

AGES 12 TO 18 - FOR THE TEACHER

Decoding the sky: physics and computing through one real system

Five lessons and a project. Each lesson takes one part of ADS-B and develops the physics or the computing behind it fully: derivations where the class can follow them, worked examples with real numbers, the demonstrations that make the idea observable, and the points where students' intuition goes wrong. The younger end of the range (12 to 14) follows the ideas and the arithmetic; the older end (15 to 18) follows the derivations and runs the project.

Learn - <https://radar.dataero.eu/learning/ages-12-18> 2026-10-22

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Before you start: why one real system is worth five lessons

Most of the physics taught between 12 and 18 is taught in pieces: a unit on waves here, one on the electromagnetic spectrum there, a topic on digital data in computing, a mention of satellites in geography. ADS-B is a single working system in which all of those pieces are load-bearing at once, and in which the class can observe the result with a receiver costing less than a textbook. An aircraft fixes its position by timing radio signals from satellites, which is trilateration and the speed of light. It encodes the result in 112 bits with a cyclic redundancy check, which is binary coding and error detection. It transmits them as a pulse-position-modulated radio wave at 1090 MHz, which is the spectrum, frequency and wavelength. The wave reaches a receiver only along a straight line that clears the Earth's curve, and arrives weaker by the inverse square of the distance, which is geometry and energy. A tuned antenna of a quarter wavelength converts it to a current, which is resonance. And a network of receivers can locate even a silent transmitter from arrival-time differences, which is the satellite problem turned inside out. Each lesson below takes one of these and develops it in its own right, with ADS-B as the running example rather than a decoration.

The reference course on the home page gives the whole system in narrative form, and the class should read its chapters 3 and 5 before lesson 3 and chapters 6 to 8 before lessons 4 and 5; its glossary is a useful handout. This page assumes you have read it and concentrates on the physics and the teaching. Numerical conventions are consistent throughout: $c = 3.00 \times 10^8$ m/s, $f = 1090$ MHz, heights in metres, distances in kilometres, and the aircraft at cruise taken as 11 000 m (flight level 360) and 250 m/s unless the example says otherwise.

Two warnings about intuition. Students arrive believing that radio waves are a kind of sound and that "radar" or "satellites" see aircraft. Both are wrong, both are dealt with explicitly in lessons 1 and 2, and both will reappear; the course is designed so that each later lesson gives you a fresh reason to correct them. And students who are comfortable with formulas are often not comfortable with magnitudes: the course leans heavily on asking "how big is that?" at every step, because 300 m per microsecond, 145 dB of path loss and 2^{24} addresses are the kind of numbers that make the physics feel real.

LESSON 1 - PHYSICS

Waves and the electromagnetic spectrum: what the message travels on

Begin from the observation the whole course rests on: an aircraft's radio message and a beam of light are the same physical phenomenon. Both are electromagnetic waves, oscillating electric and magnetic fields propagating through space without any medium, at a speed c that is the same for every frequency in vacuum and very nearly so in air: 299 792 458 m/s, which the class can take as 3.00×10^8 m/s. The quantity that distinguishes radio from visible light, and visible light from X-rays, is only the frequency f of the oscillation. Our retinas respond to frequencies between about 4×10^{14} and 8×10^{14} Hz, which we perceive as red through violet; ADS-B is transmitted at 1.09×10^9 Hz, roughly half a million times lower. Nothing about the wave is different in kind; only our eyes are selective.

Derive the wave equation for the class rather than stating it. If a wave travels at speed c and oscillates f times per second, then in one second it has advanced a distance c and has produced f complete cycles; each cycle therefore occupies a length c / f . That length is the wavelength, λ , and so $c = f \times \lambda$. Applied to ADS-B: $\lambda = 3.00 \times 10^8 / 1.09 \times 10^9 = 0.275$ m. The message between the aircraft and the receiver has crests 27.5 cm apart. Have the class place that on a spectrum they draw themselves, on a logarithmic axis: FM broadcast at 100 MHz and 3 m, ADS-B at 1 090 MHz and 27.5 cm, mobile phones at 1 800 MHz and 17 cm, Wi-Fi and microwave ovens at 2 450 MHz and 12 cm, infrared, visible light at 5.6×10^{14} Hz and 540 nm, and so on to X-rays. The exercise of placing the aircraft's wave between a phone and an oven is worth more than any table, because it makes the point that these are neighbours.

