

Multi-Sensor Counter-UAS Detection System

Technical Specification

Vendor-Agnostic Reference Design: RF Detection, LTE/Cellular Monitoring, and Acoustic Sensor Arrays

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Prepared for engineering, procurement, and systems-integration review.

Detection, classification and tracking only. Active mitigation is outside the scope of this document and is legally restricted in the jurisdictions surveyed in Section 12.

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1 Document Control and Scope

1.1 Purpose

This document specifies a vendor-agnostic reference design for a distributed, multi-sensor Counter-Unmanned Aircraft System (C-UAS) detection network built on three complementary passive sensing modalities: radio-frequency control-link detection, cellular network monitoring, and acoustic sensor arrays. It defines sensor node architectures, frequency coverage, array geometry and signal processing, data fusion and tracking algorithms, network backhaul and timing, and operational performance metrics, together with the deployment engineering needed to realise them in urban and rural environments.

The document is written to be used in three ways: as an engineering baseline from which a detailed design can be developed, as a procurement reference against which competing implementations can be compared on equal terms, and as a technical risk register that states plainly what this class of system cannot do.

1.2 Scope

The specification covers the following, each in its own numbered section: the RF detection subsystem and its band plan across ITU Regions 1, 2 and 3; the LTE and cellular monitoring subsystem for cellular-piloted aircraft; the acoustic sensor array and its rotor-signature digital signal processing chain; multi-sensor data fusion, tracking and classification; network backhaul, timing distribution, power and physical node engineering; deployment geometry and coverage engineering for urban, rural and mobile node types; operational performance metrics and their verification methods; the limitations and assumptions register; and a multi-region regulatory and legal compliance matrix.

The design is deliberately vendor-agnostic. No product is endorsed. Commercial parts, protocols and platforms are named only where they define a representative component class, an interoperability target, or a published measurement whose provenance the reader needs in order to judge the number.

1.3 Explicitly out of scope

This is a detection-only system. Mitigation of any kind is outside the scope of this specification. That includes radio-frequency jamming, protocol takeover or command spoofing, GNSS denial or spoofing directed at a target aircraft, high-power microwave or directed-energy effectors, kinetic interception, net capture and interceptor drones. These are excluded on two independent grounds. First, technical: mitigation imposes an entirely different set of engineering, safety and effect-verification requirements that would not share a design baseline with a passive sensing network. Second, and more importantly, legal: in most jurisdictions the authority to interfere with an aircraft in flight or with a licensed radio transmission is restricted to specifically designated government entities, and acquiring or operating such capability without that authority may violate spectrum, wiretap, computer-fraud and aircraft-sabotage statutes.¹ Section 12 treats this in detail by region. Any reader intending to extend this design toward mitigation must treat that as a separate programme with separate legal authorisation, not as a configuration option.

Also out of scope: radar and electro-optical or infrared sensing. Both are legitimate and, as Section 3.4 shows, necessary complements to the three modalities specified here; they are excluded because the user requirement for this document is confined to RF, cellular and acoustic sensing. Where the absence of radar or electro-optical coverage creates a capability gap, that gap is stated rather than concealed.

1.4 Intended readership

- Systems and RF engineers developing or evaluating a detailed design against this baseline.

FAA, Counter UAS (C-UAS) resources page including the DOJ/FAA/DHS/FCC advisory of 17 August 2020, ¹
https://www.faa.gov/uas/resources/c_uas

- Procurement and technical evaluation teams comparing candidate implementations, for whom the requirement identifiers and verification methods of Sections 4 to 10 form a ready-made evaluation matrix.
- Systems integrators responsible for backhaul, timing, command-system interfaces and site engineering.
- Regulatory, legal and data-protection reviewers, for whom Sections 1.3, 5.6 and 12 are the relevant material.

1.5 Requirement language

Requirement statements use the following verbs, and each carries a unique identifier of the form REQ-xx-xxx. Appendix A consolidates every identifier.

Verb	Meaning
SHALL	A mandatory requirement. Non-compliance means the implementation does not conform to this specification.
SHALL NOT	A mandatory prohibition, used here chiefly where a practice would be unsafe, legally exposed, or would produce a misleading performance claim.
SHOULD	A strong recommendation. Deviation is permitted but shall be documented with its technical justification and its performance consequence.
MAY	A permitted option carrying no obligation.

1.6 Evidence and derivation conventions

This document distinguishes rigorously between published figures and engineering estimates, because conflating the two is the most common failure mode in C-UAS technical literature and the easiest way to mislead a procurement decision.

- **Published figures** are cited to a numbered footnote containing the source name and its full URL. Where the only available source is of limited authority, for example a vendor blog or an enthusiast community page, that limitation is stated in the surrounding text rather than hidden behind the footnote number.
- **Engineering estimates** are tagged [Derived] in tables and introduced by a Derivation lead-in or a stepped calculation in prose. Every derived figure shows its inputs and arithmetic so the reader can substitute their own assumptions.
- **Unavailable figures** are recorded as not published in the reviewed sources. They are not interpolated, and no value is asserted in their place.
- **Research gaps** encountered during preparation, including documents that could not be retrieved, are listed in Section 11 rather than silently omitted.

A consequence worth stating explicitly: none of the performance figures in this document constitute a guarantee of field performance. Detection range in particular is not a property of a sensor. RF detection range depends on the emitted power of the target control link, acoustic detection range depends on the local ambient noise floor and wind, and both depend on geometry. Every range figure here is conditional on stated assumptions, and Section 10 requires that as-installed performance be established by measurement.

1.7 Definitions and abbreviations

Table 1-1 — Definitions and abbreviations

Term	Definition
AGL / AMSL	Above ground level / above mean sea level.
AoA	Angle of arrival. The estimated bearing of an emitter relative to a sensor array.
AOP	Acoustic overload point. The sound pressure level at which a microphone reaches a defined distortion limit.
ASTERIX	All Purpose Structured EUROCONTROL Surveillance Information Exchange, the surveillance data exchange format family. CAT-129 carries UAS identification reports and CAT-062 carries system tracks.
BPF	Blade passage frequency. The fundamental acoustic tone produced by a rotor, equal to blade count multiplied by rotational frequency.

Term	Definition
C2 / C-UAS	Command and control / counter-unmanned aircraft system.
CEP	Circular error probable. The radius of a circle containing 50 percent of position estimates.
CoT	Cursor on Target. A lightweight XML message format for tactical position, identity and status exchange.
CSAC	Chip-scale atomic clock. A low-power atomic frequency reference used for timing holdover.
DOA	Direction of arrival. Used here interchangeably with AoA in the acoustic context.
DroneID	A proprietary broadcast telemetry frame transmitted by certain consumer aircraft, carrying identity and position information.
[Derived]	A tag marking an engineering estimate calculated in this document rather than taken from a published source.
GDOP	Geometric dilution of precision. The multiplier relating measurement error to position error for a given sensor and target geometry.
GNSS	Global navigation satellite system, covering GPS, Galileo, GLONASS and BeiDou.
IMM	Interacting multiple model. A tracking filter structure that runs several motion models in parallel and blends them by likelihood.
ISM	Industrial, scientific and medical radio bands, used by most consumer control links.
NF	Noise figure. The degradation in signal-to-noise ratio introduced by a receiver chain.
P _D / P _{FA}	Probability of detection / probability of false alarm.
PON / GPON / XGS-PON	Passive optical network and its gigabit and 10-gigabit symmetric variants.
PTP	Precision Time Protocol, IEEE 1588, used for sub-microsecond network time distribution.
RF-silent	An aircraft emitting no detectable control-link or telemetry signal, for example one under fibre-optic tether control or flying a pre-loaded autonomous route.
SDR	Software-defined radio. A receiver in which channelisation and demodulation are performed digitally.
sUAS	Small unmanned aircraft system. In this document, Group 1 and Group 2 aircraft as defined in Section 3.1.
SyncE	Synchronous Ethernet, ITU-T G.8262, distributing frequency over the Ethernet physical layer.
TDOA	Time difference of arrival. A multilateration technique using the difference in signal arrival times at spatially separated sensors.
UKF	Unscented Kalman filter. A nonlinear state estimator using deterministic sample points.
URLLC	Ultra-reliable low-latency communication, a 3GPP service class.

1.8 Normative and informative references

The standards below are referenced in the body of this specification. Full source URLs appear in the footnotes at the point of use in each section, so that every citation sits next to the claim it supports.

Table 1-2 — Referenced standards and regulations

Designation	Title or subject	Used in
3GPP TR 36.777	Study on enhanced LTE support for aerial vehicles	Section 5
3GPP TR 38.901	Channel model for frequencies from 0.5 to 100 GHz, including urban micro and macro models	Sections 4, 9
ETSI EN 300 328	Wideband transmission systems in the 2.4 GHz ISM band	Section 4
ETSI EN 301 893	5 GHz RLAN harmonised standard	Section 4
ETSI EN 300 220	Short-range devices below 1 GHz, including the 868 MHz band	Section 4
ITU-R P.530	Propagation data and prediction methods for terrestrial line-of-sight systems	Section 8
ITU-R P.838	Specific attenuation model for rain	Section 8
ITU-R P.1411	Short-range outdoor propagation, 300 MHz to 100 GHz	Sections 4, 9

Designation	Title or subject	Used in
ITU-R P.2109	Prediction of building entry loss	Sections 4, 9
ISO 9613-2	Attenuation of sound during propagation outdoors	Section 6
IEEE 1588	Precision Time Protocol	Sections 7, 8
IEEE 802.3af / at / bt	Power over Ethernet Types 1 to 4	Section 8
IEEE 802.11ac / ax / ay	Wireless LAN and multi-gigabit point-to-point links	Section 8
ITU-T G.984	Gigabit passive optical network	Section 8
ITU-T G.9807.1	10-gigabit symmetric passive optical network	Section 8
ITU-T G.8275.1 / .2	PTP telecom profiles for full and partial timing support	Section 8
ITU-T G.8262	Synchronous Ethernet equipment clock characteristics	Section 8
ASTM F3411	Remote ID and tracking specification for unmanned aircraft	Sections 3, 8, 12
IEC 62443	Security for industrial automation and control systems	Section 8
IEC 62305	Protection against lightning, Parts 1 to 4	Section 8
IEC 61000-4-5	Surge immunity test	Section 8
NIST SP 800-53	Security and privacy controls for information systems	Section 8
NIST SP 800-82	Guide to industrial control systems security	Section 8
NIST SP 800-207	Zero trust architecture	Section 8
MIL-STD-810	Environmental engineering considerations and laboratory tests	Section 8
TIA-222-H	Structural standard for antenna-supporting structures, North America	Section 8
EN 1991-1-4	Eurocode 1: wind actions on structures	Section 8
EU 2019/945	Design and manufacture requirements for unmanned aircraft systems	Sections 8, 12
EU 2019/947	Rules and procedures for the operation of unmanned aircraft	Sections 8, 12
EU 2021/664	Regulatory framework for U-space	Section 12

2 System Overview and Architecture

2.1 Concept of operations

The system provides persistent, passive, wide-area awareness of small unmanned aircraft activity over a defined protected area, and delivers graded alerts with position, classification and confidence to a human operator or to an external command system. It does not act on the aircraft. Its output is information.

The operating cycle is continuous rather than event-driven. Each sensor node monitors its assigned RF bands, cellular signalling environment and acoustic field without interruption. When a node forms a candidate detection it estimates bearing, and where geometry allows, position, classifies the emitter or acoustic source, and reports a structured detection message to the fusion tier. The fusion tier associates reports across nodes and modalities into tracks, maintains those tracks over time, computes a calibrated multi-modality confidence, evaluates each track against declared protected volumes, and issues a graded alert. The command tier presents the resulting picture, records everything in replayable form, and exports tracks to external systems.

Three operating premises shape everything downstream, and each is a deliberate design choice rather than a limitation to be engineered away later. First, no single modality here is adequate alone: RF detection has range but is defeated by radio silence, cellular monitoring is narrow and applies only to cellular-piloted aircraft, and the acoustic array is emission-independent but short-ranged and weather-sensitive. Fusion is therefore the mechanism by which three individually inadequate sensors become an adequate system, not an enhancement layer. Second, the system must degrade gracefully: loss of backhaul, loss of GNSS timing, or loss of a modality shall reduce declared performance visibly rather than silently. Third, absence of detection is not evidence of absence of an aircraft, and the system shall never present it as such.

2.2 Three-tier architecture

Table 2-1 — Architecture tiers and functional allocation

Tier	Function	Rationale and constraints
Tier 1: Sensor node	RF wideband reception and channelisation, cellular signalling monitoring, acoustic array capture, per-modality detection and classification, bearing and time-of-arrival estimation, local buffering, health telemetry	Detection and classification are performed here rather than centrally because streaming raw signal is infeasible: Section 8.1 shows a bandwidth reduction of approximately 15 000 times between raw I/Q and detection metadata [Derived]. This tier must therefore carry real compute, power and timing hardware.
Tier 2: Fusion and aggregation	Time and space alignment, sensor registration and bias correction, association and gating, multi-target tracking, track-to-track and decision fusion, confidence calibration, threat assessment against protected volumes, graded alert generation	Sited either at an aggregation point serving a node cluster or centrally, depending on backhaul topology. Latency-critical association and tracking should sit as close to the nodes as the network topology allows.
Tier 3: Command and integration	Operator display, alert management, configuration and health management, replayable recording of all detections and fusion decisions, external export via ASTERIX, Cursor on Target or equivalent, audit logging	The recording function is a requirement rather than a convenience: without replay, missed detections and false alarms cannot be attributed to a modality, and no performance claim in Section 10 can be substantiated.

2.3 Sensor node variants

Three node types are defined. They share the same detection and reporting software and the same interfaces, and differ in sensing payload, power, timing and backhaul provisioning. Section 9 develops the deployment engineering for each.

Table 2-2 — Sensor node variants

Attribute	Type A: urban rooftop	Type B: rural mast	Type C: mobile or temporary
Primary role	Dense-area coverage with short inter-node spacing	Wide-area coverage with long inter-node spacing	Event, convoy or rapid-deployment coverage

Attribute	Type A: urban rooftop	Type B: rural mast	Type C: mobile or temporary
RF payload	Full multi-band wideband receiver, above-rooftop antennas	Full multi-band wideband receiver, mast-mounted antennas at height	Reduced-height antennas; range penalty accepted
Cellular monitoring	Yes, where local cellular coverage is monitorable	Yes where coverage exists; often absent in remote areas	Optional, coverage dependent
Acoustic payload	Selective, at protected sites only	Point defence at specific assets only	Primary short-range modality for this type
Backhaul	GPON, XGS-PON or active Ethernet; E-band or 60 GHz infill	Licensed microwave or LEO satellite; public cellular fallback	Public 4G or 5G with prioritised slice; LEO alternate
Power	Mains 24 or 48 V DC, or IEEE 802.3bt Type 4 PoE	Photovoltaic array with multi-day battery autonomy	Vehicle supply or portable battery
Timing	G.8275.1 full timing support, OCXO holdover	GNSS with rubidium or CSAC holdover, mandatory	GNSS with CSAC holdover, chosen for power class
Position and orientation	Surveyed once at installation	Surveyed once at installation	Surveyed or self-determined at every set-up
Dominant constraint	RF noise floor, acoustic ambient noise, structural and privacy consent	Backhaul cost, power autonomy, maintenance access	Opportunistic and therefore poor geometry

2.4 Top-level system requirements

Table 2-3 — System-level requirements

ID	Requirement	Verification
REQ-SYS-001	The system SHALL be passive and detection-only. It SHALL NOT transmit any signal intended to interfere with, deny, spoof or take control of a target aircraft, its control link or its navigation source.	Inspection
REQ-SYS-002	The system SHALL integrate at minimum three sensing modalities: RF control-link detection, cellular network monitoring, and acoustic sensing. No single modality SHALL be a prerequisite for the system producing an alert.	Field Trial
REQ-SYS-003	Detection, classification and bearing estimation SHALL be performed at the sensor node, and the node SHALL report structured detection and track messages rather than continuous raw signal.	Inspection
REQ-SYS-004	The system SHALL produce a graded alert carrying position or bearing, classification, calibrated confidence and per-modality contribution, and SHALL NOT reduce its output to a binary trigger.	Field Trial
REQ-SYS-005	The system SHALL NOT infer the absence of an unmanned aircraft from the absence of detections, and operator-facing displays SHALL make the difference between no detection and no aircraft explicit.	Inspection
REQ-SYS-006	The system SHALL declare its coverage per modality as separate footprints. A single combined coverage claim SHALL NOT be published.	Inspection
REQ-SYS-007	Degradation of any subsystem, including loss of backhaul, loss of GNSS timing, loss of a node or loss of a modality, SHALL be visible to the operator and SHALL be reflected in the declared confidence and accuracy of affected tracks.	Field Trial
REQ-SYS-008	End-to-end latency from first sensor detection to operator-visible corroborated alert SHALL NOT exceed 5 s, and SHALL be measured rather than modelled.	Field Trial
REQ-SYS-009	The system SHALL record all sensor detections, association decisions, track states and fusion confidences in a replayable form sufficient to reconstruct and attribute every missed detection and false alarm.	Field Trial
REQ-SYS-010	The system SHALL operate continuously and unattended, and SHALL recover automatically from node reboot, link loss and power interruption without operator intervention.	Field Trial
REQ-SYS-011	The system SHALL expose an external track export interface in at least one recognised format, and SHALL NOT require a proprietary client for interoperability with an external command system.	Inspection

ID	Requirement	Verification
REQ-SYS-012	Every quantitative performance figure declared by the implementer SHALL be accompanied by the conditions under which it was measured, including target type, range, altitude, geometry and environmental conditions.	Inspection
REQ-SYS-013	The system SHALL be architected so that no cellular user-plane content is captured, stored or decoded at any point in the processing chain.	Inspection
REQ-SYS-014	The acoustic subsystem SHALL be architected so that incidentally captured intelligible speech is discarded or irreversibly anonymised before storage, and this behaviour SHALL be demonstrable.	Bench Test
REQ-SYS-015	The implementer SHALL maintain a limitations register equivalent to Section 11 and SHALL keep it current, including any threat class the deployed configuration cannot detect.	Inspection

3 Threat Model and Design Drivers

This section establishes what the system is being asked to detect, and derives from that the coverage matrix that drives the sensor specifications in Sections 4 to 6. It is written to be uncomfortable: the most important content is Section 3.4, which identifies a class of aircraft that this system, as scoped, cannot detect at all.

3.1 Aircraft classes of interest

The United States Department of Defense group classification is the most widely used shorthand for unmanned aircraft size classes and is adopted here as vocabulary. The Congressional Research Service confirms the two key breakpoints, that 55 pounds is the upper limit of Group 2 and that Group 3 spans 55 to 1 350 pounds, and notes that DoD Directive 3800.01E treats a small UAS as a Group 1, 2 or 3 aircraft weighing up to 1 320 pounds.² The full numeric table below is reproduced from a university teaching source rather than from the primary directive, which was not retrievable during preparation; the weight breakpoints are consistent with the CRS text, but the altitude and airspeed figures should be treated as secondary-sourced.³

Table 3-1 — US DoD UAS group classification

Group	Maximum gross takeoff weight	Normal operating altitude	Airspeed	Relevance here
Group 1	0 to 20 lb	Below 1 200 ft AGL	Below 100 kt	Primary threat class
Group 2	21 to 55 lb	Below 3 500 ft	Below 250 kt	Primary threat class
Group 3	Below 1 320 lb	Below 18 000 ft MSL	Below 250 kt	Secondary; larger acoustic and RF signature
Group 4	Above 1 320 lb	Below 18 000 ft MSL	Any	Out of primary scope
Group 5	Above 1 320 lb	Above 18 000 ft	Any	Out of primary scope

Numeric table as published by the cited secondary source; weight breakpoints corroborated by the Congressional Research Service primer. AGL: above ground level. MSL: mean sea level.

This specification targets Group 1 and Group 2 aircraft. That choice drives the whole design: these are the aircraft small enough to be acoustically quiet at range, low-powered enough in their control links to be hard to detect at range, low and slow enough to be confused with birds, and cheap enough to be deployed in numbers. Group 3 and above are easier problems for every modality here and are treated as incidental capability rather than as design cases.

3.2 Control-link taxonomy and the coverage question

The decisive threat discriminator for this system is not aircraft size but how the aircraft is controlled, because that determines which modality can see it. Four control classes matter.

- **RF-controlled.** A conventional operator-piloted aircraft using a proprietary or open control link in the ISM bands or in sub-gigahertz bands. This includes proprietary consumer links, open long-range links whose documentation describes operation down to very low link rates for extended range,⁴⁵ and analogue or digital

US Congressional Research Service, Defense Primer: Categories of Uncrewed Aircraft Systems (IF12797), <https://www.congress.gov/crs-product/IF12797>²

Pennsylvania State University GEOG 892, US Department of Defense UAS Group Classification (secondary teaching source),³ <https://courses.ems.psu.edu/geog892/node/637>

ExpressLRS, Wikipedia, <https://en.wikipedia.org/wiki/ExpressLRS>⁴

ExpressLRS documentation, Long Range Operations, <https://deepwiki.com/ExpressLRS/Docs/5.3-long-range-operations>⁵

first-person-view video downlinks. Some consumer aircraft additionally broadcast a proprietary identity and position frame that yields substantially more information than mere presence when it can be decoded.⁶

- **Cellular-piloted.** An aircraft controlled over a public or private cellular network rather than a dedicated control link. 3GPP studied the airborne user-equipment case formally in TR 36.777,⁷ and its findings are the phenomenological basis of the cellular monitoring subsystem in Section 5. Such an aircraft may emit nothing recognisable as a drone control link, and is invisible to a conventional RF control-link detector.
- **Autonomous or pre-programmed.** An aircraft flying a waypoint route loaded before launch, with the control link switched off or absent. It emits no control-link signal at all, and no cellular signalling either. Its only exploitable signature in this system is acoustic.
- **Fibre-optic tethered.** An aircraft controlled over a spooled optical fibre. The control signal never leaves a shielded cable, so it cannot be jammed and, critically for this document, cannot be detected by any RF means.⁸⁹

3.3 Sensor coverage matrix

Table 3-2 — Which modality covers which control class

Control class	RF detection	Cellular monitoring	Acoustic array	Net coverage in this system
RF-controlled, proprietary or open link	Yes, primary	No	Yes, at short range	Good, with corroboration
RF-controlled with Remote ID broadcast	Yes, plus cooperative identity	No	Yes, at short range	Best case; identity available
Cellular-piloted	Limited; may emit no recognisable control link	Yes, primary	Yes, at short range	Adequate only where cellular monitoring is deployed
Autonomous, pre-programmed, link off	No	No	Yes, at short range only	Weak. Acoustic-only, therefore range-limited
Fibre-optic tethered	No	No	Yes, at short range only	Weak. Acoustic-only, therefore range-limited

This matrix is the single most important table in the document for scoping expectations. Two of five control classes have no RF or cellular coverage whatsoever and depend entirely on an acoustic sensor whose published range is 100 to 500 m.

3.4 The RF-silent detection gap

Fibre-optic-tethered first-person-view aircraft, fielded at scale in the Russia-Ukraine conflict, are a genuine blind spot for any purely RF-based sensor. Because the control signal travels inside a shielded cable, the link is physically impervious to jamming and to electronic-warfare detection alike. Reported real-world effectiveness is roughly 50 percent or better probability of a successful hit once a functional fibre-guided aircraft is launched, against under 5 percent for early long-range attempts, with common tether lengths up to 15 km for standard units and up to 30 km reported for more advanced systems.¹⁰ Corroborating reporting gives tether lengths of typically 5 to 15 km and up to 20 to 30 km in some cases, and states that no known electronic-warfare system can jam a signal travelling inside an optical fibre.¹¹

anarkiwi/samples2djidroneid, DJI DroneID sample analysis repository, <https://github.com/anarkiwi/samples2djidroneid>⁶

3GPP TR 36.777, Study on Enhanced LTE Support for Aerial Vehicles, official record, <https://www.3gpp.org/dynareport/36777.htm>⁷

The War Zone, Inside Ukraine's Fiber-Optic Drone War, <https://www.twz.com/news-features/inside-ukraines-fiber-optic-drone-war>⁸

ts2.tech, Fiber-Optic Drones in Ukraine: Evolution, Applications and Impact, <https://ts2.tech/en/fiber-optic-drones-in-ukraine-evolution-applications-and-impact/>⁹

The War Zone, Inside Ukraine's Fiber-Optic Drone War, <https://www.twz.com/news-features/inside-ukraines-fiber-optic-drone-war>¹⁰

ts2.tech, Fiber-Optic Drones in Ukraine: Evolution, Applications and Impact, <https://ts2.tech/en/fiber-optic-drones-in-ukraine-evolution-applications-and-impact/>¹¹

The defensive response documented in open sources is a shift toward acoustic and visual signature detection, with an infrared laser-sweep concept for detecting physical fibre-cable reflections proposed but not yet a fielded, proven capability.¹² Vendor guidance for C-UAS design explicitly recommends compact surveillance radar as the primary sensor against fibre-guided or otherwise RF-dark aircraft, on the straightforward grounds that RF detection has no signal to find.¹³

Design consequence, stated plainly. The RF and cellular monitoring chains specified in Sections 4 and 5 have zero detection capability against a genuinely fibre-tethered or fully autonomous RF-silent airframe. This is not an RF-subsystem shortfall that better receivers or lower noise figures can close; it is the absence of a signal. Within the scope of this document the only residual coverage is acoustic, at the 100 to 500 m ranges of Section 6, which means an RF-silent aircraft can approach to within a few hundred metres of a protected asset before this system can see it at all. Closing that gap requires a radar or electro-optical layer, which Section 1.3 places outside the scope of this specification. The gap is recorded as the first entry in the Section 11 limitations register, and any deployment against an adversary credibly capable of fibre-tethered or autonomous operation should be scoped with that additional layer from the outset.

3.5 False-alarm sources

False alarms, not missed detections, are what cause C-UAS systems to be switched off in practice. Vendor analysis of the operational problem identifies false alerts as a primary barrier to sustained use, because operator trust erodes faster than it can be rebuilt.¹⁴ The dominant confusers differ by modality.

- **Birds.** Kinematically and, for radar, spectrally similar to small aircraft; discriminating birds from drones is an active research problem addressed through kinematic feature extraction and machine learning.¹⁵¹⁶ This system excludes radar, so its bird exposure is acoustic rather than radar-derived, and Section 7 requires that the acoustic bird false-alarm contribution be characterised separately rather than folded into an aggregate figure.
- **Manned aircraft, particularly light aircraft and helicopters.** Strong acoustic sources with rotor or propeller harmonic structure that can superficially resemble a multicopter signature; the classification frame in Section 7 therefore includes manned aircraft as an explicit class rather than treating everything non-drone as noise.
- **Co-band RF emitters.** Wi-Fi access points, video links, wireless cameras and cordless devices share the ISM bands with control links, so RF detection in a dense urban environment operates against a continuously occupied spectrum rather than a quiet baseline.
- **Environmental acoustic noise.** Road traffic, ventilation plant, construction and above all wind noise at the microphone. Section 6 declares an explicit wind-speed operating limit for this reason.
- **Cellular signalling ambiguity.** A ground-level user device exhibiting anomalous uplink behaviour can resemble an airborne one. Section 5 treats this as the fundamental limit on passive cellular detection rather than as a tuning problem.

There is a broader problem behind all of this. The FAA states explicitly that there are no nationally recognised standards for UAS detection or threat classification, and that detection systems cannot themselves determine

Mittal, Forbes, Ukraine And Russia Battle To Defeat Un-Jammable Fiber-Optic Drones, ¹²
<https://www.forbes.com/sites/vikrammittal/2025/01/19/ukraine-and-russia-battle-to-defeat-un-jammable-fiber-optic-drones/>

Spotter Global, New Stealth Fiber-Optic Guided Drones (FOG-D): How To Detect Them, [https://www.spotterglobal.com/blog/spotter-blog-13](https://www.spotterglobal.com/blog/spotter-blog-3/new-stealth-fiber-optic-guided-drones-fog-d-how-to-detect-them-12)
<https://www.spotterglobal.com/blog/spotter-blog-3/new-stealth-fiber-optic-guided-drones-fog-d-how-to-detect-them-12>

D-Fend Solutions, The False Positive Dilemma: False Alerts in Drone Detection, [https://d-fendsolutions.com/blog/the-false-positive-dilemma-14](https://d-fendsolutions.com/blog/the-false-positive-dilemma-false-alerts-in-drone-detection/)
[false-alerts-in-drone-detection/](https://d-fendsolutions.com/blog/the-false-positive-dilemma-false-alerts-in-drone-detection/)

counteruavradar.com, How Radar Distinguishes Drones from Birds, [https://www.counteruavradar.com/en/knowledge-base/how-radar-15](https://www.counteruavradar.com/en/knowledge-base/how-radar-distinguishes-drones-from-birds/)
[distinguishes-drones-from-birds/](https://www.counteruavradar.com/en/knowledge-base/how-radar-distinguishes-drones-from-birds/)

TU Delft repository, Classification of Birds and Drones Exploiting Kinematic Properties for Surveillance Radars Using Machine Learning ¹⁶
Techniques, <https://repository.tudelft.nl/record/uuid:96cc142c-ddf6-4823-baf5-1a6a27b97b51>

intent or threat level.¹⁷ A published review of C-UAS sensors for unmanned traffic management surveys the sensor landscape but does not resolve that standardisation gap either.¹⁸ The practical consequence for this document is that Section 10 must define its own metrics and acceptance criteria rather than invoke an external test standard, and that any vendor performance claim encountered during evaluation was almost certainly measured under a methodology the vendor chose.

3.6 Cooperative identification as a design driver

Not every aircraft in the coverage volume is a threat, and regulation increasingly requires aircraft to identify themselves. ASTM F3411 defines both broadcast and network Remote ID,¹⁹ the European framework brought Remote ID requirements into force from 1 January 2024,²⁰ and Regulation (EU) 2021/664 establishes U-space airspace in which mandatory network identification, geo-awareness, flight authorisation and traffic information services apply.²¹ The design driver is twofold. The RF subsystem shall decode broadcast Remote ID where present, because it converts a bare detection into an identified cooperative track at negligible additional cost. Equally, the system shall never let cooperative identification substitute for non-cooperative detection, since an aircraft flown with intent to cause harm is precisely the one least likely to broadcast its identity truthfully. Cooperative and non-cooperative pictures are therefore maintained as distinct data sources throughout, a constraint carried into REQ-NW-030.

3.7 Design drivers summary

Threat characteristic	Design consequence
Group 1 and 2 aircraft are small, quiet and low-powered	Drives receiver sensitivity in Section 4 and microphone self-noise limits in Section 6
Control links are diverse and include low-rate long-range modes	Drives wideband coverage and a channelised detection architecture rather than a fixed-signature detector
Some aircraft are cellular-piloted	Requires the separate cellular monitoring subsystem of Section 5, with its own legal boundary
Some aircraft are RF-silent	Forces acoustic sensing to be a first-class modality, and forces the explicit gap declaration of Section 3.4
Low, slow flight amid birds and clutter	Drives the classification frame and separate bird false-alarm characterisation in Section 7
Dense co-band RF occupancy in urban areas	Drives dynamic range and interference-rejection requirements in Section 4, and backhaul band selection in Section 8
No recognised detection or classification test standard exists	Forces this document to define its own metrics and acceptance criteria in Section 10
Acoustic sensing captures sound in public space	Drives the privacy architecture requirements REQ-SYS-014 and the regional analysis in Section 12

FAA, UAS Detection Technical Considerations (Attachment 3), https://www.faa.gov/sites/faa.gov/files/airports/airport_safety/Attachment-3-17-UAS-Detection-Technical-Considerations.pdf

MDPI Sensors 22(1):189, Review and Simulation of Counter-UAS Sensors for Unmanned Traffic Management, <https://www.mdpi.com/1424-1898220/22/1/189>

ASTM F3411-22a, Standard Specification for Remote ID and Tracking, <https://www.astm.org/f3411-22a.html>¹⁹

EASA regulatory context, entry into force of Remote ID for UAS from 1 January 2024, <https://www.dronebydrone.com/en/news/744/entry-into-force-of-remote-id-in-uas-from-january-1-2024-per-easa-regulations.html>

EUR-Lex, Commission Implementing Regulation (EU) 2021/664 on a regulatory framework for U-space, https://eur-lex.europa.eu/eli/reg_impl/2021/664/oj/eng²¹

4 RF Detection Subsystem

4.1 Purpose and detection philosophy

The RF detection subsystem is the primary long-range sensor of the system. It is strictly receive-only: it detects, characterises, classifies and bears on the electromagnetic emissions that an unmanned aircraft and its ground control station radiate in the course of normal operation. It does not transmit, does not induce any behaviour in the target, and does not perform mitigation. Jamming, protocol spoofing, GNSS denial and control-link seizure are explicitly outside the scope of this specification and are, in most jurisdictions, unavailable to non-governmental operators.

There is no single "drone frequency". Command-and-control, video downlink and telemetry are distributed across a fragmented set of ISM and short-range-device allocations spanning 433 MHz to 5.9 GHz, with waveform, channel bandwidth and hopping behaviour varying by vendor and by protocol generation. The subsystem must therefore combine wideband energy detection across the whole candidate set with narrower protocol-signature analysis on the segments where the highest-value emitters live.

Detection layers. Three functionally distinct detection layers operate concurrently and feed the fusion engine as separate evidence streams: (i) wideband energy and burst detection, which is protocol-agnostic and detects any sufficiently strong emitter; (ii) protocol-signature classification, which identifies the emitter family from bandwidth, burst timing, hop behaviour and cyclostationary features; and (iii) broadcast-identification decode, which recovers explicit aircraft and operator identity from open remote-identification beacons and, where technically possible, from the unencrypted DJI DroneID beacon.

Acknowledged blind spot. A genuinely RF-silent airframe — most importantly a fibre-optic-tethered FPV aircraft, whose control signal never leaves a shielded cable — presents no control-link emission to detect. Fibre-tethered units are reported with tether lengths typically 5–15 km and up to 20–30 km in some cases, and are described as impervious to jamming and electronic warfare because the signal is physically contained.^{22 23} Defenders facing this threat class are consequently shifting to acoustic and visual signature detection.²⁴ Vendor design guidance likewise recommends compact surveillance radar as the primary sensor against RF-silent aircraft, since RF detection has no signal to find.²⁵ This is a physical-layer limitation of the modality, not an engineering shortfall to be closed within the RF subsystem, and it is the principal justification for the acoustic array specified in Section 6.

Residual-emission caveat. Suppressing the control and video downlink does not eliminate all emissions from the airframe: electronic speed controllers, switching converters and any onboard GNSS receiver still radiate weak transient interference. No fielded detection system identified in the source research exploits this residual emission, and multi-sensor fusion rather than RF-only detection is consistently identified as the practical path.²⁶

4.2 Frequency coverage and band plan

The subsystem SHALL monitor the bands in Table 4-1. Coverage priority is assigned on the basis of the population of emitters resident in each band and the operational consequence of missing them, not on ease of instrumentation. Regional notes are given because the same physical band carries different regulatory status, and

The War Zone, Inside Ukraine's Fiber-Optic Drone War, <https://www.twz.com/news-features/inside-ukraines-fiber-optic-drone-war>²²

ts2.tech, Fiber-Optic Drones in Ukraine: Evolution, Applications and Impact, <https://ts2.tech/en/fiber-optic-drones-in-ukraine-evolution-applications-and-impact/>²³

Forbes (V. Mittal), Ukraine And Russia Battle To Defeat Un-Jammable Fiber-Optic Drones, <https://www.forbes.com/sites/vikrammittal/2025/01/19/ukraine-and-russia-battle-to-defeat-un-jammable-fiber-optic-drones/>²⁴

Spotter Global, New Stealth Fiber-Optic Guided Drones (FOG-D): How To Detect Them (vendor), <https://www.spotterglobal.com/blog/spotter-blog-3/new-stealth-fiber-optic-guided-drones-fog-d-how-to-detect-them-12>²⁵

The War Zone, Inside Ukraine's Fiber-Optic Drone War, <https://www.twz.com/news-features/inside-ukraines-fiber-optic-drone-war>²⁶

different permitted radiated power, in each ITU Region — which changes both the expected emitter EIRP and the legality of any transmission in that band.

Table 4-1 — Monitored frequency bands, resident emitters and regional regulatory status

Band	Frequency range	Typical UAS use	Regional availability and regulatory note	Priority
433 MHz SRD	433.05–434.79 MHz	Long-range telemetry; LoRa-based long-range RC links	EU short-range-device band under ETSI EN 300 220; power limits differ from 868/915 MHz. Licensing varies by country. ²⁷	Medium
868 MHz SRD	860–885 MHz	ExpressLRS and TBS Crossfire EU variants	ITU Region 1 (Europe, Africa, Middle East). TBS specifies 860–885 MHz for Region 1. ²⁸	High
902–928 MHz ISM	902–928 MHz	ExpressLRS and TBS Crossfire Americas variants	ITU Regions 2 and 3. TBS specifies 902–927 MHz (FCC) and 915–928 MHz (AU). US operation under FCC Part 15. ²⁹	High
1.2–1.3 GHz	1240–1300 MHz (typ.)	Long-range analogue and digital FPV video	Amateur-adjacent allocations in some countries; licensing varies heavily. Not globally available.	Medium
2.4 GHz ISM	2400–2483.5 MHz	DJI OcuSync/O3/O4 dual-band mode; ExpressLRS 2.4 GHz; Wi-Fi-based drones; analogue FPV; DJI DroneID	Globally available ISM. EU: ETSI EN 300 328, max 20 dBm EIRP for adaptive FHSS equipment. US: FCC Part 15.247. ³⁰	Critical
5.15–5.35 GHz	5150–5350 MHz	DJI O4 secondary band (5170–5250 MHz); some 5 GHz Wi-Fi drones	EU: ETSI EN 301 893; 5150–5250 MHz limited to ≤200 mW EIRP indoor use per national guidance. DJI cites <23 dBm CE for this band. ^{31,32}	High
5.725–5.875 GHz	5725–5875 MHz	DJI OcuSync/O3/O4 primary band; Walksnail Avatar; HDZero; analogue 5.8 GHz FPV	Globally available ISM. DJI O4 EIRP limits: <30 dBm FCC, <14 dBm CE, <30 dBm SRRC. EU EN 300 440 limits this allocation to ≤25 mW EIRP for UAS video. Finnish guidance records 5470–5725 MHz as banned for UAS use since 13 January 2023. ^{33,34}	Critical

Priority reflects emitter population and operational consequence, not instrumentation difficulty. Regulatory limits shown constrain the expected emitter EIRP used in the link budgets of Section 4.8.

Coverage requirement. The design intent is continuous simultaneous coverage of the two Critical bands, with the remaining bands served by a scanning survey receiver. A single wideband tuner cannot observe 2.4 GHz and 5.8 GHz simultaneously; achieving true simultaneity requires either separate receive chains per band or a multi-channel converter device. Both options are dimensioned in Section 4.5.

Table 4-2 — Wideband survey plan (design allocation)

Segment	Tuning range	Instant. BW	Dwell	Revisit	Rationale
S1 — dedicated	2400–2483.5 MHz	56–100 MHz	Continuous	n/a	Whole ISM band within a single tuner span; hosts DroneID and the majority

ETSI EN 300 220-2, Short Range Devices 25 MHz to 1000 MHz, ²⁷
https://www.etsi.org/deliver/etsi_en/300200_300299/30022002/03.01.00_20/en_30022002v030100a.pdf

Team BlackSheep, TBS Crossfire manual, <https://www.team-blacksheep.com/media/files/tbs-crossfire-manual.pdf>²⁸

Team BlackSheep, TBS Crossfire manual, <https://www.team-blacksheep.com/media/files/tbs-crossfire-manual.pdf>²⁹

ETSI EN 300 328 v2.2.2, Wideband transmission systems in the 2.4 GHz band, ³⁰
https://www.etsi.org/deliver/etsi_en/300300_300399/300328/02.02.02_60/en_300328v020202p.pdf

DJI, O4 Air Unit specifications, <https://www.dji.com/o4-air-unit/specs>³¹

Traficom (Finnish Transport and Communications Agency), drone frequency guidance, <https://www.traficom.fi>³²

DJI, O4 Air Unit specifications, <https://www.dji.com/o4-air-unit/specs>³³

Traficom (Finnish Transport and Communications Agency), drone frequency guidance, <https://www.traficom.fi>³⁴

Segment	Tuning range	Instant. BW	Dwell	Revisit	Rationale
					of C2 links. Continuous staring receiver. [Derived]
S2 — dedicated	5725–5875 MHz	100–160 MHz	Continuous	n/a	Primary O3/O4 and digital-HD-FPV video band; 60 MHz maximum channel bandwidth means a 100 MHz-plus span is needed to hold a whole channel. [Derived]
S3 — scanned	5150–5350 MHz	100 MHz	100 ms	≤400 ms	O4 secondary band. Revisit chosen to be shorter than the shortest plausible transmission session. [Derived]
S4 — scanned	860–930 MHz	56 MHz	200 ms	≤1 s	Sub-GHz C2 links use low packet rates and long-dwell narrowband channels, so a longer dwell improves narrowband sensitivity. [Derived]
S5 — scanned	433.05–434.79 MHz	10 MHz	200 ms	≤1 s	Narrow allocation; single dwell covers it entirely. [Derived]
S6 — scanned	1240–1300 MHz	60 MHz	100 ms	≤2 s	Lower emitter population; longest tolerable revisit of the scanned set. [Derived]

Dwell and revisit values are design allocations derived for this specification, not measured or vendor-published figures. They must be re-validated against the scan-loss budget of the procured hardware.

