillance - Broadcast. Aircraft broadcasting their own position.

Barometric altitude

Height derived from air pressure, using a standard atmosphere; what aircraft report.

CPR

Compact position reporting, the even/odd scheme that fits a precise position into 34 bits.

CRC

Cyclic redundancy check, the 24-bit error check ending every message.

Extended squitter

The 112-bit spontaneous Mode S transmission that carries ADS-B.

GNSS

Global navigation satellite system: GPS, Galileo, GLONASS, BeiDou.

ICAO address

The permanent 24-bit identity of an aircraft's transponder.

Mode S

The selective secondary radar standard on which ADS-B is built.

Multilateration

Locating a transmitter from differences in signal arrival time at several receivers.

Path loss

The weakening of a signal with distance, following the inverse square law.

Radio horizon

The furthest distance at which a straight line between antenna and aircraft clears the Earth.

SDR

Software-defined radio: a tuner that hands raw signal samples to a computer for decoding.

SSR

Secondary surveillance radar: ground interrogates, the transponder replies.

Transponder

The aircraft radio that answers radar and transmits ADS-B on 1090 MHz.

Wavelength

Distance between successive crests of a wave: c / f , 27.5 cm at 1090 MHz.

NEXT

From theory to practice: build the receiver

Twelve chapters explained a system that you can now hold in your hand. The hands-on workshop turns them into an afternoon's work: what to buy for 100 to 150 euros, how to build and place the antenna, how to prepare a Raspberry Pi and install the Dataero feeder, and how to watch the aircraft you hear appear on the live map, credited to your station. Every chapter above has a measurement waiting for it there: the radio horizon against real aircraft, the inverse square law in the signal column, the daily rhythm of the sky.

Open the hands-on workshop <https://radar.dataero.eu/learning/workshop>