Now confront the sound confusion directly, because it is universal and because the contrast teaches both phenomena. Sound is a longitudinal pressure wave in a medium; its speed is a property of the medium, 343 m/s in air at 20 degrees, about 1 500 m/s in water, and zero in vacuum. Radio is a transverse electromagnetic wave needing no medium at all, travelling at c in vacuum and imperceptibly slower in air. Put a number on the gap: 3.00×10^8 divided by 343 is about 875 000. An aircraft 30 km away that emits a sound and a message at the same instant delivers the message in 100 microseconds and the sound in 87 seconds; by the time the sound arrives, the aircraft has flown 22 km. The demonstration is a rope in the classroom and a torch across the playing field: a rope wave visibly needs the rope and travels

at a speed the rope sets, and a torch flash reaches the far end with no delay anyone can measure. Explicitly list what the rope shares with light (a wave, a wavelength, a frequency, a fixed speed and so an inverse relation between f and λ) and what it does not (a medium, a speed of metres per second).

Finish with polarisation, which is cheap to show and pays off in lesson 5. An electromagnetic wave's electric field oscillates in a definite direction perpendicular to its travel. Aircraft transponder antennas are vertical, so the ADS-B wave is vertically polarised; a receiving antenna must also be vertical, and turned horizontal it hears almost nothing. A rope wave shaken vertically passes through a vertical slot in a cardboard box and is stopped by a horizontal one; two pieces of polarising film (from a pair of cheap 3D glasses) crossed against a window show the same thing for light. Ask the class to predict what happens to reception if a receiving antenna is laid flat. They will test the prediction in the project.

Worked example to set

The second ADS-B system, used by light aircraft in the United States, transmits at 978 MHz. What is its wavelength, and how long would a quarter-wave antenna for it be? (0.307 m; 7.7 cm.) A student who can do this has lesson 1.

LESSON 2 - PHYSICS AND MATHEMATICS

Timing and position: how the aircraft knows where it is, and how a network finds one that will not say

Everything the aircraft broadcasts about its position comes from satellite navigation, and satellite navigation is, at bottom, a measurement of time. Each GNSS satellite, orbiting at about 20 200 km, carries an atomic clock and transmits a signal stating its own position and the exact moment of transmission. A receiver notes the moment of arrival. The difference, multiplied by c , is the distance to that satellite, and a single such distance places the receiver on a sphere of that radius centred on the satellite. Let the class derive the counts: two spheres intersect in a circle, three in two points, one of which is far from the Earth's surface and can be discarded. So three satellites suffice, given a perfect clock in the receiver. It has nothing of the kind; a quartz oscillator drifts by far more than the nanoseconds required. The solution, which is the elegant heart of the subject, is to treat the receiver's clock error as a fourth unknown and use a fourth satellite: four equations in four unknowns (x , y , z and the clock offset), solved continuously. A GNSS receiver therefore needs four satellites in view, and as a by-product it keeps time to within tens of nanoseconds, which is why the receivers in lesson 5's network use the same satellites as the aircraft for their clocks.

Put the magnitudes on the board and keep returning to them. Light travels 0.300 m in a nanosecond and 300 m in a microsecond. A timing error of 1 microsecond is a range error of 300 m; the few-metre accuracy of a modern receiver corresponds to timing at the level of ten nanoseconds. The travel time from a satellite directly overhead is $20\,200\text{ km} / 3.00 \times 10^8\text{ km/s} = 0.0673\text{ s}$, and from one near the horizon about 0.086 s, so the receiver is measuring differences of a few milliseconds to a precision of a hundred-millionth of that. Ask the class what would happen if a satellite's clock were fast by one microsecond; they should see that every receiver using it would be pushed about 300 m along the line towards it, and this is why the satellite clocks are corrected from the ground several times a day.