4.3 Control-link and video-link waveform characteristics

DJI's own published specifications are the only fully authoritative source for OcuSync channelisation. The O4 Air Unit operates 5170–5250 MHz and 5725–5850 MHz with a maximum channel bandwidth of 60 MHz, in a plan comprising one 60 MHz, one 40 MHz, three 20 MHz and three 10 MHz channels depending on the paired goggles or remote.³⁵ DJI's SDK documentation gives OcuSync channel-bandwidth options of 10 MHz (up to 23 Mbps), 20 MHz (up to 46 Mbps) and 40 MHz (up to 80 Mbps, Matrice 300 only), tuned across 2400.5–2482.5 MHz in 1 MHz steps.³⁶ Per-region centre-frequency tables for the 20 MHz and 40 MHz channel plans are published by DJI directly and should be loaded into the detector as a priori channel hypotheses.³⁷ Independent RF-test-lab characterisation corroborates OcuSync 2/O3/O4 as dual-band, OFDM-based with adaptive modulation.³⁸

Caution on hop timing. A drone-detection vendor blog claims specific hop dwell times — approximately 500 µs for O3 (about 2,000 hops per second) and approximately 100 µs for O4 (about 10,000 hops per second). These figures are not corroborated by any DJI document or peer-reviewed paper in the source research and SHALL be treated as an industry estimate rather than a specification until verified against a captured signal or an independent laboratory report.³⁹ Because channelizer frame rate and burst-detector time resolution are dimensioned directly from hop dwell, this is a material design risk and is carried in the risk register.

DJI, O4 Air Unit specifications, <https://www.dji.com/o4-air-unit/specs>³⁵

DJI Mobile SDK, DJIOcuSyncLink API reference, <https://developer.dji.com/api-reference/android-36/api/Components/OcuSyncLink/DJIOcuSyncLink.html>

DJI, Transmission Channel and Frequency Table (EN),³⁷
https://dl.djicdn.com/downloads/transmission/20230809/DJI_Transmission_Channel_and_Frequency_Table_EN.pdf

MegiQ, Drone wireless technologies reference, <https://www.megiq.com/rf-measurements/drone-wireless-technologies>³⁸

counteruavhub.com, DJI OcuSync O3/O4 signal analysis (industry blog, uncorroborated), <https://counteruavhub.com/blog/dji-ocusync-o3-o4-signal-analysis/>³⁹

Table 4-3 — Control-link and video-link waveform characteristics

System	Bands	Channel / occupied bandwidth	Access and hopping behaviour	Detection signature
DJI OcuSync (general)	2400.5–2482.5 MHz in 1 MHz steps	10 MHz (≤ 23 Mbps), 20 MHz (≤ 46 Mbps), 40 MHz (≤ 80 Mbps, M300 only) ⁴⁰	OFDM with adaptive modulation; channel selection over the published per-region plan	Wide OFDM occupancy with characteristic downlink-heavy duty cycle; centre frequencies match the published DJI channel table
DJI O4 Air Unit	5170–5250 and 5725–5850 MHz ⁴¹	Max 60 MHz; plan of 1×60, 1×40, 3×20, 3×10 MHz ⁴²	OFDM, adaptive; hop dwell claimed ≈ 100 μ s by a low-authority source only ⁴³	Very wide instantaneous occupancy; requires ≥ 100 MHz receiver span to capture a whole 60 MHz channel
DJI Lightbridge / OcuSync 2	2.4 and 5.8 GHz	Vendor-published channel plan	Dual-band OFDM with adaptive modulation; rated ranges to 15 km under open-sky FCC conditions ⁴⁴	Dual-band presence of a correlated uplink/downlink pair
Wi-Fi-based drones	2.4 and 5 GHz	Standard 802.11 20/40/80 MHz	CSMA/CA; standard 802.11 beacon and data frames	Standard 802.11 MAC; DJI enhanced Wi-Fi carries DroneID in a vendor IE with OUI 26:37:12 ⁴⁵
ExpressLRS	868/915 MHz and 2.4 GHz ⁴⁶	Narrowband LoRa/FLRC channels; published Rx sensitivity -120 dBm at 25 Hz to -104 dBm at 500 Hz ⁴⁷	FHSS; packet rates to 1000 Hz on 2.4 GHz (FLRC) and to 200 Hz on sub-GHz variants; Semtech SX127x/SX1280/LR11xx radios ^{48,49}	Very short narrowband bursts at a fixed, highly regular packet rate — the periodicity is the discriminant, not the bandwidth
TBS Crossfire	860–885 MHz (R1); 902–927 MHz FCC / 915–928 MHz AU (R2/R3) ⁵⁰	LoRa-modem FSK mode: 42.48 kHz frequency shift, 85.1 kBaud ⁵¹	Update rate 150 Hz; uplink channels 0–49, downlink telemetry on channel index +50; hop sequence repeats every 150 hops; RACE mode uses channels 0–99 without the split ^{52,53}	Deterministic 150-hop sequence and the +50 uplink/downlink channel offset are a near-unique fingerprint ⁵⁴
Analogue FPV	1.2–1.3, 2.4 and 5.8 GHz	Typically 20–30 MHz per channel (FM video)	Fixed channel, continuous carrier, no hopping	Continuous unmodulated-carrier-plus-FM-video spectrum; trivially

DJI Mobile SDK, DJIOcuSyncLink API reference, <https://developer.dji.com/api-reference/android-api/Components/OcuSyncLink/DJIOcuSyncLink.html>⁴⁰

DJI, O4 Air Unit specifications, <https://www.dji.com/o4-air-unit/specs>⁴¹

DJI, O4 Air Unit specifications, <https://www.dji.com/o4-air-unit/specs>⁴²

counteruavhub.com, DJI OcuSync O3/O4 signal analysis (industry blog, uncorroborated), <https://counteruavhub.com/blog/dji-ocusync-o3-o4-signal-analysis/>⁴³

MegiQ, Drone wireless technologies reference, <https://www.megiq.com/rf-measurements/drone-wireless-technologies>⁴⁴

MDPI Sensors 2023, Drone Detection and Tracking Using RF Identification Signals, <https://www.mdpi.com/1424-8220/23/17/7650>⁴⁵

Wikipedia, ExpressLRS, <https://en.wikipedia.org/wiki/ExpressLRS>⁴⁶

ExpressLRS documentation (DeepWiki mirror), Long Range Operations, <https://deepwiki.com/ExpressLRS/Docs/5.3-long-range-operations>⁴⁷

Wikipedia, ExpressLRS, <https://en.wikipedia.org/wiki/ExpressLRS>⁴⁸

Semtech, LoRa Technology Revolutionizing Drone Communications, <https://blog.semtech.com/lora-technology-revolutionizing-drone-communications>⁴⁹

Team BlackSheep, TBS Crossfire manual, <https://www.team-blacksheep.com/media/files/tbs-crossfire-manual.pdf>⁵⁰

g3gg0.de, FPV Analysis of TBS Crossfire (independent reverse engineering), <https://www.g3gg0.de/fpv-analysis-of-tbs-crossfire/>⁵¹

Team BlackSheep, TBS Crossfire manual, <https://www.team-blacksheep.com/media/files/tbs-crossfire-manual.pdf>⁵²

g3gg0.de, FPV Analysis of TBS Crossfire (independent reverse engineering), <https://www.g3gg0.de/fpv-analysis-of-tbs-crossfire/>⁵³

g3gg0.de, FPV Analysis of TBS Crossfire (independent reverse engineering), <https://www.g3gg0.de/fpv-analysis-of-tbs-crossfire/>⁵⁴

System	Bands	Channel / occupied bandwidth	Access and hopping behaviour	Detection signature
				detectable but carries no decodable identity
Walksnail Avatar	5725–5850 MHz ⁵⁵	Proprietary "Aux" compression at ≈25 Mbps (HQ) or 12 Mbps (low latency) ⁵⁶	EIRP <30 dBm FCC, <14 dBm CE, <20 dBm SRRC, <25 dBm MIC; glass-to-glass latency ≈22 ms ⁵⁷	High-duty-cycle digital video downlink with vendor-specific framing
HDZero	5.8 GHz	Fixed ≈25 Mbps bitrate	Line-by-line, zero-frame-buffer, no retransmission; 720p60 or 540p90; latency ≈14–18 ms	Constant-bitrate, constant-occupancy downlink that does not adapt with range — distinguishable from DJI's adaptive H.265-like variable-bitrate downlink, whose 24–40 ms latency degrades with signal quality

Walksnail and HDZero figures derive from manufacturer manuals and technical blogs rather than peer-reviewed measurement, and should be treated as industry-typical rather than laboratory-verified.

4.4 Broadcast-identification decode

4.4.1 Open remote identification

Direct Remote Identification is mandatory in the European Union as of 1 January 2024 for specific-category operations and for all UAS bearing C1, C2, C3, C5 or C6 class labels. The mandated broadcast carries the operator registration number, the unique serial number, a timestamp, the geographic position and height of the aircraft, its heading and ground speed, and the geographic position of the remote pilot or take-off point — over an open, documented protocol receivable by ordinary mobile devices.^{58 59} The underlying operating framework is Commission Implementing Regulation (EU) 2019/947 and the EASA regulatory system built on it.^{60 61 62} Because the protocol is open by regulatory design, a compliant passive receiver can decode it straightforwardly and lawfully. The subsystem SHALL treat open remote-ID decode as its highest-confidence identification path, while recognising that a non-compliant or deliberately hostile operator will simply disable it, so it can never be the sole detection mechanism.

4.4.2 DJI DroneID

The proprietary DJI DroneID beacon is a distinct mechanism from the regulated remote-ID broadcast, and the most authoritative open study of it is the NDSS 2023 paper by Schiller and colleagues.⁶³ The central finding is that DroneID transmissions are not encrypted: with commercial off-the-shelf SDR hardware, the aircraft position, the

Walksnail Avatar HD user manual, <https://manuals.plus/asin/B0DRPJGR8M>⁵⁵

Walksnail Avatar HD user manual, <https://manuals.plus/asin/B0DRPJGR8M>⁵⁶

Walksnail Avatar HD user manual, <https://manuals.plus/asin/B0DRPJGR8M>⁵⁷

EUR-Lex, Commission Delegated Regulation (EU) 2020/1058 amending (EU) 2019/945, <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R1058>⁵⁸

dronebydrone.com, Entry into force of Remote ID in UAS from 1 January 2024 per EASA regulations, <https://www.dronebydrone.com/en/news/744/entry-into-force-of-remote-id-in-uas-from-january-1-2024-per-easa-regulations.html>⁵⁹

EUR-Lex, Commission Implementing Regulation (EU) 2019/947, https://eur-lex.europa.eu/eli/reg_impl/2019/947/oj/eng⁶⁰

EASA, Commission Implementing Regulation (EU) 2019/947 document library entry, <https://www.easa.europa.eu/en/document-library/regulations/commission-implementing-regulation-eu-2019947>⁶¹

EASA, Understanding European Drone Regulations and the Aviation Regulatory System, <https://www.easa.europa.eu/en/domains/drones-air-mobility/drones-air-mobility-landscape/Understanding-European-Drone-Regulations-and-the-Aviation-Regulatory-System>⁶²

Schiller et al., Drone Security and the Mysterious Case of DJI's DroneID, NDSS Symposium 2023, https://www.ndss-symposium.org/wp-content/uploads/2023/02/ndss2023_f217_paper.pdf⁶³

home point, and — operationally most significant — the remote pilot's own GPS position can be recovered.⁶⁴ Open-source receiver implementations exist for both the OcuSync-carried and Wi-Fi-carried variants,^{65 66} and the enhanced-Wi-Fi frame format has been independently confirmed by separate academic reverse-engineering theses.^{67 68}

Table 4-4 — DJI DronelD signal structure (OcuSync-carried and Wi-Fi-carried variants)

Parameter	Value	Note
Packet length (OcuSync)	9 OFDM symbols ⁶⁹	Symbols 4 and 6 are Zadoff-Chu synchronisation sequences; the remaining 7 carry data
Modulation (OcuSync)	QPSK on 601 subcarriers (600 data + 1 DC) ⁷⁰	Constellation is fixed, simplifying blind demodulation
Subcarrier spacing	15 kHz ⁷¹	Identical numerology to LTE — an LTE-derived receiver front end can be reused
FFT / active subcarriers	1024-point FFT, active k=212 to k=813, DC null at k=512 ⁷²	Defines the exact channelizer configuration required for decode
Cyclic prefix	80 samples (first and last symbol), 72 samples (intermediate) ⁷³	Non-uniform CP must be handled explicitly in the symbol timing recovery
Application layer	DUML packet: Header (magic 0x55, length, version, CRC-8), Transit (source/destination ID and type, sequence counter, 32 known endpoint types), Command (command type, ack type, encryption flag, command-set ID across 17 known sets, command ID), Payload with trailing CRC-16 ⁷⁴	The encryption flag field is present but the ID broadcast itself is unencrypted
Wi-Fi-carried variant	5 MHz occupied bandwidth, FHSS on 2.4/5.8 GHz, embedded in 802.11 beacon management frames via a vendor-specific information element with OUI 26:37:12 ⁷⁵	Regulated Remote ID uses OUI 6a:5c:35 on the same beacon mechanism — the two must be distinguished by OUI

Schiller et al., DJI drone IDs are not encrypted, arXiv:2207.10795, <https://arxiv.org/abs/2207.10795>⁶⁴

Open-source DronelD receiver implementation, DroneDefence/DD_DroneSecurity, https://github.com/DroneDefence/DD_DroneSecurity⁶⁵

Open-source OcuSync DronelD receiver, anarkiwi/samples2djidroneid, <https://github.com/anarkiwi/samples2djidroneid>⁶⁶

Politecnico di Milano, DJI protocol reverse-engineering thesis, <https://www.politesi.polimi.it/handle/10589/235041>⁶⁷

JKU Linz / digidow.eu, DJI Protocol Reverse Engineering master thesis, https://www.digidow.eu/publications/2021-christof-masterthesis/Christof_2021_MasterThesis_DJIProtocolReverseEngineering.pdf⁶⁸

Schiller et al., Drone Security and the Mysterious Case of DJI's DronelD, NDSS Symposium 2023, https://www.ndss-symposium.org/wp-content/uploads/2023/02/ndss2023_f217_paper.pdf⁶⁹

Schiller et al., Drone Security and the Mysterious Case of DJI's DronelD, NDSS Symposium 2023, https://www.ndss-symposium.org/wp-content/uploads/2023/02/ndss2023_f217_paper.pdf⁷⁰

Schiller et al., Drone Security and the Mysterious Case of DJI's DronelD, NDSS Symposium 2023, https://www.ndss-symposium.org/wp-content/uploads/2023/02/ndss2023_f217_paper.pdf⁷¹

Schiller et al., Drone Security and the Mysterious Case of DJI's DronelD, NDSS Symposium 2023, https://www.ndss-symposium.org/wp-content/uploads/2023/02/ndss2023_f217_paper.pdf⁷²

Schiller et al., Drone Security and the Mysterious Case of DJI's DronelD, NDSS Symposium 2023, https://www.ndss-symposium.org/wp-content/uploads/2023/02/ndss2023_f217_paper.pdf⁷³

Schiller et al., Drone Security and the Mysterious Case of DJI's DronelD, NDSS Symposium 2023, https://www.ndss-symposium.org/wp-content/uploads/2023/02/ndss2023_f217_paper.pdf⁷⁴

MDPI Sensors 2023, Drone Detection and Tracking Using RF Identification Signals, <https://www.mdpi.com/1424-8220/23/17/7650>⁷⁵

Parameter	Value	Note
Wi-Fi subcommand cadence	Subcommands 0x10 (flight telemetry and location) and 0x11 (user-entered flight information) alternate every 200 ms ⁷⁶	The 200 ms alternation is a usable detection periodicity even before decode
Reported decode performance	A 2025 transformer-based demodulator (TranSIC-Net) reports 100% frame decode at close range, falling to 91.8% at long range under non-line-of-sight conditions ⁷⁷	Research result, not a fielded product; treat as best-case and do not use for capability planning

Design and legal boundary. Passive reception of an unencrypted broadcast beacon that any receiver in range would observe is categorically different from decoding a protected control link. The subsystem SHALL implement broadcast-beacon decode only, and SHALL NOT attempt demodulation of the command-and-control payload of any link, nor of any communications content. DroneID decode capability is additionally model- and firmware-dependent: DJI may change the beacon at any firmware revision, so decode SHALL be implemented as a software-updatable plug-in and SHALL NOT be a load-bearing dependency of the detection chain.

4.5 Receiver chain architecture

Each RF sensor node comprises an antenna subsystem, a preselection and protection stage, a low-noise amplification and downconversion stage, a digitiser, and an edge processing engine. The chain is specified as component classes with representative parts; no specific vendor is mandated.

- **Antenna subsystem.** Three options with different capability and cost: (i) omnidirectional collection, giving maximum probability of intercept but no bearing information; (ii) sectorised arrays, giving coarse bearing by comparing received power across sectors; and (iii) a dedicated direction-finding array — uniform circular or interferometric — for precision angle-of-arrival. The reference design specifies omnidirectional collection for detection plus a co-located DF array for bearing.
- **Preselection and protection.** A switched filter bank per monitored segment is required. Without preselection, a strong in-band emitter — a nearby cellular base station, a broadcast transmitter, or a co-sited radar — will drive the front end into compression and desensitise the receiver across its whole span. A limiter stage protects against high-power transients.
- **Low-noise amplification.** An external LNA ahead of the transceiver sets the system noise figure. The AD9361-class transceiver achieves a receiver noise figure of approximately 2 dB at an 800 MHz local oscillator with an external LNA, with overall dynamic range about 74 dB, input IP3 about –18 dBm, and RSSI measurement accurate to ± 2 dB over a 100 dB range.⁷⁸ Noise figure degrades at the top of the tuning range, and cabling and filter losses ahead of the LNA add directly to system noise figure.
- **Digitiser.** Instantaneous bandwidth is the binding constraint. A 60 MHz OcuSync channel cannot be characterised by a 56 MHz-span device without segmentation, so the 5.8 GHz chain requires a device class with at least 100 MHz of instantaneous bandwidth.

Table 4-5 — Digitiser and transceiver component classes (representative, non-mandatory)

Component class	Instantaneous BW	Converter	Tuning range	Applicability in this design
Single-RFIC USRP B-series	Up to 56 MHz (1×1); 30.72 MHz (2×2 MIMO) ⁷⁹	12-bit, 61.44 MS/s ⁸⁰	70 MHz – 6 GHz	Lowest-cost option. Adequate for the sub-GHz and 2.4 GHz chains; insufficient span for a 60 MHz O4 channel

MDPI Sensors 2023, Drone Detection and Tracking Using RF Identification Signals, <https://www.mdpi.com/1424-8220/23/17/7650>⁷⁶

Sensors (via PubMed Central), TranSIC-Net transformer-based DroneID demodulation, <https://pmc.ncbi.nlm.nih.gov/articles/PMC12567810/>⁷⁷

Analog Devices, AD9361 RF Agile Transceiver datasheet, <https://www.analog.com/en/products/ad9361.html>⁷⁸

Ettus Research / NI, USRP knowledge base and device datasheets, <https://kb.ettus.com/>⁷⁹

Ettus Research / NI, USRP knowledge base and device datasheets, <https://kb.ettus.com/>⁸⁰

Component class	Instantaneous BW	Converter	Tuning range	Applicability in this design
GigE USRP N200/N210 class	25 MHz (host-limited via GigE) ⁸¹	14-bit @ 100 MS/s ADC; 16-bit @ 400 MS/s DAC ⁸²	Daughterboard-dependent	Legacy; not recommended for new build — host-limited span
Multi-channel USRP N300/N310 class	100 MHz per channel, 4 RX / 4 TX ⁸³	16-bit ADC / 14-bit DAC, 122.88–153.6 MS/s ⁸⁴	10 MHz – 6 GHz	Preferred for the DF array: four phase-coherent receive channels on one device
High-throughput USRP X300/X310 class	Up to 160 MHz ⁸⁵	14-bit @ 200 MS/s ADC; 16-bit @ 800 MS/s DAC ⁸⁶	10 MHz – 6 GHz (daughterboard-dependent)	Preferred for the 5.8 GHz staring chain — span holds a full 60 MHz channel with margin
AD9361-class transceiver IC	<200 kHz to 56 MHz configurable ⁸⁷	Integrated; NF ≈2 dB at 800 MHz LO with external LNA; dynamic range ≈74 dB; IIP3 ≈–18 dBm ⁸⁸	70 MHz – 6 GHz	Embedded integration path for a cost-reduced node variant
ADRV9009-class transceiver IC	200 MHz RX instantaneous ⁸⁹	Dual TX/RX plus observation receiver; integrated phase noise ≈0.4° RMS ⁹⁰	75 MHz – 6000 MHz	Wideband embedded option; low phase noise benefits coherent DF
RFSoc ZCU111 class	Multi-GHz aggregate	RF-ADC/RF-DAC sample rates ≈2048–6554 MSPS depending on configuration, up to 4.096 GSPS for one complex channel; 8 ADC + 8 DAC channels	Device-dependent	Enables simultaneous multi-band staring across several ISM bands from one device
RFSoc ZCU208 class	Multi-GHz aggregate	Zynq UltraScale+ ZU48DR: 8× 14-bit 5 GSPS RF-ADC, 8× 14-bit 10 GSPS RF-DAC	Device-dependent	Highest-capability option; power and thermal cost must be carried in the node budget of Section 8

4.5.1 Noise-figure cascade

Derivation: system noise figure follows the Friis cascade. For stages with gains $G_1, G_2, \dots$ and noise factors $F_1, F_2, \dots$:

$$F_{\text{sys}} = F_1 + (F_2 - 1)/G_1 + (F_3 - 1)/(G_1 G_2) + \dots$$

Worked example for the 5.8 GHz chain, with all values as design allocations rather than measured figures:

Step 1 — Antenna feed and connector loss ahead of the LNA: 1.5 dB. This loss adds directly and irrecoverably to system noise figure. [Derived]

Step 2 — Preselect filter insertion loss: 1.0 dB, also ahead of the LNA. Cumulative pre-LNA loss 2.5 dB. [Derived]

Step 3 — LNA: noise figure 1.2 dB, gain 20 dB. [Derived]

Ettus Research / NI, USRP knowledge base and device datasheets, <https://kb.ettus.com/>⁸¹

Ettus Research / NI, USRP knowledge base and device datasheets, <https://kb.ettus.com/>⁸²

Ettus Research / NI, USRP knowledge base and device datasheets, <https://kb.ettus.com/>⁸³

Ettus Research / NI, USRP knowledge base and device datasheets, <https://kb.ettus.com/>⁸⁴

Ettus Research / NI, USRP knowledge base and device datasheets, <https://kb.ettus.com/>⁸⁵

Ettus Research / NI, USRP knowledge base and device datasheets, <https://kb.ettus.com/>⁸⁶

Analog Devices, AD9361 RF Agile Transceiver datasheet, <https://www.analog.com/en/products/ad9361.html>⁸⁷

Analog Devices, AD9361 RF Agile Transceiver datasheet, <https://www.analog.com/en/products/ad9361.html>⁸⁸

Analog Devices, ADRV9009 wideband transceiver datasheet, <https://www.analog.com/en/products/adrv9009.html>⁸⁹

Analog Devices, ADRV9009 wideband transceiver datasheet, <https://www.analog.com/en/products/adrv9009.html>⁹⁰

Step 4 — Transceiver receiver: noise figure 8 dB at 5.8 GHz, degraded from the approximately 2 dB achieved at 800 MHz. [Derived, extrapolated from the AD9361 datasheet figure]

$$F_{\text{sys}}(\text{dB}) = 2.5 + 1.2 + 10 \cdot \log_{10}(1 + (10^{(8/10)} - 1)/10^{(20/10)})$$

$$= 2.5 + 1.2 + 10 \cdot \log_{10}(1 + 5.31/100) = 2.5 + 1.2 + 0.22 = 3.92 \text{ dB}$$

The allocation adopted for the link budgets of Section 4.8 is a system noise figure of 6 dB at 5.8 GHz, which carries roughly 2 dB of margin over this derivation to absorb temperature drift, ageing, filter-bank switch loss and manufacturing spread. The pre-LNA loss term dominates the result, so the single highest-leverage design decision in the receive chain is mounting the LNA at the antenna rather than at the enclosure.

4.6 Detection and characterisation signal processing

The edge processing chain converts the digitised stream into a small number of structured detection reports. Streaming raw samples to a central site is not viable — the data-rate derivation in Section 8.1 shows why — so all of the following runs at the node.

- **Polyphase channelizer.** The wideband stream is decomposed into a bank of uniform subchannels, giving simultaneous fine-resolution observation of the whole span at fixed cost per output channel.
- **Spectral estimation and noise-floor tracking.** A running order-statistic estimate of the noise floor per subchannel, updated slowly enough to be unaffected by the bursts being detected.
- **CFAR detection.** Cell-averaging constant-false-alarm-rate thresholding per subchannel, with the threshold multiplier set from the target per-channel false-alarm probability rather than a fixed dB offset. This is what makes the false-alarm rate stable as the ambient environment changes between a quiet rural site and a congested urban rooftop.
- **Burst detection and descriptor extraction.** Each detected burst yields a descriptor: centre frequency, occupied bandwidth, start time, duration, peak and mean power, and rise/fall characteristics. This descriptor stream is the atomic unit passed to classification and to fusion.
- **Hop-sequence tracking.** Descriptors are grouped into hop sequences by testing periodicity and channel-set membership. For TBS Crossfire the deterministic 150-hop sequence and the +50 uplink/downlink channel offset are directly testable hypotheses.⁹¹ For ExpressLRS the fixed packet rate — 25, 50, 100, 150, 250, 500 or 1000 Hz — is the discriminant.^{92,93}
- **Protocol fingerprinting.** Cyclostationary feature analysis and matched detection against the a priori channel plans, including the published DJI per-region centre-frequency tables,⁹⁴ produce an emitter-family hypothesis with a confidence value.
- **Broadcast decode.** Open remote-ID and, where present, DroneID beacons are decoded per Section 4.4 to yield explicit identity and self-reported position.

Table 4-6 — Detection DSP parameter allocations

Parameter	Allocated value	Basis
Channelizer subchannel width	250 kHz (sub-GHz segments), 1 MHz (2.4/5 GHz segments)	Sub-GHz emitters are narrowband LoRa/FSK channels; wideband OFDM emitters need only coarse resolution for energy detection. [Derived]
Analysis frame rate	≥20 kframe/s per subchannel	Must resolve the shortest plausible hop dwell. If the unverified ≈100 μs O4 dwell figure is correct, 20 kframe/s gives two frames per dwell; a higher rate is required for reliable dwell measurement. [Derived; sensitive to the unverified figure]

g3gg0.de, FPV Analysis of TBS Crossfire (independent reverse engineering), <https://www.g3gg0.de/fpv-analysis-of-tbs-crossfire/>⁹¹

Wikipedia, ExpressLRS, <https://en.wikipedia.org/wiki/ExpressLRS>⁹²

ExpressLRS documentation (DeepWiki mirror), Long Range Operations, <https://deepwiki.com/ExpressLRS/Docs/5.3-long-range-operations>⁹³

DJI, Transmission Channel and Frequency Table (EN),⁹⁴
https://dl.djicdn.com/downloads/transmission/20230809/DJI_Transmission_Channel_and_Frequency_Table_EN.pdf

Parameter	Allocated value	Basis
Resolution bandwidth for survey	≤30 kHz in sub-GHz segments	Chosen below the 42.48 kHz Crossfire FSK frequency shift so that the two FSK tones are resolvable. [Derived from the published Crossfire shift]
Integration time, energy detection	1–10 ms adaptive	Longer integration buys sensitivity but blurs short bursts; adaptive selection per segment. [Derived]
Required SNR, energy detection	≈0 dB	Energy detection is far less demanding than demodulation, which typically needs 10–15 dB. Used directly in the Section 4.8 budget. [Derived]
Required SNR, protocol classification	10–15 dB	Demodulation-class requirement; classification range is therefore materially shorter than detection range. [Derived]
DroneID decode configuration	1024-point FFT, 15 kHz subcarrier spacing, active bins k=212–813, DC null k=512, CP 80/72 samples	Taken directly from the published DroneID physical-layer analysis. ⁹⁵

4.7 Direction finding and geolocation

Bearing is what converts a detection into a track. Four technique families are available, with materially different hardware cost and accuracy.

Table 4-7 — Direction-finding techniques and reported accuracy

Technique	Principle	Hardware requirement	Reported accuracy	Evidence class
Power difference of arrival	Compare received power across directional sectors or antennas	Sectorised antenna set; one receiver with a switch, or one receiver per sector	Coarse — sector-level only; no published figure in the source research	Design judgement
Phase interferometry	Measure phase difference across a known baseline	Two or more phase-coherent receive channels; calibrated baseline	Average error 1.15° static and 1.86° dynamic reported for a UAV direction-finding system ⁹⁶	Published research
MUSIC / ESPRIT super-resolution	Eigen-decomposition of the array covariance matrix to resolve angle of arrival	Multi-element coherent array; significant compute	RMSE as low as 0.007°–0.012° reported for a modified-ESPRIT study — idealised simulation only	Simulation only; NOT a field baseline
Switched uniform circular array	Sequentially switch elements of a UCA into one SDR receiver	UCA plus RF switch plus one receiver — lowest cost coherent option	Mean absolute angle error 4.7° ± 4.5° over a full rotation under real-world conditions; sidelobe suppression 12.3 dB in an anechoic chamber versus 6 dB in the real world ⁹⁷	Real hardware — use as the planning baseline
Time difference of arrival	Cross-node arrival-time differences give hyperbolic loci and a position fix	Three or more geographically separated nodes with nanosecond-class time synchronisation	Accuracy is geometry- and sync-limited; see the synchronisation derivation in Section 7	Standard technique

Planning baseline. For system planning the specification adopts a real-world direction-finding accuracy budget of 2° to 5° RMS for a well-engineered multi-element SDR-based array. Sub-degree figures SHALL be treated as best-case or simulation-only until demonstrated on the specific hardware procured, and the real-hardware 4.7° ± 4.5° result is the more defensible planning number.⁹⁸ A separate vendor claim of ±3° accuracy within 100 m range

Schiller et al., Drone Security and the Mysterious Case of DJI's DroneID, NDSS Symposium 2023, https://www.ndss-symposium.org/wp-content/uploads/2023/02/ndss2023_f217_paper.pdf⁹⁵

Switched uniform circular array direction finding with SDR back end, arXiv:2502.08592, <https://arxiv.org/abs/2502.08592>⁹⁶

Switched uniform circular array direction finding with SDR back end, arXiv:2502.08592, <https://arxiv.org/abs/2502.08592>⁹⁷

Switched uniform circular array direction finding with SDR back end, arXiv:2502.08592, <https://arxiv.org/abs/2502.08592>⁹⁸

appears in commercial marketing material and was not independently verified in the source research; it SHALL NOT be used for design.

Table 4-8 — RF direction-finding requirements

ID	Requirement	Verification
REQ-RF-001	The DF array SHALL provide azimuth bearing on any detected emitter meeting the classification SNR threshold, with an accuracy of $\leq 5^\circ$ RMS over 360° of azimuth.	Field Trial
REQ-RF-002	The DF array SHALL be phase-calibrated at commissioning and SHALL support in-service recalibration without physical access to the elements.	Inspection
REQ-RF-003	The node SHOULD report a per-bearing uncertainty estimate rather than a scalar bearing, so that fusion can weight it correctly.	Bench Test
REQ-RF-004	Where three or more nodes observe the same emitter, the system SHALL compute a position fix and SHALL report the associated geometric dilution of precision.	Analysis

4.8 Link budget and detection range

Status of this section. Everything in Section 4.8 is an engineering derivation combining standard propagation and receiver-sensitivity equations with the published emitter EIRP and hardware noise-figure figures cited above. These are planning estimates. They are not measured detection ranges and SHALL NOT be quoted as capability claims without field validation of the procured hardware.

4.8.1 Governing equations

Free-space path loss, with distance in kilometres and frequency in megahertz:

$$FSPL(dB) = 20 \cdot \log_{10}(d_{km}) + 20 \cdot \log_{10}(f_{MHz}) + 32.44$$

Receiver sensitivity by the thermal-noise-floor method, where -174 dBm/Hz is the Johnson-Nyquist noise density at 290 K:

$$P_{sens}(dBm) = -174 + 10 \cdot \log_{10}(BW_{Hz}) + NF(dB) + SNR_{req}(dB)$$

Geometric radio horizon, with heights in metres and result in kilometres:

$$d_{horizon}(km) = 3.57 \cdot (\sqrt{h_{rx_m}} + \sqrt{h_{tx_m}})$$

4.8.2 Worked case — 5.8 GHz video downlink

Assumptions: emitter EIRP 30 dBm, the FCC 5.8 GHz limit published by DJI for the O4 Air Unit;⁹⁹ frequency 5800 MHz; system noise figure 6 dB per the allocation in Section 4.5.1; detection bandwidth 20 MHz matching a typical OcuSync channel; required SNR 0 dB for energy detection.

Step 1 — Sensitivity: $P_{sens} = -174 + 10 \cdot \log_{10}(20e6) + 6 + 0 = -174 + 73.0 + 6 = -95$ dBm. [Derived]

Step 2 — Maximum tolerable path loss: $FSPL_{max} = EIRP - P_{sens} = 30 - (-95) = 125$ dB. [Derived]

Step 3 — Solve for range: $20 \cdot \log_{10}(d) = 125 - 20 \cdot \log_{10}(5800) - 32.44 = 125 - 75.27 - 32.44 = 17.29$. [Derived]

Step 4 — $d = 10^{(17.29/20)} = 7.3$ km. [Derived]

This roughly 7 km figure is a best-case, true-line-of-sight, zero-clutter result for pure energy detection of the video downlink, and is an upper bound only.

DJI, O4 Air Unit specifications, <https://www.dji.com/o4-air-unit/specs>⁹⁹

4.8.3 Worked case — sub-GHz control link, and why the horizon binds

Assumptions: EIRP approximately 27 dBm, corresponding to a 500 mW long-range ExpressLRS power level; frequency 915 MHz; using the published ExpressLRS receiver sensitivity of -120 dBm at the 25 Hz packet rate as the narrowband detector benchmark.¹⁰⁰

Step 1 — $FSPL_{max} = 27 - (-120) = 147$ dB. [Derived]

Step 2 — $20 \cdot \log_{10}(d) = 147 - 20 \cdot \log_{10}(915) - 32.44 = 147 - 59.23 - 32.44 = 55.33$, giving $d = 584$ km. [Derived]

Step 3 — This result is physically meaningless and demonstrates that FSPL-only arithmetic fails at high processing gain. The binding constraint is geometry, not path loss.

Step 4 — Radio horizon for a receive antenna at 30 m and an aircraft at 120 m: $d = 3.57 \cdot (\sqrt{30}) + \sqrt{120} = 3.57 \cdot (5.48 + 10.95) = 58.6$ km. [Derived]

For the sub-GHz bands the practical ceiling in open terrain is therefore set by line-of-sight geometry — tens of kilometres — with substantial spare link margin. In cluttered terrain this collapses to sub-kilometre and low-kilometre ranges dominated by obstruction, as in the 5.8 GHz case.

4.8.4 Environment-corrected planning ranges

Free-space arithmetic materially overstates real range because of multipath, foliage, building clutter and non-line-of-sight geometry. The excess-loss allowances below are engineering estimates, not measured C-UAS figures.

Table 4-9 — Environment-corrected RF detection range (all values derived)

Environment	Excess loss allowance	5.8 GHz range	Sub-GHz behaviour and binding constraint
Open rural, true line of sight	0 dB [Derived]	≈7 km (ceiling) [Derived]	Horizon-limited at tens of kilometres; link budget has large spare margin. Antenna height dominates. [Derived]
Suburban, partial obstruction	10–15 dB [Derived]	≈1.3–2.3 km [Derived]	Several kilometres; transition region where both clutter and geometry matter. [Derived]
Dense urban, significant NLOS	20–30 dB [Derived]	≈0.2–0.7 km [Derived]	Sub-kilometre; obstruction-dominated, and effectively equivalent to the 5.8 GHz case. [Derived]

The consolidated planning assumption adopted by this specification is a 1–3 km realistic suburban detection radius, degrading to 200–700 m in dense urban clutter, and extending to several kilometres or tens of kilometres in open line-of-sight rural terrain. Every figure is derived, not certified, and must be validated by field test before use in any capability claim.

Two further corrections apply and make the table optimistic. First, these ranges are for the video or control downlink, which is the strongest emission present; the DJI DroneID beacon and low-duty-cycle sub-GHz control bursts are weaker or briefer and will be detected at shorter range. Second, detection range and classification range are not the same: classification needs 10–15 dB SNR against the roughly 0 dB assumed for energy detection, so the radius within which the system can say what it has seen is substantially smaller than the radius within which it can say that something is there.

4.9 RF subsystem requirements

Table 4-10 — RF detection subsystem requirements

ID	Requirement	Verification
REQ-RF-005	The RF subsystem SHALL be receive-only. It SHALL NOT contain any intentional radiator in any monitored band, and SHALL NOT implement jamming, spoofing or control-link seizure.	Inspection
REQ-RF-006	The subsystem SHALL provide continuous, uninterrupted coverage of 2400–2483.5 MHz and 5725–5875 MHz at every node.	Bench Test

ExpressLRS documentation (DeepWiki mirror), Long Range Operations, <https://deepwiki.com/ExpressLRS/Docs/5.3-long-range-operations>¹⁰⁰

ID	Requirement	Verification
REQ-RF-007	The subsystem SHALL additionally cover 433.05–434.79 MHz, 860–930 MHz, 1240–1300 MHz and 5150–5350 MHz, by scanning where continuous coverage is not provided.	Bench Test
REQ-RF-008	Where a band is scanned, the revisit interval SHALL NOT exceed 1 s for the sub-GHz segments and 400 ms for the 5150–5350 MHz segment, and the resulting scan loss SHALL be quantified and declared.	Analysis
REQ-RF-009	The 5725–5875 MHz receive chain SHALL provide at least 100 MHz of instantaneous bandwidth, so that a 60 MHz OcuSync channel is captured without segmentation.	Bench Test
REQ-RF-010	System noise figure SHALL NOT exceed 6 dB at 5.8 GHz and 4 dB at 900 MHz, measured at the antenna port.	Bench Test
REQ-RF-011	The low-noise amplifier SHALL be mounted at the antenna. Cumulative loss ahead of the first active stage SHALL NOT exceed 2.5 dB.	Inspection
REQ-RF-012	Each monitored segment SHALL be preselected by a filter, so that a strong out-of-segment emitter cannot desensitise the receiver across its whole span.	Bench Test
REQ-RF-013	The front end SHALL survive, without damage or permanent degradation, an in-band incident power level consistent with co-siting on a shared mast with cellular or broadcast transmitters.	Bench Test
REQ-RF-014	Detection SHALL use per-subchannel constant-false-alarm-rate thresholding referenced to a tracked noise floor, and SHALL NOT use a fixed absolute threshold.	Inspection
REQ-RF-015	The node SHALL emit, for every detected burst, a descriptor containing centre frequency, occupied bandwidth, timestamp, duration, and peak and mean received power.	Bench Test
REQ-RF-016	All detection, classification and decode processing SHALL execute at the node. Raw sample streams SHALL NOT be transported over the backhaul in normal operation.	Inspection
REQ-RF-017	The node SHALL support operator-triggered capture of a bounded raw sample window to local storage, for forensic review and for offline classifier retraining.	Bench Test
REQ-RF-018	The classifier SHALL identify emitter family, and SHALL report a calibrated confidence value with every classification.	Field Trial
REQ-RF-019	The a priori channel-plan database, including the published per-region DJI centre-frequency tables, SHALL be field-updatable without firmware replacement.	Inspection
REQ-RF-020	The subsystem SHALL decode open Direct Remote Identification broadcasts and SHALL report all mandated fields, including the reported position of the remote pilot or take-off point.	Field Trial
REQ-RF-021	The subsystem MAY decode the unencrypted DJI DroneID beacon. Where implemented, it SHALL be a software-updatable module and SHALL NOT be a dependency of the detection chain.	Inspection
REQ-RF-022	The subsystem SHALL NOT demodulate, store or forward the payload of any command-and-control link, nor any communications content of any kind.	Inspection
REQ-RF-023	The subsystem SHALL distinguish regulated Remote ID broadcasts (OUI 6a:5c:35) from proprietary DJI DroneID broadcasts (OUI 26:37:12) and SHALL report them as distinct evidence types.	Bench Test
REQ-RF-024	The node SHALL maintain and export a continuous record of the measured noise floor per segment, to support siting decisions and post-incident analysis of missed detections.	Bench Test
REQ-RF-025	Declared detection ranges SHALL be established by field trial on the procured hardware. Derived link-budget figures SHALL NOT be published as specifications.	Field Trial
REQ-RF-026	The subsystem SHOULD report separate detection and classification ranges, reflecting the differing SNR requirements of energy detection and demodulation.	Analysis
REQ-RF-027	Node documentation SHALL state explicitly that the RF subsystem has no detection capability against a fibre-tethered or otherwise RF-silent airframe.	Inspection

5 LTE and Cellular Monitoring Subsystem

5.1 Rationale

An unmanned aircraft piloted over a public cellular network presents no proprietary control-link emission in any ISM band. From the network's point of view it is simply a subscriber terminal that happens to be airborne, and the RF detection subsystem of Section 4 will see nothing beyond, at most, an incidental video downlink. 3GPP studied this operating mode formally in TR 36.777, a Release-15 study item that ran from March 2017 to December 2017 under joint Ericsson and NTT DOCOMO rapporteurship.^{101 102}

The bandwidth involved is modest and therefore easy to satisfy on a commercial network: command-and-control traffic is characterised as requiring 60–100 kbps in each direction, with a 50 ms one-way latency target between the base station and the aerial terminal and a packet error rate around 10^{-3} , while payload video can demand up to 50 Mbps on the uplink.¹⁰³ One peer-reviewed source explicitly notes an internal inconsistency across 3GPP-adjacent documents on the C2 uplink figure — 100 kbps in one place, 200 kbps in another, 60–100 kbps in a summary table — so no single number should be treated as definitive.¹⁰⁴

Role in the sensor mix. The LTE monitoring subsystem is a corroborating sensor, not a primary one. It cannot, by passive means and without network cooperation, produce a confident standalone declaration that a specific airborne object exists at a specific place. What it can do is contribute independent evidence that an airborne terminal is present within the monitored cells, which materially raises confidence when the acoustic array has a weak contact and the RF subsystem has nothing. Its evidence is weighted accordingly in the fusion design of Section 7.