Separate the two altitudes, because the message carries both and students always ask. The satellite solution gives a geometric height above the Earth's reference ellipsoid. Aircraft nonetheless report barometric altitude: the static pressure outside the fuselage converted to height through the International Standard Atmosphere, which assumes 1013.25 hPa and 15 degrees at sea level and a fall of 6.5 degrees per kilometre. On a day when the real pressure differs from standard, every aircraft's barometric altitude is wrong by the same amount, which is exactly what separation needs: two aircraft reading flight levels 350 and 360 are 1 000 ft apart whatever the weather. ADS-B position messages carry the barometric altitude in 25-foot steps; the velocity message carries the difference between barometric and geometric height, so a receiver can recover both. For the older group, the ISA relation $p = p_0 (1 - 0.0065 h / 288.15)^{5.255}$ makes a good spreadsheet exercise: invert it to find h from p and check that 11 000 m corresponds to about 227 hPa, a fifth of sea-level pressure.

Now turn the problem inside out. Some aircraft transmit on 1090 MHz without a satellite position: older transponders replying to radar with only identity and altitude, or aircraft whose GNSS is jammed. A network of receivers can still locate them. Suppose four receivers with synchronised clocks record the arrival time of the same transmission. The transmitter is unknown, the receivers are known: this is the GNSS problem with the roles of known and unknown exchanged. A message that arrived at receiver A one microsecond before receiver B was sent from a point 300 m nearer A than B, and the locus of such points is a hyperboloid with A and B as foci. Three independent pairs from four receivers give three hyperboloids, whose intersection is the aircraft. This is multilateration, and it needs the receivers' clocks agreeing to about 100 ns, which they get from the satellites. For the class, reduce it to two dimensions with the playground exercise: three students with stopwatches at surveyed points, a fourth hidden somewhere claps, the three record their reaction-time-corrected delays, and the class draws the hyperbolae (or, more simply, uses trial positions on a scale drawing) to find the clapper, using 343 m/s. Then ask what the timing precision would have to be to do the same with radio over 200 km, and let them feel the gap between a stopwatch and an atomic clock.

Worked example to set

Two receivers 60 km apart record a message 50 microseconds apart. By how much nearer the first receiver was the aircraft? (15 km.) If the clocks were wrong relative to each other by 1 microsecond, what error would that put in the answer? (300 m.) A student who can explain why the second answer does not depend on the distance has understood what multilateration demands.

LESSON 3 - COMPUTING

The digital message: 112 bits, how they are sent, and how errors are caught

The aircraft's transponder sends its ADS-B data as a Mode S extended squitter: an 8-microsecond preamble followed by 112 data bits at exactly one bit per microsecond. Start the lesson with the preamble, because it answers a question students have not yet thought to ask: how does a receiver know a message has started, when the channel is full of noise and of other aircraft? The preamble is a fixed pattern of four pulses at 0, 1, 3.5 and 4.5 microseconds. A decoder is constantly looking for that pattern;

when it finds it, it knows both that a message follows and precisely when each bit slot begins. Every digital protocol the students have met, from Wi-Fi to a QR code, has an equivalent, and this is a good moment to say so.

Then the modulation. A radio can be on or off; how do you send a 1 or a 0? ADS-B uses pulse position modulation: each one-microsecond bit slot is divided into two halves, and a pulse in the first half followed by silence means 1, silence followed by a pulse means 0. Draw a few bits on the board as pulses and have the class read them. Then ask why this is better than the obvious scheme of "pulse means 1, no pulse means 0". Two reasons emerge with a little prompting. There is always exactly one pulse per bit, so the receiver can keep its timing locked even through a run of zeros, and it can decide each bit by asking which half was louder rather than whether a pulse cleared some absolute threshold, which makes the decoding insensitive to how strong the signal happens to be. A long run of zeros in the naive scheme would be indistinguishable from silence; in PPM it is a steady drumbeat of second-half pulses.