5.2 Band coverage

The bands to be monitored depend entirely on the ITU Region of deployment and on the operators actually present at the site. Table 5-1 gives the globally referenced band plan for the allocations most relevant to a monitoring node.

Table 5-1 — 3GPP bands relevant to passive cellular monitoring, by ITU Region

3GPP band	Uplink (MHz)	Downlink (MHz)	Duplex	Primary ITU Region and deployment note
Band 1 (2100 IMT)	1920–1980	2110–2170	FDD	Global; heavily deployed across Europe, Asia and Japan (Regions 1 and 3)
Band 2 (1900 PCS)	1850–1910	1930–1990	FDD	Region 2 — North America and Latin America
Band 3 (1800 DCS)	1710–1785	1805–1880	FDD	Global, especially Regions 1 and 3
Band 4 (AWS-1)	1710–1755	2110–2155	FDD	Region 2 — North America
Band 5 (850 cellular)	824–849	869–894	FDD	Region 2 — North America, Australia, Latin America
Band 7 (2600 IMT-E)	2500–2570	2620–2690	FDD	Regions 1 and 2 — Europe and Latin America; used for global roaming across all three Regions
Band 8 (900 E-GSM)	880–915	925–960	FDD	Regions 1 and 2 — Europe and Latin America

3GPP, TR 36.777 Study on Enhanced LTE Support for Aerial Vehicles (specification record), <https://www.3gpp.org/dynareport/36777.htm>¹⁰¹

Ericsson, Internet of drones: the sky is not the limit, <https://www.ericsson.com/en/blog/2021/6/internet-of-drones-sky-is-not-the-limit>¹⁰²

5G Americas, 3GPP Releases 14–16 report, https://www.5gamericas.org/wp-content/uploads/2019/07/3GPP_Rel_14-16_10.22-final_for_upload.pdf¹⁰³

Zulkifley et al., Mobile Network Performance and Technical Feasibility of LTE for Drone Communication, Sensors 2021, <https://pmc.ncbi.nlm.nih.gov/articles/PMC8073316/>¹⁰⁴

3GPP band	Uplink (MHz)	Downlink (MHz)	Duplex	Primary ITU Region and deployment note
Bands 12/13/14/17 (700)	≈698–798 (varies)	≈728–798 (varies)	FDD	Region 2 only — the US-specific 700 MHz plan
Band 20 (800 EU)	832–862	791–821	FDD	Region 1 only — Europe
Band 28 (APT700)	703–748	758–803	FDD	Global roaming across Regions 1, 2 and 3

ITU Region 1 = Europe, Africa and the Middle East; Region 2 = the Americas; Region 3 = Asia-Pacific. A Region 1 deployment should prioritise Bands 1, 3, 7, 8, 20 and 28; a Region 2 deployment should prioritise Bands 2, 4, 5 and 12/13/14/17. Band 8 uplink (880–915 MHz) overlaps the sub-GHz UAS control segment monitored in Section 4, so the two subsystems must share a coordinated front-end plan at that frequency.

5.3 Airborne-terminal phenomenology

The core conclusion of TR 36.777 is that terrestrial LTE networks can serve aerial terminals, but that uplink and downlink interference and mobility performance both degrade, and the degradation worsens as the number of simultaneously airborne terminals in a cell increases. The mechanism is geometric: an airborne terminal has line-of-sight visibility to far more base stations than a ground terminal, so it both receives more downlink interference from neighbouring cells and causes more uplink interference to them.¹⁰⁵ The Release-15 work item identified five improvement areas — interference detection, uplink interference mitigation, downlink interference mitigation, mobility and handover performance, and aerial-terminal identification — and specified mechanisms including a subscription-based aerial terminal identifier with network authorisation, height and location reporting triggered by an altitude threshold, terminal-specific fractional path-loss compensation for uplink power control, and signalled flight-path information.^{106 107} The existence of a standardised aerial-terminal identity and authorisation mechanism is significant for this specification: where the network operator cooperates, identification becomes a network query rather than an RF measurement problem.

The line-of-sight probability model reproduced from TR 36.777 in the peer-reviewed literature is height-dependent, approaching unity above 100 m altitude, with a transitional model between 22.5 m and 100 m and a closed-form model below 22.5 m involving a horizontal-distance threshold near 18 m.¹⁰⁸ The corresponding line-of-sight path loss takes the near-in form $PL = 28 + 22 \cdot \log_{10}(d_{3D}) + 20 \cdot \log_{10}(f_c)$, transitioning to a breakpoint-distance model at greater range, while the non-line-of-sight path loss for low-altitude terminals is $PL_{NLOS} = 13.54 + 39.08 \cdot \log_{10}(d_{3D}) + 20 \cdot \log_{10}(f_c) - 0.6 \cdot (h_{UT} - 1.5)$.¹⁰⁹

The most concrete independently measured data available comes from a peer-reviewed field trial on a live commercial LTE network in Malaysia.¹¹⁰ From ground level to 170 m, RSRP fell by roughly 20 dBm and RSRQ by roughly 10 dB, with measured RSRP clustering between –65 dBm and –85 dBm across altitudes. At around 170 m the RSRQ degradation becomes especially pronounced, attributed to the umbrella effect of down-tilted base-station antennas combined with severe downlink interference from neighbouring cells — the same mechanism TR 36.777 flags qualitatively.

3GPP Release-15 overview for aerial vehicles, arXiv:1805.00826, <https://arxiv.org/pdf/1805.00826>¹⁰⁵

3GPP, TR 36.777 Study on Enhanced LTE Support for Aerial Vehicles (specification record), <https://www.3gpp.org/dynareport/36777.htm>¹⁰⁶

3GPP Release-15 overview for aerial vehicles, arXiv:1805.00826, <https://arxiv.org/pdf/1805.00826>¹⁰⁷

Zulkifley et al., Mobile Network Performance and Technical Feasibility of LTE for Drone Communication, Sensors 2021,¹⁰⁸
<https://pmc.ncbi.nlm.nih.gov/articles/PMC8073316/>

Zulkifley et al., Mobile Network Performance and Technical Feasibility of LTE for Drone Communication, Sensors 2021,¹⁰⁹
<https://pmc.ncbi.nlm.nih.gov/articles/PMC8073316/>

Zulkifley et al., Mobile Network Performance and Technical Feasibility of LTE for Drone Communication, Sensors 2021,¹¹⁰
<https://pmc.ncbi.nlm.nih.gov/articles/PMC8073316/>

Table 5-2 — Measured aerial-terminal performance on a live commercial LTE network

Elevation	Mean uplink	Mean downlink	Mean delay	Observation
0 m (ground)	6451 kbps	41332 kbps	25.4 ms	Baseline ground-terminal performance on the same route. ¹¹¹
40 m	5245 kbps	20164 kbps	24.7 ms	Downlink halves; a drone at this height handed over from cell 11 to cell 41 with RSRP moving -78 to -84 dBm and RSRQ -11 to -9 dB, while a ground terminal on the same route suffered three ping-pong handovers at RSRP near -95 dBm. ¹¹²
80 m	5051 kbps	24699 kbps	23.4 ms	Uplink remains sufficient for C2 by a wide margin. ¹¹³
170 m	6737 kbps	7893 kbps	36.6 ms	Downlink collapses to roughly one fifth of the ground value and delay rises — the umbrella effect and neighbour-cell interference. ¹¹⁴

The same study measured a direct drone-to-ground-station non-cellular link over a 4.2 km route at 1303 kbps down / 20 kbps up with 94 ms delay — nearly double the 50 ms 3GPP latency target, illustrating the gap between the standard's target and field-measured performance.

5.4 Passive detection techniques

Detection hinges on distinguishing an airborne terminal's radio signature from a ground terminal's using entirely receive-only techniques. Even idle, unconnected terminals performing initial cell search and random access periodically transmit PRACH preambles, which are structured, well-known sequences that a passive receiver can detect and process without network or terminal cooperation; once connected, Sounding Reference Signals can be used to refine position estimates.¹¹⁵

Table 5-3 — Passive airborne-terminal detection techniques

Technique	Observable	Node capability required	Confidence	Principal limitation
PRACH preamble detection	Structured random-access preambles from idle and connecting terminals	Uplink-band receiver with knowledge of the cell PRACH configuration	Low alone	Detects that a terminal is present, not that it is airborne. Requires PRACH configuration, obtained from broadcast system information. ¹¹⁶
SRS observation	Uplink sounding reference signals from connected terminals	Narrowband uplink receiver; a 1.4 MHz channel is sufficient	Medium	A non-serving passive receiver using SRS alone reported localisation error under 3 m rural and under 8 m urban —

Zulkifley et al., Mobile Network Performance and Technical Feasibility of LTE for Drone Communication, Sensors 2021, ¹¹¹
<https://pmc.ncbi.nlm.nih.gov/articles/PMC8073316/>

Zulkifley et al., Mobile Network Performance and Technical Feasibility of LTE for Drone Communication, Sensors 2021, ¹¹²
<https://pmc.ncbi.nlm.nih.gov/articles/PMC8073316/>

Zulkifley et al., Mobile Network Performance and Technical Feasibility of LTE for Drone Communication, Sensors 2021, ¹¹³
<https://pmc.ncbi.nlm.nih.gov/articles/PMC8073316/>

Zulkifley et al., Mobile Network Performance and Technical Feasibility of LTE for Drone Communication, Sensors 2021, ¹¹⁴
<https://pmc.ncbi.nlm.nih.gov/articles/PMC8073316/>

University of Padova, Malikov thesis on passive cellular UE detection, https://thesis.unipd.it/retrieve/c3bbe65e-9f3d-4efa-bdc1-efdc71b46ddf/Malikov_Andrey.pdf¹¹⁵

University of Padova, Malikov thesis on passive cellular UE detection, https://thesis.unipd.it/retrieve/c3bbe65e-9f3d-4efa-bdc1-efdc71b46ddf/Malikov_Andrey.pdf¹¹⁶

Technique	Observable	Node capability required	Confidence	Principal limitation
				single-paper best-case results requiring replication. ¹¹⁷
RSRP anomaly	Received power unusually strong for the terminal's distance from the serving cell	Downlink measurement plus a serving-cell geometry model	Medium	Confounded by terminals at height in buildings and by unusual propagation
RSRQ anomaly	Poor signal quality coincident with strong received power — the multi-cell interference signature	Downlink measurement across neighbour cells	Medium-high	The strong-RSRP-with-poor-RSRQ combination is the practical fingerprint, consistent across the 3GPP study and independent field measurement. ¹¹⁸
Neighbour-cell visibility	Abnormally many neighbour cells visible at comparable signal strength	Multi-cell scanning receiver	Medium-high	Requires a site-specific baseline of normal neighbour visibility from the ground
Combined measurement classification	Joint RSRP/RSRQ pattern over time	Standard radio measurement reporting; no special hardware	High	A classification algorithm using only standard RSRP/RSRQ measurement reports distinguished airborne from terrestrial terminals with 99% likelihood in three of four tested scenarios and 95% in the fourth — but this used network-side measurement reports, not passive off-air observation. ¹¹⁹
Uplink interference rise	Elevated PUSCH interference across multiple cells	Uplink-band wideband power measurement	Low-medium	Measured and documented as attributable to aerial vehicles, but it is an aggregate indicator that does not localise or count aircraft. ¹²⁰

The critical caveat. The highest-performing published classification results were obtained from network-side radio measurement reports — measurements the network already collects from the terminal.¹²¹ A passive off-air node does not have those reports. It must instead infer the equivalent quantities from its own observation position, which is a materially harder problem and one for which no comparable published accuracy figure exists in the source research. The specification therefore treats passive off-air LTE detection as a moderate-confidence corroborating input, and identifies operator-cooperative access to network measurement data as the single change that would most improve this subsystem's contribution.

5.5 Monitoring-node architecture

- **Cell survey receiver.** Scans the downlink bands of Table 5-1, identifies the physical cell identities present, and decodes broadcast system information to recover the cell configuration — including the PRACH configuration needed by the uplink detector. Decoding broadcast system information is decoding a public announcement transmitted to every receiver in range; it is not interception of communications.
- **Uplink monitor.** Observes the paired uplink bands for PRACH preambles, SRS and aggregate interference rise. This is the airborne-terminal detection path proper.

Passive SRS-only 5G uplink localization, arXiv:2511.13171, <https://arxiv.org/html/2511.13171v1>¹¹⁷

Zulkifley et al., Mobile Network Performance and Technical Feasibility of LTE for Drone Communication, Sensors 2021, ¹¹⁸
<https://pmc.ncbi.nlm.nih.gov/articles/PMC8073316/>

Aalborg University, Method for Detection of Airborne UEs Based on LTE Radio Measurements, <https://vbn.aau.dk/da/publications/method-for-detection-of-airborne-ues-based-on-lte-radio-measureme/>¹¹⁹

Aalborg University, Measured Uplink Interference Caused by Aerial Vehicles, <https://vbn.aau.dk/ws/files/293138377/08369158.pdf>¹²⁰

Aalborg University, Method for Detection of Airborne UEs Based on LTE Radio Measurements, <https://vbn.aau.dk/da/publications/method-for-detection-of-airborne-ues-based-on-lte-radio-measureme/>¹²¹

- **Baseline learning.** Maintains a site-specific statistical baseline of normal ground-terminal behaviour — neighbour-cell visibility, RSRP distribution, interference level by time of day. Anomaly detection against a learned baseline is what makes the technique usable; absolute thresholds are not portable between sites.
- **Evidence formatter.** Emits a bounded, time-stamped evidence record to fusion. It does not emit tracks and does not emit identity.

5.6 Legal boundary

This subsection is normative and constrains the design. Under US law, 18 U.S.C. §2511 prohibits intentional interception of wire, oral or electronic communications, and the Department of Justice describes this prohibition as absolute, subject only to specific exemptions.^{122 123} Operating an active IMSI catcher — a device that transmits and induces terminals to attach to it, in the manner of a rogue base station — to obtain subscriber identity or location data requires at minimum a court order under the pen-register and trap-and-trace statute; the September 2015 DOJ policy additionally requires a warrant for law-enforcement use, explicitly prohibits any add-on content-collection capability, and requires deletion of incidentally collected data.¹²⁴

The 2020 joint advisory from the FCC, FAA, DOJ and DHS is the clearest cross-agency statement of the line: RF-based detection of a drone's control or telemetry link can itself implicate the pen-register statute and the Wiretap Act depending on implementation, while mitigation — jamming, spoofing, or hacking the link — separately implicates the Computer Fraud and Abuse Act at 18 U.S.C. §1030, the radio-interference statute at 18 U.S.C. §1367, and the statute against destroying the means of US communication at 18 U.S.C. §1362, on top of the Aircraft Sabotage Act at 18 U.S.C. §32(a) and the Aircraft Piracy Act at 49 U.S.C. §46502.¹²⁵

Table 5-4 — Permitted and prohibited monitoring activities

Activity	Design status	Basis and note
Passive measurement of uplink and downlink power, PRACH timing and energy, SRS timing, and cell-identity broadcasts	Permitted — implemented	Metadata already present in the standard physical and MAC layers that any receiver in range would observe, with no transmission and no decoding of identity fields or user content. This is how the cited passive SRS-only and measurement-based classification research is designed. ¹²⁶¹²⁷¹²⁸
Decoding broadcast system information (MIB/SIB)	Permitted — implemented	A public broadcast to all receivers in range; not communications content.
Demodulating IMSI, GUTI or any subscriber identity field	Prohibited — not implemented	Implicates the Wiretap Act and the pen-register statute; requires judicial authorisation that a commercial operator does not hold. ¹²⁹¹³⁰¹³¹

18 U.S.C. §2511, Cornell Legal Information Institute, <https://www.law.cornell.edu/uscode/text/18/2511>¹²²

US DOJ, Criminal Resource Manual §1050 — Scope of 18 U.S.C. §2511 Prohibitions, <https://www.justice.gov/archives/jm/criminal-resource-manual-1050-scope-18-usc-2511-prohibitions>¹²³

ACLU of Northern California, cell-site simulator (Stingray) policy analysis, <https://www.aclunorcal.org>¹²⁴

FCC/FAA/DOJ/DHS (2020), Advisory on the Application of Federal Laws to the Acquisition and Use of Technology to Detect and Mitigate UAS, <https://www.fcc.gov/document/federal-agencies-release-advisory-drone-detection-mitigation-tech>¹²⁵

University of Padova, Malikov thesis on passive cellular UE detection, https://thesis.unipd.it/retrieve/c3bbe65e-9f3d-4efa-bdc1-efdc71b46ddf/Malikov_Andrey.pdf¹²⁶

Passive SRS-only 5G uplink localization, arXiv:2511.13171, <https://arxiv.org/html/2511.13171v1>¹²⁷

Aalborg University, Method for Detection of Airborne UEs Based on LTE Radio Measurements, <https://vbn.aau.dk/da/publications/method-for-detection-of-airborne-ues-based-on-lte-radio-measureme/>¹²⁸

18 U.S.C. §2511, Cornell Legal Information Institute, <https://www.law.cornell.edu/uscode/text/18/2511>¹²⁹

US DOJ, Criminal Resource Manual §1050 — Scope of 18 U.S.C. §2511 Prohibitions, <https://www.justice.gov/archives/jm/criminal-resource-manual-1050-scope-18-usc-2511-prohibitions>¹³⁰

FCC/FAA/DOJ/DHS (2020), Advisory on the Application of Federal Laws to the Acquisition and Use of Technology to Detect and Mitigate UAS, <https://www.fcc.gov/document/federal-agencies-release-advisory-drone-detection-mitigation-tech>¹³¹

Activity	Design status	Basis and note
Any user-plane or control-plane content interception	Prohibited — not implemented	Directly within the §2511 prohibition, described by DOJ as absolute subject only to specific exemptions. ¹³²
Operating a false base station or IMSI catcher	Prohibited — not implemented	Requires a court order at minimum, and a warrant under DOJ policy; also an intentional radiator, which REQ-RF-005 forbids. ¹³³
Any transmission in a cellular band	Prohibited — not implemented	Jamming is illegal for all private parties in the US without exception, including on one's own property, under Sections 301, 302(b) and 333 of the Communications Act of 1934. ¹³⁴¹³⁵

Jurisdictional caveat. The analysis above is US-centric because that is where the cross-agency guidance is most explicit. In the European Union, spectrum monitoring, interception and data protection are governed by national law implementing EU instruments, and the position varies by member state. In every jurisdiction the boundary between permitted passive measurement and prohibited interception SHALL be confirmed with qualified counsel for the specific deployment before commissioning. This specification does not constitute legal advice.

One structural point works in favour of a detection-only design: 49 U.S.C. §44801(5) defines a counter-UAS system as one capable of lawfully and safely disabling, disrupting or seizing control of an aircraft — a definition that by its terms excludes detection-only systems. Statutory authority to mitigate is confined to four categories of US federal actor: the Department of Defense under 10 U.S.C. §130i, the Department of Energy under 50 U.S.C. §2661, and the Department of Justice and Department of Homeland Security jointly under 6 U.S.C. §124n, per the Preventing Emerging Threats Act of 2018 enacted within the FAA Reauthorization Act of 2018.¹³⁶ A correctly designed passive detection product therefore sits outside the most restrictive part of that framework. Note however that US federal mitigation authority has been subject to expiration and reauthorisation cycles tied to broader funding legislation, and its current status SHALL be re-verified against the latest DHS and DOJ guidance before being relied upon in any customer-facing or compliance document.

5.7 LTE subsystem requirements

Table 5-5 — LTE and cellular monitoring subsystem requirements

ID	Requirement	Verification
REQ-LTE-001	The LTE subsystem SHALL be receive-only and SHALL NOT transmit in any cellular band under any circumstance, including for calibration.	Inspection
REQ-LTE-002	The subsystem SHALL be configurable at commissioning to the band set applicable to the deployment ITU Region and to the operators present at the site.	Inspection
REQ-LTE-003	The subsystem SHALL survey downlink bands, enumerate physical cell identities present, and decode broadcast system information sufficient to configure the uplink detector.	Bench Test
REQ-LTE-004	The subsystem SHALL detect PRACH preamble activity in the monitored uplink bands and SHALL report detection events with timestamp and received power.	Bench Test
REQ-LTE-005	The subsystem SHOULD observe uplink SRS where the cell configuration permits, and SHOULD report the resulting timing observables to fusion.	Bench Test

US DOJ, Criminal Resource Manual §1050 — Scope of 18 U.S.C. §2511 Prohibitions, <https://www.justice.gov/archives/jm/criminal-resource-manual-1050-scope-18-usc-2511-prohibitions>¹³²

ACLU of Northern California, cell-site simulator (Stingray) policy analysis, <https://www.aclunorcal.org>¹³³

FCC, Jammer Enforcement, <https://www.fcc.gov/general/jammer-enforcement>¹³⁴

FCC Enforcement Advisory DA-11-249 on cell jammers, GPS jammers and other jamming devices, <https://www.fcc.gov/document/fcc-enforcement-advisory-cell-jammers-gps-jammers-and-other-jamming-devices>¹³⁵

US DHS, Counter-UAS Legal Authorities fact sheet, https://www.dhs.gov/sites/default/files/publications/dhs_cuas-legal-authorities_fact-sheet_190506-508.pdf¹³⁶

ID	Requirement	Verification
REQ-LTE-006	The subsystem SHALL learn and maintain a site-specific statistical baseline of normal ground-terminal behaviour, and SHALL detect airborne-terminal candidates as anomalies against that baseline rather than against absolute thresholds.	Field Trial
REQ-LTE-007	The subsystem SHALL evaluate the joint strong-RSRP-with-poor-RSRQ signature and the abnormal-neighbour-cell-visibility signature as its primary airborne discriminants.	Analysis
REQ-LTE-008	The subsystem SHALL NOT demodulate, log or forward IMSI, GUTI or any other subscriber identity field.	Inspection
REQ-LTE-009	The subsystem SHALL NOT demodulate, log or forward any user-plane or dedicated control-plane content.	Inspection
REQ-LTE-010	Evidence emitted to fusion SHALL be an anonymous, aggregate airborne-terminal-presence indication with a confidence value, and SHALL NOT identify any subscriber or device.	Inspection
REQ-LTE-011	The subsystem SHALL be declared to fusion as a corroborating sensor, and its evidence weight SHALL reflect that no published accuracy figure exists for passive off-air airborne-terminal classification.	Analysis
REQ-LTE-012	Where the Band 8 or Band 20 uplink overlaps the sub-GHz UAS control segment of Section 4, the two subsystems SHALL share a coordinated front-end and filter plan to avoid mutual desensitisation.	Bench Test
REQ-LTE-013	The subsystem SHOULD provide an interface for operator-cooperative ingest of network-side aerial-terminal identification, where a network operator agreement exists, as the highest-confidence identification path.	Inspection
REQ-LTE-014	Legal review of the monitoring configuration SHALL be completed and recorded for each deployment jurisdiction before commissioning.	Inspection

6 Acoustic Sensor Array Subsystem

6.1 Rationale and role in the sensor mix

The acoustic array is the only modality in this specification that detects the aircraft itself rather than its radio emissions. Its value is therefore structural, not incremental: it is independent of whether the aircraft transmits at all. A fibre-tethered FPV aircraft, a fully autonomous waypoint mission flown with the radio silenced, and an aircraft whose control link the RF subsystem has failed to classify all still displace air with rotating blades, and all still radiate a strongly structured tonal signature.

The cost of that independence is range. Acoustic detection is reliably reported in the 100 m to 500 m band, with rural best cases extending toward 1 km, against the kilometre-scale ranges available to RF detection. The array is consequently specified as a short-range inner layer and as a corroborating sensor, not as a wide-area surveillance instrument. Its three concrete roles are: to close the RF-silent gap at close range; to provide an independent confirmation channel that raises fusion confidence on weak RF contacts; and to provide bearing and, in a multi-node geometry, position on aircraft that the RF chain cannot geolocate.

6.2 Rotor acoustic phenomenology

6.2.1 Blade-pass frequency and the harmonic series

A rotating propeller radiates a discrete tonal spectrum at the blade-pass frequency and its harmonics, superimposed on a broadband turbulent floor. The governing relation is standard across the aeroacoustics literature and is written identically by NASA Ames, by London South Bank University, and by recent array-design work:^{137 138 139}

$$f_{\text{BPF}} = (N_{\text{blades}} * \text{RPM}) / 60 \quad [\text{Hz}]$$

Derivation of the design band for the rotor speeds in scope, using the equation directly:

Step 1 — Two-blade propeller at 3000 RPM: $f_{\text{BPF}} = (2 * 3000)/60 = 100 \text{ Hz}$. [Derived]

Step 2 — Two-blade propeller at 6000 RPM: $f_{\text{BPF}} = (2 * 6000)/60 = 200 \text{ Hz}$, with harmonics at 400, 600 and 800 Hz. [Derived]

Step 3 — Two-blade propeller at 9000 RPM: $f_{\text{BPF}} = (2 * 9000)/60 = 300 \text{ Hz}$. [Derived]

Step 4 — The design fundamental band for conventional small multirotors is therefore approximately 100–300 Hz, extending to roughly 2.6 kHz for the very small, very high-RPM propellers used on micro platforms. [Derived]

Energy is not confined to the fundamental. NASA Langley's rotor-airframe-interaction work documents harmonics from twice the blade-pass frequency up to thirty-five times it, with rotor-airframe proximity amplifying selected harmonics by as much as 30 dB relative to an isolated rotor.¹⁴⁰ For an isolated rotor the fundamental usually dominates: DLR rotor measurements found the blade-pass tone exceeds the higher harmonics by more than 10 dB and therefore sets the overall sound pressure level,¹⁴¹ and AIAA measurements report a dominant tonal

NASA/TM-2018-219894, Schatzman et al., Acoustic and Performance Measurements of Small Rotors, ¹³⁷
https://rotorcrafterc.nasa.gov/Publications/files/Schatzman_TM_2018_219894_Final.pdf

London South Bank University (2021), Attack of the Drones — drone acoustics study, ¹³⁸
<https://openresearch.lsbu.ac.uk/download/38c51c5b5f5315ed53b7202d1932249ad5b94bb514a71b957fbd2fc0a1073ae2/692185/Attack%20of%20the%20Drones%20JN%20&%20SD%202021%20v4.pdf>

MDPI Sensors 25(22):7057, outdoor microphone and windscreen range tests for UAS detection, <https://www.mdpi.com/1424-8220/25/22/7057> ¹³⁹

NASA NTRS 20240015223, Reducing Rotor-Airframe Interaction Noise, ¹⁴⁰
<https://ntrs.nasa.gov/api/citations/20240015223/downloads/Reducing%20Rotor-Airframe%20Interaction.pdf>

DLR ELIB 136456, rotor acoustic measurements, <https://elib.dlr.de/136456/1/ELIB-Eintrag-2020-LoessleF-136456-PaperPublished.pdf> ¹⁴¹

component roughly 20 dB above the broadband floor in hover, with a compact dipole directivity pattern.¹⁴² Directivity matters operationally: a dipole pattern means detection range is a function of aspect angle, not a circle.

Table 6-1 — Measured and derived blade-pass frequencies for small rotors

Source and platform	RPM	Blade-pass freq.	Note
NASA Langley small multirotor, 2-blade	5400	180 Hz	Measured. ¹⁴³
NASA Langley small multirotor, hover	≈4650	≈155 Hz	Measured. ¹⁴⁴
NASA Langley, forward flight, forward and aft rotor	—	135 Hz / 165 Hz	The two rotors run at different speeds in forward flight, producing two distinct tonal families that a classifier can exploit. ¹⁴⁵
Embry-Riddle propeller study (APC, DJI, Master Airscrew)	3000–7900	—	Fundamental-tone SPL rises from 51 dB at 3000 RPM to 73 dB at 7900 RPM — a 22 dB source-level swing across the normal operating range, which dominates detection-range variability. ¹⁴⁶
FAA ASSURE worked example, 2-blade	3500	117 Hz	Calculated as $3500/60 \times 2$. ¹⁴⁷
Korea University LBM study (APC 1147SF, DJI 9443CF)	3600–6000	—	Blade-pass tone plus even-harmonic decay validated against NASA SPL data. ¹⁴⁸
NATO STO small UAS signature study, 4-blade	6000	400 Hz	Measured; illustrates that blade count shifts the fundamental as strongly as rotor speed. ¹⁴⁹
MDPI array-development study, 2–8.7 inch props	up to ≈51430	up to ≈2.6 kHz	Upper bound of the design band, set by micro platforms. ¹⁵⁰

6.2.2 Tonal, broadband and interaction mechanisms

- **Tonal harmonic noise.** Deterministic discrete-frequency content at integer multiples of the blade-pass frequency, generated by periodic blade thickness displacement and steady aerodynamic loading. This is the signal that narrowband detection and direction-of-arrival algorithms actually exploit.¹⁵¹
- **Broadband turbulent and vortex noise.** Continuous-spectrum noise from turbulent boundary-layer trailing-edge interaction, tip vortex formation and wake ingestion. NASA's wind-tunnel study of a small quadcopter rotor found broadband noise can be comparable in amplitude to the blade-pass tone and its harmonics for

AIAA AVIATION Forum 2023-4524, Aeroacoustics of Drones, <https://arc.aiaa.org/doi/abs/10.2514/6.2023-4524>¹⁴²

NASA NTRS 20180002208, small UAS acoustics summary, <https://ntrs.nasa.gov/api/citations/20180002208/downloads/20180002208.pdf>¹⁴³

NASA NTRS 20180002208, small UAS acoustics summary, <https://ntrs.nasa.gov/api/citations/20180002208/downloads/20180002208.pdf>¹⁴⁴

NASA NTRS 20180002208, small UAS acoustics summary, <https://ntrs.nasa.gov/api/citations/20180002208/downloads/20180002208.pdf>¹⁴⁵

Embry-Riddle Aeronautical University, Aerodynamic and Aeroacoustic Performance of Small UAV Propellers,¹⁴⁶
<https://portfolio.erau.edu/ws/portalfiles/portal/39867521/Aerodynamic%20and%20Aeroacoustic%20Performance%20of%20Small%20UAV%20Propellers.pdf>

FAA ASSURE (Stalnov), UAS acoustics report, <https://assureuas.com/wp-content/uploads/2022/05/2022-05-26-Report-final-Prof-Stalnov.pdf>¹⁴⁷

Korea University, Computational study on the steady loading noise of drone propellers,¹⁴⁸
<https://pure.korea.ac.kr/en/publications/computational-study-on-the-steady-loading-noise-of-drone-propellers/>

NATO STO-MP-MSG-SET-183, small UAS signature study, <https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-MSG-SET-183/MP-MSG-SET-183-09.pdf>¹⁴⁹

MDPI Sensors 25(22):7057, outdoor microphone and windscreen range tests for UAS detection, <https://www.mdpi.com/1424-8220/25/22/7057>¹⁵⁰

FAA ASSURE (Stalnov), UAS acoustics report, <https://assureuas.com/wp-content/uploads/2022/05/2022-05-26-Report-final-Prof-Stalnov.pdf>¹⁵¹

small-scale rotors — unlike full-scale helicopter rotors, where tonal content dominates — with self-noise peaking around 10–16 kHz owing to the blunt trailing-edge geometry typical of manufactured small propellers.¹⁵²

- **Rotor-airframe interaction noise.** A hybrid mechanism in which the rotor wake impinges on nearby airframe structure, exciting blade-pass harmonics well above isolated-rotor levels and sometimes dominating total sound pressure level.¹⁵³ Going from two non-adjacent rotors to four increases broadband noise substantially through interaction effects, and for a quadcopter, tones at the blade-pass frequency, the shaft rate and their harmonics dominate the spectrum up to roughly 6 kHz. A University of Stuttgart study using a 512-element MEMS array confirmed the blade-pass tone is the dominant and most exploitable spectral feature in most tested conditions.¹⁵⁴

6.2.3 Motor commutation tones

Brushless motors radiate structure-borne tones tied to electromagnetic commutation and pulse-width-modulation switching, in addition to the aerodynamic tones. NASA Langley's dedicated study found significant acoustic radiation at frequencies coinciding with the motor housing's second structural vibration mode across most tested speeds — an electromechanical resonance rather than a purely aerodynamic tone.¹⁵⁵ At the controller level, whine is driven by switching frequency: low switching frequencies fall in the audible range, and raising the switching frequency toward 24 kHz or moving from six-step to sinusoidal or field-oriented commutation reduces the tone.¹⁵⁶ A classifier can therefore use a secondary tonal feature independent of the blade-pass frequency, but because switching frequency is controller- and firmware-dependent rather than an aerodynamic invariant, it SHALL be treated as a corroborating cue only.

6.2.4 Doppler shift

For a source in relative radial motion the classical acoustic Doppler relation applies, with the speed of sound taken as 343 m/s.¹⁵⁷ For a stationary array and radial velocity small relative to the speed of sound this reduces to the linear approximation:

$$\text{delta_f} = f_0 * (v_r / c) * \cos(\text{theta})$$

Derivation of the expected shift for a typical multirotor, to establish whether it is exploitable:

Step 1 — Take $f_0 = 200$ Hz (mid-band blade-pass tone), $v_r = 10$ m/s (cruise), $c = 343$ m/s, $\text{theta} = 0$ (direct approach). [Derived]

Step 2 — $\text{delta_f} = 200 * (10/343) = 5.83$ Hz. Across the plausible speed range of 5–15 m/s and fundamental range 150–300 Hz the shift spans roughly 2–13 Hz. [Derived]

Step 3 — To resolve a 2 Hz shift the analysis bin must be narrower than 2 Hz, requiring a coherent integration window longer than 0.5 s. This is achievable for a hovering or steadily transiting target but not for an aggressively manoeuvring one. [Derived]

Step 4 — Conclusion: Doppler is usable to disambiguate approach from recession and to estimate closing radial velocity as a complement to angular tracking, but it is not a primary observable. [Derived]

NASA NTRS 20220010078, Pettingill et al., broadband noise of small rotors,¹⁵²
https://ntrs.nasa.gov/api/citations/20220010078/downloads/SUI_BB-VFS2019_Paper-Pettingill.pdf

NASA NTRS 20180001470, rotor-airframe interaction noise, <https://ntrs.nasa.gov/citations/20180001470>¹⁵³

University of Stuttgart eLib, 512-element MEMS array rotor aeroacoustics, <https://elib.uni-stuttgart.de/bitstream/11682/15203/1/s13272-023-00680-z.pdf>¹⁵⁴

NASA NTRS 20180007415, Electric Motor Noise from Small Quadcopters: Part II,¹⁵⁵
<https://ntrs.nasa.gov/api/citations/20180007415/downloads/20180007415.pdf>

Leanmotor, Common causes of BLDC motor noise and how to reduce it, <https://www.leanmotor.com/common-causes-of-bldc-motor-noise-and-how-to-reduce-it.html>¹⁵⁶

OpenStax University Physics via LibreTexts, The Doppler Effect,¹⁵⁷
[https://phys.libretexts.org/Bookshelves/University_Physics/University_Physics_\(OpenStax\)/Book:_University_Physics_I_-_Mechanics_Sound_Oscillations_and_Waves_\(OpenStax\)/17:_Sound/17.08:_The_Doppler_Effect](https://phys.libretexts.org/Bookshelves/University_Physics/University_Physics_(OpenStax)/Book:_University_Physics_I_-_Mechanics_Sound_Oscillations_and_Waves_(OpenStax)/17:_Sound/17.08:_The_Doppler_Effect)

The mechanism is well established at higher frequencies — a published example for a fan-blade tip speed of 17.3 m/s at 40 kHz emission gives a shift of approximately 4.2 kHz¹⁵⁸ — which is why the effect is far more exploitable in active ultrasonic sensing than in passive detection of a low-frequency rotor tone.

6.3 Propagation and detection-range budget

6.3.1 Source levels

Table 6-2 — Measured small-UAS source sound pressure levels

Platform	Metric	Value	Source note
DJI Mavic 2 Pro	SPL at -30° incidence, 1 m	71.2 dB(A)	Directly measured; the anchor figure used in the budget below. ¹⁵⁹
Generic small quadcopter	SPL at 1 m, -30° off rotor plane, free field	Reference condition	The reference geometry adopted by the EU drone-noise study. ¹⁶⁰
Small to large multirotor	Fundamental-tone SPL, 3000 to 7900 RPM	51 to 73 dB	A 22 dB swing driven by rotor speed alone. ¹⁶¹

6.3.2 Geometric spreading and atmospheric absorption

For a point source in a free field, sound pressure level falls by geometric divergence, giving the familiar 6 dB reduction per doubling of distance.¹⁶²

$$\text{SPL}(R) = \text{SPL}(R_0) - 20 \cdot \log_{10}(R / R_0)$$

ISO 9613-2 defines a frequency-, temperature- and humidity-dependent atmospheric attenuation coefficient applied as $A_{\text{atm}} = \alpha \cdot d / 1000$ for distance d in metres.^{163 164} The standard is valid from 50 Hz to 10 kHz, -20 °C to +50 °C and 10–100% relative humidity.¹⁶⁵

¹⁵⁸ University of Maryland / HotMobile, rotor-blade Doppler acoustic sensing poster, https://icosmos.cs.umd.edu/images/2_publication/posters_demo/writeup/Dopplerdodge_poster_hotmobile20_nirupam.pdf

¹⁵⁹ PMC8198898, Drone Noise Emission Characteristics, <https://pmc.ncbi.nlm.nih.gov/articles/PMC8198898/>

¹⁶⁰ European Environment Agency / EPANET Interest Group on Noise, Noise from Drones, https://epanet.eea.europa.eu/reports-letters/reports-and-letters/interest-group-noise_noise-from-drones-1.pdf

¹⁶¹ Embry-Riddle Aeronautical University, Aerodynamic and Aeroacoustic Performance of Small UAV Propellers, <https://portfolio.erau.edu/ws/portalfiles/portal/39867521/Aerodynamic%20and%20Aeroacoustic%20Performance%20of%20Small%20UAV%20Propellers.pdf>

¹⁶² European Environment Agency / EPANET Interest Group on Noise, Noise from Drones, https://epanet.eea.europa.eu/reports-letters/reports-and-letters/interest-group-noise_noise-from-drones-1.pdf

¹⁶³ EMD windPRO Appendix A, ISO 9613-2 atmospheric absorption reference table, https://help.emd.dk/knowledgebase/content/windPRO4.2/Appendix_A_DECIBEL.pdf

¹⁶⁴ ISO 9613-2:1996, Acoustics — Attenuation of sound during propagation outdoors, Part 2, [https://www.omegawestdocuments.com/media/documents/43/CD43.14%20-%20International%20Standards%20Organisation%20\(1996\).%20ISO%209613-2.%20Acoustics%20%E2%80%93%20Attenuation%20of%20sound%20during%20propagation%20outdoors%20%E2%80%93%20Part%202%20General%20method%20of%20calculation.pdf](https://www.omegawestdocuments.com/media/documents/43/CD43.14%20-%20International%20Standards%20Organisation%20(1996).%20ISO%209613-2.%20Acoustics%20%E2%80%93%20Attenuation%20of%20sound%20during%20propagation%20outdoors%20%E2%80%93%20Part%202%20General%20method%20of%20calculation.pdf)

¹⁶⁵ DataKustik CadnaA documentation, ISO 9613 meteorological validity range, https://doku.datakustik.com/CadnaA/en/Meteorologie_ISO.html

Table 6-3 — ISO 9613-2 atmospheric absorption at 10 °C and 70% relative humidity

Octave band centre (Hz)	63	125	250	500	1000	2000	4000	8000
alpha (dB/km) ¹⁶⁶	0.1	0.4	1.0	1.9	3.7	9.7	32.8	117

Attenuation at 8 kHz is roughly 300 times greater per kilometre than at 500 Hz. This is the single most important propagation fact for this subsystem: the fundamental blade-pass tone at 100–300 Hz suffers negligible atmospheric absorption over hundreds of metres, while the broadband high-frequency content above a few kilohertz is attenuated aggressively. Long-range detection SHALL therefore prioritise the fundamental and low-order harmonics, not high-frequency broadband content.

Ground effect. Interference between the direct and ground-reflected rays modifies the simple spherical model, particularly at low source and receiver heights and low frequencies; ISO 9613-2 carries a dedicated ground-effect term alongside divergence, atmospheric, barrier and foliage terms.¹⁶⁷ For a low-flying aircraft at 10–50 m above ground observed by a near-ground array, interference nulls and reinforcements of several decibels should be expected depending on frequency and geometry. [Derived] This is a second-order correction relative to spreading and absorption and is neglected in the first-pass budget below, but it matters for fine SNR prediction and for siting.

6.3.3 Ambient noise floors

Table 6-4 — Broadband ambient noise floors by environment

Environment	Typical level, dB(A)	Source and note
Wilderness / rural night, no traffic	25–35	Wilderness day-night level below 35; rural night around 25. ^{168,169}
Rural residential	30 night / 40 day	Standard reference table. ¹⁷⁰
Suburban, quiet	39–45	Measured environmental impact statement data. ¹⁷¹
Suburban, normal	45–55	Standard reference table. ¹⁷²
Urban residential	50–60	Standard reference table. ¹⁷³
Urban, dense downtown	55–75	Environmental impact report data. ¹⁷⁴

EMD windPRO Appendix A, ISO 9613-2 atmospheric absorption reference table, ¹⁶⁶
https://help.emd.dk/knowledgebase/content/windPRO4.2/Appendix_A_DECIBEL.pdf

ISO 9613-2:1996, Acoustics — Attenuation of sound during propagation outdoors, Part 2, ¹⁶⁷
[https://www.omegawestdocuments.com/media/documents/43/CD43.14%20-%20International%20Standards%20Organisation%20\(1996\).%20ISO%209613-2.%20Acoustics%20%E2%80%93%20Attenuation%20of%20sound%20during%20propagation%20outdoors%20%E2%80%93%20Part%202%20General%20method%20of%20calculation.pdf](https://www.omegawestdocuments.com/media/documents/43/CD43.14%20-%20International%20Standards%20Organisation%20(1996).%20ISO%209613-2.%20Acoustics%20%E2%80%93%20Attenuation%20of%20sound%20during%20propagation%20outdoors%20%E2%80%93%20Part%202%20General%20method%20of%20calculation.pdf)

California Public Utilities Commission, environmental impact report noise appendix, ¹⁶⁸
https://ia.cpuc.ca.gov/environment/info/aspen/dpv2/feir/d08_noise.pdf

US Bureau of Land Management, noise evaluation reference table, ¹⁶⁹
https://eplanning.blm.gov/public_projects/nepa/54345/75288/83026/Att_Q_-_Noise_Evaluation.pdf

US Bureau of Land Management, noise evaluation reference table, ¹⁷⁰
https://eplanning.blm.gov/public_projects/nepa/54345/75288/83026/Att_Q_-_Noise_Evaluation.pdf

King County NERTS draft EIS, ambient noise chapter, <https://your.kingcounty.gov/dnrp/library/solid-waste/facilities/NERTS-draft-EIS-Ch-3.10.pdf>, ¹⁷¹

US Bureau of Land Management, noise evaluation reference table, ¹⁷²
https://eplanning.blm.gov/public_projects/nepa/54345/75288/83026/Att_Q_-_Noise_Evaluation.pdf

US Bureau of Land Management, noise evaluation reference table, ¹⁷³
https://eplanning.blm.gov/public_projects/nepa/54345/75288/83026/Att_Q_-_Noise_Evaluation.pdf

California Public Utilities Commission, environmental impact report noise appendix, ¹⁷⁴
https://ia.cpuc.ca.gov/environment/info/aspen/dpv2/feir/d08_noise.pdf

Background levels rarely fall below about 40 dB(A) even in quiet rural and suburban settings, and rise to 45–50 dB(A) in dense urban areas away from major roads.

Table 6-5 — Octave-band night-time ambient levels, dB

Octave band (Hz)	63	125	250	500	1000	2000	4000	8000
Rural night ¹⁷⁵	42	37	32	27	22	18	14	12
Suburban night	47	42	37	32	27	23	19	17
Urban night	52	47	42	37	32	28	24	22

Octave-band data is more useful than broadband A-weighted levels for this design, because the detector operates in the 125–500 Hz bands where the blade-pass fundamental lives, and the ambient level in those bands is what actually sets the range.

6.3.4 SNR budget and range derivation

Combining the terms above with the array gain derived in Section 6.5.3 gives the first-order acoustic link budget:

$$\text{SNR}(R) = \text{SPL}_{1\text{m}} - 20 \cdot \log_{10}(R) - \alpha(f) \cdot R / 1000 - L_{\text{ambient}}(f) + 10 \cdot \log_{10}(M)$$

Worked example, all values derived from the cited inputs:

Step 1 — Inputs: SPL at 1 m = 70 dB(A), from the measured DJI Mavic 2 Pro figure; suburban night ambient = 45 dB(A); absorption dominated by the 500 Hz band with $\alpha = 1.9$ dB/km. [Derived from the cited source levels and tables]

Step 2 — Single microphone, SNR = 0 dB threshold: $0 = 70 - 20 \cdot \log_{10}(R) - 1.9 \cdot R / 1000 - 45$. [Derived]

Step 3 — Solving iteratively: $20 \cdot \log_{10}(R) = 25$, giving $R = 178$ m. The atmospheric term contributes under 0.4 dB at this range and is negligible. [Derived]

Step 4 — Adding an 8-element array, array gain = $10 \cdot \log_{10}(8) = 9$ dB, so $20 \cdot \log_{10}(R) = 34$ and $R = 500$ m. [Derived]

Step 5 — Adding a 32-element array, array gain = $10 \cdot \log_{10}(32) = 15$ dB, so $20 \cdot \log_{10}(R) = 40$ and $R = 1000$ m in theory. This last figure SHALL be treated with suspicion: real arrays do not achieve ideal gain, and the published field envelope does not support 1 km as a planning number. [Derived]

Reconciliation with measured field data. The derivation above tracks published field results closely, which is the main reason to trust it. A field study directly measuring the trade-off reports realised SNR falling quickly below –25 dB at 500 m for a single sensor, and quotes a practical acoustic detection envelope of 100–250 m urban, 250–500 m suburban and 500–1000 m rural.¹⁷⁶ An independent field study measured practical recognition distances of 150 m for small-class drones up to 500 m for medium and large classes, with 96.3% average detection accuracy across the test range.¹⁷⁷ An industry review puts the typical practical envelope at 300–500 m, citing background noise, wind and temperature as the range-limiting factors.¹⁷⁸ A commercial system advertises up to 1000 m depending on drone type and environment, which should be read as a best case and not a guaranteed range.¹⁷⁹

EngineeringToolbox, Outdoor Ambient Sound Pressure Levels, https://www.engineeringtoolbox.com/outdoor-noise-d_62.html¹⁷⁵

MicrodB, QuietDrone 2020 monitoring report (Pinel-Lamotte), https://microdb.fr/wp-content/uploads/sites/3/2024/04/4-Monitoring_A108_QuietDrone2020_Pinel-Lamotte-final.pdf¹⁷⁶

PMC7506852, Development of an Acoustic System for UAV Detection, <https://pmc.ncbi.nlm.nih.gov/articles/PMC7506852/>¹⁷⁷

Robin Radar Systems, Pros and Cons of Acoustic Drone Detection, <https://www.robinradar.com/blog/acoustic-sensors-drone-detection>¹⁷⁸

MicrodB ALARM environmental monitoring product page (vendor claim), <https://microdb.fr/en/product/environmental-monitoring/>¹⁷⁹

Table 6-6 — Acoustic detection range planning figures

Environment	Single element	8-element array	Basis and cross-check
Urban	≈50–100 m [Derived]	100–250 m	Published field envelope for urban conditions; the higher ambient floor forces shorter range for the same source level. ¹⁸⁰
Suburban	≈178 m [Derived]	250–500 m	The derived 178 m single-element and 500 m 8-element figures bracket the published suburban envelope. ¹⁸¹
Rural	≈300 m [Derived]	500–1000 m	Published rural envelope. Treat 1000 m as best case, achievable only in low wind and low ambient conditions. ¹⁸²¹⁸³

Planning figures adopted by this specification: 150 m urban, 350 m suburban and 600 m rural for the 8-element node, as conservative points within the published envelopes. Ranges are strongly aspect-dependent because of the dipole directivity of the source, and degrade sharply with wind.

6.4 Microphone element specification

Table 6-7 — Microphone technology comparison

Type	Frequency range	Accuracy	Characteristics	Suitability for this design
Embedded MEMS	100 Hz – 10 kHz	±2–3 dB	Reflow-solderable, drift-stable, shock and humidity resistant ¹⁸⁴¹⁸⁵	Selected. Tight unit-to-unit sensitivity and phase consistency across temperature and supply voltage matters more for an 8–64 element beamformer than single-channel fidelity
USB electret, measurement class	20 Hz – 20 kHz	±1 dB individually calibrated	IEC 61672 Class 2 ¹⁸⁶	Not suitable — no practical multi-channel synchronous interface
XLR electret, professional	15 Hz – 20 kHz	±2 dB	Requires phantom power ¹⁸⁷	Usable for a small directional-microphone node variant; poor scalability
Calibrated electret, precision	5–30 Hz to 30–40 kHz	±0.2–0.5 dB	IEC 61672 Class 1/2, traceable certificate ¹⁸⁸	Reference and calibration use only
Laboratory condenser	6 Hz – 40 kHz	±0.1 dB	Traceable, IEC 61672 Class 1 ¹⁸⁹	Commissioning reference against which the production array is calibrated

MicrodB, QuietDrone 2020 monitoring report (Pinel-Lamotte), https://microdb.fr/wp-content/uploads/sites/3/2024/04/4-Monitoring_A108_QuietDrone2020_Pinel-Lamotte-final.pdf¹⁸⁰

MicrodB, QuietDrone 2020 monitoring report (Pinel-Lamotte), https://microdb.fr/wp-content/uploads/sites/3/2024/04/4-Monitoring_A108_QuietDrone2020_Pinel-Lamotte-final.pdf¹⁸¹

MicrodB, QuietDrone 2020 monitoring report (Pinel-Lamotte), https://microdb.fr/wp-content/uploads/sites/3/2024/04/4-Monitoring_A108_QuietDrone2020_Pinel-Lamotte-final.pdf¹⁸²

MicrodB ALARM environmental monitoring product page (vendor claim), <https://microdb.fr/en/product/environmental-monitoring/>¹⁸³

SonaVyx, measurement microphone comparison, <https://sonavyx.com/en/compare/measurement-mic-comparison>¹⁸⁴

PUI Audio, ECM versus MEMS microphones — key differences and applications, <https://puiaudio.com/news/ecm-vs-mems-microphones-key-differences-applications-and-new-solutions/>¹⁸⁵

SonaVyx, measurement microphone comparison, <https://sonavyx.com/en/compare/measurement-mic-comparison>¹⁸⁶

SonaVyx, measurement microphone comparison, <https://sonavyx.com/en/compare/measurement-mic-comparison>¹⁸⁷

SonaVyx, measurement microphone comparison, <https://sonavyx.com/en/compare/measurement-mic-comparison>¹⁸⁸

SonaVyx, measurement microphone comparison, <https://sonavyx.com/en/compare/measurement-mic-comparison>¹⁸⁹

Bottom-port MEMS designs generally achieve better signal-to-noise ratio than top-port designs because of a larger usable back volume, and are preferred for this application.

6.4.1 Element parameters and achievable values

Table 6-8 — MEMS element parameters, definitions and achievable values

Parameter	Definition	Typical value	Representative achieved figures
Sensitivity	Output level for a 94 dB SPL, 1 kHz reference tone	−38 to −26 dBFS or dBV	Commercial MEMS families span −26 to −42 dBV; a 2025 array study summarises typical MEMS as −40 to −45 dBV/Pa. ¹⁹⁰
Self-noise (equivalent input noise)	Input-referred A-weighted noise floor — the parameter that sets detection range	23.5–29 dB(A) SPL	25 dB SPL nominal and 28 dB maximum for one commercial part; 29 dB(A) for an earlier low-noise generation. A 2025 survey gives 30–35 dB(A) as typical for array-grade parts. ¹⁹³
Signal-to-noise ratio	Difference between the 94 dB reference and self-noise, A-weighted	58–72 dB(A)	65 dB(A) for the first generation to reach that level; 69 dB(A) achieved by current parts from at least two vendors. ¹⁹⁶
Acoustic overload point	SPL at 10% total harmonic distortion	118–133 dB SPL	122 dB and 133 dB SPL for two commercial parts; 128–130 dB SPL for another. ¹⁹⁹
Frequency response	Usable flat-response band	≈50 Hz – 20 kHz	Low-frequency roll-off point varies by part and must be checked against the 100 Hz design floor. ²⁰¹

PUI Audio, ECM versus MEMS microphones — key differences and applications, <https://puiaudio.com/news/ecm-vs-mems-microphones-key-differences-applications-and-new-solutions/>¹⁹⁰

Knowles, MEMS microphone portfolio comparison, <https://cdn.thomasnet.com/ccp/30973684/351950.pdf>¹⁹¹

PMC12656299, outdoor microphone range tests — typical MEMS specification summary, <https://pmc.ncbi.nlm.nih.gov/articles/PMC12656299/>¹⁹²

Knowles MM20-33639 MEMS microphone datasheet, https://www.knowles.com/docs/default-source/default-document-library/mm20-33639-000.pdf?Status=Master&sfvrsn=bfb071b1_0¹⁹³

Analog Devices MS-2348, Low Self-Noise: The First Step to High-Performance MEMS Microphone Applications, <https://www.analog.com/media/en/technical-documentation/technical-articles/Low-Self-Noise-The%20First-Step-to-High-Performance-MEMS-Microphone-Applications-MS-2348.pdf>¹⁹⁴

PMC12656299, outdoor microphone range tests — typical MEMS specification summary, <https://pmc.ncbi.nlm.nih.gov/articles/PMC12656299/>¹⁹⁵

Analog Devices MS-2348, Low Self-Noise: The First Step to High-Performance MEMS Microphone Applications, <https://www.analog.com/media/en/technical-documentation/technical-articles/Low-Self-Noise-The%20First-Step-to-High-Performance-MEMS-Microphone-Applications-MS-2348.pdf>¹⁹⁶

Infineon XENSIV MEMS microphones product selection guide, <https://www.infineon.com/assets/row/public/documents/24/66/infineon-xensiv-mems-microphones-productselectionguide-en.pdf>¹⁹⁷

Knowles MM25-33663 MEMS microphone datasheet, https://www.knowles.com/docs/default-source/default-document-library/mm25-33663-000.pdf?Status=Master&sfvrsn=c3ae71b1_0¹⁹⁸

PUI Audio, ECM versus MEMS microphones — key differences and applications, <https://puiaudio.com/news/ecm-vs-mems-microphones-key-differences-applications-and-new-solutions/>¹⁹⁹

Infineon XENSIV MEMS microphones product selection guide, <https://www.infineon.com/assets/row/public/documents/24/66/infineon-xensiv-mems-microphones-productselectionguide-en.pdf>²⁰⁰

Infineon XENSIV MEMS microphones product selection guide, <https://www.infineon.com/assets/row/public/documents/24/66/infineon-xensiv-mems-microphones-productselectionguide-en.pdf>²⁰¹

Parameter	Definition	Typical value	Representative achieved figures
Digital interface	Output format	PDM or I2S/TDM	PDM is one bit and clock-driven; I2S and TDM support synchronous multi-channel capture, which is what an array requires. ²⁰²
Dynamic range	Overload point minus self-noise	<95 dB	Typical for array-grade MEMS. ²⁰³

6.4.2 Phase matching between elements

Phase and amplitude matching between elements directly bounds beamforming accuracy and sidelobe suppression, and is the specification that most often causes a paper array design to underperform in hardware. A beamforming application note specifies a phase tolerance within 1.5° maximum at 200 Hz across a 100-microphone window, with a measured phase spread of only 0.13–0.33° across positions in the example.²⁰⁴ Independent characterisation work found that MEMS datasheets commonly specify sensitivity tolerance of ± 1 dB and phase tolerance of $\pm 10^\circ$ at 1 kHz.²⁰⁵ A large-array study found systematic phase-error residuals under 125 μ s with individual outlier channels up to about 25 μ s after geometric-bias correction, and notes that phase errors are negligible for beamforming when they remain below 5° at the Nyquist frequency — about 3.5 μ s equivalent — while up to 10° of phase error is common in low-cost MEMS owing to manufacturing tolerance, and is correctable by calibration because the errors are systematic and stationary.²⁰⁶ A three-dimensional MEMS array built for wind-tunnel aeroacoustics measured under 3 dB of sensitivity dispersion from 80 Hz to 10 kHz and good phase homogeneity up to 6 kHz, degrading above that.²⁰⁷

Design consequence. Because the datasheet phase tolerance of typical low-cost MEMS ($\pm 10^\circ$ at 1 kHz) exceeds the tolerance that beamforming theory requires (under 5° at Nyquist), per-element phase calibration is not optional in this design — it is the mechanism by which commodity parts are made usable. Fortunately the errors are systematic and stationary, so a factory calibration table with periodic in-service verification is sufficient. The favourable point for this application is that the phase homogeneity of MEMS arrays is best at low frequency, which is exactly where the blade-pass fundamental sits.

Table 6-9 — Normative microphone element requirements

ID	Requirement	Verification
REQ-AC-001	Elements SHALL be digital MEMS microphones with a synchronous multi-channel interface (I2S or TDM). Independently clocked single-channel interfaces SHALL NOT be used.	Inspection
REQ-AC-002	Element self-noise SHALL NOT exceed 30 dB(A) SPL equivalent input noise, and SHOULD NOT exceed 26 dB(A).	Bench Test
REQ-AC-003	Element signal-to-noise ratio SHALL be at least 65 dB(A) and SHOULD be at least 69 dB(A).	Bench Test
REQ-AC-004	Element acoustic overload point SHALL be at least 120 dB SPL, so that near-field passes and impulsive urban events do not clip the array.	Bench Test
REQ-AC-005	Element response SHALL be within ± 3 dB from 100 Hz to 8 kHz, covering the blade-pass fundamental through the low-order harmonics.	Bench Test

Infineon XENSIV MEMS microphones product selection guide, <https://www.infineon.com/assets/row/public/documents/24/66/infineon-xensiv-mems-microphones-productselectionguide-en.pdf>²⁰²

PMC12656299, outdoor microphone range tests — typical MEMS specification summary,²⁰³
<https://pmc.ncbi.nlm.nih.gov/articles/PMC12656299/>

Knowles AN-26, Phase Sequenced MEMS Microphones, https://www.knowles.com/docs/default-source/default-document-library/an-26-phase-sequenced-mems-microphones.pdf?sfvrsn=cce94cb1_6²⁰⁴

ICASSP 2021, MEMS microphone sensitivity and phase characterisation, <https://sstuijk.estue.nl/publications/icassp21.pdf>²⁰⁵

MDPI Sensors 26(12):3899, MxArray large-aperture MEMS array calibration, <https://www.mdpi.com/1424-8220/26/12/3899>²⁰⁶

HAL hal-03092919, 3D MEMS array for aeroacoustics, https://hal.science/hal-03092919v1/file/bebec2020_HAL.pdf²⁰⁷

ID	Requirement	Verification
REQ-AC-006	Residual inter-element phase error after calibration SHALL NOT exceed 5° at the array Nyquist frequency.	Bench Test
REQ-AC-007	Each array SHALL carry a per-element amplitude and phase calibration table applied in the processing chain, established at manufacture against a traceable reference.	Inspection
REQ-AC-008	The array SHALL support in-service verification of element health and calibration validity without physical disassembly, and SHALL report any element failure or out-of-tolerance channel.	Field Trial
REQ-AC-009	Bottom-port element packages SHOULD be preferred over top-port, for signal-to-noise ratio.	Inspection

6.5 Array geometry and aperture design

6.5.1 Geometry options

Table 6-10 — Array geometry comparison

Geometry	Direction-finding capability	Aliasing behaviour	Practical note
Uniform linear	One-dimensional angle of arrival with front-back ambiguity	Periodic grating lobes at regular angles	Simplest and cheapest, but has a documented directionally dependent estimation bias and a limited field of view. Not suitable as a standalone node. ²⁰⁸
Uniform circular	Full 360° azimuth, and azimuth plus elevation simultaneously	Grating lobes present but distributed more benignly than a linear array	The most common choice in dedicated drone-acoustic systems; a representative 32-element circular implementation was reported as a practical accuracy-versus-complexity trade-off. Selected as the baseline for this design. ²⁰⁹
Spherical or three-dimensional	Full three-dimensional direction of arrival without planar ambiguity	Depends on element distribution	Best capability; higher element count, volume and cost. An 8-element cube array is used in the DREGON dataset. ²¹⁰
Tetrahedral (4 elements)	Minimum geometry for unambiguous three-dimensional localisation	Coarse; sparse aperture	Useful for a very low-cost auxiliary node contributing bearing only. ²¹¹
Random or non-uniform	Depends on layout	Deliberately irregular spacing avoids periodic grating-lobe structure, pushing aliasing artefacts to less predictable and often less problematic angles	Explicitly recommended for wideband arrays. Adopted for the outer sub-aperture in this design. ²¹²

University of Paderborn, Bias of DOA Estimation with Linear Arrays, https://groups.uni-paderborn.de/nt/pubs/2016/JacobHaeb_ITG2016.pdf²⁰⁸

EURASIP Journal on Wireless Communications and Networking, Classification, positioning and tracking of drones by HMM using acoustic circular microphone array, <https://jwcn-urasipjournals.springeropen.com/articles/10.1186/s13638-019-1632-9>²⁰⁹

DREGON project (Inria), drone egonoise and source localisation dataset, <http://dregon.inria.fr/>²¹⁰

MicrodB, QuietDrone 2020 monitoring report (Pinel-Lamotte), https://microdb.fr/wp-content/uploads/sites/3/2024/04/4-Monitoring_A108_QuietDrone2020_Pinel-Lamotte-final.pdf²¹¹

GFal Tech, Frequency range of microphone arrays, <https://www.gfaitech.com/knowledge/faq/frequency-range-microphone-array>²¹²

6.5.2 Spatial Nyquist and element spacing

By direct analogy with temporal sampling, the array must satisfy a spatial sampling condition to avoid grating lobes and directional ambiguity at the highest frequency of interest:^{213 214}

$$d \leq \lambda_{\min} / 2 = c / (2 * f_{\max})$$

Derivation of the required spacings for this design, with $c = 343$ m/s:

Step 1 — For the blade-pass band only, $f_{\max} = 2.6$ kHz: $d \leq 343/(2*2600) = 6.6$ cm. This is a comfortable constraint that permits a compact array. [Derived]

Step 2 — For the low-order harmonic band, $f_{\max} = 4$ kHz: $d \leq 4.3$ cm. [Derived; consistent with the published worked example]

Step 3 — For $f_{\max} = 8$ kHz: $d \leq 2.1$ cm. [Derived; consistent with the published worked example]

Step 4 — For full-band coherence including broadband content to 20 kHz: $d \leq 0.86$ cm, which is impractical at any useful aperture. [Derived]

Step 5 — Conclusion: the array is designed for the tonal band, not the full audio band. This is also the correct engineering choice on propagation grounds, since Table 6-3 shows the high-frequency content does not survive the range anyway. [Derived]

The published worked spacings corroborate this arithmetic: 4.3 cm maximum spacing for a 4 kHz upper limit and 2.1 cm for 8 kHz,²¹⁵ with the equivalent statement that the spatial aliasing frequency for a given spacing is $c/(2d)$. A caveat from array-processing research is that the classical spatial Nyquist criterion has limited practical importance for microphone arrays in many real, non-plane-wave, reverberant conditions,²¹⁶ so it SHALL be treated as a design guideline rather than a hard limit — particularly for the urban node, where the propagation environment is decidedly not free-field.

6.5.3 Aperture, angular resolution and array gain

Angular resolution scales inversely with aperture measured in wavelengths:

$$\theta \approx \lambda / D \quad (\text{radians})$$

Derivation of the aperture needed for a useful beamwidth at the design frequency:

Step 1 — At 200 Hz the wavelength is $\lambda = 343/200 = 1.72$ m. [Derived]

Step 2 — For a 20° beamwidth (0.35 rad), the required aperture is $D = 1.72/0.35 = 4.9$ m. [Derived]

Step 3 — For a practical 1 m aperture at 200 Hz, $\theta = 1.72/1.0 = 1.72$ rad, i.e. about 98°. The array has essentially no resolving power at the fundamental with a 1 m aperture. [Derived]

Step 4 — At the fourth harmonic, 800 Hz, $\lambda = 0.43$ m and a 1 m aperture gives $\theta = 0.43$ rad, about 25°. [Derived]

Step 5 — Conclusion: direction finding must be performed on the harmonics, not on the fundamental, unless the aperture is several metres across. Detection uses the fundamental because it survives the range; bearing uses the harmonics because they fit the aperture. This split is the central design insight of the acoustic subsystem. [Derived]

A single dense array cannot simultaneously satisfy the small spacing needed at high frequency and the large aperture needed for resolution at low frequency. The standard solution is nested sub-arrays — concentric or overlapping sub-apertures at different element spacings, each optimised for a frequency sub-band and combined

Stanford CCRMA, Plane Wave Sampling Theory, https://ccrma.stanford.edu/~jos/huygens/Plane_Wave_Sampling_Theory.html²¹³

vocal.com, Spatial aliasing in a microphone array, <https://vocal.com/echo-cancellation/spatial-aliasing-in-a-microphone-array/>²¹⁴

Texas Instruments E2E, Microphone Beamforming application note, https://e2e.ti.com/cfs-file/__key/communityserver-discussions-components-files/6/3036.Microphone-Beamforming.pdf²¹⁵

Technion, On Spatial Aliasing in Microphone Arrays, <https://cris.technion.ac.il/en/publications/on-spatial-aliasing-in-microphone-arrays/>²¹⁶

for wideband operation.²¹⁷ Sparse and nested geometries can preserve array gain with far fewer elements than a full dense array.²¹⁸

For M omnidirectional elements receiving a coherent signal in spatially incoherent noise, the gain from coherent summation is:

$$G_{\text{array}} = 10 * \log_{10}(M) \quad [\text{dB}]$$

This follows because self-noise sums incoherently across channels while the coherent signal sums in amplitude, and is derived rigorously in the array-processing literature.²¹⁹ With adaptive processing and an interference-to-noise advantage, array gain can exceed the ideal figure — a 1000-element hydrophone array achieving 40 dB against the naive 30 dB prediction is the canonical example. Practical benchmarks show real achieved gains of roughly 9.4–14.5 dB for 4–8 element arrays depending on algorithm,²²⁰ with 10–15 dB of suppression reported for 4–8 element linear and circular arrays.²²¹ Against this, partial noise correlation across channels, reverberation and off-axis signal spreading mean real gain is often sub-ideal, and one large-aperture study found gain growing less than proportionally with the square root of element count in practice. The specification therefore allocates 80% of theoretical array gain as the planning figure. [Derived allocation]

6.5.4 Recommended array design

The reference array is a nested two-aperture design. All parameters below are design choices derived from the constraints above, not published figures.

Table 6-11 — Reference nested array design (all values derived)

Sub-aperture	Elements	Spacing	Aperture	Band served and rationale
Inner circular	8, uniform circular	4.0 cm	10.5 cm dia.	800 Hz – 4 kHz. Spacing satisfies spatial Nyquist to 4 kHz with margin; aperture gives roughly 25° resolution at 800 Hz and better above. [Derived]
Outer non-uniform ring	16, non-uniform	18–33 cm	1.0 m dia.	200 Hz – 900 Hz. Non-uniform spacing suppresses the grating-lobe structure that this spacing would otherwise produce above 520 Hz; provides the aperture needed for bearing on the low-order harmonics. [Derived]
Combined	24 total	—	1.0 m dia.	Ideal array gain $10 \cdot \log_{10}(24) = 13.8$ dB, planning allocation 11 dB at 80% efficiency. Detection uses the full aperture on the fundamental; bearing uses frequency-dependent sub-aperture selection. [Derived]

A 24-element node is a deliberate mid-point. The published record contains built arrays from 8 to 512 elements (Table 6-12); element count buys array gain logarithmically while buying cost, power, calibration effort and data rate linearly, so the knee of that curve sits in the low tens for a fielded outdoor sensor.

aplu.ch, Microphone Arrays tutorial, https://www.aplu.ch/home/download/microphone_array.pdf²¹⁷

JASA 146(3):EL306, coprime array coherent processing and array gain, https://pubs.aip.org/asa/jasa/article-pdf/146/3/EL306/15342423/el306_1_online.pdf²¹⁸

Norsonic technical note on array gain, <https://norsonic.no/wp-content/uploads/2023/09/TN-array-gain.pdf>²¹⁹

MathWorks, Acoustic Beamforming Using a Microphone Array, <https://www.mathworks.com/help/audio/ug/acoustic-beamforming-using-a-microphone-array.html>²²⁰

Microsoft Research (Tashev), microphone array beamformer design, ICASSP 2005, https://www.microsoft.com/en-us/research/wp-content/uploads/2016/02/Tashev_MABeamforming_ICASSP_05.pdf²²¹

Table 6-12 — Published built MEMS arrays, for benchmarking

Array	Elements	Configuration	Application
University of Valladolid	64 (8×8)	2.125 cm uniform spacing, rectangular PCB	UAV propeller noise and distress-signal discrimination. ²²²
Commercial C-UAS array board	64, expandable to 192	460×460×20 mm multi-arm spiral	Passive UAV acoustic localisation (vendor specification). ²²³
University of Stuttgart	512	Positioned 1.35 m below the rotor plane	Rotor aeroacoustics research; confirmed the blade-pass tone as the dominant exploitable feature. ²²⁴
DREGON (Inria)	8	Cube-shaped, aircraft-embedded	Sound source localisation dataset. ²²⁵
HMM circular-array drone system	32	Uniform circular array	Drone classification, positioning and tracking. ²²⁶

6.6 Beamforming and direction-of-arrival estimation

Table 6-13 — Direction-of-arrival algorithms and reported accuracy

Algorithm	Principle	Compute cost	Reported accuracy in a drone or acoustic context
Delay-and-sum	Time-align and coherently sum	Low	RMSE about 4.0° at –10 dB array SNR on an 8-element circular array (synthetic). ²²⁷
MVDR (Capon)	Minimum-variance distortionless response with adaptive weighting	Moderate — requires covariance inversion	RMSE about 1.6° at –10 dB array SNR on the same 8-element circular array; outperforms delay-and-sum at low SNR. ²²⁸
MUSIC	Subspace eigen-decomposition	High	RMSE about 2.3° at –10 dB SNR (synthetic); under 3° error for a fielded 32-element circular-array system. ^{229,230}
SRP-PHAT	Steered response power with phase transform	High — grid search	Localisation ranges of 40–80 m, the best of three methods tested against GCC-PHAT and differential evolution. ²³¹

MDPI Sensors 20(3):597, University of Valladolid 64-element MEMS array, <https://www.mdpi.com/1424-8220/20/3/597>²²²

Otomo Semiconductor LS8118F UAV acoustic localisation array (vendor), <https://otomosemi.com/pages/uav-acoustic-localization-system>.²²³
ls8118f

University of Stuttgart eLib, 512-element MEMS array rotor aeroacoustics, <https://elib.uni-stuttgart.de/bitstream/11682/15203/1/s13272-023-00680-z.pdf>²²⁴

DREGON project (Inria), drone egonoise and source localisation dataset, <http://dregon.inria.fr/>²²⁵

EURASIP Journal on Wireless Communications and Networking, Classification, positioning and tracking of drones by HMM using acoustic circular microphone array, <https://jwcn-urasipjournals.springeropen.com/articles/10.1186/s13638-019-1632-9>²²⁶

arXiv 2606.29589, EchoHawk acoustic UAS detection pipeline, <https://arxiv.org/pdf/2606.29589>²²⁷

arXiv 2606.29589, EchoHawk acoustic UAS detection pipeline, <https://arxiv.org/pdf/2606.29589>²²⁸

arXiv 2606.29589, EchoHawk acoustic UAS detection pipeline, <https://arxiv.org/pdf/2606.29589>²²⁹

EURASIP Journal on Wireless Communications and Networking, Classification, positioning and tracking of drones by HMM using acoustic circular microphone array, <https://jwcn-urasipjournals.springeropen.com/articles/10.1186/s13638-019-1632-9>²³⁰

TU Delft, comparison of acoustic UAV localisation methods, https://pure.tudelft.nl/ws/portafiles/portal/176937511/full_paper_525_20230331135235478.pdf²³¹

Algorithm	Principle	Compute cost	Reported accuracy in a drone or acoustic context
GCC-PHAT time-difference-of-arrival	Cross-correlation with phase-transform whitening	Low	Elevation error bounded to 3.7° average in a drone identification and localisation study; detection ranges to 100 m. ^{232,233}
Circular array with HMM tracking	Circular-array beamforming plus hidden Markov model tracking	Moderate	Scanning error under 3°; detection about 95% under ideal conditions and above 80% at 2 dB SNR. ²³⁴
Cross-shaped array	Custom four-arm geometry	Moderate	Detected at up to 350 m with 4° average precision; 71.4% localisation accuracy at a 2.0 m tolerance. ²³⁵

The consistent finding is that MVDR and MUSIC outperform delay-and-sum at low signal-to-noise ratio because their narrower main lobes resolve the source against the noise floor, while all methods converge toward sub-degree accuracy at high SNR. Achievable field accuracy for practical circular arrays clusters at 3–10°, with sub-3° reported under favourable SNR on 8- to 32-element geometries. The IEEE Signal Processing Cup 2019 scoring criterion — azimuth and elevation both within 10° of ground truth — is a reasonable reflection of what the field considered a correct localisation.

Allocation. This specification adopts MVDR as the primary estimator with delay-and-sum as a low-cost fallback, and allocates an azimuth accuracy requirement of 5° RMS at 10 dB post-array SNR degrading to 10° RMS at 0 dB. Elevation accuracy is allocated at twice the azimuth figure, reflecting the weaker elevation aperture of a predominantly planar array. [Derived allocation, bounded by the published figures above] The 10° figure is also the community benchmark used as the correctness threshold in the IEEE Signal Processing Cup 2019 localisation task.²³⁶

6.7 Signal processing and classification chain

6.7.1 Acquisition, framing and features

Published systems span 16 kHz sampling for a recurrent detection network, 44.1 kHz for the DREGON dataset, and 96 kHz for a microphone range-test array covering blade-pass frequencies to 2.6 kHz with substantial headroom.^{237 238 239} Framing choices reported include a 512-sample window with 256-sample hop at 16 kHz, and 2048-point transforms with 512 or 1024 hop in mel and MFCC pipelines.^{240 241}

Feature extraction options and their trade-off are well characterised. The mel filterbank maps the linear spectrum into perceptual sub-bands via $\text{mel}(f) = 2595 \cdot \log_{10}(1 + f/700)$, and the log of the summed energy per filter forms

HAL / SPIE 11169-13 (Baron et al.), drone localisation and identification, https://hal.science/hal-02385442/file/proc_SPIE_11169-13_ValentinBaron.pdf²³²

TU Delft, comparison of acoustic UAV localisation methods,²³³
https://pure.tudelft.nl/ws/portafiles/portal/176937511/full_paper_525_20230331135235478.pdf

EURASIP Journal on Wireless Communications and Networking, Classification, positioning and tracking of drones by HMM using acoustic circular microphone array, <https://jwcn-urasipjournals.springeropen.com/articles/10.1186/s13638-019-1632-9>²³⁴

Cross-shaped acoustic array for UAV detection (Semantic Scholar),²³⁵
<https://pdfs.semanticscholar.org/7160/92dd6722854349bf970e19314bc5356d9654.pdf>

IEEE Signal Processing Cup 2019 syllabus and scoring criteria,²³⁶
https://signalprocessingsociety.org/sites/default/files/uploads/get_involved/docs/SPCup%202019%20Document.pdf

Real-time audio detection of UAV drones using GRU and attention mechanism, <https://juyeuav.com/real-time-audio-detection-of-uav-drones-using-gru-and-attention-mechanism/>²³⁷

DREGON project (Inria), drone egonoise and source localisation dataset, <http://dregon.inria.fr/>²³⁸

MDPI Sensors 25(22):7057, outdoor microphone and windscreen range tests for UAS detection, <https://www.mdpi.com/1424-8220/25/22/7057>²³⁹

Real-time audio detection of UAV drones using GRU and attention mechanism, <https://juyeuav.com/real-time-audio-detection-of-uav-drones-using-gru-and-attention-mechanism/>²⁴⁰

HAL hal-04532239, From Sound to Sight, https://hal.science/hal-04532239/file/From_Sound_to_Sight_HAL_Version.pdf²⁴¹

the log-mel spectrogram used directly as network input.²⁴² MFCCs are derived by applying a discrete cosine transform to the log-mel energies, typically with 13–26 static coefficients plus first and second differences.^{243 244} The comparative finding that matters operationally is that MFCCs have strong drone-detection capability but a higher false-alarm rate, while log-mel spectrograms have a lower false-alarm rate but weaker raw detection sensitivity.²⁴⁵ Because false-alarm rate is the binding constraint in a fielded urban deployment, this specification places log-mel as the primary feature with MFCC as a parallel branch, consistent with published dual-branch fusion work.²⁴⁶

6.7.2 Blade-pass frequency extraction

The harmonic product spectrum multiplies frequency-compressed copies of the magnitude spectrum so that energy aligned with the true fundamental and its harmonics reinforces multiplicatively:²⁴⁷

$$\text{HPS}(f) = \text{product over } h=1..H \text{ of } |X(h*f)|$$

$$f_0\text{-hat} = \text{argmax over } f \text{ in } [f_{\text{min}}, f_{\text{max}}] \text{ of } \text{HPS}(f)$$

A synthetic validation with a true fundamental of 110 Hz returned an estimate of 109 Hz.²⁴⁸ A log-domain formulation, $f_0 = \text{argmax over } f \text{ of the sum over } k \text{ of } \log_{10}|X(k*f)|$, was used in a direction-of-arrival study that applies pitch-tracked harmonic bins to focus energy-based direction decisions, reporting accurate blade-pass estimation down to –14 dB SNR for the harmonic product spectrum and –16 dB SNR for a related spectral harmonic correlation method with a 2048-point transform.²⁴⁹ Cepstral pitch tracking operates in the log-spectral domain and is referenced alongside the harmonic product spectrum in the same pipeline.²⁵⁰ Extracting the fundamental at –14 dB SNR is a materially stronger result than detecting the aircraft at 0 dB SNR, and it is the reason the processing chain is built around harmonic structure rather than broadband energy.