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



Now the layout of the 112 bits, which the class should be able to reproduce from memory by the end of the lesson. Bits 1 to 5 are the downlink format, 17 for ADS-B from a transponder. Bits 6 to 8 are a capability code. Bits 9 to 32 are the 24-bit ICAO address, the aircraft's permanent identity. Bits 33 to 88 are the 56-bit message field, whose first five bits, the type code, say what the remaining 51 contain: an identification message (type codes 1 to 4) carries the eight-character call sign as eight 6-bit characters; an airborne position (9 to 18) carries 12 bits of barometric altitude, a flag saying whether this is an even or odd frame, and 17 bits each of encoded latitude and longitude; a velocity message (19) carries the east-west and north-south components of ground speed, the vertical rate, and the barometric-geometric height difference. Bits 89 to 112 are the 24-bit parity. Set the arithmetic: 24 bits of address give $2^{24} = 16\,777\,216$ aircraft; eight 6-bit characters allow 64 symbols each, enough for letters, digits and space; 12 bits of altitude in 25-foot steps cover 102 400 feet; and 17 bits of latitude, if used naively over 180 degrees, would resolve only 1.4 km, which raises the question compact position reporting answers. Explain CPR in one paragraph: the 17 bits give position within a zone to a few metres, not which zone; the aircraft alternates between two zone grids, even and odd, and a receiver that has one of each can resolve the zone unambiguously and then track from single messages. It is a neat example of getting more precision from the same bits by using time.

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)

Give the class a real message and let them dissect it. The hexadecimal string 8D4840D6202CC371C32CE0576098 is 28 hex digits, 112 bits. Converting the first two digits, 8D, to binary gives 10001 101: DF = 17, CA = 5. The next six digits, 4840D6, are the ICAO address, which the allocation tables assign to the Netherlands. The following digits, 20 ..., begin with 00100, type code 4, an identification message, and decoding the 6-bit characters that follow gives the call sign KLM1023. The last six digits, 576098, are the parity. A class with a spreadsheet or a few lines of Python can do the whole decode in a lesson, and the ability to take a string of hex and say "that is a KLM aircraft announcing its flight number" is the outcome to aim for.

8D 4840D6 202CC371C32CE0 576098

8D: downlink format 17, capability 5. 4840D6: ICAO address, allocated to the Netherlands. 20...: type code 4, identification, call sign KLM1023. 576098: the 24-bit parity.

End with the parity, because it is the computing idea most worth developing. Over a busy airport, messages from different aircraft overlap at a receiver constantly, and pulses are also lost to noise; a decoder will inevitably assemble wrong bits. The 24-bit field at the end is a cyclic redundancy check: the 88 message bits are treated as a long binary number and divided, in a special arithmetic in which subtraction is exclusive-or, by a fixed 25-bit generator; the remainder is the CRC. The receiver repeats the division on the bits it decoded and compares. Any single corrupted bit, any two, and any burst of errors up to 24 bits long changes the remainder, so the corrupted message is rejected. Demonstrate the idea at small scale with a 4-bit CRC on an 8-bit message done by hand, or with the simpler analogue of a check digit on a barcode; then have the older group implement the real CRC-24 in a few lines of code and verify that the example message's parity comes out right, and that flipping one bit makes it fail. This is error detection as every modern system does it, met in a context where a missed error could put a phantom aircraft on a controller's screen.

Worked example to set

How long does a complete transmission last, and if a transponder sends 4.5 extended squitters a second, what fraction of the time is it transmitting ADS-B? (120 microseconds; 540 microseconds per second, 0.054 percent.) How many aircraft could in principle share the channel before it was continuously busy, ignoring everything else transmitted on it? (About 1 850, which is why congestion over the busiest airspace is a real engineering concern.)

LESSON 4 - PHYSICS

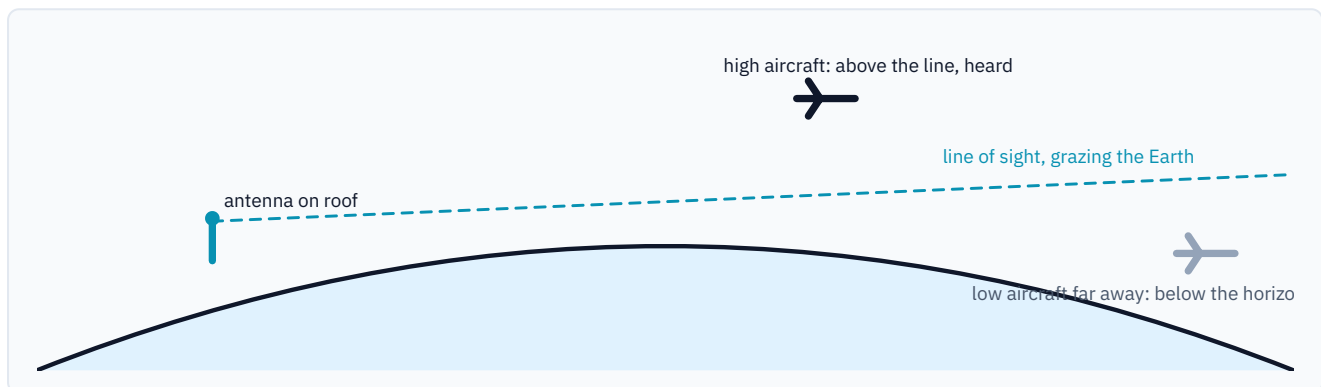
Propagation and range: the curve of the Earth and the inverse square law

How far away can a receiver hear an aircraft? The question has two independent answers, geometric and energetic, and the lesson's purpose is to derive both and discover that the designers arranged for them to agree. Take geometry first. At 1090 MHz, radio does not diffract usefully around the Earth; it behaves like light and travels in straight lines. A receiver can therefore hear only aircraft above its horizon, that is, aircraft from which a straight line to the antenna does not pass through the ground. Derive the horizon distance with the class. An antenna at height h above a sphere of radius R sees a horizon where its line of sight is tangent to the sphere. The tangent, the radius to the tangent point and the radius to the antenna

form a right angle at the tangent point, so by Pythagoras $d^2 + R^2 = (R + h)^2$, giving $d^2 = 2Rh + h^2$. Since h is tiny next to R , $d = \sqrt{2Rh}$. With $R = 6\,371$ km and h in metres, d in kilometres = $\sqrt{2 \times 6371 \times h / 1000} = 3.57 \sqrt{h}$. The atmosphere's density, and so its refractive index, falls with height, which bends radio rays slightly downward; the standard correction treats the Earth as if it had four-thirds its true radius, replacing 3.57 by 4.12. The full line of sight from an antenna at h_1 to an aircraft at h_2 is the sum of the two horizon distances:

$$d \text{ (km)} = 4.12 \times (\sqrt{h_1} + \sqrt{h_2}) \quad \text{with } h_1, h_2 \text{ in metres}$$

Antenna on a 20 m roof, aircraft at 11 000 m: $4.12 \times (4.47 + 104.9) = 451$ km. Same antenna, aircraft at 1 000 m: $4.12 \times (4.47 + 31.6) = 149$ km. Aircraft on the runway 30 km away: $4.12 \times (4.47 + 2) = 27$ km, so not heard.



Have the class plot d against h_2 for their own school's antenna height; the curve, steep at first and flattening, explains the shape of every receiver's coverage: a circle of 400 km and more for cruising traffic, a few tens of kilometres for aircraft on approach, and nothing on the ground except at the airport next door. It also explains why height matters more than any other property of a receiver, and why a hill between you and the airport, or the aircraft's own wing when it banks away, cuts a track instantly. The playground demonstration from the primary course, seeing further from a bench than crouching, is not beneath this age group if you follow it with the derivation; the point is that they now know why.