Table 6-14 — Recommended processing chain parameters (all values derived)

Parameter	Allocated value	Rationale
Sampling rate	48 kHz, 24-bit	Covers the tonal band to 2.6 kHz with large headroom and the harmonic band to 8 kHz comfortably; 24-bit accommodates the 95 dB element dynamic range without gain ranging. [Derived]
Anti-alias filtering	Integral to the digital MEMS decimation chain	Digital PDM-to-PCM decimation provides the anti-alias response; no analogue filter design is required. [Derived]
Transform size and hop	2048-point, 512-sample hop	Gives 23.4 Hz bin spacing at 48 kHz, sufficient to resolve blade-pass harmonics but not the 2–13 Hz Doppler shift; a parallel 16384-point branch is specified for Doppler estimation. [Derived]
Doppler branch	16384-point transform, 0.34 s window	Gives 2.9 Hz bin spacing, at the edge of resolving the smallest expected shift. [Derived]
Window	Hann or Hamming	Standard practice in the cited pipelines; sidelobe suppression matters because the harmonic series must be resolved against adjacent bins. [Derived]

arXiv 2606.29589, EchoHawk acoustic UAS detection pipeline, <https://arxiv.org/pdf/2606.29589>²⁴²

IJEETC 15(4):267, MFCC-based drone acoustic analysis, <https://www.ijeetc.com/vol15/IJEETC-V15N4-267.pdf>²⁴³

PMC11054550, RF and acoustic fusion for drone detection, <https://pmc.ncbi.nlm.nih.gov/articles/PMC11054550/>²⁴⁴

SCITEPRESS, How Far Can a Drone Be Detected? A Drone Detection Study, <https://www.scitepress.org/Papers/2023/117910/117910.pdf>²⁴⁵

Springer Multimedia Tools and Applications, log-mel and MFCC dual-branch fusion for drone sound detection,²⁴⁶
<https://link.springer.com/article/10.1007/s11042-022-12964-3>

arXiv 2606.29589, EchoHawk acoustic UAS detection pipeline, <https://arxiv.org/pdf/2606.29589>²⁴⁷

arXiv 2606.29589, EchoHawk acoustic UAS detection pipeline, <https://arxiv.org/pdf/2606.29589>²⁴⁸

PMC9182957, Acoustic Estimation of Direction of Arrival with harmonic pitch tracking, <https://pmc.ncbi.nlm.nih.gov/articles/PMC9182957/>²⁴⁹

PMC9182957, Acoustic Estimation of Direction of Arrival with harmonic pitch tracking, <https://pmc.ncbi.nlm.nih.gov/articles/PMC9182957/>²⁵⁰

Parameter	Allocated value	Rationale
Primary features	Log-mel spectrogram, 64 bands, 50 Hz – 8 kHz	Lower false-alarm rate than MFCC, which is the binding constraint in urban deployment. [Derived]
Secondary features	20 MFCCs plus deltas, and harmonic-product-spectrum fundamental estimate with confidence	Dual-branch fusion of complementary features, plus an explicit physical feature the classifier cannot learn away. [Derived]
Classifier	Convolutional or convolutional-recurrent network with attention	Consistent with the strongest published results; must be retrainable on site-specific negatives. [Derived]

6.7.3 Published classification performance

Table 6-15 — Published acoustic classification results

System or model	Task	Reported result	Note
Self-organising-map / convolutional classifier	Drone detection over a 150–500 m range test	96.3% average accuracy	Field test, not laboratory only — one of the more credible figures in this table. ²⁵¹
Conventional beamforming with supervised learning	Drone identification, two-class and one-class	99.5% and 95.6%	Also reported 3.7° average elevation localisation error on the same dataset. ²⁵²
AcousticPrint	Drone make and model identification	94% closed-set, 80% open-set	The 14-point closed-to-open-set drop is the key result, not the headline accuracy. ²⁵³
Convolutional network	UAV detection and identification	97.13% detection, 93.25% identification	Public acoustic drone dataset. ²⁵⁴
Conformer architectures (CNN / CRNN / RNN)	Drone acoustic classification	98% / 97% / 88%	Custom dataset. ²⁵⁵
Log-mel and MFCC dual-branch fusion	Drone sound detection	94.5%	Improved on single-feature baselines — the basis for the dual-branch allocation above. ²⁵⁶
Recurrent architectures (LSTM best)	UAV detection and identification	+4% detection, +5% identification over prior CRNN and CNN	Public drone acoustic dataset benchmark. ²⁵⁷
Fused spectral, temporal and latent features	Binary and multiclass drone recognition	99.92% synthetic; 98.51% real binary, F1 0.9837	The synthetic-versus-real gap is instructive. ²⁵⁸

PMC7506852, Development of an Acoustic System for UAV Detection, <https://pmc.ncbi.nlm.nih.gov/articles/PMC7506852/>²⁵¹

HAL / SPIE 11169-13 (Baron et al.), drone localisation and identification, https://hal.science/hal-02385442/file/proc_SPIE_11169-13_ValentinBaron.pdf²⁵²

WiSec 2020, AcousticPrint — acoustic fingerprinting of drones, <https://wisec2020.ins.jku.at/proceedings/wisec20-5.pdf>²⁵³

Frontiers in Communications and Networks (2024), acoustic UAV detection and identification, <https://www.frontiersin.org/journals/communications-and-networks/articles/10.3389/frcmn.2024.1440727/full>²⁵⁴

JISIS 2025.I2.046, conformer architectures for drone acoustic classification, <https://jisis.org/wp-content/uploads/2025/07/2025.I2.046.pdf>²⁵⁵

Springer Multimedia Tools and Applications, log-mel and MFCC dual-branch fusion for drone sound detection, <https://link.springer.com/article/10.1007/s11042-022-12964-3>²⁵⁶

PUCPR SecPLab, benchmarking recurrent architectures for UAV acoustic detection, <https://secplab.ppgia.pucpr.br/files/papers/2022cps.pdf>²⁵⁷

arXiv 2512.20407, AUDRON fused-feature drone recognition, <https://arxiv.org/html/2512.20407v1>²⁵⁸

System or model	Task	Reported result	Note
Recurrent models on mel spectrograms	Loaded, unloaded and background discrimination	98% best, per-class precision/recall/F1 96–100%	Payload-state discrimination — a finer-grained task than presence detection. ²⁵⁹
Attention CRNN on ESC-50	General environmental sound, as a false-positive context	State of the art on ESC-10 and ESC-50	Critically, the Helicopter class is only 52.5% recognised and is frequently confused with Airplane — direct evidence that acoustically similar rotorcraft classes are a persistent confusion pair even for strong models. ²⁶⁰
Convolutional networks on ESC-50	General environmental sound	82.1–86.4%; 63% rising to 90% with augmentation	Establishes the realistic ceiling for the background-rejection task and the large value of augmentation. ²⁶¹

How to read this table. These accuracies are dataset-bound, and most are reported on curated datasets with favourable signal-to-noise ratio. Field performance will be lower, sometimes substantially. The figures SHALL NOT be used as acceptance criteria; the acceptance criteria in Section 10 are derived from operational requirements and must be demonstrated by field trial on the delivered system. The two most operationally informative numbers in the table are the ones that are not headline accuracies: the 14-point closed-to-open-set drop, and the 52.5% helicopter recognition rate with airplane confusion.

6.8 Wind and self-noise mitigation

Wind is the single largest field-condition confound for this subsystem. Field-quantified results from a 2025 outdoor range-test study directly comparing microphone and windscreen combinations give the most usable numbers: a directional microphone with a windshield extended detection range over the bare microphone by roughly 31–131% depending on azimuth under strong wind, lowered the low-frequency noise floor by 2–3 dB, and matched or improved wideband signal-to-noise ratio by 1.8–4.4 dB.²⁶² Under high-wind conditions the windshield extended detection range from 34.8 m to 45.6 m, a 31% improvement. Directional microphones with windshields, and a parabolic configuration, achieved the best combination of mean signal-to-noise ratio at roughly 10–11 dB and the longest detection ranges at roughly 85–95 m across all wind conditions tested.²⁶³ Separately, windscreens are reported to provide up to about 7 dB of turbulence-noise reduction in general acoustic monitoring, rising to about 10 dB in the infrasound range under moderate wind near 15 km/h.²⁶⁴

Note the absolute ranges in that study. The 34.8 m to 95 m figures are an order of magnitude below the 100–500 m envelope of Section 6.3, because they were measured under strong wind. This is the clearest available evidence that wind, not source level or array gain, sets the achievable range in adverse conditions, and it is why an operating wind limit must be declared rather than hidden.

- **Element spacing as wind mitigation.** Wind-induced pressure fluctuations are spatially correlated only over short distances, so wider element spacing decorrelates wind noise across the array while the acoustic signal remains coherent. This can be exploited by differential or adaptive combination, subject to the spatial Nyquist constraint of Section 6.5.2. The outer non-uniform ring of the reference design serves this purpose as well as its aperture purpose. [Derived]

MDPI Drones 7(1):26, RNN drone sound detection including payload state, https://www.mdpi.com/2504-446X/7/1/26?type=check_update&version=1²⁵⁹

ar5iv 1907.02230, attention CRNN for environmental sound classification, <https://ar5iv.labs.arxiv.org/html/1907.02230>²⁶⁰

MDPI Sensors 21(16):5500, CNN sub-spectrogram methods on ESC-50, <https://www.mdpi.com/1424-8220/21/16/5500>²⁶¹

MDPI Sensors 25(22):7057, outdoor microphone and windscreen range tests for UAS detection, <https://www.mdpi.com/1424-8220/25/22/7057>²⁶²

MDPI Sensors 25(22):7057, outdoor microphone and windscreen range tests for UAS detection, <https://www.mdpi.com/1424-8220/25/22/7057>²⁶³

Euracoustics FA2025, wind filter arrays for outdoor acoustic monitoring, <https://dael.euracoustics.org/confs/fa2025/data/articles/000141.pdf>²⁶⁴

- **Differential and adaptive processing.** Differential beamforming toward multiple principal directions enhances initial detection without corrupting the spectral signature; a differential configuration is documented achieving roughly 6 dB of uncorrelated noise reduction with acceptable bias error, under 0.5 dB at 10 kHz for 0.5 cm spacing.²⁶⁵ Robust generalised-sidelobe-canceller architectures combined with deep networks have been used to handle rotor ego-noise and extract target signals at signal-to-noise ratios down to -30 dB.²⁶⁶
- **Augmentation-trained classifiers.** A published model benchmark against real wind clips illustrates the performance cliff precisely: recall and F1 remain at or above 0.996 and 0.998 down to 0 dB signal-to-noise ratio for an augmentation-trained model, but recall drops to roughly 86–89% once wind is 1.8 times louder than the drone signal, below -5 dB; a non-augmented baseline collapses entirely at 0 dB, with F1 of 0.353.²⁶⁷ This is one model's benchmark rather than a physical law, but it establishes both how steep the cliff is and how much noise-augmented training mitigates it.

Declared operating limit. The specification requires the supplier to declare a wind-speed limit above which acoustic detection performance is not guaranteed, and to report measured wind speed alongside every acoustic detection so that fusion can down-weight acoustic evidence automatically in high wind. Based on the evidence above, a declared limit in the region of 8–10 m/s at the array is realistic for a windshielded design. [Derived allocation]

6.9 Platform-signature classification feasibility

Identification of make and model from acoustic signature alone is demonstrably possible but degrades sharply outside a known set. AcousticPrint achieved 94% accuracy in a closed-set scenario and 80% in the open-set case using the combined signature from propellers, motor and mechanical body vibration.²⁶⁸ A beamforming-based identification study achieved 99.5% two-class and 95.6% one-class accuracy on its own array dataset.²⁶⁹ Payload state — loaded versus unloaded, a finer-grained variant of type classification based on rotor loading — was discriminated at 96–98% accuracy across several recurrent variants.²⁷⁰ The physical basis is the harmonic structure itself: different airframes use different propeller diameters, blade counts and rotor-speed ranges, producing distinct fundamentals and harmonic decay profiles, and measurements show measurably different overall level, directivity and harmonic loading-noise contributions even among superficially similar small propellers.²⁷¹

Allocation. Given the demonstrated 80–99% range of published closed- and open-set accuracies and the requirement for a labelled reference library of known-platform fingerprints, the subsystem SHALL be expected to distinguish drone from non-drone and broad size or class categories with high confidence, while fine-grained make and model identification against unseen or lightly modified platforms SHALL be reported as a secondary, lower-confidence cue rather than a primary output — consistent with the 14 to 20 percentage-point accuracy drop from closed-set to open-set conditions. [Derived allocation]

HAL hal-02088346, source localisation and identification with a compact array, <https://hal.science/hal-02088346v1/document>²⁶⁵

arXiv 2508.06310, egonoise-resilient source localisation with GSC and deep networks, <https://arxiv.org/pdf/2508.06310>²⁶⁶

Hugging Face, AntoineNaccache/drone-audio-detector model card and wind-noise benchmark, ²⁶⁷
<https://huggingface.co/AntoineNaccache/drone-audio-detector>

WiSec 2020, AcousticPrint — acoustic fingerprinting of drones, <https://wisec2020.ins.jku.at/proceedings/wisec20-5.pdf>²⁶⁸

HAL / SPIE 11169-13 (Baron et al.), drone localisation and identification, https://hal.science/hal-02385442/file/proc_SPIE_11169-13_ValentinBaron.pdf²⁶⁹

MDPI Drones 7(1):26, RNN drone sound detection including payload state, https://www.mdpi.com/2504-446X/7/1/26?type=check_update&version=1²⁷⁰

Embry-Riddle Aeronautical University, Aerodynamic and Aeroacoustic Performance of Small UAV Propellers, ²⁷¹
<https://portfolio.erau.edu/ws/portalfiles/portal/39867521/Aerodynamic%20and%20Aeroacoustic%20Performance%20of%20Small%20UAV%20Propellers.pdf>

6.10 Acoustic subsystem requirements

Table 6-16 — Acoustic sensor array subsystem requirements

ID	Requirement	Verification
REQ-AC-010	The array SHALL detect and report tonal content in the 100 Hz to 8 kHz band, with the 100–300 Hz fundamental band and the first four harmonics as the primary detection target.	Bench Test
REQ-AC-011	The array SHALL comprise at least 16 elements, and the reference configuration SHALL comprise 24 elements in a nested two-aperture geometry.	Inspection
REQ-AC-012	Element spacing in the inner sub-aperture SHALL satisfy the spatial Nyquist condition $d \leq c/(2 \cdot f_{\text{max}})$ for the highest frequency that sub-aperture is used to beamform.	Analysis
REQ-AC-013	The outer sub-aperture SHALL use non-uniform element spacing, to avoid the periodic grating-lobe structure of a uniformly spaced aperture at that spacing.	Inspection
REQ-AC-014	All channels SHALL be sampled synchronously from a single clock domain at not less than 48 kHz and not less than 24-bit resolution.	Bench Test
REQ-AC-015	The processing chain SHALL extract the blade-pass fundamental using a harmonic-structure method, and SHALL report the estimate with a confidence value, independently of the learned classifier output.	Bench Test
REQ-AC-016	The classifier SHALL use log-mel features as its primary input, and SHOULD fuse a parallel MFCC branch.	Inspection
REQ-AC-017	The classifier SHALL be trainable and retrainable on site-specific negative examples collected at the deployed location, and the retraining process SHALL be documented and repeatable.	Field Trial
REQ-AC-018	The subsystem SHALL provide azimuth bearing with an accuracy of $\leq 5^\circ$ RMS at 10 dB post-array signal-to-noise ratio and $\leq 10^\circ$ RMS at 0 dB.	Field Trial
REQ-AC-019	The subsystem SHOULD provide elevation, and where provided the accuracy requirement SHALL be twice the corresponding azimuth figure.	Field Trial
REQ-AC-020	Direction-finding SHALL be performed on harmonic content matched to the available aperture, and SHALL NOT rely on the fundamental alone where the aperture is under 2 m.	Analysis
REQ-AC-021	The primary direction-of-arrival estimator SHALL be an adaptive method such as MVDR, with delay-and-sum available as a reduced-capability fallback on processor overload.	Bench Test
REQ-AC-022	Every element SHALL be fitted with a windscreen appropriate to the declared operating wind limit.	Inspection
REQ-AC-023	The node SHALL measure wind speed at the array and SHALL report it with every detection, so that fusion can down-weight acoustic evidence in high wind automatically.	Bench Test
REQ-AC-024	The supplier SHALL declare the wind speed above which detection performance is not guaranteed, and SHALL demonstrate performance at and below that limit by field trial.	Field Trial
REQ-AC-025	The subsystem SHALL report Doppler-derived radial velocity where the target motion and integration time permit, as a supplementary observable.	Bench Test
REQ-AC-026	The subsystem SHALL classify drone versus non-drone and broad size class as primary outputs, and MAY report make or model as an explicitly lower-confidence secondary output.	Field Trial
REQ-AC-027	The subsystem SHALL be characterised against the rotorcraft and fixed-wing aircraft confusion classes, and the measured confusion rate against those classes SHALL be reported.	Field Trial
REQ-AC-028	All beamforming, feature extraction and classification SHALL execute at the node. Multi-channel raw audio SHALL NOT be streamed over the backhaul in normal operation.	Inspection

ID	Requirement	Verification
REQ-AC-029	Continuous audio recording to persistent storage SHALL be disabled by default, and any recording capability SHALL be subject to the privacy controls of Section 12.	Inspection
REQ-AC-030	Declared detection ranges SHALL be established by field trial in the deployment environment. Derived budget figures SHALL NOT be published as specifications.	Field Trial
REQ-AC-031	The subsystem SHALL report a per-detection signal-to-noise ratio estimate and the measured ambient level in the detection band, to allow fusion to weight the evidence and to allow post-incident analysis of missed detections.	Bench Test

7 Data Fusion, Tracking and Classification

This section specifies how the three sensing modalities of Sections 4 to 6 are combined into a single track picture with a calibrated confidence value. The design premise is that no individual modality in this system is adequate alone: RF detection has range but is defeated by radio silence, LTE monitoring is narrow and applies only to cellular-piloted aircraft, and the acoustic array is independent of emissions but short-ranged and weather-sensitive. Fusion is therefore not an optimisation layer bolted onto three good sensors; it is the mechanism by which three individually inadequate sensors become an adequate system.

7.1 Fusion architecture

7.1.1 Reference model

The architecture is described against the JDL data fusion model, originally published as a four-level model by the Joint Directors of Laboratories Data Fusion Subpanel of the US Department of Defense in 1985, substantially revised in the 1990s and extended in 2004 by Blasch, Bosse and Lambert into a six-level model adding sub-object assessment at Level 0 and user refinement at Level 5.²⁷² The Cranfield University review attributes the framework to the same JDL sub-panel and cites the level definitions of Llinas and Hall.²⁷³ The model is explicitly a conceptual taxonomy rather than a software architecture specification, and different implementations place level boundaries differently;²⁷⁴ it is also criticised in the literature for implying strictly sequential levels and for inadequately representing the human in the loop, which the DFIG extension attempts to address.²⁷⁵ It is used here as a common vocabulary for allocating function, not as a mandated processing order.

Table 7-1 — JDL/DFIG fusion levels mapped to this system

Level	JDL/DFIG designation	Allocation in this system
0	Source pre-processing / sub-object data assessment	Executes at the sensor node. RF channelisation and energy or feature detection (Section 4), LTE off-air signalling decode (Section 5), acoustic beamforming and blade-pass extraction (Section 6). Output is a structured detection with an explicit measurement uncertainty. ²⁷⁶
1	Object assessment / object refinement	Split between node and central fusion. Decomposed by Llinas and Hall into data alignment, data association, object state estimation and object identity — which map onto Section 7.2, Section 7.3, Section 7.4 and Section 7.6 respectively. ²⁷⁷
2	Situation assessment	Executes centrally. Relates each track to protected volumes, approach corridors and declared airspace status (Section 9).
3	Impact / threat assessment	Executes centrally. Forward-projects the track to estimate closest point of approach and time to a protected volume (Section 7.6.4).
4	Process refinement / resource management	Executes centrally. Monitors fusion quality and re-tasks sensors — narrowing RF dwell to a suspected band, or cueing a node into a higher-rate acoustic mode on a bearing.

Corvus Intelligence, JDL data fusion model — levels and implementation, <https://corvusintell.com/blog/data-integration/jdl-data-fusion-model/>²⁷²

Cranfield University, A Review of Data Fusion Models and Architectures, <https://dspace.lib.cranfield.ac.uk/bitstreams/71a21f06-2427-418b-b649-00182f576009/download>²⁷³

Corvus Intelligence, JDL data fusion model — levels and implementation, <https://corvusintell.com/blog/data-integration/jdl-data-fusion-model/>²⁷⁴

Wikipedia, Data fusion — JDL/DFIG level summary, https://en.wikipedia.org/wiki/Data_fusion²⁷⁵

Corvus Intelligence, JDL data fusion model — levels and implementation, <https://corvusintell.com/blog/data-integration/jdl-data-fusion-model/>²⁷⁶

Cranfield University, A Review of Data Fusion Models and Architectures, <https://dspace.lib.cranfield.ac.uk/bitstreams/71a21f06-2427-418b-b649-00182f576009/download>²⁷⁷

Level	JDL/DFIG designation	Allocation in this system
5	User refinement	Operator interaction. Added in the 2004 revision to model how operator queries and attention shape and are shaped by the fused picture. ²⁷⁸

7.1.2 Where fusion occurs

- **Signal or data level.** Raw or minimally processed samples are combined before feature extraction — for example raw IQ from co-located RF receivers, or raw microphone waveforms within one acoustic array. Preserves maximum information but demands the tightest registration and the highest inter-node bandwidth. In this design it is used only within a single node, never between nodes.
- **Feature level.** Each sensor emits a feature vector — RF modulation class, centre frequency, bandwidth and hop pattern; acoustic log-mel and MFCC features; LTE reference-signal received power, received signal strength, signal-to-interference-plus-noise ratio and cell-report counts — and features are combined before a joint estimation or classification step. Used within a node across its own sub-sensors.
- **Decision level.** Each sensor chain reaches an independent local decision and a fusion rule combines the decisions. This is the most bandwidth-efficient and the most tolerant of heterogeneous asynchronous sensors, which is why most fielded multi-sensor counter-UAS systems fuse RF, radar, acoustic and electro-optical evidence at decision level with cross-cueing.²⁷⁹ Used between nodes and at the central fusion function.

7.1.3 Topology

Table 7-2 — Fusion topology trade-off

Topology	Description	Assessment for this system
Centralised	All measurements are transmitted to a single fusion centre which performs association and estimation jointly over the complete measurement set.	Information-theoretically optimal when the models are correct, and the achievable bound against which any distributed scheme is measured. Rejected as the primary architecture: it requires high backhaul bandwidth and creates a single point of failure.
Distributed / decentralised	Each node runs its own tracker and transmits only track summaries — state estimate plus covariance.	Far more bandwidth-efficient and fault-tolerant. Generally sub-optimal unless track-to-track correlation is accounted for, which is the subject of Section 7.1.4.
Hierarchical / hybrid	Signal-level fusion inside a co-located RF array, feature-level fusion inside an acoustic array, and decision or track-level fusion across modalities at a central node.	Selected. The three modalities have fundamentally different native rates, latencies and detection geometries — RF and LTE report at radio-frame timescales with bearing or received-signal-strength measurements, acoustic arrays at audio-frame timescales with bearing or time-difference measurements — which makes raw signal-level fusion across modalities impractical and makes feature- or track-level fusion at a central node the natural integration point.

7.1.4 Track-to-track fusion and the cross-covariance problem

Where each subsystem maintains its own local track and only summaries are exchanged, combining two local estimates of the same target is the track-to-track fusion problem. The foundational treatment is Bar-Shalom's

Corvus Intelligence, JDL data fusion model — levels and implementation, <https://corvusintell.com/blog/data-integration/jdl-data-fusion-model/>²⁷⁸

counteruavradar.com, How Radar Distinguishes Drones from Birds, <https://www.counteruavradar.com/en/knowledge-base/how-radar-distinguishes-drones-from-birds/>²⁷⁹

1981 paper on track-to-track correlation,²⁸⁰ extended with Campo into the two-sensor formulas that remain the standard reference and further generalised to the multi-sensor case.²⁸¹

The trap. Two local tracks of the same target are not statistically independent, because both trackers observe correlated process noise — the same target dynamics — even when their measurement noises are independent. Combining them as if independent underestimates the fused covariance and produces an overconfident estimate. This failure mode is silent: the fused track looks better than it is, and the resulting optimistic covariance then corrupts the gating decisions of Section 7.3. Correct fusion requires the cross-covariance between the two local track errors.

For two sensors with local estimates x_1 , x_2 , error covariances P_1 , P_2 and cross-covariance P_{12} , the optimal memoryless track-to-track fusion is the Bar-Shalom/Campo formula:²⁸²

$$x_c = x_1 + [P_1 - P_{12}] * [P_1 + P_2 - P_{12} - P_{21}]^{-1} * [x_2 - x_1]$$

with P_{21} the transpose of P_{12} . Generalised to L sensors, with m the stacked vector of local estimates, J the block joint-covariance matrix whose (i,j) block is the cross-covariance of estimates i and j , and H a stack of identity blocks mapping each local state into the common fused state space:²⁸³

$$P = [H^T * J^{-1} * H]^{-1} \quad x = P * H^T * J^{-1} * m$$

Where the cross-covariance is unavailable — the normal case in a loosely coupled, bandwidth-constrained architecture in which nodes do not share raw measurement histories — two standard remedies apply. Maximum-likelihood fusion simply ignores the cross-term, which is acceptable when process-noise correlation is small relative to measurement noise; for N sensors, with I a stacking matrix of identity blocks:²⁸⁴

$$x_{ML} = (I^T * P^{-1} * I)^{-1} * I^T * P^{-1} * X \quad P_{dis} = (I^T * P^{-1} * I)^{-1}$$

This distributed fuser has strictly larger error than the optimal centralised estimator, which quantifies the accuracy cost of decentralisation and provides the metric by which the architecture choice of Table 7-2 should be audited during acceptance.²⁸⁵ The alternative is covariance intersection, which provides a consistent — that is, never overconfident — fused estimate without requiring the true cross-covariance, at the cost of conservatism; it was proposed by Julier and Uhlmann and is the standard robust choice when the cross-covariance is unknown.²⁸⁶ This specification requires covariance intersection as the default and permits the Bar-Shalom/Campo or maximum-likelihood forms only where the cross-covariance is computed or the correlation is demonstrated to be negligible. An overconfident track is more dangerous than a conservative one, because it silently corrupts every downstream gate and threat calculation.

Track-to-track association. Deciding whether an RF bearing track and an acoustic bearing track represent the same physical object, before fusing them, uses the same chi-square gating logic as measurement-to-track association in Section 7.3, applied to the difference of the two state vectors, with the sum of their covariances — less twice the cross-covariance where known — as the test covariance.

Solmaz Kia (UC Irvine), A Track-to-Track Fusion Method for Tracks with Unknown Correlations, ²⁸⁰
https://solmaz.eng.uci.edu/Papers/L_CSS_Mahboubbeh.pdf

Karlsruhe Institute of Technology, Radtke et al., Comparative Study of Track-to-Track Fusion Methods (MFI 2019), ²⁸¹
https://isas.iar.kit.edu/pdf/MFI19_Radtke.pdf

ISIF Journal of Advances in Information Fusion, Tian & Bar-Shalom, Track-to-Track Fusion Configurations and Association in a Sliding Window, ²⁸²
https://isif.org/files/isif/2024-01/JAIF_article_tracktotrack.pdf

Karlsruhe Institute of Technology, Radtke et al., Comparative Study of Track-to-Track Fusion Methods (MFI 2019), ²⁸³
https://isas.iar.kit.edu/pdf/MFI19_Radtke.pdf

Chen, Kirubarajan & Bar-Shalom, Performance Limits of Track-to-Track Fusion versus Centralized Estimation, ²⁸⁴
<https://scispace.com/pdf/performance-limits-of-track-to-track-fusion-versus-ywrnppalvr.pdf>

Chen, Kirubarajan & Bar-Shalom, Performance Limits of Track-to-Track Fusion versus Centralized Estimation, ²⁸⁵
<https://scispace.com/pdf/performance-limits-of-track-to-track-fusion-versus-ywrnppalvr.pdf>

EURASIP Journal on Advances in Signal Processing, A robust fusion estimation with unknown cross-covariance in distributed systems, ²⁸⁶
<https://asp-eurasipjournals.springeropen.com/articles/10.1186/s13634-019-0640-6>

7.2 Time and space alignment

Fusion across RF, LTE and acoustic subsystems is valid only if all sensors report on a common time base and in a common spatial frame. Errors in either become errors in the fused position and velocity directly, and — worse — appear as apparently well-formed tracks in the wrong place rather than as obvious faults.

Table 7-3 — Timing synchronisation technologies and accuracy

Technology	Typical accuracy	Note
NTP	1–10 ms	Adequate for logging and for event correlation, but not for any time-difference-of-arrival function. ²⁸⁷
IRIG time code	1–10 μ s	Legacy interface; adequate for acoustic time-difference work. ²⁸⁸
Software-only PTP (IEEE 1588)	$\approx$ 100 μ s on a single link	Software timestamping is the limiting factor, not the protocol. ²⁸⁹
Hardware-timestamped PTP / 1588v2	20–100 ns typical; sub-10 ns achievable	A measured 7.9 ns standard deviation and –869 ps mean offset over a single link with precision PHY hardware. ²⁹⁰²⁹¹
PTP with boundary or transparent clocks	20–100 ns	Multi-hop performance depends on clock support at every intermediate switch. ²⁹²
IEEE 1588v2 transparent clocks, best case	better than 1 ns	Best-case figure from the working-group summary. ²⁹³
White Rabbit (PTP plus Synchronous Ethernet)	sub-nanosecond, picosecond jitter	Demonstrated across networks spanning tens to hundreds of kilometres with more than 1000 nodes. ²⁹⁴²⁹⁵
GNSS-disciplined oscillator	$\approx$ 30 ns RMS or better to UTC	The pragmatic choice for geographically dispersed nodes with no synchronous network path. ²⁹⁶

White Rabbit, developed at CERN and GSI for the LHC and FAIR accelerator complexes, combines IEEE 1588 with Synchronous Ethernet physical-layer clock recovery and hardware timestamping to achieve deterministic

Microchip / Syncworks white paper, IEEE 1588 PTP: The New Standard in Time Synchronization, https://syncworks.com/wp-content/uploads/2025/06/Microchip_IEEE_1588_PTP_New_Standard_in_Time_Synchronization_White_Paper.pdf²⁸⁷

Microchip / Syncworks white paper, IEEE 1588 PTP: The New Standard in Time Synchronization, https://syncworks.com/wp-content/uploads/2025/06/Microchip_IEEE_1588_PTP_New_Standard_in_Time_Synchronization_White_Paper.pdf²⁸⁸

Texas Instruments Application Note AN-1728, IEEE 1588 Precision Time Protocol Time Synchronization, <https://www.ti.com/lit/pdf/snla098>²⁸⁹

Microchip / Syncworks white paper, IEEE 1588 PTP: The New Standard in Time Synchronization, https://syncworks.com/wp-content/uploads/2025/06/Microchip_IEEE_1588_PTP_New_Standard_in_Time_Synchronization_White_Paper.pdf²⁹⁰

Texas Instruments Application Note AN-1728, IEEE 1588 Precision Time Protocol Time Synchronization, <https://www.ti.com/lit/pdf/snla098>²⁹¹

Microchip / Syncworks white paper, IEEE 1588 PTP: The New Standard in Time Synchronization, https://syncworks.com/wp-content/uploads/2025/06/Microchip_IEEE_1588_PTP_New_Standard_in_Time_Synchronization_White_Paper.pdf²⁹²

IEEE 802.1 working group, IEEE 1588 Version 2 summary, <https://www.ieee802.org/1/files/public/docs2008/as-garner-1588v2-summary-0908.pdf>²⁹³

CERN, White Rabbit: Sub-Nanosecond Timing over Ethernet, <https://indico.cern.ch/event/143656/papers/1378076/files/1031-WHITE.pdf>²⁹⁴

ARMMS RF & Microwave Society, An Introduction to White Rabbit, <https://www.armms.org/media/uploads/sub-nanosecond-network-synchronisation---an-intro.pdf>²⁹⁵

Microchip / Syncworks white paper, IEEE 1588 PTP: The New Standard in Time Synchronization, https://syncworks.com/wp-content/uploads/2025/06/Microchip_IEEE_1588_PTP_New_Standard_in_Time_Synchronization_White_Paper.pdf²⁹⁶

sub-nanosecond synchronisation, and its extensions were folded into the IEEE 1588-2019 revision as the High-Accuracy Delay Request-Response Default PTP Profile.^{297 298}

7.2.1 Derivation of the timing requirement

Time-difference-of-arrival localisation estimates a source position from arrival-time differences of a common wavefront. For a sensor pair the range-difference measurement and the propagation of a clock error into it are:

$$\Delta r = c * \Delta t \quad \text{error: } d(\Delta r) = c * dt$$

To first order in a well-conditioned multilateration geometry the position error is comparable, giving the required synchronisation accuracy for a target error budget:

$$dt_{\text{required}} = dx / c$$

Step 1 — Acoustic, $c = 343$ m/s, for 1 m localisation error: $dt = 1/343 = 2915 \mu\text{s}$, i.e. about 2.9 ms. For 0.1 m: 292 μs . [Derived]

Step 2 — Inverted: 1 μs of clock error yields 0.3 mm of acoustic range-difference error; 10 μs yields 3.4 mm; 100 μs yields 34 mm. [Derived]

Step 3 — RF, $c = 2.998 \times 10^8$ m/s, for 1 m localisation error: $dt = 3.34$ ns. For 0.5 m: 1.67 ns. For 0.1 m: 0.33 ns. [Derived]

Step 4 — Inverted: 1 ns of clock error yields 0.30 m of RF error; 10 ns yields 3.0 m; 100 ns yields 30.0 m. [Derived]

Step 5 — The ratio of requirements is about 875,000 to 1, the ratio of the speed of light to the speed of sound. RF time-difference localisation therefore needs roughly three orders of magnitude tighter synchronisation than acoustic for the same position error. [Derived]

Design consequences. Acoustic time-difference arrays need only microsecond-level synchronisation to achieve sub-decimetre range-difference accuracy, comfortably met by a GNSS-disciplined oscillator or by network PTP. The dominant error source in fielded acoustic geolocation is therefore not clock synchronisation but uncertainty in the actual speed of sound under wind and temperature gradients, together with microphone-position calibration error. Conversely, hardware-timestamped PTP at 20–100 ns gives roughly 6 to 30 m of RF time-difference error, which is marginal for precision RF geolocation, so any RF time-difference baseline requiring better than about 10 m must be served by a White-Rabbit-class or GNSS-disciplined-oscillator-class source.^{299 300} The practical outcome for this architecture is that a common PTP grandmaster can serve both subsystems without compromising acoustic performance, provided the RF receivers are hardware-timestamped rather than software-timestamped PTP clients.

7.2.2 Coordinate frames and registration

Two frames are relevant. WGS84 — latitude, longitude and ellipsoidal height — is the global geodetic frame used by GNSS and for absolute-position reporting. ENU — East, North, Up — is a local tangent-plane Cartesian frame centred on the site, which avoids the nonlinearity of geodetic coordinates over short baselines and is therefore the working frame for filtering and covariance propagation. The pipeline converts each native measurement — RF or LTE bearing or received-signal-strength range estimate, acoustic bearing or time-difference-derived position — into ENU relative to a common site origin, propagates the measurement covariance through the corresponding Jacobian, performs association and estimation in ENU, and converts back to WGS84 for reporting.

Sensor registration is the estimation and correction of systematic bias between sensors — residual boresight misalignment in a direction-finding antenna, clock bias between subsystems, or geometric calibration error in an

CERN Ventureconnect, White Rabbit, <https://ventureconnect.cern/white-rabbit/>²⁹⁷

CERN, White Rabbit: Sub-Nanosecond Timing over Ethernet, <https://indico.cern.ch/event/143656/papers/1378076/files/1031-WHITE.pdf>²⁹⁸

Microchip / Syncworks white paper, IEEE 1588 PTP: The New Standard in Time Synchronization, https://syncworks.com/wp-content/uploads/2025/06/Microchip_IEEE_1588_PTP_New_Standard_in_Time_Synchronization_White_Paper.pdf²⁹⁹

CERN, White Rabbit: Sub-Nanosecond Timing over Ethernet, <https://indico.cern.ch/event/143656/papers/1378076/files/1031-WHITE.pdf>³⁰⁰

acoustic array — so that tracks of the same target agree in the common frame. Unregistered bias is a classical source of ghost tracks and systematically offset fused tracks, which is why bias and registration terms are explicit in the JDL Level 1 data-alignment step.³⁰¹ In practice registration bias is estimated online by comparing tracks of common, often opportunistic and cooperative targets seen simultaneously by two sensors, and solving a least-squares or Kalman bias-estimation problem for the angular, range and clock offsets that best reconcile the two reports.

7.3 Association and gating

7.3.1 Chi-square gating

Before a measurement updates a track it is tested against a validation gate. The squared Mahalanobis distance of the innovation is:³⁰²

$$d2 = (z - \hat{z})^T S^{-1} (z - \hat{z})$$

where z is the measurement, $\hat{z}$ the predicted measurement and S the innovation covariance. For Gaussian innovations $d2$ is chi-square distributed with degrees of freedom equal to the measurement dimension m , so the gate threshold must be taken as the chi-square quantile at m degrees of freedom for the desired gate probability — not a universal three-sigma rule, because the correct threshold depends on measurement dimension.³⁰³

Published thresholds: 9.21 for a 99% gate at two measurement dimensions and 11.34 at three.³⁰⁴ A measurement is accepted when:

$$d2 \leq \gamma = \chi^2(m, 1 - \alpha)$$

Best-practice guidance from the same source, adopted by this specification: prefer global nearest neighbour over simple nearest neighbour for negligible extra cost and a globally optimal assignment; derive the gate threshold from the chi-square quantile rather than a fixed number; include an explicit cost for the no-assignment option so that false associations are not forced; and tighten or loosen the gate probability adaptively with local track density.³⁰⁵

7.3.2 Association algorithms

Table 7-4 — Data association algorithms

Algorithm	Principle	Allocation in this system
Global nearest neighbour	Builds a cost matrix of gated squared Mahalanobis distances over all track-measurement pairs and solves one global assignment problem, for example by the Hungarian or auction algorithm, minimising total cost subject to single use of each track and measurement. ³⁰⁶	Baseline for within-modality measurement-to-track association at every scan.

Cranfield University, A Review of Data Fusion Models and Architectures, <https://dspace.lib.cranfield.ac.uk/bitstreams/71a21f06-2427-418b-b649-00182f576009/download>³⁰¹

Tracker Component Library documentation, Assignment and Data Association,³⁰²
https://pytcl.readthedocs.io/en/latest/assignment_association.html

Tracker Component Library documentation, Assignment and Data Association,³⁰³
https://pytcl.readthedocs.io/en/latest/assignment_association.html

Tracker Component Library documentation, Assignment and Data Association,³⁰⁴
https://pytcl.readthedocs.io/en/latest/assignment_association.html

Tracker Component Library documentation, Assignment and Data Association,³⁰⁵
https://pytcl.readthedocs.io/en/latest/assignment_association.html

Tracker Component Library documentation, Assignment and Data Association,³⁰⁶
https://pytcl.readthedocs.io/en/latest/assignment_association.html

Algorithm	Principle	Allocation in this system
Joint probabilistic data association	Computes for each track a probabilistically weighted combination of all gated measurements, weighted by joint association probabilities across all tracks simultaneously.	Required for the cluttered, closely spaced case — a drone swarm, or a drone within a bird flock — where a hard assignment is brittle.
Multi-hypothesis tracking	Maintains multiple hypothesis trees of alternative association histories across several scans, prunes and merges low-probability branches, and commits to the maximum-likelihood hypothesis only once evidence has accumulated. Originates with Reid's 1979 formulation.	Reserved for the cross-modality track-to-track correlation stage rather than every raw-detection scan, because it is computationally heavy.
Random finite set methods — PHD, GLMB, LMB	Reformulates multi-target tracking as estimation of a set-valued random variable, handling unknown and time-varying target number, missed detections and false alarms without an explicit association step. PHD propagates the first-order intensity function; GLMB is an exact conjugate solution with persistent track labels; LMB is an efficient multi-Bernoulli approximation of GLMB.	Permitted as an alternative to the GNN/JPDA/MHT stack. Attractive here because all three modalities have imperfect, count-varying detection probability and clutter, which is exactly the case these filters were built for. Where track identity must persist, GLMB or LMB SHALL be used rather than PHD, which is unlabelled.

7.4 State estimation and motion models

Table 7-5 — Filter selection

Filter	Characteristics	Applicability
Kalman filter	Optimal minimum-mean-square-error estimator for linear-Gaussian models.	Cartesian-state constant-velocity segments with direct position measurements only.
Extended Kalman filter	Linearises nonlinear motion and measurement models by first-order Taylor expansion around the current estimate.	Standard for bearing-and-range measurements, which are nonlinear in Cartesian state, but can diverge under strong nonlinearity or poor initialisation.
Unscented Kalman filter	Propagates deterministic sigma points through the true nonlinear model rather than linearising, giving second-order accuracy in mean and covariance without Jacobians.	Selected as the baseline. Preferred over the extended form for highly manoeuvrable targets, where nonlinear bearing or time-difference measurements combine with abrupt velocity change to stress linearisation.
Particle filter	Represents the posterior with weighted random samples, handling arbitrary non-Gaussian multimodal posteriors at higher computational cost.	Required for the genuinely multimodal cases — ambiguous bearings-only geometry from a single acoustic array, or multimodal hypotheses arising from evidential fusion.

7.4.1 Motion models for small multirotors

Small multirotor dynamics are qualitatively unlike fixed-wing or ballistic targets: the aircraft can hover, reverse direction abruptly, and accelerate or decelerate rapidly with no turn-rate constraint. A single fixed motion model will not cover the regime set.

- **Constant velocity.** State of position and velocity with zero-mean acceleration process noise. A reasonable baseline for steady cruise, but it systematically underestimates manoeuvre capability and will lag every turn.
- **Constant acceleration.** State extended to acceleration with process noise on jerk. Captures smooth speed change but not abrupt reversal.
- **Singer model.** Models target acceleration as a first-order Gauss-Markov, exponentially time-correlated random process rather than white noise, parameterised by a manoeuvre time constant and a maximum expected acceleration. Historically the standard manoeuvring-target model and a natural fit to the semi-random, bounded-acceleration motion of a hovering and manoeuvring multirotor.
- **Interacting multiple model.** Runs several motion models in parallel filter banks, each producing its own estimate and likelihood, and combines them by Markov-chain model-transition probabilities and likelihood-weighted mixing at every scan. Selected as the mandatory baseline for this system, because the target

switches between qualitatively different regimes — hover, straight transit, evasive manoeuvre — and the mixture adaptively weights toward whichever model currently explains the measurements.

What is achievable. For context on dense passive geometry: a multistatic Doppler-based drone tracking system using downlink LTE base stations as illuminators and three passive receivers demonstrated 90% of trajectory tracking errors below 0.9 m, with the aircraft roughly 200 m from the base stations and roughly 20 m from the receivers, reconstructing the trajectory purely from bistatic Doppler measurements by minimum-mean-squared-error optimisation without directly measuring range or angle.³⁰⁷ Two cautions apply before this figure is used for planning. First, the 20 m receiver standoff is far closer than any realistic perimeter geometry. Second, the result is a demonstration of Doppler diversity substituting for precision timing, not a general performance claim. It does however establish that dense multistatic geometry can deliver sub-metre accuracy without time-difference-grade timing, which is a useful architectural option where a synchronous timing network cannot be provided.