Now energy. A transponder radiates a peak power of a few hundred watts, roughly uniformly in all horizontal directions. At distance d that power has spread over a sphere of area $4 \pi d^2$, so the power intercepted by an antenna of fixed effective area falls as $1 / d^2$: the inverse square law, which the class should derive from the sphere's area rather than memorise. Twice the distance, a quarter of the power; ten times, a hundredth. Radio engineers express the loss between an isotropic transmitter and an isotropic receiver in decibels, and the standard formula, which the older group can take on trust or derive from the effective area of an antenna, $\lambda^2 / 4 \pi$, is:

$$\text{path loss (dB)} = 20 \log_{10}(d \text{ in km}) + 20 \log_{10}(f \text{ in MHz}) + 32.44$$

At 400 km and 1090 MHz: $20 \times 2.60 + 20 \times 3.04 + 32.44 = 52.0 + 60.7 + 32.4 = 145$ dB. A 250 W transmitter is +54 dBm; the received power is $54 - 145 = -91$ dBm, about 8×10^{-13} W, or a millionth of a millionth of a watt.

Spend a few minutes on decibels if the class has not met them, because they turn a multiplication across fourteen orders of magnitude into an addition, and because the number itself is instructive: a receiver on a roof is detecting a signal $10^{14.5}$ times weaker than the one that left the aircraft. A good hobby receiver can decode down to around -100 dBm, so there is about 9 dB in hand at 400 km, which is to say

that the energetic limit and the geometric horizon for a cruising airliner fall in the same place. That is not an accident; the transponder power and the receiver standards were specified so that an aircraft is audible to the horizon and not much beyond, which keeps the channel from being flooded by transmissions from the next country.

Two refinements for the older group. First, Doppler: an aircraft approaching at 250 m/s shifts the received frequency by $f \times v / c = 1.09 \times 10^9 \times 250 / 3 \times 10^8 = 908$ Hz, less than one part in a million of the carrier, which a receiver never notices; contrast this with the audible Doppler shift of the aircraft's sound, where v / c is $250 / 343$ and the pitch changes by most of an octave as it passes. Second, the signal time of flight: 400 km at c is 1.33 ms, so the position in the message is already 1.33 ms old, during which the aircraft has moved 33 cm; negligible for a map, decisive for the multilateration of lesson 2, which lives on exactly these microseconds.

Worked example to set

A receiver on a 10 m mast hears a cruising aircraft at 11 000 m but not a light aircraft at 600 m that is 130 km away. Is the light aircraft below the horizon? (Horizon: $4.12 \times (3.16 + 24.5) = 114$ km, so yes.) How high would the receiver need to be to hear it? (Need $4.12 \times (\sqrt{h_1} + 24.5) = 130$, so $\sqrt{h_1} = 7.05$, $h_1 = 50$ m.)

LESSON 5 - PHYSICS AND ENGINEERING

Antennas and receivers: from a 27-centimetre wave to a dot on a map

An antenna is a conductor in which a passing electromagnetic wave induces an alternating current; the receiving antenna and the transmitting antenna are the same device run in opposite directions, a reciprocity the class should be told explicitly. The induced current is largest when the conductor resonates: when its length is such that the current distribution along it fits the wave's oscillation, exactly as a string of the right length resonates with a particular note or a swing with a particular rhythm of pushes. A straight conductor's fundamental resonance is at half a wavelength, 13.75 cm at 1090 MHz, with current greatest in the middle and zero at the ends. The practical ADS-B antenna, on the aircraft and on most receivers, is a quarter-wave monopole: a vertical element of 6.9 cm standing on a conducting ground plane, which mirrors it electrically so that element and image together form the half-wave dipole. On the aircraft the fuselage is the ground plane; a bought 1090 MHz antenna hides the same geometry inside its tube, stacked several times over to concentrate its sensitivity towards the horizon. A model built in class from a 6.9 cm rod on a tin lid shows the geometry and the length, measured with a ruler against the 27.5 cm wave; the receiver of the project, though, uses the factory-tuned antenna, because a few millimetres of error detune a home-made one and it hears a fraction of the sky.