7.5 Detection-level fusion mathematics

7.5.1 Neyman-Pearson framing

Each sensor chain is a binary hypothesis test between the null hypothesis of no target and the alternative of a target present, characterised by its probability of false alarm and probability of detection. The Neyman-Pearson criterion selects the rule maximising probability of detection subject to a constraint on probability of false alarm, and the Neyman-Pearson lemma shows the optimal rule is always a likelihood-ratio test — decide the alternative when the ratio of the two conditional densities exceeds a threshold set to achieve the target false-alarm rate.³⁰⁸ The receiver operating characteristic plots the achievable pairs as the threshold varies; it passes through the origin and the unit point, is concave, and every point on it satisfies probability of detection at least equal to probability of false alarm.^{309 310} Raising a threshold lowers both quantities together: there is no free lunch, and every sensor in this system sits at a chosen point on its own curve.

$$P_{FA} = \Pr(\text{decide } H_1 \mid H_0) \quad P_D = \Pr(\text{decide } H_1 \mid H_1)$$

$$\text{Lambda}(x) = f(x \mid H_1) / f(x \mid H_0) > \text{threshold} \Rightarrow \text{declare detection}$$

A directly relevant published worked example is the received-signal-strength energy detector analysed for RF drone detection in the presence of aggregate interference: under the null hypothesis the received signal strength is chi-square distributed with two degrees of freedom, giving a closed-form false-alarm probability $P_{FA} = \exp(-\gamma_{thr} / (2 * \sigma^2))$, and under the alternative with a line-of-sight component the detection probability takes a noncentral chi-square or Marcum-Q form with noncentrality proportional to transmit power and inversely proportional to squared range.³¹¹ The same analysis carries a counter-intuitive result of direct architectural relevance: detection probability can vary non-monotonically with sensor deployment density, because additional RF sensors also add mutual RF interference.³¹² More sensors is therefore not automatically better, and node density must be justified by analysis rather than assumed.

7.5.2 Hard-decision fusion rules

For n sensors making independent binary decisions, the standard distributed-detection rules — in the classical Chair-Varshney framework for optimal fusion of independent local decisions — are as follows. Independence of

arXiv 2509.25732, Doppler-Based Multistatic Drone Tracking via Cellular Networks, <https://arxiv.org/html/2509.25732v1>³⁰⁷

Iowa State University ECE 527, lecture notes on Neyman-Pearson testing,³⁰⁸
https://www.ece.iastate.edu/~namrata/EE527_Spring08/I5c_2.pdf

Iowa State University ECE 527, lecture notes on Neyman-Pearson testing,³⁰⁹
https://www.ece.iastate.edu/~namrata/EE527_Spring08/I5c_2.pdf

Purdue University ECE 645, lecture notes on Neyman-Pearson testing,³¹⁰
<https://engineering.purdue.edu/ChanGroup/ECE645Notes/StudentLecture02.pdf>

ar5iv / arXiv 1905.03471, RSS-Based Detection of Drones in the Presence of RF Interferers, <https://ar5iv.labs.arxiv.org/html/1905.03471>³¹¹

ar5iv / arXiv 1905.03471, RSS-Based Detection of Drones in the Presence of RF Interferers, <https://ar5iv.labs.arxiv.org/html/1905.03471>³¹²

the decision errors is the assumption that makes these product forms exact, and it is an assumption this specification requires to be tested rather than asserted.

$$\begin{aligned} \text{OR (1-of-n): } P_D &= 1 - \prod_i (1 - P_{D_i}) & P_{FA} &= 1 - \prod_i (1 - P_{FA_i}) \\ \text{AND (n-of-n): } P_D &= \prod_i P_{D_i} & P_{FA} &= \prod_i P_{FA_i} \\ \text{k-of-n: } P_D &= \sum_{r=k..n} \text{sum over subsets } S \text{ of size } r \text{ of} \\ & [\prod_{\{i \text{ in } S\}} P_{D_i}] * [\prod_{\{j \text{ not in } S\}} (1 - P_{D_j})] \end{aligned}$$

7.5.3 Worked fusion example

The following worked example uses illustrative per-sensor operating points broadly consistent with the modality assessments of Sections 4 to 6. The arithmetic is derived; the operating points are illustrative inputs, not measured values for any specific equipment, and the conclusion drawn is about the shape of the trade-off rather than about the absolute numbers.

Table 7-6 — Illustrative per-sensor operating points

Sensor	Probability of detection	Probability of false alarm
RF	0.95	1×10^{-3}
Acoustic	0.70	1×10^{-2}
LTE	0.60	1×10^{-3}

OR rule — $P_D = 1 - (0.05)(0.30)(0.40) = 1 - 0.006 = 0.994$. [Derived]

OR rule — $P_{FA} = 1 - (0.999)(0.99)(0.999) = 0.011979$, about 1.2×10^{-2} . [Derived]

AND rule — $P_D = 0.95 \times 0.70 \times 0.60 = 0.399$. [Derived]

AND rule — $P_{FA} = (1e-3)(1e-2)(1e-3) = 1 \times 10^{-8}$. [Derived]

2-of-3 — $P_D = 0.266000 + 0.171000 + 0.021000 + 0.399000 = 0.857000$, summing the RF-and-acoustic, RF-and-LTE, acoustic-and-LTE and all-three terms. [Derived]

2-of-3 — $P_{FA} = 9.99e-6 + 9.90e-7 + 9.99e-6 + 1.00e-8 = 2.098 \times 10^{-5}$. [Derived]

Table 7-7 — Fusion rule comparison (all values derived)

Fusion rule	Combined P_D	Combined P_{FA}	Assessment
OR (1-of-3)	0.994	1.198×10^{-2}	Highest detection probability, but false-alarm rate is dominated by the weakest sensor and is worse than every individual sensor except acoustic. The classic OR-rule weakness.
2-of-3	0.857	2.098×10^{-5}	Selected as the default alerting rule. Detection probability falls only modestly below the standalone RF figure while false-alarm rate improves by roughly three orders of magnitude relative to OR.
AND (3-of-3)	0.399	1.00×10^{-8}	Extremely low false-alarm rate, but detection probability collapses below every individual sensor because the two weaker sensors must both agree with RF and their mediocre detection probabilities compound multiplicatively.

This is why fielded multi-sensor counter-UAS systems favour 2-of-n or weighted-voting cross-cueing over simple OR-triggered alerting, consistent with the combined-evidence confirmation logic described for operational systems. A structural caveat applies to this system specifically: with only three modalities and one of them (LTE) applicable to a minority of aircraft, a strict 2-of-3 rule cannot fire at all on an RF-silent, non-cellular aircraft outside acoustic range. The alerting policy of Section 7.5.5 therefore uses a graded scheme rather than a single rule.

7.5.4 Soft Bayesian fusion

Under conditional independence of the sensor reports given the true hypothesis, the combined likelihood ratio is the product of the individual ratios, and Bayes' rule in odds form converts it to a posterior:

$$LR_{combined} = \prod_i LR_i \quad LR_i = P_{D_i} / P_{FA_i} \quad (\text{positive report})$$

$$\text{posterior_odds} = \text{prior_odds} * LR_{combined}$$

Individual ratios from Table 7-6: RF = 950 ($\log_{10} = 2.98$), acoustic = 70 (1.85), LTE = 600 (2.78). [Derived]

All three positive: $LR_{combined} = 950 \times 70 \times 600 = 3.99 \times 10^7$, $\log_{10} \approx 7.60$. [Derived]

With an illustrative prior probability of a drone being present of 1×10^{-4} , prior odds $\approx 1.0001 \times 10^{-4}$, the posterior probability given all three positive is about 0.9997. [Derived]

The value of soft fusion over hard voting is that the fusion centre computes a continuous posterior that scales gracefully with the number and strength of corroborating reports, and can incorporate a context-dependent prior — for example a raised baseline during a scheduled event or a declared elevated threat state. The cost is that the likelihood ratios must be calibrated: an uncalibrated confidence score fed into this machinery produces a confident wrong answer, which is operationally worse than an honest uncertain one.

7.5.5 Evidential fusion for conflicting reports

Dempster-Shafer theory, introduced by Dempster in 1967 and developed by Shafer in 1976, generalises Bayesian probability by allowing evidence to be assigned to sets of hypotheses rather than only to single hypotheses, which is valuable when sensors disagree or report partial evidence.³¹³ A mass function over the frame of discernment — for this system the set {drone, bird, manned aircraft, other} — satisfies a zero mass on the empty set and unit total mass. Belief and plausibility bound the true probability of a hypothesis, with belief never exceeding plausibility.³¹⁴

$$\text{Bel}(A) = \sum_{B \subset A} m(B)$$

$$\text{Pl}(A) = \sum_{B \text{ with } B \cap A \neq \emptyset} m(B)$$

Two independent bodies of evidence are combined by Dempster's rule, where K quantifies the conflict between the sources:³¹⁵

$$(m_1 \oplus m_2)(A) = \left[\sum_{X, Y \text{ with } X \cap Y = A} m_1(X) * m_2(Y) \right] / (1 - K)$$

$$K = \sum_{X, Y \text{ with } X \cap Y = \emptyset} m_1(X) * m_2(Y)$$

A well-documented pitfall applies directly to this system: classical Dempster combination can produce counter-intuitive results when the evidence is highly conflicting — exactly the case of a strong RF drone report against a weak, partially conflicting acoustic bird report. This motivates alternatives such as the proportional conflict redistribution rule PCR5 from Dezert-Smarandache theory, which redistributes conflicting mass more sensibly than Dempster's normalisation.³¹⁶ More recent work weights each source by a reliability factor derived from an evidence-distance metric such as the Hellinger distance together with an uncertainty measure such as Deng entropy before combination, specifically to avoid that failure mode.³¹⁷

MDPI Sensors 23(11):5141, Multisensor Data Fusion in IoT Environments in Dempster-Shafer Theory, <https://www.mdpi.com/1424-8220/23/11/5141>.³¹³

ONERA, Dezert, Overview of Dempster-Shafer and Belief Function Tracking Methods, SPIE 2013, ³¹⁴
<https://www.onera.fr/sites/default/files/297/C086-Dezert-SPIE2013Baltimore.pdf>

ONERA, Dezert, Overview of Dempster-Shafer and Belief Function Tracking Methods, SPIE 2013, ³¹⁵
<https://www.onera.fr/sites/default/files/297/C086-Dezert-SPIE2013Baltimore.pdf>

ONERA, Dezert, Overview of Dempster-Shafer and Belief Function Tracking Methods, SPIE 2013, ³¹⁶
<https://www.onera.fr/sites/default/files/297/C086-Dezert-SPIE2013Baltimore.pdf>

MDPI Sensors 23(11):5141, Multisensor Data Fusion in IoT Environments in Dempster-Shafer Theory, <https://www.mdpi.com/1424-8220/23/11/5141>.³¹⁷

When to prefer evidential over Bayesian fusion. Evidential fusion is preferable where a sensor can genuinely report that it does not know — assigning mass to the whole frame, as an RF sensor does when it detects an unidentified 2.4 GHz emission with no protocol match — rather than being forced to commit a full probability distribution across the classes. This is a common real situation for RF and acoustic classifiers operating at the edge of their range or confidence, and forcing such a sensor into a hard distribution manufactures information that does not exist.

Selected alerting policy. The system SHALL compute a continuous fused confidence by soft likelihood-ratio fusion where calibrated scores are available and by evidential fusion where a modality reports explicit ignorance, and SHALL expose graded alert states rather than a single binary trigger: a single-modality contact at low confidence, a corroborated two-modality contact at high confidence, and an uncorroborated single-modality contact that persists over a defined dwell as a distinct intermediate state. The 2-of-3 hard rule of Table 7-7 SHALL be available as a fallback where a subsystem cannot provide calibrated confidence. [Derived allocation]

7.6 Classification and threat assessment

7.6.1 Discriminating drones from birds and aircraft

Distinguishing small UAS from birds is explicitly identified as one of the hardest problems in counter-UAS sensing, because birds and small drones share similar radar cross-section, altitude and speed envelopes.^{318 319} Fielded approaches combine several discriminating features rather than relying on one:

- **Kinematic and track features.** Speed, acceleration, turn rate, dwell time, altitude profile, track stability and zone-entry behaviour. A bird flock crossing distant airspace scores lower risk than a slow target loitering on a perimeter boundary.³²⁰
- **Periodic modulation signature.** Rotor blade flash and bird wingbeat both produce periodic modulation that in principle separates rotorcraft from birds, but this is explicitly stated to be imperfect in practice and best used as one signal among several.³²¹ In this detection-only system the equivalent observable is the acoustic blade-pass harmonic series of Section 6.7.2 rather than radar micro-Doppler.
- **RF emission presence.** The presence of a command-and-control or video-downlink signature strongly favours the drone hypothesis, since birds emit no radio. The converse inference is invalid and SHALL NOT be drawn: absence of RF does not favour the bird hypothesis, because an autonomous or tethered aircraft is also RF-silent.
- **Cross-modal confirmation.** The described operational logic is that confidence increases when one sensor detects a likely drone, a second sees a related emission, and a third confirms the airframe — decision-level fusion applied to classification rather than to raw detection.³²²

counteruavradar.com, How Radar Distinguishes Drones from Birds, <https://www.counteruavradar.com/en/knowledge-base/how-radar-distinguishes-drones-from-birds/>³¹⁸

TU Delft repository, Classification of Birds and Drones Exploiting Kinematic Properties for Surveillance Radars Using Machine Learning Techniques, <https://repository.tudelft.nl/record/uuid:96cc142c-ddf6-4823-baf5-1a6a27b97b51>³¹⁹

counteruavradar.com, How Radar Distinguishes Drones from Birds, <https://www.counteruavradar.com/en/knowledge-base/how-radar-distinguishes-drones-from-birds/>³²⁰

counteruavradar.com, How Radar Distinguishes Drones from Birds, <https://www.counteruavradar.com/en/knowledge-base/how-radar-distinguishes-drones-from-birds/>³²¹

counteruavradar.com, How Radar Distinguishes Drones from Birds, <https://www.counteruavradar.com/en/knowledge-base/how-radar-distinguishes-drones-from-birds/>³²²

7.6.2 Published classification performance

Table 7-8 — Published classification results across modalities

System or modality	Reported result	Source note
Radar-only, radar cross-section plus trajectory, current fielded systems	85–88% small-UAS versus bird discrimination; 4–5 s detection-to-classification latency in a multi-modal system	Naval assessment citing Liu et al. 2021. The 85–88% figure is a useful reality check against laboratory claims above 95%. ³²³
Recurrent-network classifier, experimental	Consistently above 90%, as high as 98%	The source itself qualifies this as needing verification in different environments. ³²⁴
Acoustic tetrahedral microphone array	99.5% probability of detection at a 3% false-alarm rate	A 3% false-alarm rate is unusably high for continuous unattended operation; see Section 10. ³²⁵
Radar machine-learning classifier on real data	Above 98% drone versus no-drone; above 93% fixed-wing versus rotary-wing	NATO test-campaign result on real radar collections. ³²⁶
Radar decision-tree classifier	97% true-positive rate with 3% false negatives on synthetic data; 93.4% on real radar data	The synthetic-to-real gap of about 3.6 points is itself the informative result. ³²⁷
Convolutional network, real versus synthetic radar data	89.7% on real data, 86.6% on the highest-fidelity synthetic data; false-alarm probability 8.9% for birds and 11.6% for drones	One of the few sources that separates bird and drone false-alarm rates explicitly. ³²⁸
Acoustic convolutional detector, session-grouped cross-validation	At a 1% false-alarm rate, detects 93.8% of drones against 72.3% for a hand-designed-feature baseline	Session-grouped validation is a materially stricter protocol than random splits, which makes this figure more trustworthy than most. ³²⁹
LTE/cellular network classifier on received-power and cell-report features	Drone versus regular handset true-positive rate above 99% at a false-positive rate at or below 0.5%, at 60 m altitude and above	Network-side measurement reports, not passive off-air observation — see the limitation recorded in Section 11. ³³⁰

7.6.3 Birds as the dominant false-alarm source

Several independent sources identify birds as the single largest source of counter-UAS false alarms, and the numbers are large enough to dominate system design rather than merely complicate it. A commercial false-positive analysis states that radar systems alone can generate up to 1000 potential targets per hour in complex urban environments, and that field trials indicate false-positive rates can exceed 35% in areas of high bird activity.³³¹ The radar-classification study above measured a false-alarm probability of 8.9% for birds against

DTIC AD1212947, Naval report on sUAS detection and classification, <https://apps.dtic.mil/sti/trecms/pdf/AD1212947.pdf>³²³

DTIC AD1212947, Naval report on sUAS detection and classification, <https://apps.dtic.mil/sti/trecms/pdf/AD1212947.pdf>³²⁴

MDPI Sensors 22(1):189, Review and Simulation of Counter-UAS Sensors for Unmanned Traffic Management,³²⁵
<https://www.mdpi.com/1424-8220/22/1/189>

NATO STO-MP-SET-315-25, Automatic Classification of UAVs,³²⁶
<https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-SET-315/MP-SET-315-25.pdf>

NATO STO-MP-MSG-SET-183-15P, Tracking and Classification of Drones,³²⁷
<https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-MSG-SET-183/MP-MSG-SET-183-15P.pdf>

University of Birmingham, radar UAV classification with synthetic data (Revised Manuscript), [https://pure-³²⁸
oai.bham.ac.uk/ws/portalfiles/portal/208677443/RevisedManuscript.pdf](https://pure-oai.bham.ac.uk/ws/portalfiles/portal/208677443/RevisedManuscript.pdf)

arXiv 2606.29589, EchoHawk: A Reproducible Acoustic Pipeline for Drone Detection, <https://arxiv.org/pdf/2606.29589>³²⁹

Aalto University, Drone Detection and Classification Using Cellular Network: A Machine Learning Approach,³³⁰
https://acris.aalto.fi/ws/portalfiles/portal/36192831/AALTO_Drone_Detection_and_Classification_Using_Cellular_Network_A_Machine_Learning_Approach.pdf

GreyB / xray, False Positive Signal Reduction using AI in Counter UAS, <https://xray.greyb.com/drones/false-positive-counter-uas>³³¹

11.6% for drones on real benchmark data.³³² Industry procurement guidance states plainly that distinguishing drones from birds is one of the hardest tasks in counter-UAS radar, that operational systems rarely eliminate false alarms completely, and that the practical evaluation question is whether bird false alarms can be reduced to an acceptable level without missing real drones — not whether they can be eliminated.³³³ A vendor discussion of the false-positive dilemma names birds alongside consumer radio devices in the same bands as the primary false-alarm drivers.³³⁴

Consequence for this system. Because this specification excludes radar, the bird problem presents differently: birds emit no radio, so they cannot generate RF or LTE false alarms, and the exposure is confined to the acoustic subsystem. That is a genuine architectural advantage over radar-centric designs and should be stated as such. It is not an exemption — wing-beat and wind-in-foliage acoustic events remain a false-alarm source, and Section 6.7.3 records that even strong acoustic models confuse rotorcraft classes at high rates. The measured false-alarm contribution of birds and other wildlife to the acoustic subsystem SHALL be characterised separately during field trial rather than folded into an aggregate figure.

7.6.4 Threat assessment and confidence scoring

The practical pattern across the literature and vendor documentation is late, decision- or score-level fusion of independently trained per-modality classifiers, whose confidence scores are then combined by the machinery of Section 7.5: Bayesian likelihood-ratio combination where class-conditional score distributions are known and validated, evidential combination where a sensor may be legitimately uncertain rather than forced into a hard decision, and hard-decision cross-cueing where only binary alerts are available.³³⁵ Detection-to-classification latency for multi-modal fielded systems is reported at 4 to 5 seconds from initial detection to a classified alert requiring human confirmation when confidence is marginal.³³⁶

Threat assessment is JDL Level 3 and is a kinematic and contextual projection, not a classification output. The system SHALL compute, for each confirmed track: closest point of approach to each declared protected volume; time to that point at current velocity; whether the track has entered a declared restricted volume; and a persistence measure distinguishing a transiting aircraft from a loitering one. Classification confidence and threat score SHALL be reported as separate quantities and SHALL NOT be collapsed into one number, because a confidently identified aircraft on a harmless trajectory and an unidentified contact on an intercept course require different operator responses. [Derived allocation]

7.7 Applicable standards and test frameworks

No single unified counter-UAS detection test standard analogous to a product-certification standard was identified in the research underpinning this specification, and this should be treated as a genuine gap in the state of the art rather than an omission here. The relevant framework is assembled from several bodies.

- **ASTM Committee F38 on Unmanned Aircraft Systems** addresses design, performance, quality-acceptance testing and safety monitoring for UAS, with jurisdiction over roughly a dozen published standards spanning airworthiness, remote identification (F3411) and detect-and-avoid performance

University of Birmingham, radar UAV classification with synthetic data (Revised Manuscript), <https://pure-oai.bham.ac.uk/ws/portalfiles/portal/208677443/RevisedManuscript.pdf>³³²

counteruavradar.com, How Radar Distinguishes Drones from Birds, <https://www.counteruavradar.com/en/knowledge-base/how-radar-distinguishes-drones-from-birds/>³³³

D-Fend Solutions, The False Positive Dilemma: False Alerts in Drone Detection, <https://d-fendsolutions.com/blog/the-false-positive-dilemma-false-alerts-in-drone-detection/>³³⁴

NATO STO-MP-MSG-SET-183-15P, Tracking and Classification of Drones, <https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-MSG-SET-183/MP-MSG-SET-183-15P.pdf>³³⁵

DTIC AD1212947, Naval report on sUAS detection and classification, <https://apps.dtic.mil/sti/trecms/pdf/AD1212947.pdf>³³⁶

(F3442).^{337 338} F3442 is cited as a reference implementation basis for the joint FAA and RTCA ACAS sXu detect-and-avoid minimum operational performance standard.³³⁹ Committee membership spans more than 528 members across 25 countries overseeing roughly 25 UAS-related standards.³⁴⁰ Note that these are UAS standards, not counter-UAS detection standards; F3411 remote identification is directly relevant because it defines a cooperative identification broadcast that this system can receive.

- **FAA Airport UAS Detection and Mitigation Research Program** committed to testing at least ten detection and counter-UAS systems at five US airports, explicitly to inform a future certification, permitting and authorisation framework. As of the Office of Inspector General report of March 2022 the FAA had not completed the necessary testing, meaning the agency could not yet fully assess the impact of these technologies on aviation safety and security and might not understand those impacts for several more years; the FAA concurred with the recommendations to improve strategic planning and mandated testing.³⁴¹ A subsequent UAS Detection and Mitigation Systems Aviation Rulemaking Committee published a final report in January 2024 addressing airport deployment policy.³⁴²
- **Joint federal advisory guidance.** The US Department of Justice, FAA, Department of Homeland Security and FCC jointly issued advisory guidance on 17 August 2020 clarifying which federal laws apply to non-federal public and private entities seeking to detect and mitigate UAS threats — a foundational document for any US deployment, independent of the technical test question. See Section 12.³⁴³
- **Test infrastructure and multinational records.** NUAIR operates airspace-awareness test infrastructure supporting detection-system evaluation and feeding the wider FAA and ASTM test ecosystem.³⁴⁴ NATO Science and Technology Organization meeting proceedings function as a de facto multinational test-and-evaluation record for sensor classification performance, including the results in Table 7-8.^{345 346}

Research gaps declared. Targeted searches for UK DSTL-specific counter-UAS trial reports, a formal NIST counter-UAS test-methodology guide, and the EU Joint Research Centre report on technical developments in counter-drone technology (JRC140692) did not yield retrievable primary documents in the research supporting this specification. The JRC document's existence and title were confirmed but its content could not be retrieved owing to a repository access restriction. These SHALL be treated as gaps for follow-up rather than as confirmed non-existence, and re-checked before any acceptance test plan is finalised.

ASTM International, Committee F38 on Unmanned Aircraft Systems, <https://www.astm.org/membership-participation/technical-committees/committee-f38>.³³⁷

ASTM regional portal, Unmanned Aerial Systems (Drone) Standards, <https://regional.astm.org/emerging-technology/uas-standards>.³³⁸

Unmanned Airspace, Standards bodies ASTM and RTCA collaborate on ACAS sXu detect and avoid capability for drones, <https://www.unmannedairspace.info/uncategorized/standards-bodies-astm-and-rtca-collaborate-on-acas-sxu-detect-and-avoid-capability-for-drones/>.³³⁹

DroneWatch.eu, ASTM International to cooperate with ASD-STAN on Remote ID for drones, <https://www.dronewatch.eu/astm-international-to-cooperate-with-asd-stan-on-remote-id-for-drones/>.³⁴⁰

US DOT Office of Inspector General, FAA Counter-UAS final report, 30 March 2022, https://www.oig.dot.gov/sites/default/files/FAA%20Counter-UAS%20Final%20Report_3.30.2022.pdf.³⁴¹

FAA, UAS Detection and Mitigation Systems Aviation Rulemaking Committee Final Report, January 2024, https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/UAS-Detection-Mitigation-Systems-ARC_Final-Report_02052024.pdf.³⁴²

FAA, Counter UAS (C-UAS) resources page, https://www.faa.gov/uas/resources/c_uas.³⁴³

NUAIR, Airspace Awareness, <https://www.nuair.org/airspaceawareness>.³⁴⁴

NATO STO-MP-SET-315-25, Automatic Classification of UAVs, <https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-SET-315/MP-SET-315-25.pdf>.³⁴⁵

NATO STO-MP-MSG-SET-183-15P, Tracking and Classification of Drones, <https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-MSG-SET-183/MP-MSG-SET-183-15P.pdf>.³⁴⁶

7.8 Fusion subsystem requirements

Table 7-9 — Data fusion, tracking and classification requirements

ID	Requirement	Verification
REQ-FU-001	The system SHALL implement a hierarchical fusion architecture: signal- and feature-level fusion within each node, and track- or decision-level fusion across modalities at the central fusion function.	Inspection
REQ-FU-002	Raw multi-channel sensor data SHALL NOT be transported between nodes and the fusion centre in normal operation.	Inspection
REQ-FU-003	The central fusion function SHALL continue to operate in a degraded but defined mode on loss of any single node, and SHALL report which nodes are contributing to each track.	Field Trial
REQ-FU-004	Track-to-track fusion SHALL use a method that is consistent in the absence of a known cross-covariance. Covariance intersection SHALL be the default; the Bar-Shalom/Campo or maximum-likelihood forms MAY be used only where the cross-covariance is computed or correlation is demonstrated negligible.	Analysis
REQ-FU-005	The fused covariance SHALL NOT be optimistic. Consistency SHALL be demonstrated by normalised estimation error squared testing against recorded ground-truth trials.	Field Trial
REQ-FU-006	All nodes SHALL be synchronised to a common time base. Acoustic time-difference functions SHALL be served to better than 10 μ s and RF time-difference functions, where implemented, to better than 100 ns.	Bench Test
REQ-FU-007	RF receivers used for any time-difference function SHALL be hardware-timestamped PTP clients. Software timestamping SHALL NOT be used for time-difference measurement.	Inspection
REQ-FU-008	The system SHALL report the current timing source, its holdover state and its estimated accuracy, and SHALL degrade time-difference-derived outputs explicitly when the timing source is lost.	Field Trial
REQ-FU-009	All measurements SHALL be transformed into a common local East-North-Up frame with covariance propagated through the appropriate Jacobian, and results converted to WGS84 for reporting.	Analysis
REQ-FU-010	The system SHALL provide online sensor registration to estimate and correct inter-sensor angular, range and clock biases, and SHALL report current bias estimates and their uncertainty.	Field Trial
REQ-FU-011	Validation gates SHALL be derived from the chi-square quantile at the measurement dimension for the configured gate probability. A fixed multiple-of-sigma gate SHALL NOT be used.	Inspection
REQ-FU-012	The association cost structure SHALL include an explicit cost for the no-assignment option, so that false associations are not forced.	Inspection
REQ-FU-013	Gate probability SHALL be adaptable to local track density, either automatically or by configuration.	Bench Test
REQ-FU-014	The association function SHALL be at least global nearest neighbour, and SHALL provide a probabilistic or multi-hypothesis mode for the closely spaced multi-target case.	Bench Test
REQ-FU-015	Where a random-finite-set filter is used and persistent track identity is required, a labelled variant SHALL be used; the unlabelled PHD filter alone SHALL NOT be relied upon for track continuity.	Analysis
REQ-FU-016	State estimation SHALL use a nonlinear filter appropriate to the measurement geometry. An unscented or equivalent derivative-free filter SHALL be the baseline; a particle filter SHALL be used where the posterior is genuinely multimodal, such as bearings-only geometry from a single array.	Analysis
REQ-FU-017	The tracker SHALL use an interacting-multiple-model motion-model bank covering at minimum a hover or near-stationary model, a steady-transit model and a high-maneuvre model.	Bench Test
REQ-FU-018	The system SHALL compute a continuous fused confidence value rather than only a binary decision, and SHALL expose the per-modality contributions to that value.	Inspection

ID	Requirement	Verification
REQ-FU-019	Per-modality confidence scores used in likelihood-ratio fusion SHALL be calibrated, and the calibration SHALL be verifiable against recorded trial data.	Field Trial
REQ-FU-020	The fusion function SHALL accept an explicit ignorance report from a modality and SHALL NOT force a modality to commit a full distribution across classes when it cannot support one.	Inspection
REQ-FU-021	Where evidential fusion is used, the implementation SHALL address the highly conflicting evidence case by a conflict-redistribution or source-reliability-weighting method, and SHALL report the conflict measure.	Analysis
REQ-FU-022	Alerting SHALL be graded, distinguishing at minimum a low-confidence single-modality contact, a persistent single-modality contact, and a corroborated multi-modality contact. A single binary trigger SHALL NOT be the only output.	Field Trial
REQ-FU-023	The system SHALL NOT infer the absence of a UAS from the absence of RF emissions. An acoustic-only contact SHALL be capable of generating an alert without RF corroboration.	Field Trial
REQ-FU-024	The fusion function SHALL be configurable to a hard k-of-n rule as a fallback where a subsystem cannot provide calibrated confidence.	Inspection
REQ-FU-025	Classification confidence and threat score SHALL be computed and reported as separate quantities and SHALL NOT be collapsed into a single number.	Inspection
REQ-FU-026	For each confirmed track the system SHALL compute closest point of approach to each declared protected volume, time to that point at current velocity, restricted-volume entry status, and a loiter-versus-transit persistence measure.	Bench Test
REQ-FU-027	The classification frame SHALL include at minimum drone, bird, manned aircraft and unknown, and the measured confusion matrix across those classes SHALL be reported from field trial rather than an aggregate accuracy figure.	Field Trial
REQ-FU-028	The false-alarm contribution of birds and other wildlife to the acoustic subsystem SHALL be characterised separately during field trial and SHALL NOT be folded into an aggregate system false-alarm figure.	Field Trial
REQ-FU-029	The assumption of independence between modality decision errors SHALL be tested against recorded trial data, and any measured dependence SHALL be reflected in the fusion rule or in the declared performance.	Analysis
REQ-FU-030	The system SHALL record all sensor detections, association decisions, track states and fusion confidences in a replayable form, so that missed detections and false alarms can be reconstructed and attributed post hoc.	Field Trial
REQ-FU-031	Node density SHALL be justified by an interference and coverage analysis. Additional RF nodes SHALL NOT be assumed to improve detection probability monotonically, since added receivers also add mutual interference.	Analysis
REQ-FU-032	Detection-to-classification latency SHALL be measured and reported, and SHALL NOT exceed 5 s for a corroborated multi-modality contact.	Field Trial

Cellular-network signalling analysis as an operational detection route is discussed further in the LTE monitoring section; a general treatment of the approach is available in the published literature.³⁴⁷

Melrose Networks, Detecting Cellular-Connected Drones Through Mobile Network Signalling Analysis,³⁴⁷
<https://melrosenetworks.com/insights/detecting-cellular-connected-drones-through-mobile-network-signalling-analysis>

8 Network, Backhaul, Timing and Power

This section specifies the transport, synchronisation, power and integration engineering that turns the individual sensor nodes of Sections 4 to 6 into a network. The dominant architectural decision is taken here rather than in the sensor sections: whether the nodes ship raw signal or ship decisions. Section 8.1 shows that the answer is forced by arithmetic, not preference, and every subsequent choice in this section follows from it.

8.1 Data-rate budget per sensor node

8.1.1 Raw RF I/Q streaming as the worst case

A software-defined radio front end captures complex baseband I/Q samples at a rate essentially equal to its instantaneous bandwidth, because complex sampling makes the captured bandwidth approximately equal to the sample rate.³⁴⁸ A 56 MHz-wide capture, representative of the wideband receiver assumed in Section 4, therefore produces about 56 Mega-complex-samples per second. Most 12-bit converter front ends transport samples as 16-bit words, so the packed 16-bit format is the common on-the-wire case,³⁴⁹³⁵⁰ while some designs bit-pack at the native 12 bits to save transport bandwidth, as in the Analog Devices AD9363-class reference designs.³⁵¹

Derivation [Derived]. Data rate = sample rate x 2 components (I and Q) x bits per component:

$$16\text{-bit: } 56\text{e6 Sa/s} \times 2 \times 16 \text{ bit} = 1.792 \text{ Gbit/s} \quad (\sim 224 \text{ MB/s})$$

$$12\text{-bit: } 56\text{e6 Sa/s} \times 2 \times 12 \text{ bit} = 1.344 \text{ Gbit/s} \quad (\sim 168 \text{ MB/s})$$

At 1.792 Gbit/s sustained, a single node generates approximately 19.4 TB per day [Derived]. That figure alone eliminates unlicensed Wi-Fi links, every public cellular uplink and every satellite link as candidate full-time transports for raw I/Q from one node, let alone from a fleet.

8.1.2 Acoustic array data rate

The acoustic front end of Section 6 uses between 4 and 64 microphone channels. Rotor-signature work runs at conventional audio rates; a published reference implementation for impulsive acoustic events uses omnidirectional microphones at 48 kHz and 16-bit per channel,³⁵² whereas shockwave-resolving front ends sometimes sample at 150 kHz to 500 kHz per channel to capture microsecond-scale rise times.³⁵³³⁵⁴ This specification adopts 48 kHz at 24-bit per channel for rotor and propeller signature extraction; the higher rates are noted only to bound the design space.

Table 8-1 — Acoustic array raw data rate by channel count (48 kHz, 24-bit) [Derived]

Channels	Raw rate	Raw rate (MB/s)	Comment
8	9.216 Mbit/s	1.15	Minimum viable array for 3D bearing
16	18.432 Mbit/s	2.30	Baseline array assumed in Section 6

PySDR, IQ Sampling, <https://pysdr.org/content/sampling>³⁴⁸

Reddit r/RTLSDR, discussion of the relation between sample rate and data rate,³⁴⁹
https://www.reddit.com/r/RTLSDR/comments/futwl8/whats_the_relation_between_sample_rate_and_data/

PySDR, IQ Files and SigMF, https://pysdr.org/content/iq_files.html³⁵⁰

Analog Devices, Software-Defined Radio for Engineers (2018), Chapter 5, https://www.analog.com/media/en/training-seminars/design-handbooks/Software-Defined-Radio-for-Engineers-2018/SDR4Engineers_CH05.pdf³⁵¹

Maher, Acoustical Characterization of Gunshots, IEEE SAFE 2007,³⁵²
https://www.montana.edu/rmaher/publications/maher_ieeesafe_0407_109-113.pdf

Maher, Modeling and Signal Processing of Acoustic Gunshot Recordings, IEEE DSP Workshop 2006,³⁵³
https://www.montana.edu/rmaher/publications/maher_ieeedsp_0906_257-261.pdf

Gridbots, BAT acoustic shooter-detection system, <https://www.gridbots.com/bat.html>³⁵⁴

Channels	Raw rate	Raw rate (MB/s)	Comment
32	36.864 Mbit/s	4.61	Improved aperture and sidelobe control
64	73.728 Mbit/s	9.22	Upper bound considered in this design

Derived from channels x 48 000 Sa/s x 24 bit. High-fidelity shockwave capture at 500 kHz and 16-bit would instead reach 64 Mbit/s for 8 channels and 128 Mbit/s for 16 channels [Derived], comparable to a full-HD video stream per node.

The 500 kHz shockwave case is documented in the anechoic gunshot-waveform recording literature and is retained here only as an upper design bound, not as a requirement of this system.³⁵⁵

8.1.3 Edge-processed detection metadata: the practical load

Both the RF and the acoustic chains run detection, classification and, for RF, direction finding or time-difference estimation on node-local compute, and transmit structured reports rather than waveforms.

Derivation [Derived]. A detection or track message carrying timestamp, sensor identity, estimated position or bearing and range, signal-to-noise ratio, modulation or acoustic class, confidence and track identifier serialises compactly into roughly 200 to 500 bytes. Using 300 bytes and one report per second per track:

Concurrent tracks	Metadata rate	Notes
1	2.4 kbit/s	Single-target nominal case
10	24.0 kbit/s	Busy site
50	120.0 kbit/s	Dense swarm scenario, design ceiling

All values [Derived] from 300 bytes per report at 1 Hz. Node health and heartbeat telemetry at 1 Hz and about 200 bytes adds approximately 1.6 kbit/s [Derived].

Why this is the architecture, not an optimisation. Comparing the raw-I/Q case at 1.792 Gbit/s against the worst-case 50-track metadata stream at 120 kbit/s gives a bandwidth reduction of approximately 15 000 times [Derived]. Edge processing therefore does four things that no transport choice can do: it decouples node count from backhaul capacity, it bounds recurring transport cost, it keeps detection latency independent of wide-area network load, and it permits graceful degradation, because a node can continue reporting detections over a link that has collapsed to kilobit-class throughput. Selective raw-I/Q snapshot upload, for example a few seconds of capture around a high-confidence detection for forensic use or training-data collection, is scheduled opportunistically over higher-capacity links rather than streamed continuously.

8.2 Backhaul options

8.2.1 Fibre

- **GPON (ITU-T G.984).** 2.488 Gbit/s downstream and 1.244 Gbit/s upstream shared across a PON port, 1490 nm down and 1310 nm up, 20 km maximum physical reach with logical reach to 60 km, and split ratios up to 1:64 or 1:128 in practice.³⁵⁶³⁵⁷
- **XGS-PON (ITU-T G.9807.1).** Symmetric 9.95328 Gbit/s in both directions, 1577 nm down and 1270 nm up, the same 20 km physical and 60 km logical reach as GPON, and wavelength-division coexistence with GPON on the same optical distribution network because the wavelength plans do not overlap.³⁵⁸³⁵⁹

Routh and Maher, Recording anechoic gunshot waveforms, Acoustical Society of America 2016, ³⁵⁵
https://www.montana.edu/rmaher/publications/routh_maher_asa_0516.pdf

Elfcam, GPON networks and the ITU-T G.984 series, <https://eu.elfcams.com/article/gpon-reseaux>³⁵⁶

ZTE, XGS-PON Technical White Paper, <https://www.zte.com.cn/content/dam/zte-site/res-www-zte-com-cn/index-resource/global/enterprise/homepage/b1-campus-network/XGS-PON%20Technical%20White%20Paper-1.pdf>³⁵⁷

ITU-T Recommendation G.9807.1, <https://www.itu.int/rec/T-REC-G.9807.1>³⁵⁸

ITU-T G.9807.1 (02/2023), scope and status, <https://www.itu.int/ITU-T/recommendations/rec.aspx?rec=G.9807.1>³⁵⁹

- **Active Ethernet, 1 or 10 GbE point to point.** No passive splitting, so the full rate is dedicated to one node; reach is set by the optical transceiver class, typically 10 to 80 km on single-mode fibre, rather than by a PON standard.

Optical power budget classes N1, N2, E1 and E2 for XGS-PON span 14 to 35 dB depending on split ratio and distance,³⁶⁰ which is the practical constraint on how far a sensor node can sit from its optical line terminal. Both GPON upstream and XGS-PON upstream exceed the metadata requirement of Section 8.1.3 by orders of magnitude, and XGS-PON alone comfortably carries a full raw-I/Q stream from a single node. Fibre is nonetheless capital-intensive to trench to remote mast sites, so it is the default only for urban and fixed-infrastructure nodes with existing duct access.

8.2.2 Licensed microwave and E-band (71 to 86 GHz)

E-band offers 10 GHz of aggregate spectrum across 71 to 76 GHz and 81 to 86 GHz, essentially free of the oxygen absorption that limits 60 GHz, which enables multi-gigabit point-to-point links.³⁶¹ Channel bandwidths from 250 MHz to 2 GHz are available with modulation to 256QAM; a single 250 MHz channel at 64QAM already exceeds 1 Gbit/s and a 500 MHz channel exceeds 2 Gbit/s.³⁶² A field-tested 1.4 km E-band link demonstrated 40 Gbit/s with under 100 ms round-trip latency.³⁶³

Rain fade is the dominant availability constraint. ITU-R P.530 defines the terrestrial line-of-sight design methodology and refers to P.837 for rain-rate climatology and P.838 for the frequency- and polarisation-dependent specific attenuation used to compute attenuation exceeded for a given time percentage.^{364,365} In practical terms, E-band attenuation is roughly 10 dB/km at a 25 mm/h rain rate and rises above 30 dB/km near tropical rates of 100 mm/h,³⁶⁶ which bounds high-availability hop length to about 3 km for 99.999 percent availability, extending to roughly 6 km only in clear air.³⁶⁷ Dense-urban planning therefore assumes hops of 5 km or less at 10 Gbit/s-class capacity.³⁶⁸ For longer rural hops the traditional 6 to 42 GHz bands remain preferable despite lower per-channel capacity, because their rain sensitivity is far lower.

8.2.3 Unlicensed point-to-point and mesh

- **5 GHz, 802.11ac class.** Up to approximately 1.36 Gbit/s with channel aggregation across 5.15 to 5.96 GHz.³⁶⁹
- **6 GHz, Wi-Fi 6E class.** Up to 3.0 Gbit/s point-to-point IP throughput.³⁷⁰

ZTE, XGS-PON Technical White Paper, <https://www.zte.com.cn/content/dam/zte-site/res-www-zte-com-cn/index-resource/global/enterprise/homepage/b1-campus-network/XGS-PON%20Technical%20White%20Paper-1.pdf>³⁶⁰

NEC, The Next Generation Backhaul Networks: E-band white paper, https://in.nec.com/en_IN/pdf/Whitepaper-TheNextGenerationBackhaulNetworksEband.pdf³⁶¹

Huawei, E-band RTN380 field trial report, <https://www.scribd.com/document/470246869/Huawei-E-band-RTN380-Field-trial-report>³⁶²

Rahman et al., MDPI Remote Sensing 12(6):1045, 2020, <https://www.mdpi.com/2072-4292/12/6/1045>³⁶³

ITU-R Recommendation P.530-19 (09/2025), https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.530-19-202509-!!!PDF-E.pdf³⁶⁴

Microwave-Link.com, ITU-R P.530 recommendation summary, <https://www.microwave-link.com/itu-r-p-530-recommendation/>³⁶⁵

Sewe, University of Nairobi, E-band link availability thesis, <https://erepository.uonbi.ac.ke/bitstream/handle/11295/104383/Sewe%20Stephen.pdf?sequence=2&isAllowed=y>³⁶⁶

Sewe, University of Nairobi, E-band link availability thesis, <https://erepository.uonbi.ac.ke/bitstream/handle/11295/104383/Sewe%20Stephen.pdf?sequence=2&isAllowed=y>³⁶⁷

Rahman et al., MDPI Remote Sensing 12(6):1045, 2020, <https://www.mdpi.com/2072-4292/12/6/1045>³⁶⁸

Cambium Networks, PTP 550 datasheet, <https://www.eengineering.com/cambium-networks/ptp-550.htm>³⁶⁹

Mimosa, B6x product specification, <https://old.mimosa.co/product/b6x>³⁷⁰

- **60 GHz, IEEE 802.11ay-2021.** Standardised for at least 20 Gbit/s, and up to 30 Gbit/s in later scope extensions, measured at the MAC service access point, targeting short-range multi-gigabit fixed wireless.³⁷¹

Unlicensed bands trade interference exposure, and for 60 GHz very short range and high atmospheric absorption, against zero licensing cost and low-cost multi-gigabit capacity. They suit dense urban mesh topologies with hops under one to two kilometres between nodes or to a nearby aggregation point. A C-UAS network has a specific additional concern: its own unlicensed backhaul radios operate in the same 2.4 GHz and 5.8 GHz bands the RF sensor is trying to monitor, so backhaul radio selection and sensor band plan interact directly and are constrained together in Section 9.3.

8.2.4 Cellular, private networks and shared spectrum

CBRS (United States, 3.55 to 3.70 GHz, 3GPP Band 48 and n48). A three-tier shared-spectrum model: Tier 1 incumbents including naval radar and fixed satellite service, Tier 2 Priority Access Licences of up to 70 MHz auctioned at county level for ten years, and Tier 3 General Authorized Access of roughly 80 MHz, licence-exempt but coordinated by a Spectrum Access System. Private LTE on Band 48 typically delivers 20 to 50 ms latency and about 1 000 devices per cell, while private 5G on n48 adds lower-latency and mmWave options.³⁷²

European local and shared spectrum. Germany reserved 100 MHz at 3.7 to 3.8 GHz, plus 26 GHz, for local site-specific non-public network licences allocated in 10 MHz TDD blocks for up to ten years and renewable to 2040; more than 340 such local licences had been granted by mid-2023, demonstrating strong uptake of a CBRS-equivalent shared-licensing model in Europe.³⁷³³⁷⁴ This route is directly relevant to an operator wanting interference-protected private backhaul without a national licence.

Network slicing and URLLC. 3GPP Release 15 defines URLLC targets of 1 ms one-way user-plane radio-layer latency at 99.999 percent reliability, with Releases 16 and 17 pushing to 0.5 ms and up to 99.99999 percent reliability for selected industrial profiles, plus 1 microsecond time-synchronisation support.³⁷⁵³⁷⁶ That 1 ms figure must be read carefully: ITU-R Report M.2410-0 defines it as a radio-interface-only, single-user, zero-payload floor, not an end-to-end guarantee on a loaded network.³⁷⁷ LTE radio-layer end-to-end latency is typically around 4 ms under Release 14.³⁷⁸ For this system, a slice on a private 5G core isolates low-latency detection alerts from bulk telemetry and log upload on the same physical radio.

IEEE SA, IEEE 802.11ay-2021, <https://standards.ieee.org/ieee/802.11ay/6142/>³⁷¹

iFactory, Private LTE CBRS and private 5G overview, <https://ifactoryapp.com/greenfield-consulting/private-lte-cbrs-private-5g-manufacturing-facilities>³⁷²

Digital Regulation Platform, Spectrum licensing for local and private networks, <https://digitalregulation.org/spectrum-licensing-local-and-private-networks/>³⁷³

European Commission RSPG23-040 final, RSPG Opinion on 5G developments and 6G spectrum needs, https://radio-spectrum-policy-group.ec.europa.eu/system/files/2023-10/RSPG23-040final-RSPG_Opinion_on_5G_developments_and_6G_spectrum_needs.pdf³⁷⁴

IEEE Xplore document 10353007, survey of URLLC evolution, <https://ieeexplore.ieee.org/document/10353007/>³⁷⁵

3GPP, 5G for the Connected World, <https://www.3gpp.org/news-events/3gpp-news/5g-for-the-connected-world>³⁷⁶

5G6G Academy, Is 5G really 1 ms? A URLLC reality check against ITU-R M.2410-0, <https://www.5g6gacademy.com/learn/is-5g-really-1ms-urllc-reality-check>³⁷⁷

5G Americas, New Services and Applications with 5G URLLC white paper, https://www.5gamericas.org/wp-content/uploads/2019/07/5G_Americas_URLLC_White_Paper_Final__updateJW.pdf³⁷⁸

8.2.5 Satellite

GEO VSAT. At 35 786 km altitude the one-way propagation delay alone is about 120 ms directly overhead, rising to 125 to 140 ms for realistic slant ranges, giving a round-trip time of 480 to 600 ms or more, and 500 to 700 ms once terminal, modem and network processing are included.³⁷⁹³⁸⁰³⁸¹

LEO. Starlink published data shows United States median latency reduced from 48.5 ms to 33 ms during peak hours, with p99 peak-hour latency falling from over 150 ms to under 65 ms.³⁸² Independent measurement reports median round-trip time of roughly 40 to 50 ms globally,³⁸³ and Ookla notes that the highest recorded Starlink latency in its 2025 global report, 282 ms in the Marshall Islands, was still less than half the fastest GEO measurement.³⁸⁴ Typical throughput cited across sources is 25 to 220 Mbit/s down and 5 to 25 Mbit/s up.³⁸⁵

Table 8-2 — Backhaul option comparison

Option	Typical capacity	Latency	Availability	Standard	Role here
GPON	2.488 / 1.244 Gbit/s shared	Sub-ms	Greater than 99.99 percent	ITU-T G.984 ³⁸⁶	Urban primary
XGS-PON	9.95 Gbit/s symmetric, shared ³⁸⁷	Sub-ms	Greater than 99.99 percent	ITU-T G.9807.1	Urban primary, raw-IQ capable
Active Ethernet	1 to 10 Gbit/s dedicated	Sub-ms	Greater than 99.99 percent	IEEE 802.3	Aggregation trunk
E-band 71 to 86 GHz	1 to 40 Gbit/s per hop, 3 to 6 km ³⁸⁸³⁸⁹	Under 100 ms link latency	99.9 to 99.999 percent, rain-dependent	ITU-R P.530, P.838 ³⁹⁰	Urban trunk, short hop
Unlicensed 60 GHz	At least 20 Gbit/s, short range ³⁹¹	Low ms	Interference and weather dependent	IEEE 802.11ay	Urban mesh infill
Unlicensed 5 / 6 GHz	1 to 3 Gbit/s ³⁹²³⁹³	Low ms	Interference dependent	IEEE 802.11ac / ax	Infill, but co-band with RF sensor

SatcomIndex, Satellite latency comparison, <https://www.satcomindex.com/id/blog/satellite-latency-comparison>³⁷⁹

OrionSat, LEO versus GEO satellite technology, <https://orionsat.com.au/remote-connectivity-insights/leo-vs-geo-which-satellite-technology-for-your-operation>³⁸⁰

Orbital Radar, Satellite internet speeds and latency, <https://orbitalradar.com/satellite-internet/speeds-and-latency>³⁸¹

Starlink, Starlink Latency report, <https://starlink.com/public-files/StarlinkLatency.pdf>³⁸²

Mohan et al., A Multifaceted Look at Starlink Performance, WWW 2024, <https://www.nitindermohan.com/documents/2024/pubs/starlinkWWW2024.pdf>³⁸³

Ookla, 2025 Global Satellite Broadband Performance Report, <https://www.ookla.com/articles/2025-global-satellite-broadband-performance-report>³⁸⁴

Orbital Radar, Satellite internet speeds and latency, <https://orbitalradar.com/satellite-internet/speeds-and-latency>³⁸⁵

Elfcam, GPON networks and the ITU-T G.984 series, <https://eu.elfcams.com/article/gpon-reseaux>³⁸⁶

ITU-T Recommendation G.9807.1, <https://www.itu.int/rec/T-REC-G.9807.1>³⁸⁷

Rahman et al., MDPI Remote Sensing 12(6):1045, 2020, <https://www.mdpi.com/2072-4292/12/6/1045>³⁸⁸

Sewe, University of Nairobi, E-band link availability thesis, <https://erepository.uonbi.ac.ke/bitstream/handle/11295/104383/Sewe%20Stephen.pdf?sequence=2&isAllowed=y>³⁸⁹

ITU-R Recommendation P.530-19 (09/2025), https://www.itu.int/dms_pubrec/itu-r-rec/p/R-REC-P.530-19-202509-!PDF-E.pdf³⁹⁰

IEEE SA, IEEE 802.11ay-2021, <https://standards.ieee.org/ieee/802.11ay/6142/>³⁹¹

Cambium Networks, PTP 550 datasheet, <https://www.eengineering.com/cambium-networks/ptp-550.htm>³⁹²

Mimosa, B6x product specification, <https://old.mimosa.co/product/b6x>³⁹³

Option	Typical capacity	Latency	Availability	Standard	Role here
Private 5G / CBRS n48	Tens to hundreds of Mbit/s per device ³⁹⁴	1 to 10 ms URLLC slice, 20 to 50 ms eMBB	Carrier-grade if licensed or PAL tier	3GPP Band 48 / n48	Campus and semi-urban
Public 4G LTE	Tens of Mbit/s typical	About 4 ms radio layer ³⁹⁵	Public-network SLA, varies	3GPP Rel-14	Rural fallback, mobile nodes
LEO satellite	25 to 220 down / 5 to 25 Mbit/s up ³⁹⁶	20 to 50 ms typical RTT ³⁹⁷	Weather and obstruction sensitive	Non-standardised	Remote rural primary
GEO VSAT	Tens of Mbit/s typical	480 to 700 ms RTT ³⁹⁸	Rain-fade limited at Ku and Ka	ITU-R Ku/Ka propagation series	Last-resort remote

Implication: edge-processed metadata at kilobit scale is compatible with every option in this table, including GEO VSAT. Raw I/Q at gigabit scale is compatible only with fibre or short-hop E-band and 60 GHz microwave. This reinforces edge processing as the default, with high-capacity links reserved for aggregation nodes, trunking and occasional forensic snapshot upload.

8.3 Timing distribution

Time-difference-of-arrival multilateration, specified in Sections 4 and 9.2, is only as accurate as the common time base across nodes. Radio waves travel approximately 30 cm per nanosecond, so a 1 ns inter-node timing error maps directly to about 30 cm of range error and timing architecture is a first-order design driver rather than a housekeeping detail.

8.3.1 GNSS timing and its vulnerability

Civil GPS standard positioning service typically achieves better than 13 m horizontal and 22 m vertical accuracy at 95 percent confidence, and the United States Department of Defense performance standard notes that well-designed receivers achieve about 3 m horizontal and 5 m vertical accuracy 95 percent of the time in practice.³⁹⁹⁴⁰⁰ Timing accuracy from a locked receiver, as distinct from position accuracy, is typically in the tens of nanoseconds in normal operation.

The critical design fact is that the open civil GNSS signal is unauthenticated and arrives at roughly -130 dBm, so it is vulnerable both to jamming, which denies the signal by overpowering it with noise, and to spoofing, in which counterfeit GNSS-like signals are accepted by the receiver and produce false position and time whose effects can persist after the attack ends. Both threat classes are documented by aviation and United Nations sources.⁴⁰¹⁴⁰² Multi-constellation reception across GPS, Galileo, GLONASS and BeiDou improves availability and geometric diversity but does not by itself defeat spoofing, because all four use structurally similar open signals. This matters more here than in a generic sensor network: a C-UAS system is by definition deployed against an adversary who

iFactory, Private LTE CBRS and private 5G overview, <https://ifactoryapp.com/greenfield-consulting/private-lte-cbrs-private-5g-394>
manufacturing-facilities

5G Americas, New Services and Applications with 5G URLLC white paper, https://www.5gamericas.org/wp-content/uploads/2019/07/5G_Americas_URLLC_White_Paper_Final__updateJW.pdf-395

Orbital Radar, Satellite internet speeds and latency, <https://orbitalradar.com/satellite-internet/speeds-and-latency-396>

Starlink, Starlink Latency report, <https://starlink.com/public-files/StarlinkLatency.pdf-397>

SatcomIndex, Satellite latency comparison, <https://www.satcomindex.com/id/blog/satellite-latency-comparison-398>

PMC article PMC11397858, review of GPS performance citing the US DoD GPS Standard Positioning Service Performance Standard, <https://pmc.ncbi.nlm.nih.gov/articles/PMC11397858/399>

University of Vaasa, GNSS timing study, <https://osuva.uwasa.fi/bitstreams/9419b460-91e3-4d35-baa5-3627b3c1e45b/download-400>

FAA, GPS/GNSS Interference Resource Guide, https://www.faa.gov/about/office_org/headquarters_offices/avs/offices/afx/afs/afs400/afs410/GNSS/GPS_GNSS_Interference_Resource_Guide.pdf401

UNOOSA, GNSS vulnerability briefing, 2023, https://www.unoosa.org/documents/pdf/psa/activities/2023/GNSS2023/GNSS2023_06_01.pdf402

may also possess GNSS jamming capability, so the timing chain must be assumed to be under attack at the moment the system is most needed.

8.3.2 Packet timing profiles and SyncE

IEEE 1588v2 Precision Time Protocol distributes sub-microsecond time over packet networks. Telecom-grade deployments use the ITU-T profiles rather than the default profile: G.8275.1 is the full timing support profile, in which every network element in the path is PTP-aware, giving the tightest achievable accuracy; G.8275.2 is the partial timing support profile, in which only a subset of elements need be PTP-aware, trading accuracy for deployability across networks that cannot be fully upgraded.⁴⁰³⁴⁰⁴

Synchronous Ethernet, ITU-T G.8262, distributes frequency rather than time of day over the Ethernet physical layer and is therefore immune to packet load and jitter. Free-run frequency accuracy is specified at 4.6 ppm, with defined bandwidth, noise generation, noise tolerance and transfer, and phase-transient limits, across interfaces from 100 Mbit/s to 100 Gbit/s.⁴⁰⁵⁴⁰⁶ The normal pairing is SyncE for frequency stability plus PTP for absolute phase and time of day.

8.3.3 Holdover: OCXO, rubidium and chip-scale atomic clocks

When GNSS is jammed, spoofed or simply unavailable, node-local oscillators must hold over the last known-good reference. Published free-running drift figures span roughly three orders of magnitude across the practical oscillator tiers.

Table 8-3 — Holdover oscillator comparison

Type	Typical power	1-hour drift	24-hour drift	Notes
OCXO	2 to 5 W	About 100 ns to 2 us	About 1 to 10 us, some specifications quote plus or minus 1.5 us ⁴⁰⁷⁴⁰⁸	Lowest cost; adequate only for rare, short GNSS outages
Rubidium	10 to 20 W	About 5 to 20 ns	About 100 to 500 ns, premium units under 120 ns ⁴⁰⁹⁴¹⁰	Used for G.8275.1 grandmaster holdover, defence and regulated finance
Chip-scale atomic clock	Sub-watt class ⁴¹¹	Not published in reviewed sources	About 1.5 us typical over temperature; monthly drift below 9e-10 implies roughly 2.3	Reported as about 100 times better holdover than a TCXO in GNSS-denied conditions; suits tight power budgets on solar or battery rural nodes ⁴¹³

ITU-T, Flyer for Recommendations G.8275.1 and G.8275.2, https://www.itu.int/en/ITU-T/studygroups/2022-4032024/15/Documents/flyers/Flyer_ITU-T_G.8275.1-2.pdf

ITU-T Recommendation G.8275.2 (02/2026), <https://www.itu.int/ITU-T/recommendations/rec.aspx?rec=16548404>

ITU-T Recommendation G.8262 (10/2024), Timing characteristics of synchronous equipment slave clocks, <https://www.itu.int/epublications/zh/publication/itu-t-g-8262-2024-10-timing-characteristics-of-synchronous-equipment-clocks/en>

Calnex Solutions, ITU-T G.8262 one-page summary, <https://calnexsolutions.atlassian.net/wiki/spaces/GDW/pages/10420373/ITU-T+G.8262+One-Page+Summary>

Timebeat, OCXO versus rubidium holdover, <https://timebeat.app/learn/ocxo-vs-rubidium-holdover407>

Timebeat, Oscillator tier selection, <https://timebeat.app/learn/oscillator-tier-selection408>

Timebeat, OCXO versus rubidium holdover, <https://timebeat.app/learn/ocxo-vs-rubidium-holdover409>

Timebeat, Oscillator tier selection, <https://timebeat.app/learn/oscillator-tier-selection410>

Microsemi, Miniature Atomic Clock (SA.35m) datasheet, https://cdn.sparkfun.com/assets/7/3/c/6/b/Microsemi_Miniature_Atomic_Clock_Datasheet.pdf

RF Essentials, Chip-scale atomic clock glossary entry, <https://rfessentials.com/resources/rf-glossary/chip-scale-atomic-clock413>

Type	Typical power	1-hour drift	24-hour drift	Notes
			us per day in some parts ⁴¹²	

Figures as published by the cited sources. The CSAC 1-hour figure was not stated in the reviewed material and is recorded as unknown rather than interpolated.

Engineering read [Derived]. For fixed urban nodes on mains or PoE power, where both GNSS jamming risk and expected holdover duration are modest, an OCXO-stabilised grandmaster with G.8275.1 full timing support is adequate. For rural, solar-powered or higher-threat nodes expecting longer or more frequent outages, a rubidium or CSAC holdover stage is justified by direct arithmetic: a rubidium unit holding under 500 ns across 24 hours keeps the TDOA range-error contribution below roughly 150 m even after a full day without GNSS, whereas a free-running OCXO drifting several microseconds over the same interval produces kilometre-scale error. Applying the 30 cm per nanosecond relation:

$$\text{Rb: } 500 \text{ ns} \times 0.2998 \text{ m/ns} = 150 \text{ m} \quad \text{range-error contribution}$$

$$\text{OCXO: } 5\,000 \text{ ns} \times 0.2998 \text{ m/ns} = 1\,499 \text{ m} \quad \text{range-error contribution}$$

The difference is decisive for multilateration geometry and is the reason holdover class, not GNSS receiver quality, is the governing timing requirement for rural nodes.

8.4 Power and physical node engineering

8.4.1 Node power budget

Table 8-4 — Sensor node continuous power budget [Derived]

Subsystem	Estimated power	Basis
SDR receiver, 56 MHz-class front end	15 W	Section 4 receiver assumption
Edge inference compute, embedded GPU or SoC	20 W	Sections 4 to 7 processing load
Acoustic front end, 16-channel ADC and preamplifiers	5 W	Section 6 array
Backhaul radio or modem	8 W	Section 8.2
GNSS and timing module plus housekeeping	7 W	Section 8.3
Total continuous load	55 W	Sum

All values [Derived] as early-stage sizing estimates, not vendor guarantees.

The estimate is consistent with published measurements. An SDR-based 5G research platform reports about 24.8 W average consumption for the radio subsystem alone,⁴¹⁴ a compact embedded SDR in the USRP B206 class powered over USB draws under 5 W by itself,⁴¹⁵ and research-grade ultra-low-power SDRs can idle in the tens of microwatts to hundreds of milliwatts but do not offer the 56 MHz instantaneous bandwidth assumed here.⁴¹⁶ The 55 W total should be re-derived against actual selected hardware before any site power design is committed.

Microsemi, Miniature Atomic Clock (SA.35m) datasheet, ⁴¹²
https://cdn.sparkfun.com/assets/7/3/c/6/b/Microsemi_Miniature_Atomic_Clock_Datasheet.pdf

Preprint, power measurement of an SDR-based 5G research deployment, ⁴¹⁴
https://d197for5662m48.cloudfront.net/documents/publicationstatus/182758/preprint_pdf/db172cab3af61a5cf4a6c34c2edde408.pdf

Ettus Research knowledge base, AI-Based Spectrum Sensing with NVIDIA Jetson and USRP, https://kb.ettus.com/AI-Based_Spectrum_Sensing_with_Nvidia_Jetson_and_USRP, ⁴¹⁵

Hessar et al., tinySDR: Low-Power SDR Platform for Over-the-Air Programmable IoT Testbeds, ⁴¹⁶
<https://homes.cs.washington.edu/~gshyam/Papers/tinysdr.pdf>

8.4.2 Power over Ethernet

Table 8-5 — PoE standards and available power

Standard	Type	Power at PSE	Guaranteed at PD
IEEE 802.3af (2003)	Type 1	15.4 W	12.95 W
IEEE 802.3at (2009)	Type 2, PoE+	30.0 W	25.5 W
IEEE 802.3bt (2018)	Type 3	60 W	51 W
IEEE 802.3bt (2018)	Type 4	90 W	71.3 W

Values as published for IEEE 802.3af, 802.3at and 802.3bt.

The values above are as published for the three PoE generations.⁴¹⁷ [Derived] The 55 W node load of Table 8-4 exceeds the 25.5 W available under 802.3at and therefore requires an 802.3bt Type 3 or Type 4 power sourcing equipment, offering 51 W or 71.3 W at the powered device. Type 3 is feasible but leaves very little headroom for enclosure heaters or link redundancy, so Type 4 is the recommended choice where PoE is used at all. Many urban node designs will instead take a local 24 or 48 V DC supply from a small mains rectifier at the mast base, reserving PoE for lighter nodes such as acoustic-only or single-band RF sensors.

8.4.3 Solar and battery sizing, rural worked example

Assumptions [Derived]: 55 W continuous load from Table 8-4; worst-month insolation of 2.0 peak-sun-hours per day, a realistic winter figure for temperate rural sites in central or northern Europe; 75 percent system derating as the standard off-grid allowance for temperature, soiling, wiring and charge-controller losses;⁴¹⁸ three-day battery autonomy at 80 percent depth of discharge on lithium iron phosphate chemistry, following the same design logic as the AS/NZS 4509.2 stand-alone power system methodology.⁴¹⁹

Step 1 — Daily energy demand:

$$55 \text{ W} \times 24 \text{ h} = 1\,320 \text{ Wh/day} = 1.32 \text{ kWh/day}$$

Step 2 — Required photovoltaic array:

$$1\,320 \text{ Wh} / (2.0 \text{ PSH} \times 0.75) = 880 \text{ W of panel capacity}$$

Step 3 — Battery capacity for three-day autonomy at 80 percent depth of discharge:

$$(1\,320 \text{ Wh} \times 3) / 0.80 = 4\,950 \text{ Wh} = \sim 206 \text{ Ah at } 24 \text{ V}$$

Cross-check: a published off-grid example needing 3 000 Wh per day in a 4.5 peak-sun-hour region sizes to roughly 900 W of solar and about 11 kWh of battery,⁴²⁰ a similar watt-hour-per-panel-watt ratio to the figures above once adjusted for the lower node load and shorter worst-month insolation, which confirms the derivation is in a sane engineering range. Real deployments must re-run this calculation against site-specific typical-meteorological-year irradiance data rather than the round-number peak-sun-hour value assumed here.

8.4.4 Enclosure, environmental and structural standards

- **Ingress protection.** IP66 is dust-tight and protected against powerful water jets from a 12.5 mm nozzle, suiting washdown- or heavy-rain-exposed housings; IP67 is dust-tight and withstands temporary immersion to 1 m for 30 minutes, the normal choice for buried junction boxes and outdoor sensor housings.⁴²¹

Wikipedia, Power over Ethernet, citing IEEE 802.3af/at/bt, https://en.wikipedia.org/wiki/Power_over_Ethernet⁴¹⁷

Off Grid Collective, How to size an off-grid solar system, <https://offgridcollective.co/us/guides/power-systems/how-to-size-off-grid-solar-system/>⁴¹⁸

AS/NZS 4509.2 stand-alone power system sizing, technical walkthrough, <https://www.youtube.com/watch?v=hiwQY2ezBGc>⁴¹⁹

Off Grid Collective, How to size an off-grid solar system, <https://offgridcollective.co/us/guides/power-systems/how-to-size-off-grid-solar-system/>⁴²⁰

SolidShell, NEMA and IP rating guide, <https://www.solidshell.co/en/nema-and-ip>⁴²¹

- **NEMA cross-reference.** NEMA 4 and 4X, covering outdoor windblown dust and rain, hose-directed water and ice, map approximately to IP66. NEMA and IP numbering are not linearly equivalent, so cross-reference tables must be consulted per product rather than assumed.⁴²²
- **MIL-STD-810.** The United States Department of Defense environmental engineering test standard, defining chamber-replicated test methods for temperature, humidity, vibration, shock and altitude rather than directly mimicking real environments, and now used commercially as a de facto ruggedisation benchmark. Method 514.8 covers the vibration levels and durations relevant to mast-mounted equipment.⁴²³⁴²⁴⁴²⁵
- **Lightning protection, IEC 62305.** A four-part suite adopted in Europe as EN/IEC 62305, covering risk assessment and physical damage prevention, with Part 4 specifying surge protection measures for electrical and electronic systems against lightning electromagnetic impulse.⁴²⁶⁴²⁷
- **Surge immunity, IEC 61000-4-5.** Defines surge test set-up, waveforms, procedures and severity classification for equipment exposed to induced lightning transients and switching surges on power and data lines, complementing the system-level design guidance of IEC 62305.⁴²⁸
- **Structural loading.** TIA-222-H is the North American structural standard for antenna-supporting structures, defining dead, ice, wind, seismic and temperature load combinations with return periods drawn from ASCE 7. EN 1991-1-4 is the European wind-action equivalent, defining basic wind velocity by direction and season at 10 m height over terrain category III and applying to buildings up to 200 m and guyed masts or lattice towers up to 300 m.⁴²⁹⁴³⁰⁴³¹

Node antenna and enclosure mounts on existing masts must be re-checked against the structure original TIA-222 or EN 1991-1-4 rating. Added wind-catching area from enclosures, radomes and cable runs is a common and frequently overlooked cause of tower-loading non-compliance in retrofit sensor deployments, and it is a real programme risk for this system specifically, because acoustic arrays and RF antenna panels are both physically bulky relative to their mass.

8.5 Transport security and zero trust

Every sensor node is a physically exposed, remotely sited endpoint on a network that may traverse third-party carrier or satellite transport. It must therefore be treated as untrusted. Mutual TLS, which authenticates both ends rather than only the server, is the default for node-to-aggregator and aggregator-to-command links. NIST SP 800-207, published in August 2020, is the governing zero-trust reference: it defines zero trust as the removal of implicit trust in users, services and devices, requiring per-request authentication and authorisation instead of perimeter-based trust,⁴³² and SP 800-207A extends the model to access control in cloud-native, multi-location application

Tripp Lite (Eaton), Enclosure ratings NEMA-to-IP cross-reference, <https://tripplite.eaton.com/products/enclosure-ratings>⁴²²

Wikipedia, MIL-STD-810, <https://en.wikipedia.org/wiki/MIL-STD-810>⁴²³

MIL-STD-810 original standard text, archival copy via EB Industries, <https://ebindustries.com/wp-content/uploads/2021/11/MIL-STD-810.pdf>⁴²⁴

MIL-STD-810H Method 514.8, Vibration, <https://cvgstrategy.com/wp-content/uploads/2019/08/MIL-STD-810H-Method-514.8-Vibration.pdf>⁴²⁵

EN IEC 62305-4:2024, Protection against lightning, Part 4, <https://standards.iteh.ai/catalog/standards/clc/e35b197f-5fb3-4d30-a277-7e888727412b/en-iec-62305-4-2024>⁴²⁶

Furse, Guide to BS EN/IEC 62305 lightning protection, 3rd edition, https://www.lightning.gg/wp-content/uploads/2021/09/z.Furse-Guide_3rd-Edition.pdf⁴²⁷

Wikipedia, IEC 61000-4-5 surge immunity test, https://en.wikipedia.org/wiki/IEC_61000-4-5⁴²⁸

TIA-222-H Commentary, Revision 1, <https://www.towermx.com/downloads/TIA-222-H-Commentary-Rev-1-03252022.pdf>⁴²⁹

EN 1991-1-4:2026, Eurocode 1 Part 1-4 wind actions, scope, <https://standards.iteh.ai/catalog/standards/cen/ba31a01d-2e1e-4f24-9d60-a2b1acb68f86/en-1991-1-4-2026>⁴³⁰

Kisfali, Calculating wind load on antennas per Eurocode EN 1991-1-4, <https://kisfali.com/blog/how-to-calculate-wind-load-on-5g-antennas-as-per-eurocode>⁴³¹

NIST SP 800-207, Zero Trust Architecture, <https://csrc.nist.gov/pubs/sp/800/207/final>⁴³²

environments,⁴³³ which is precisely the shape of a distributed sensor fleet reporting into a centralised or federated backend. In implementation terms this means workload identity, mutual TLS at every hop rather than only at the network edge, and explicit per-request policy evaluation rather than a single perimeter firewall.⁴³⁴ IPsec remains appropriate for site-to-site tunnels between aggregation points and backhaul hubs where a network-layer VPN is preferred over application-layer TLS, particularly across untrusted carrier or satellite links.

At the control-system level, NIST SP 800-53 Revision 5 provides the baseline security and privacy control catalogue across twenty control families including access control, audit and accountability, configuration management, incident response, system and communications protection, and supply chain risk management.⁴³⁵ NIST SP 800-82 applies those controls specifically to industrial control and operational technology systems, addressing their distinct performance, reliability and safety constraints,⁴³⁶⁴³⁷ which is the correct lens for these nodes because they are functionally remote field devices rather than IT servers. IEC 62443 is the international counterpart, covering industrial automation and control system security across general, policy, system and component layers and assigning requirements separately to asset owners, system integrators and product suppliers.⁴³⁸

8.6 Interoperability, data formats and command integration

- **Remote ID, ASTM F3411.** Defines message formats, transmission methods and minimum performance for both broadcast Remote ID, transmitted directly from the aircraft to nearby receivers, and network Remote ID, mediated over the internet by a service provider, across very-low-level airspace including rural, urban, network-degraded and network-denied environments. The RF sensors of Section 4 are natural broadcast Remote ID receivers and shall decode it as a high-confidence cooperative-target source, kept explicitly distinct from the non-cooperative detection problem.⁴³⁹
- **European equivalent.** Regulation (EU) 2019/945 sets design and manufacture requirements for unmanned aircraft and remote identification add-ons, while 2019/947 sets operational rules and defines direct remote identification as the local broadcast of aircraft information, including marking, obtainable without physical access to the aircraft.⁴⁴⁰⁴⁴¹
- **ASTERIX CAT-129.** The EUROCONTROL surveillance data exchange category for unmanned aircraft identification reports, carrying manufacturer, model and serial identifiers, WGS-84 position, altitude above mean sea level and above ground level, and operational risk level. A United States study on airspace-

NIST SP 800-207A initial public draft, Zero Trust Architecture model for access control in cloud-native application environments,⁴³³
<https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.800-207A.ipd.pdf>

The Engineering Codex, Service mesh and zero trust, [https://the-engineering-codex.vercel.app/courses/cloud-security/chapters/service-](https://the-engineering-codex.vercel.app/courses/cloud-security/chapters/service-mesh-zero-trust)⁴³⁴
mesh-zero-trust

NIST SP 800-53 Revision 5, Security and Privacy Controls for Information Systems and Organizations,⁴³⁵
<https://csrc.nist.gov/pubs/sp/800/53/r5/upd1/final>

NIST SP 800-82 Revision 1, Guide to Industrial Control Systems Security,⁴³⁶
<https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.800-82r1.pdf>

NIST SP 800-82 Revision 2, status and withdrawal notice, <https://nvlpubs.nist.gov/nistpubs/specialpublications/nist.sp.800-82r2.pdf>⁴³⁷

JPCERT/CC, IEC 62443 series overview, <https://www.jpCERT.or.jp/ics/information02.html>⁴³⁸

ASTM F3411-22a, Standard Specification for Remote ID and Tracking, <https://www.astm.org/f3411-22a.html>⁴³⁹

EUR-Lex, Commission Implementing Regulation (EU) 2019/947, https://eur-lex.europa.eu/eli/reg_impl/2019/947/oj/eng⁴⁴⁰

EUR-Lex, Commission Delegated Regulation (EU) 2019/945, consolidated text, [https://eur-lex.europa.eu/legal-](https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0945)⁴⁴¹
content/EN/TXT/PDF/?uri=CELEX:32019R0945

awareness architecture recommends pairing CAT-129 for cooperative Remote-ID-equipped aircraft with ASTERIX CAT-062 for general, including non-cooperative, surveillance track fusion.⁴⁴²⁴⁴³⁴⁴⁴

- **Messaging: MQTT and Kafka.** MQTT is a lightweight publish and subscribe protocol built for constrained devices and unreliable links, with typical latency under 5 ms and a two-byte fixed header, whereas Apache Kafka is a distributed, persistent, high-throughput event-streaming platform suited to backend aggregation, replay and multi-consumer fan-out at correspondingly higher latency of roughly 10 to 100 ms. The natural split is MQTT from sensor node to aggregator and Kafka from aggregator into the backend analytics and command pipeline, matching each protocol to the segment its design targets.⁴⁴⁵⁴⁴⁶
- **Cursor on Target and TAK.** CoT is a lightweight extensible XML message format originally developed for sharing position, identity and status between heterogeneous tactical systems without central coordination, and has become the de facto tactical-edge interoperability format. A TAK Server federates CoT event streams between connected clients over TCP and TLS, persisting a common operational picture and enabling multi-site or multi-national sharing with classification-based filtering. Publishing detections as CoT events into a TAK Server is the most direct route to interoperability with existing defence and public-safety command ecosystems, and has been demonstrated feeding drone-detection data into allied common operating pictures during multinational exercises.⁴⁴⁷⁴⁴⁸⁴⁴⁹

NATO tactical data links. This research did not surface a C-UAS-specific STANAG mapping, and none is asserted here. Link 16 is the NATO tactical data link for near-real-time exchange of track and identity data between military platforms; a network intended for military or coalition integration would normally bridge its native CoT or ASTERIX output into a Link 16 gateway rather than implement Link 16 waveforms at the sensor node. This remains an architecture placeholder requiring direct engagement with the customer specific command and control integration requirements, and is recorded as a declared gap in Section 11 rather than as a specified capability.

8.7 Network, timing and power requirements

Table 8-6 — Network, backhaul, timing and power requirements

ID	Requirement	Verification
REQ-NW-001	Each sensor node SHALL perform detection, classification and bearing or time-difference estimation locally and SHALL transmit structured detection and track reports rather than continuous raw I/Q or raw audio.	Inspection
REQ-NW-002	The nominal steady-state backhaul load per node SHALL NOT exceed 200 kbit/s for detection metadata plus health telemetry at the 50-concurrent-track design ceiling.	Bench Test
REQ-NW-003	Each node SHALL support opportunistic upload of a bounded raw I/Q or raw multichannel audio snapshot around a high-confidence detection, and this upload SHALL be rate-limited so that it cannot pre-empt detection-alert traffic.	Bench Test

EUROCONTROL, ASTERIX Category 129 specification, Part 29,⁴⁴²

<https://www.eurocontrol.int/sites/default/files/content/documents/nm/asterix/cat129p29ed11.pdf>

EUROCONTROL, CAT129 publication page, <https://www.eurocontrol.int/publication/cat129-eurocontrol-specification-surveillance-data-exchange-asterix-part-29-category>⁴⁴³

US DOT/FAA, Low Altitude Authorization and Airspace Awareness interface report,⁴⁴⁴

https://rosap.ntl.bts.gov/view/dot/73158/dot_73158_DS1.pdf

FlowFuse, Kafka versus MQTT, <https://flowfuse.com/blog/2025/12/kafka-vs-mqtt>⁴⁴⁵

i-flow.io, Comparison of message brokers: MQTT, Kafka, AMQP and NATS, <https://i-flow.io/en/ressources/mqtt-kafka-amqp-or-nats-comparison-of-message-brokers/>⁴⁴⁶

Corvus Intelligence, Cursor on Target (CoT) format overview, <https://corvusintell.com/blog/c2-systems/cursor-on-target-cot-format>⁴⁴⁷

Corvus Intelligence, TAK ecosystem C2 integration, <https://corvusintell.com/blog/field-apps/tak-ecosystem-c2-integration-custom>⁴⁴⁸

FSG-A, Lisa 26 / JEF exercise TAK integration case study, <https://fsg-a.com/chapters/lisa26-jef-integration.html>⁴⁴⁹

ID	Requirement	Verification
REQ-NW-004	Detection-alert traffic SHALL be carried on a separately prioritised class, slice or queue from bulk telemetry, log and snapshot traffic.	Inspection
REQ-NW-005	Each node SHALL continue local detection, classification and alert generation, and SHALL buffer reports for later delivery, during total loss of backhaul for at least 24 h.	Field Trial
REQ-NW-006	Backhaul selection per node SHALL be justified against a documented link budget. E-band hops SHALL be dimensioned using ITU-R P.530 with P.837 rain climatology and P.838 specific attenuation for the declared availability target.	Analysis
REQ-NW-007	E-band hops specified for 99.999 percent availability SHALL NOT exceed 3 km unless a site-specific rain-rate analysis supports a longer path.	Analysis
REQ-NW-008	Where unlicensed 2.4 GHz or 5 GHz backhaul radios are co-located with RF sensor nodes, an interference analysis SHALL demonstrate that backhaul emissions do not desensitise the sensor in the bands it is required to monitor.	Field Trial
REQ-NW-009	Nodes backhauled over GEO satellite SHALL NOT be relied upon for any function whose specified latency budget is below 1 s.	Analysis
REQ-NW-010	Published URLLC latency figures SHALL NOT be used as end-to-end network budgets. Latency budgets SHALL be established by measurement on the deployed transport under representative load.	Field Trial
REQ-NW-011	Inter-node time synchronisation error SHALL be below 100 ns root mean square for nodes participating in RF time-difference-of-arrival multilateration.	Bench Test
REQ-NW-012	Inter-node time synchronisation error SHALL be below 10 us for nodes participating only in acoustic time-difference processing.	Bench Test
REQ-NW-013	Time distribution SHALL use IEEE 1588v2 under ITU-T G.8275.1 where the transport path is fully PTP-aware, and MAY use G.8275.2 only where partial timing support is unavoidable, with the resulting accuracy degradation quantified.	Analysis
REQ-NW-014	Where the transport is Ethernet-based, Synchronous Ethernet per ITU-T G.8262 SHOULD be used for frequency stabilisation alongside PTP phase and time-of-day distribution.	Inspection
REQ-NW-015	Each node SHALL use a multi-constellation GNSS timing receiver with anti-jamming and anti-spoofing features, and SHALL report GNSS lock status, constellation count and any spoofing indication as part of health telemetry.	Inspection
REQ-NW-016	The system SHALL NOT treat GNSS availability as an assumption. Loss or corruption of GNSS SHALL raise an operator-visible degraded-timing condition, and the affected nodes SHALL be flagged in the fused track picture.	Field Trial
REQ-NW-017	Nodes participating in RF multilateration SHALL provide a holdover oscillator maintaining the REQ-NW-011 timing budget for a declared minimum outage duration. Rubidium or chip-scale atomic holdover SHALL be used where the declared duration exceeds 1 h.	Bench Test
REQ-NW-018	OCXO-only holdover SHALL NOT be used on nodes whose declared GNSS-denial exposure exceeds 1 h, since multi-microsecond drift degrades multilateration range error to the kilometre scale.	Analysis
REQ-NW-019	The per-node continuous power budget SHALL be re-derived against selected hardware before site power design, and the 55 W figure of Table 8-4 SHALL be treated as an estimate rather than a specification.	Analysis
REQ-NW-020	Where PoE powers a full multi-sensor node, IEEE 802.3bt Type 3 or Type 4 power sourcing equipment SHALL be used. IEEE 802.3at SHALL NOT be used for a full node.	Inspection
REQ-NW-021	Off-grid nodes SHALL be sized against site-specific typical-meteorological-year irradiance data, with a documented worst-month calculation, a stated system derating factor and a stated autonomy period.	Analysis
REQ-NW-022	Off-grid nodes SHALL provide a minimum of three days autonomy at the declared continuous load without solar input.	Bench Test
REQ-NW-023	Node enclosures SHALL meet IP66 as a minimum, and IP67 where temporary immersion or flooding is credible at the site.	Bench Test

ID	Requirement	Verification
REQ-NW-024	Mast-mounted node hardware SHALL be qualified for temperature, humidity, vibration and shock against MIL-STD-810 methods appropriate to the site, including Method 514.8 for vibration.	Bench Test
REQ-NW-025	Node installations SHALL implement lightning protection per IEC 62305, including Part 4 surge protection measures, and node electronics SHALL pass IEC 61000-4-5 surge immunity at a severity level appropriate to the site.	Bench Test
REQ-NW-026	Every mast or building mounting SHALL be verified against the structure original TIA-222 or EN 1991-1-4 structural rating, accounting for the added projected wind area of enclosures, radomes, antennas and cabling.	Analysis
REQ-NW-027	All node-to-aggregator and aggregator-to-command links SHALL use mutual TLS with per-node cryptographic identity. Network location SHALL NOT be used as an authentication factor.	Inspection
REQ-NW-028	The system SHALL be designed to NIST SP 800-207 zero-trust principles, with per-request authorisation, and SHALL apply an operational-technology control baseline derived from NIST SP 800-82 or IEC 62443.	Inspection
REQ-NW-029	Node firmware and configuration updates SHALL be cryptographically signed, and a node SHALL refuse to execute unsigned or unverifiable images.	Bench Test
REQ-NW-030	The system SHALL decode broadcast Remote ID per ASTM F3411 where present and SHALL present it as a distinct cooperative-identification source, never merged into non-cooperative detection confidence.	Field Trial
REQ-NW-031	The system SHALL export track data in at least one recognised external format, from ASTERIX CAT-129 or CAT-062 or Cursor on Target, and the selected format SHALL be validated against an independent receiving system.	Field Trial
REQ-NW-032	Node-to-aggregator transport SHOULD use MQTT or an equivalent lightweight publish and subscribe protocol; aggregator-to-backend transport SHOULD use a persistent event-streaming platform supporting replay.	Inspection
REQ-NW-033	Any NATO tactical data link integration SHALL be achieved through an external gateway translating the native export format. Link 16 or equivalent waveforms SHALL NOT be implemented at the sensor node.	Inspection

9 Deployment Scenarios and Coverage Engineering

This section converts sensor performance into siting geometry and node counts, then instantiates the three node types of Section 2 into concrete urban, rural and mobile deployment scenarios. Two cautions govern the whole section. First, all node-count arithmetic below is geometric, treating detection range as a circle of fixed radius; real coverage is a ragged, terrain- and clutter-dependent volume, and the numbers are sizing estimates rather than coverage guarantees. Second, the three modalities have detection ranges that differ by more than an order of magnitude, so a single node grid cannot provide uniform multi-modality coverage, and pretending otherwise is the most common error in C-UAS network planning.