Develop the radiation pattern, because it predicts something the class can observe. A vertical monopole radiates and receives most strongly towards the horizon and not at all along its own axis; its sensitivity, plotted in three dimensions, is a ring doughnut with the antenna through the hole. So a receiver typically hears aircraft 300 km away perfectly and loses one passing directly overhead for a few seconds, and the class can watch this happen on their own receiver. A collinear antenna, several resonant elements stacked, squeezes the doughnut flatter, increasing sensitivity at the horizon where distant aircraft are, at

the cost of the overhead hole: this is antenna gain, expressed in dBi, and it comes from redistributing sensitivity, never from creating it. Polarisation, from lesson 1, now has a practical consequence the project will test: the antenna must be vertical.

Between the antenna and the computer are three stages, each a small lesson. A band-pass filter passes 1090 MHz and rejects the far stronger mobile-phone transmissions a few hundred megahertz away, which would otherwise saturate the amplifier. A low-noise amplifier, placed at the antenna rather than at the receiver, multiplies the signal a thousandfold before it enters the cable; the order matters, because a coaxial cable at 1090 MHz loses roughly half the signal, 3 dB, every ten metres, and amplifying after the loss would amplify the cable's noise along with the signal. Then the software-defined radio: a 20-euro USB device originally made as a television tuner, which mixes the signal down to baseband and samples it two million times a second into a stream of numbers. From that point the radio problem is a programming problem. Free software scans the sample stream for the preamble pattern, measures which half of each microsecond slot carries more energy, assembles 112 bits, computes the CRC, and if it passes, decodes the fields. A tracker then pairs even and odd position frames, merges position, velocity and identification by ICAO address, and holds each aircraft's state until messages stop arriving.

Give the chain to the class as a diagram they draw themselves, with the quantity at each stage: nanovolts of alternating current at the antenna; microvolts after the amplifier; two million 8-bit numbers a second out of the SDR; 112-bit frames out of the decoder, perhaps a few hundred a second; one record per aircraft out of the tracker. The point to land is that a dot on a map is the far end of a chain in which each link is an idea they now understand: resonance, filtering, amplification, sampling, pattern matching, decoding, error checking, aggregation.

Worked example to set

A cable loses 3 dB per 10 m at 1090 MHz. A 20 m run therefore loses what fraction of the signal? (6 dB, three quarters.) If the receiver's limit is -100 dBm and the signal at the antenna from an aircraft at 400 km is -91 dBm, can the signal survive the cable without an amplifier? (Only just: -97 dBm. Any further loss, rain on the connectors or a longer run, and the aircraft at the horizon disappears. This is why the amplifier goes at the antenna.)

PROJECT - TWO TO FOUR WEEKS

Build a receiver and test the physics against the sky

The project turns the five lessons into measurements. The equipment is a USB software-defined radio dongle (about 25 euros), a factory-tuned 1090 MHz antenna (50 to 70 euros), a few metres of coaxial cable, and a laptop or a Raspberry Pi running one of the free decoders (dump1090 and its descendants are the standard). Installation takes an afternoon and the software shows, within minutes, a table of aircraft with their ICAO addresses, call signs, positions, altitudes and speeds, and a map. Everything in the project is receive-only; nothing transmits, and the class should understand that transmitting on aviation frequencies would be both illegal and dangerous. Roof access needs the usual school approval; a window on an upper floor facing the main traffic flows is a perfectly good start. The Become a feeder page on this site walks through the same installation step by step and lets the school's receiver feed the live map.

The first investigation is the radio horizon. The decoder reports, for each aircraft, the distance and altitude at which it was last heard. Over a day, collect the maximum range at which aircraft in several altitude bands were received and plot range against altitude. The students have the formula from lesson 4 and the antenna height; they should predict the curve before they see the data, then compare. The agreement is usually good for high aircraft and worse for low ones, and the discussion of why (buildings, terrain, the antenna's overhead hole, the aircraft's own shadowing) is the kind of confrontation between theory and measurement that a textbook cannot offer. A map of the furthest aircraft heard in each direction, which the software draws, shows the terrain of the whole region as shadows in the coverage.

The second is the antenna. Compare message rates and maximum range with the antenna indoors, at a window, and on the roof; vertical and laid horizontal; standing on a metal surface and held away from any metal. Each comparison tests a specific claim from lessons 1 and 5, and each result should be predicted first. The polarisation test is the most striking: laid flat, the antenna loses most of its aircraft.

The third is data. Log a full day of traffic and ask questions of it: the busiest hour, the distribution of cruise altitudes (students expect a spread and find most airliners between 10 000 and 12 000 m), the climb rate of departures from the nearest airport, the states whose aircraft pass most often (from the ICAO address allocation). The older group can decode raw messages themselves, from the hex the software logs, and verify the CRC in their own code. A class with a second receiver at a partner school 30 or more kilometres away, both with GNSS-timestamped output, can attempt a two-dimensional multilateration of an aircraft both can hear and compare it with the position the aircraft broadcast: the most ambitious outcome of the course, and a real one.

End with the questions that the system raises and does not answer. The messages are unsigned, so a transmitter could broadcast a phantom aircraft; what defends the system, and what would a signed version cost? The aircraft depends on satellites that can be jammed; what happens to a controller's picture when they are? The data identifies aircraft, and an aircraft can identify a person; who should be able to follow whom? A class that has built the receiver has earned these questions, and they make a good final essay or debate.

Answers to the student's challenges

The student's page sets eight challenges, one or two per lesson, which can be used for homework or as an end-of-course test. The answers, with the reasoning a full-mark response should contain:

1. Wavelength at 1090 MHz: $\lambda = c / f = 3.00 \times 10^8 / 1.09 \times 10^9 = 0.275$ m. Quarter-wave element: 6.9 cm. Reasoning: $c = f \times \lambda$, with the fixed speed of light forcing an inverse relation.
2. Light is faster than sound by $3.00 \times 10^8 / 343$, about 875 000 times. Over 30 km the message takes 100 microseconds and the sound 87 s; the aircraft at 250 m/s moves 22 km in that time.
3. A 2-microsecond clock error gives a range error of $2 \times 10^{-6} \times 3 \times 10^8 = 600$ m. Four satellites are needed because the receiver's clock offset is a fourth unknown alongside x, y and z.
4. $2^{24} = 16\,777\,216$ addresses. A 112-bit message at 1 bit per microsecond lasts 112 microseconds, 120 with the preamble.
5. In 8D4840D6..., 8D is 10001101: the first five bits 10001 are 17, so DF = 17, an ADS-B message from a Mode S transponder; the next three, 101, give CA = 5. 4840D6 is the ICAO address.

6. Radio horizon from a 15 m antenna to an aircraft at 9 000 m: $4.12 \times (3.87 + 94.9) = 407$ km. For an aircraft at 300 m: $4.12 \times (3.87 + 17.3) = 87$ km.
7. Doubling the distance quarters the received power, because the same transmitted power is spread over a sphere of four times the area. Path loss at 200 km and 1090 MHz: $20 \times 2.30 + 60.7 + 32.4 = 139$ dB, 6 dB less than at 400 km, consistent with a factor of four.
8. An antenna laid horizontal is cross-polarised to the vertically polarised wave and receives very little; the induced current depends on the component of the electric field along the conductor. A receiver on the ground floor loses range because its horizon distance, $4.12 \times \sqrt{h_1}$, shrinks, and because buildings block the line of sight.

NEXT

The project, step by step

The project of lesson 6 assumed a receiver; the hands-on workshop builds it. It is written for someone who has never used a Raspberry Pi: the shopping list with prices, the antenna to choose, its placement and the cable loss, preparing the Pi, the three commands that install the Dataero feeder, claiming the station, tuning the gain, and five measurements, one per lesson, that test the physics against the sky. A station that feeds Dataero gives the class a dashboard, a coverage map and a year of history to work with.

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