9.1 Coverage geometry and node count

Hexagonal packing, as used in cellular planning, is applied here. For a sensor of usable detection radius r , the effective non-overlapping coverage of a hexagonal cell inscribed with circumradius r is:

$$A_{\text{hex}} = (3 \times \sqrt{3} / 2) \times r^2 = 2.598 \times r^2$$

This is larger than a naive πr^2 circle count suggests, because hexagons tile the plane without gaps or excess overlap.

Table 9-1 — Published detection ranges used for coverage sizing

Modality	Published range	Notes and sensitivity
RF	1 to 5 km typical, up to about 10 km with favourable line of sight and high antennas ⁴⁵⁰⁴⁵¹⁴⁵²	Urban RF noise reduces range significantly; range is emitter-power dependent, not a fixed sensor property
Acoustic	100 to 500 m typical for small consumer-class aircraft, up to about 1 km for larger aircraft in quiet conditions ⁴⁵³⁴⁵⁴⁴⁵⁵	Highly sensitive to the urban ambient noise floor; 10 to 50 times shorter than RF
LTE monitoring	Coverage-footprint dependent rather than range-limited	Applies only to cellular-connected aircraft; see Section 5

9.1.1 Urban worked example

Assumption: 5 km usable RF detection radius per node [Derived from the published 1 to 5 km typical range, taking the upper bound for an above-rooftop urban installation].

$$A_{\text{hex}}(5 \text{ km}) = 2.598 \times 5^2 = 65.0 \text{ km}^2 \text{ per node}$$

$$\text{City area, 15 km effective radius} = \pi \times 15^2 = 707 \text{ km}^2$$

$$N_{\text{urban}} = \text{ceil}(707 / 65.0) = 11 \text{ nodes}$$

CounterUAVHub, RF detection range calculator, <https://counteruavhub.com/tools/rf-detection-range/>⁴⁵⁰

LZTech, RF detection versus radar versus optical sensors, <https://lzttech.tech/rf-detection-vs-radar-vs-optical-sensors-which-counter-drone-technology-fits-your-site/>⁴⁵¹

Dedrone, RF-160 radio frequency sensor announcement, <https://www.dedrone.com/press/dedrone-introduces-next-generation-radio-frequency-sensor-rf-160-for-suas-detection-and-threat-mitigation>⁴⁵²

Jared Watkins, Acoustic drone detection review, <https://www.jaredwatkins.com/research/drone-detection/detection-methods/acoustic-detection/>⁴⁵³

MicrodB, ALARM acoustic environmental monitoring sensor, <https://microdb.fr/en/product/environmental-monitoring/>⁴⁵⁴

Pinel-Lamotte et al., acoustic drone monitoring, Quiet Drones 2020 e-Symposium, https://microdb.fr/wp-content/uploads/sites/3/2024/04/4-55-Monitoring_A108_QuietDrone2020_Pinel-Lamotte-final.pdf⁴⁵⁵

9.1.2 Rural worked example

Assumption: 20 km usable RF detection radius per node [Derived], reflecting mast-height and clear-line-of-sight advantage; note this exceeds the published 10 km favourable-conditions figure of Table 9-1 and must be validated by site survey before it is relied upon.

$$A_{\text{hex}}(20 \text{ km}) = 2.598 \times 20^2 = 1\,039.2 \text{ km}^2 \text{ per node}$$

$$\text{Region area, } 50 \text{ km effective radius} = \pi \times 50^2 = 7\,854 \text{ km}^2$$

$$N_{\text{rural}} = \text{ceil}(7\,854 / 1\,039.2) = 8 \text{ nodes}$$

The central economic trade-off [Derived]. A rural node covers roughly 16 times the area of an urban node, 1 039 km-squared against 65 km-squared, which is exactly the 4-times range ratio squared. Rural coverage therefore needs far fewer nodes per unit area, but each node demands longer and harder backhaul from Section 8.2 and standalone power from Section 8.4.3. Urban coverage needs a denser grid but can normally exploit existing fibre and street-furniture power with short-hop unlicensed or E-band backhaul. Cost per square kilometre and cost per node move in opposite directions between the two cases.

The acoustic sub-grid problem. The areas above are single-modality RF coverage. Acoustic sensors, with 10 to 50 times shorter range, would require a correspondingly denser sub-grid layered inside the same footprint if acoustic corroboration were required everywhere. [Derived] At a 500 m acoustic radius the hexagonal cell is $2.598 \times 0.5\text{-squared} = 0.65 \text{ km-squared}$, so blanket acoustic coverage of the 707 km-squared city of Section 9.1.1 would need approximately 1 088 acoustic nodes against 11 RF nodes, a ratio of about 99 to 1. This is why acoustic nodes are deployed only at higher-priority, close-range sites such as airport perimeters, critical-infrastructure boundaries and event venues, rather than blanketing the RF footprint. Any claim of uniform multi-modality coverage across a wide area should be treated as an error.

9.2 Multilateration geometry and dilution of precision

Time-difference-of-arrival multilateration relates root-mean-square three-dimensional position error to root-mean-square measurement error through the geometric dilution of precision factor, as formally defined in EUROCONTROL wide-area multilateration surveillance guidance:⁴⁵⁶

$$\sigma_{\text{xyz}} = \text{GDOP} \times \sigma_{\text{TDOA}}$$

GDOP is not a fixed system property. It varies with target position relative to the sensor layout, so identical timing accuracy yields different position accuracy depending on where in the coverage area the target is, and geometry quality generally improves as more well-distributed sensors observe the same target.⁴⁵⁷ Three consequences follow directly and constrain siting more tightly than range does.

- Targets near the centroid of a sensor polygon see the best, lowest GDOP. Targets outside the convex hull of the sensor layout, or aligned nearly collinearly with only two sensors, see severely degraded GDOP even at short range.
- Node siting shall favour irregular, well-distributed geometries over straight-line or clustered layouts. A row of nodes along a road or a fence line is close to the worst case, and is unfortunately also the easiest layout to permit and cable.
- Coverage-edge performance shall be modelled explicitly and never assumed equal to centroid performance. A single quoted position accuracy figure for a network is meaningless without the target position it applies to.

Because position error scales directly with measurement error, and measurement error is bounded below by inter-node clock synchronisation error, the sub-100 ns timing requirement of REQ-NW-011 is what makes tens-of-metres positioning achievable at all. This closes the loop with Section 8.3: timing class is a coverage-quality parameter, not an infrastructure detail.

EUROCONTROL, Wide Area Multilateration surveillance report, <https://www.eurocontrol.int/sites/default/files/2019-05/surveillance-report-456-wide-area-multilateration-200508.pdf>

Dialnet article 4991531, estimated position error and GDOP in multilateration, <https://dialnet.unirioja.es/descarga/articulo/4991531.pdf>⁴⁵⁷

9.3 Urban propagation and siting

- **ITU-R P.1411.** Propagation prediction methods for short-range outdoor systems from 300 MHz to 100 GHz, explicitly modelling that below 1 km building and tree clutter dominate over terrain elevation, and categorising cell types by base antenna height relative to rooftop level: small macro-cell 0.5 to 3 km, micro-cell 100 to 500 m, pico-cell under 100 m.⁴⁵⁸
- **ITU-R P.2109.** Building entry loss model from 80 MHz to 100 GHz, used in sharing and compatibility studies to quantify wall and window attenuation on outdoor-to-indoor paths. This is directly relevant to estimating how much a ground controller signal is attenuated when the operator is inside a building, which is a realistic and awkward case for RF detection.⁴⁵⁹
- **3GPP TR 38.901 urban models.** The standard system-level path-loss models: Urban Micro street-canyon with the base station below rooftop level, and Urban Macro with the base station above rooftop and a larger cell radius, each with explicit line-of-sight and non-line-of-sight equations. The Urban Macro line-of-sight case is $PL = 28.0 + 22 \log_{10}(d) + 20 \log_{10}(fc)$ dB for 10 m less than d less than 5 km.⁴⁶⁰⁴⁶¹

Siting implications differ sharply by modality, which is the practical reason node siting cannot be delegated to a single rule. Urban RF nodes should be mounted above average rooftop level, matching the small macro-cell category of P.1411, to reduce non-line-of-sight and shadowing loss. Acoustic sensors detect airborne sound rather than an RF path and are therefore governed by different physics: urban reverberation from building facades extends decay time and smears arrival-time estimates, and the elevated ambient noise floor from traffic, ventilation plant and wind directly erodes the 100 to 500 m nominal range of Table 9-1. Acoustic placement should favour a clear unobstructed line to likely approach corridors and distance from major noise sources, for example rooftops set back from street level or courtyards shielded from traffic. An optimal RF position and an optimal acoustic position on the same building are frequently not the same position.

9.4 Urban deployment scenario, Node Type A

Table 9-2 — Urban scenario, rooftop node (Type A)

Parameter	Urban rooftop node
Siting	Above average rooftop level per ITU-R P.1411 small macro-cell category; RF and acoustic mounting positions optimised independently
Assumed RF detection radius	5 km [Derived, upper bound of published 1 to 5 km typical range]
Hex cell per node	65.0 km-squared [Derived]
Nodes for a 15 km-radius city	11 [Derived]
Acoustic coverage	Selective only, at protected sites; blanket coverage would need roughly 99 acoustic nodes per RF node [Derived]
Primary backhaul	GPON or XGS-PON where duct access exists; active Ethernet for aggregation nodes
Secondary backhaul	E-band hop of 5 km or less, or 60 GHz mesh infill; public LTE as tertiary fallback
Power	Mains-derived 24 or 48 V DC at mast base, or IEEE 802.3bt Type 4 PoE
Timing	G.8275.1 full timing support over the fibre path, OCXO grandmaster holdover, SyncE frequency assist

ITU-R Recommendation P.1411, propagation data for short-range outdoor systems, https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-458-P.1411-0-199910-S!!PDF-E.pdf

ITU-R Recommendation P.2109-2 (08/2023), prediction of building entry loss, https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.2109-2-459-202308-1!!PDF-E.pdf

RF Essentials, 3GPP channel model glossary entry summarising TR 38.901, <https://rfessentials.com/resources/rf-glossary/3gpp-channel-model/>

3GPP TR 38.901, Study on channel model for frequencies from 0.5 to 100 GHz, https://panel.castle.cloud/view_spec/38901-f10/pdf/⁴⁶¹

Parameter	Urban rooftop node
Dominant limitations	Elevated RF noise floor reduces effective range; acoustic range eroded by ambient noise and reverberation; structural loading and planning consent on third-party rooftops
Dominant regulatory driver	Privacy and data protection exposure from the acoustic layer in public space; see Section 12

9.5 Rural deployment scenario, Node Type B

Table 9-3 — Rural scenario, mast node (Type B)

Parameter	Rural mast node
Siting	Existing telecommunications mast or purpose-built tower; irregular, non-collinear network geometry for GDOP per Section 9.2
Assumed RF detection radius	20 km [Derived, requires site survey validation since it exceeds the published 10 km favourable-conditions figure]
Hex cell per node	1 039.2 km-squared [Derived]
Nodes for a 50 km-radius region	8 [Derived]
Acoustic coverage	Point defence only at specific assets; wide-area acoustic coverage is not economically or physically achievable
Primary backhaul	Licensed microwave in the 6 to 42 GHz bands for long hops, or LEO satellite where no terrestrial path exists
Secondary backhaul	Public LTE where coverage exists; GEO VSAT only as last resort, subject to REQ-NW-009
Power	880 W photovoltaic array with 4 950 Wh, about 206 Ah at 24 V, battery for three-day autonomy [Derived, Section 8.4.3]
Timing	Rubidium or chip-scale atomic holdover mandatory per REQ-NW-017 given extended GNSS-denial exposure and limited network timing support
Dominant limitations	Backhaul cost and availability; power autonomy in worst-month insolation; long unattended maintenance intervals; lightning exposure on tall isolated structures
Dominant regulatory driver	Spectrum authorisation for backhaul links; aviation coordination where masts sit near approach paths

9.6 Mobile and temporary deployment scenario, Node Type C

Table 9-4 — Mobile or rapid-deployment node (Type C)

Parameter	Mobile or temporary node
Siting	Vehicle-mounted or tripod-deployed at event perimeters; geometry established at set-up and surveyed, not assumed
Assumed RF detection radius	Reduced relative to Type A because antenna height is low; site-specific and shall be measured at set-up rather than inherited from Table 9-1
Acoustic coverage	Primary short-range modality for this node type, since the low mast height penalises RF more than acoustics
Primary backhaul	Public 4G or 5G with a prioritised slice where available; LEO satellite terminal as alternate
Power	Vehicle supply or portable battery; the 55 W continuous load of Table 8-4 implies about 1.32 kWh per 24 h of unattended operation [Derived]
Timing	GNSS-primary with chip-scale atomic clock holdover, chosen for its sub-watt power class rather than for best drift
Position and attitude	Node position and array orientation SHALL be surveyed or self-determined at every set-up; a mobile node cannot inherit a surveyed position
Dominant limitations	Poor and variable GDOP because geometry is opportunistic; low antenna height; vibration and wind loading on temporary mounts; short set-up time budget

Parameter	Mobile or temporary node
Dominant regulatory driver	Temporary spectrum authorisation and local permission at each site

9.7 Comparative deployment matrix

Table 9-5 — Urban, rural and mobile comparison

Dimension	Urban (Type A)	Rural (Type B)	Mobile (Type C)
Node density	High: 11 nodes for 707 km-squared [Derived]	Low: 8 nodes for 7 854 km-squared [Derived]	Ad hoc, event-scoped
Area per node	65.0 km-squared [Derived]	1 039.2 km-squared [Derived]	Not applicable
Cost driver	Node count and site access	Backhaul and autonomous power	Set-up labour and recurring cellular or satellite cost
Backhaul difficulty	Low where duct exists	High	Medium, depends on public network coverage
Power difficulty	Low, mains or PoE available	High, off-grid sizing governs	Medium, vehicle or battery limited
Timing difficulty	Low, full PTP support available	High, holdover class governs	High, GNSS-only with limited holdover power
GDOP quality	Good if layout is deliberately irregular	Moderate, constrained by available mast sites	Poor and variable
RF range realised	Reduced by urban noise floor	Best case	Reduced by low antenna height
Acoustic viability	Degraded by noise and reverberation	Good in quiet conditions, wind-limited	Primary modality for this node type
Principal risk	Privacy exposure and structural consent	Maintenance access and power autonomy	Geometry quality and authorisation lead time

9.8 Deployment requirements

Table 9-6 — Deployment and coverage requirements

ID	Requirement	Verification
REQ-DP-001	Node counts and spacing SHALL be derived from a documented coverage calculation stating the assumed per-modality detection radius, the packing geometry used and the source of the radius assumption.	Analysis
REQ-DP-002	Detection radius assumptions SHALL be validated by site survey before installation. Published or vendor-quoted ranges SHALL NOT be used as as-installed performance.	Field Trial
REQ-DP-003	The system SHALL NOT claim uniform multi-modality coverage across the RF footprint. Acoustic coverage SHALL be declared as a separate, explicitly bounded sub-footprint.	Inspection
REQ-DP-004	Acoustic nodes SHALL be sited at declared protected volumes and approach corridors rather than distributed to blanket the RF coverage area.	Inspection
REQ-DP-005	Node layouts SHALL be irregular and non-collinear. A geometric dilution of precision map SHALL be produced across the intended coverage volume before siting is frozen.	Analysis
REQ-DP-006	Declared position accuracy SHALL be stated together with the target location or GDOP condition it applies to. A single network-wide accuracy figure SHALL NOT be published without that qualification.	Inspection
REQ-DP-007	Coverage-edge and convex-hull-exterior performance SHALL be modelled and reported separately from centroid performance.	Analysis
REQ-DP-008	Urban RF nodes SHOULD be mounted above average local rooftop level, and where they cannot be, the resulting non-line-of-sight loss SHALL be quantified using ITU-R P.1411 or 3GPP TR 38.901 urban models.	Analysis

ID	Requirement	Verification
REQ-DP-009	Acoustic node placement SHALL be assessed for local ambient noise floor and facade reverberation, and the site-specific achievable detection range SHALL be measured rather than assumed.	Field Trial
REQ-DP-010	RF and acoustic mounting positions at a shared site SHALL be optimised independently, and any compromise driven by installation constraints SHALL be documented with its performance cost.	Inspection
REQ-DP-011	Rural node siting SHALL account for worst-month insolation, unattended maintenance interval, lightning exposure and physical access, and SHALL document each.	Analysis
REQ-DP-012	Mobile nodes SHALL determine or be surveyed for their own position and array orientation at every set-up, and SHALL NOT report tracks using an inherited or assumed position.	Bench Test
REQ-DP-013	Mobile nodes SHALL report an explicit geometry-quality indication to the operator, and the fused picture SHALL degrade declared accuracy accordingly when geometry is poor.	Field Trial
REQ-DP-014	The as-built network SHALL be re-verified by flight trial against a cooperative reference aircraft covering centroid, mid-cell and coverage-edge positions at a minimum of two altitudes.	Field Trial
REQ-DP-015	Any change to node siting, antenna height or array orientation after acceptance SHALL trigger re-verification of the affected coverage and GDOP claims.	Inspection

10 Operational Performance Metrics and Verification

This section defines how the system is measured and accepted. It has to define its own framework, because no external one exists to invoke: the FAA states explicitly that there are no nationally recognised standards for UAS detection or threat classification, and that detection systems cannot determine intent or threat level.⁴⁶² The consequence for any procurement is uncomfortable but important — two vendors quoting the same detection range are almost certainly quoting different measurements, and neither is verifiable without a defined methodology. Everything below exists to remove that ambiguity.

10.1 Metric definitions

Table 10-1 — Performance metric definitions

Metric	Definition	Reporting requirement
P_D versus range	Probability that a target of a declared class, at a declared range, altitude and geometry, produces a confirmed track within the declared latency budget.	Reported as a curve against range, never as a single number. Separate curve per modality and for the fused system.
P_FA	Probability that a decision opportunity with no target present produces a detection declaration.	Reported per modality with the decision opportunity rate stated, since P_FA without a rate is uninterpretable.
False alarms per hour	Count of operator-visible alerts per hour with no corresponding aircraft, measured over a continuous representative period.	This is the operationally decisive metric, because false alerts are the primary cause of systems being switched off in service.
Detection latency	Elapsed time from first sensor-level detection to operator-visible alert, decomposed into node processing, backhaul transport, fusion and display.	Reported as a distribution with median and 95th percentile, not a mean.
Detection-to-classification latency	Elapsed time from first detection to a stable declared class for a corroborated multi-modality contact.	Bounded by REQ-FU-032 at 5 s.
Track continuity	Fraction of the target trajectory duration for which a single continuous track identity is maintained, plus the count of track breaks and identity swaps.	Reported with track-break count, since a high continuity fraction can hide frequent brief breaks.
Localisation CEP and RMSE	Circular error probable and root-mean-square error of estimated position against surveyed truth.	Reported together with the target position or geometric dilution of precision condition, per REQ-DP-006.
Bearing accuracy	Root-mean-square angular error of estimated bearing at a declared range and signal-to-noise ratio.	Reported separately per modality; acoustic and RF bearing accuracy are not comparable quantities.
Classification accuracy	Per-class performance across the declared classification frame of drone, bird, manned aircraft and unknown.	Reported as a confusion matrix. An aggregate accuracy percentage SHALL NOT be the primary figure.
Availability and MTBF	Fraction of scheduled operating time during which the declared coverage is met, and mean time between failures per node type.	Reported per node type, since urban mains-powered and rural solar-powered nodes have materially different failure profiles.
Coverage volume	The volume within which declared P_D is met, per modality.	Reported as three separate volumes, per REQ-SYS-006.

10.2 Why the geometry qualifier is not optional

Localisation accuracy figures are meaningless without the geometry they were measured in. Position error scales directly with the geometric dilution of precision factor, which varies with target position relative to the sensor

FAA, UAS Detection Technical Considerations (Attachment 3), https://www.faa.gov/sites/faa.gov/files/airports/airport_safety/Attachment-3-462
UAS-Detection-Technical-Considerations.pdf

layout,⁴⁶³ so the same system measured at the centroid of its node polygon and at the edge of its coverage will yield accuracy figures that differ by a large factor while both are technically true. This specification therefore requires that every accuracy claim be reported at a minimum of three conditions: centroid, mid-cell and coverage edge. Any single-figure accuracy claim encountered during evaluation should be assumed to have been measured at the most favourable geometry available.

10.3 Acceptance criteria

The targets below are the acceptance baseline for this reference design. They are stated separately for urban and rural deployment because the two environments differ in noise floor, clutter, node density and geometry, and a single target set would be wrong for both. All values are [Derived] engineering targets consistent with the published capability figures cited in Sections 4 to 9, not measurements. They are to be negotiated against site survey results before contract acceptance, and the negotiation record retained.

Table 10-2 — Acceptance criteria, urban and rural

Criterion	Urban target	Rural target	Method	Notes
P_D, RF-controlled Group 1 aircraft at 2 km	At least 0.90	At least 0.90	Field Trial	Cooperative reference aircraft with a representative control link
P_D, RF-controlled Group 1 aircraft at declared maximum range	At least 0.50	At least 0.50	Field Trial	Defines the declared range as the 50 percent point, which SHALL be stated
P_D, acoustic-only detection at 300 m, wind below 5 m/s	At least 0.80	At least 0.90	Field Trial	Urban target lower because of ambient noise floor
P_D, acoustic-only detection at 300 m, wind 8 to 10 m/s	At least 0.50	At least 0.60	Field Trial	Above 10 m/s the acoustic subsystem is declared out of specification
P_D, RF-silent aircraft anywhere beyond 500 m	Not achievable	Not achievable	Analysis	Declared limitation, not a target. See Sections 3.4 and 11
Operator-visible false alerts per node per hour	At most 1	At most 0.5	Field Trial	Measured over a continuous 168 h period including dawn and dusk bird activity
Detection latency, 95th percentile	At most 3 s	At most 5 s	Field Trial	Rural allowance reflects backhaul latency; excludes GEO satellite paths
Detection-to-classification latency, corroborated contact	At most 5 s	At most 5 s	Field Trial	Per REQ-FU-032
Track continuity within declared coverage	At least 0.90 with at most 2 breaks per 5 min pass	At least 0.95 with at most 1 break per 5 min pass	Field Trial	Identity swaps counted separately and SHALL be zero for isolated targets
Localisation CEP at polygon centroid	At most 50 m	At most 100 m	Field Trial	Requires the sub-100 ns timing of REQ-NW-011
Localisation CEP at coverage edge	At most 200 m	At most 400 m	Field Trial	Reported separately per REQ-DP-007; degradation is geometric, not a defect
Bearing accuracy, acoustic, at 200 m	At most 10 degrees RMS	At most 5 degrees RMS	Field Trial	Urban figure degraded by facade reverberation
Classification, drone versus bird, acoustic	Confusion matrix reported; no aggregate threshold accepted	Confusion matrix reported	Field Trial	Per REQ-FU-027 and REQ-FU-028
Node availability, excluding scheduled maintenance	At least 99.5 percent	At least 99.0 percent	Field Trial	Rural allowance reflects worst-month solar autonomy risk

EUROCONTROL, Wide Area Multilateration surveillance report, <https://www.eurocontrol.int/sites/default/files/2019-05/surveillance-report-463-wide-area-multilateration-200508.pdf>

Criterion	Urban target	Rural target	Method	Notes
Operation through 24 h GNSS denial	Timing budget maintained	Timing budget maintained	Bench Test	Per REQ-NW-017; rural nodes require atomic-class holdover
Operation through 24 h total backhaul loss	Local detection and buffering maintained	Local detection and buffering maintained	Field Trial	Per REQ-NW-005

All targets [Derived]. The RF-silent row is deliberately included as a declared non-capability so that it cannot be quietly omitted from an acceptance matrix.

10.4 Verification methods

Method	Definition
Inspection	Examination of design documentation, configuration, source-level architecture or physical build, without operating the system.
Analysis	Calculation, modelling or simulation from documented inputs, with the inputs and method recorded and reviewable.
Bench Test	Controlled laboratory measurement with injected or emulated signals and a known reference, including timing, sensitivity and holdover measurement.
Field Trial	Measurement on the installed system against a cooperative reference aircraft with surveyed truth positions, under recorded environmental conditions.

10.5 Test methodology and its limits

Field trial design should draw on the small body of institutional work that does exist. ASTM Committee F38 is the standards committee responsible for unmanned aircraft systems standards,^{464,465} and the FAA has since 2016 issued guidance on detection and mitigation technology at airports covering legal considerations, electromagnetic interference to aviation communication and navigation equipment, and on-airport airspace case processing.⁴⁶⁶ The FAA Airport UAS Detection and Mitigation Research Program, established under Section 383 of the FAA Reauthorization Act of 2018, has continued to test systems at designated test airports,⁴⁶⁷ the DOT Office of Inspector General reviewed FAA counter-UAS activity in 2022,⁴⁶⁸ and the FAA UAS Detection and Mitigation Systems Aviation Rulemaking Committee reported in January 2024.^{469,470} NATO Science and Technology Organization meeting proceedings on automatic UAV classification and on drone tracking and classification provide relevant measurement methodology from the defence research community.^{471,472}

ASTM International, Committee F38 on Unmanned Aircraft Systems, <https://www.astm.org/membership-participation/technical-committees/committee-f38>⁴⁶⁴

ASTM International, Unmanned Aerial Systems (Drone) Standards, <https://regional.astm.org/emerging-technology/uas-standards>⁴⁶⁵

FAA, UAS detection and mitigation response at airports, https://www.faa.gov/airports/new_entrants/uas_detection_mitigation_response⁴⁶⁶

Unmanned Airspace, FAA selects D-Fend EnforceAir for airport test programme, <https://www.unmannedairspace.info/counter-uas-systems-and-policies/faq-selects-d-fends-enforceair-counter-drone-system-for-airport-test-programme/>⁴⁶⁷

US DOT Office of Inspector General, FAA Counter-UAS final report, 30 March 2022, https://www.oig.dot.gov/sites/default/files/FAA%20C-UAS%20Final%20Report_3.30.2022.pdf⁴⁶⁸

FAA, UAS Detection and Mitigation Systems Aviation Rulemaking Committee Final Report, January 2024, https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/UAS-Detection-Mitigation-Systems-ARC_Final-Report_02052024.pdf⁴⁶⁹

FAA, Counter UAS (C-UAS) resources page, https://www.faa.gov/uas/resources/c_uas⁴⁷⁰

NATO STO-MP-SET-315-25, Automatic Classification of UAVs, <https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-SET-315/MP-SET-315-25.pdf>⁴⁷¹

NATO STO-MP-MSG-SET-183-15P, Tracking and Classification of Drones, <https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-MSG-SET-183/MP-MSG-SET-183-15P.pdf>⁴⁷²

Declared limitation of this section. None of the above constitutes a unified, citable C-UAS detection test standard, and this specification does not claim one exists. Several documents that would have strengthened this section could not be retrieved during preparation and are recorded as gaps in Section 11. Where a published review of C-UAS sensors was available, it surveys the sensor landscape without resolving the standardisation gap.⁴⁷³ Any implementer or evaluator should therefore expect to negotiate the trial methodology explicitly rather than reference a standard, and should treat the acceptance table above as a starting point for that negotiation.

10.6 Verification requirements

Table 10-3 — Verification and acceptance requirements

ID	Requirement	Verification
REQ-VV-001	Every declared performance figure SHALL be accompanied by the target class, range, altitude, geometry, environmental conditions and measurement date under which it was obtained.	Inspection
REQ-VV-002	Probability of detection SHALL be reported as a curve against range and SHALL NOT be reported as a single value.	Inspection
REQ-VV-003	Declared maximum detection range SHALL be defined as the range at which probability of detection falls to 0.50 for the declared target class, and that definition SHALL be stated wherever the range is quoted.	Inspection
REQ-VV-004	Probability of false alarm SHALL be reported together with the decision opportunity rate to which it applies.	Inspection
REQ-VV-005	Operator-visible false alerts per hour SHALL be measured over a continuous period of at least 168 h that includes dawn and dusk periods of elevated bird activity.	Field Trial
REQ-VV-006	Detection latency SHALL be reported as a distribution with median and 95th percentile, decomposed into node processing, transport, fusion and display components.	Field Trial
REQ-VV-007	Localisation accuracy SHALL be measured at centroid, mid-cell and coverage-edge geometries, and all three SHALL be reported.	Field Trial
REQ-VV-008	Classification performance SHALL be reported as a per-class confusion matrix across drone, bird, manned aircraft and unknown. An aggregate accuracy percentage SHALL NOT be presented as the primary classification result.	Field Trial
REQ-VV-009	Track continuity SHALL be reported with track-break count and identity-swap count, not as a continuity fraction alone.	Field Trial
REQ-VV-010	Field trials SHALL use a cooperative reference aircraft with independently surveyed truth positions, and truth data SHALL be recorded at a rate sufficient to resolve the declared latency budget.	Field Trial
REQ-VV-011	Acoustic subsystem performance SHALL be measured at declared wind-speed bands, and the wind speed above which the subsystem is out of specification SHALL be declared.	Field Trial
REQ-VV-012	The system SHALL be verified under 24 h GNSS denial and under 24 h total backhaul loss, and the resulting degraded performance SHALL be recorded rather than the tests being treated as pass or fail only.	Bench Test
REQ-VV-013	Simulation and modelling results SHALL be labelled as such and SHALL NOT be presented alongside measured results without that distinction being visible.	Inspection
REQ-VV-014	The trial methodology SHALL be documented and agreed before trials begin, and SHALL NOT be adjusted after results are known without the adjustment and its rationale being recorded.	Inspection
REQ-VV-015	All trial data SHALL be retained in replayable form per REQ-SYS-009 so that reported results can be independently recomputed.	Inspection
REQ-VV-016	Where a required capability is not achievable, it SHALL be recorded as a declared non-capability in the acceptance matrix rather than omitted.	Inspection

MDPI Sensors 22(1):189, Review and Simulation of Counter-UAS Sensors for Unmanned Traffic Management,⁴⁷³
<https://www.mdpi.com/1424-8220/22/1/189>

11 Risks, Limitations and Assumptions

This section exists because a specification that lists only what a system does is not usable for risk-based decision making. Every entry below is a real constraint on this design as scoped, and several cannot be engineered away within that scope.

11.1 Limitations register

Table 11-1 — Limitations and risks

Ref	Limitation	Impact	Mitigation or handling
LIM-01	RF-silent aircraft, whether fibre-optic tethered or fully autonomous, emit no detectable control link. Tether lengths of 5 to 15 km and up to 30 km are reported. ⁴⁷⁴	Complete loss of RF and cellular coverage against this class. Residual coverage is acoustic only, at 100 to 500 m.	Cannot be mitigated within the scope of this document. Requires a radar or electro-optical layer, which vendor guidance recommends explicitly for RF-dark aircraft. Declared in Section 3.4 and in the acceptance matrix as a non-capability. ⁴⁷⁵
LIM-02	Consumer control-link hop and dwell parameters used in Section 4 rest partly on a low-authority community source rather than a manufacturer specification or measurement.	Channelizer dwell-time and revisit design may be based on incorrect timing assumptions.	Flagged at the point of use in Section 4. Shall be re-measured on representative hardware before detector timing is frozen.
LIM-03	Acoustic detection range is 100 to 500 m for small aircraft and is eroded further by urban ambient noise and facade reverberation.	Acoustic corroboration is unavailable across most of the RF coverage footprint, so RF-silent aircraft can approach to within a few hundred metres undetected.	Acoustic nodes sited only at declared protected volumes and approach corridors, per REQ-DP-004. Coverage declared as a separate footprint, per REQ-SYS-006.
LIM-04	The acoustic subsystem is wind-limited, with a declared operating limit of 8 to 10 m/s.	Performance collapses in the weather conditions under which some operations are most likely.	Wind speed reported as part of node health telemetry; declared performance degraded automatically above the limit, per REQ-VV-011.
LIM-05	Passive off-air cellular classification has no published accuracy figure. The best published result, exceeding 99 percent true-positive rate at 0.5 percent or less false-positive rate, was obtained using network-side measurement reports at 60 m altitude or above, not passive off-air observation. ⁴⁷⁶	Section 5 performance cannot be quantified from published evidence, and the published figure must not be transferred to this architecture.	Stated explicitly in Section 5. Cellular monitoring is specified as a corroborating modality, never as a primary detection source, and its accuracy shall be established by measurement.
LIM-06	The whole system depends on GNSS for time. The open civil signal is unauthenticated and arrives at approximately -130 dBm, making it vulnerable to both jamming and spoofing. ^{477,478}	Loss or corruption of timing degrades multilateration accuracy from tens of metres to kilometres. The adversary who motivates the system may also possess the means to attack its clock.	Multi-constellation anti-jam and anti-spoof receivers, atomic-class holdover on exposed nodes per REQ-NW-017, and mandatory operator-visible degraded-timing indication per REQ-NW-016.

The War Zone, Inside Ukraine's Fiber-Optic Drone War, <https://www.twz.com/news-features/inside-ukraines-fiber-optic-drone-war>⁴⁷⁴

Spotter Global, New Stealth Fiber-Optic Guided Drones (FOG-D): How To Detect Them, <https://www.spotterglobal.com/blog/spotter-blog-475/3/new-stealth-fiber-optic-guided-drones-fog-d-how-to-detect-them-12>

Aalto University, Drone Detection and Classification Using Cellular Network: A Machine Learning Approach, ⁴⁷⁶
https://acris.aalto.fi/ws/portalfiles/portal/36192831/AALTO_Drone_Detection_and_Classification_Using_Cellular_Network_A_Machine_Learning_g_Approach.pdf

FAA, GPS/GNSS Interference Resource Guide, ⁴⁷⁷
https://www.faa.gov/about/office_org/headquarters_offices/avs/offices/afx/afs/afs400/afs410/GNSS/GPS_GNSS_Interference_Resource_Guide.pdf

UNOOSA, GNSS vulnerability briefing, 2023, ⁴⁷⁸
https://www.unoosa.org/documents/pdf/psa/activities/2023/GNSS2023/GNSS2023_06_01.pdf

Ref	Limitation	Impact	Mitigation or handling
LIM-07	Birds and other wildlife are a persistent false-alarm source, and false alerts are a primary cause of C-UAS systems being distrusted or switched off. ⁴⁷⁹	Operator trust erodes faster than it can be rebuilt, which is an operational failure even when the technical system meets specification.	Because this system excludes radar, bird exposure is acoustic only. Bird false-alarm contribution characterised separately per REQ-FU-028, and graded rather than binary alerting per REQ-FU-022.
LIM-08	No unified C-UAS detection or threat-classification test standard exists, and detection systems cannot determine intent. ⁴⁸¹	Performance claims across vendors are not comparable, and acceptance cannot reference an external standard.	This document defines its own metrics and acceptance criteria in Section 10, and requires the trial methodology to be agreed before trials begin per REQ-VV-014.
LIM-09	United States federal counter-UAS authority is legislatively volatile, having been extended and amended repeatedly, and the governing advisory dates from 2020. ⁴⁸²	A legal position established at design time may not hold at deployment time.	Section 12 states the position as of the issue date of this document and requires re-verification with counsel at deployment. No legal conclusion in this document should be relied upon without that step.
LIM-10	The acoustic layer captures sound in public space, and audio of identifiable individuals is personal data under European data protection law.	Regulatory and reputational exposure independent of technical performance.	Architectural requirement REQ-SYS-014 to discard or irreversibly anonymise incidental speech, plus a data protection impact assessment before deployment. See Section 12.
LIM-11	Coverage and node-count figures throughout Section 9 are geometric, treating detection range as a fixed-radius circle.	Real coverage is terrain- and clutter-dependent and will be smaller and more ragged than the arithmetic suggests.	All such figures tagged [Derived]. Site survey validation required before installation per REQ-DP-002, and flight-trial re-verification per REQ-DP-014.
LIM-12	Increasing RF node density does not monotonically improve detection, because additional receivers and their supporting radios add mutual interference.	Naive densification can reduce performance while increasing cost.	Interference and coverage analysis required to justify node density per REQ-FU-031, and co-band backhaul analysis per REQ-NW-008.
LIM-13	E-band backhaul availability is rain-limited, restricting high-availability hops to roughly 3 km. ⁴⁸⁵	Urban backhaul topology is constrained more tightly than raw capacity figures imply.	Link budgets computed per ITU-R P.530 with regional rain climatology, per REQ-NW-006 and REQ-NW-007.
LIM-14	The node power budget of 55 W, the solar array of 880 W and the battery of 4 950 Wh are derived estimates against assumed hardware and assumed insolation.	Under-sizing a rural node produces winter outages that are expensive to correct after installation.	Re-derivation against selected hardware and site-specific irradiance data required before site power design, per REQ-NW-019 and REQ-NW-021.
LIM-15	No C-UAS-specific NATO STANAG mapping was identified during preparation, so military integration remains an architecture placeholder.	Coalition or military integration effort cannot be scoped from this document alone.	External gateway approach mandated by REQ-NW-033; integration requirements to be established directly with the customer command and control authority.

D-Fend Solutions, The False Positive Dilemma: False Alerts in Drone Detection, <https://d-fendsolutions.com/blog/the-false-positive-dilemma-false-alerts-in-drone-detection/>⁴⁷⁹

counteruavradar.com, How Radar Distinguishes Drones from Birds, <https://www.counteruavradar.com/en/knowledge-base/how-radar-distinguishes-drones-from-birds/>⁴⁸⁰

FAA, UAS Detection Technical Considerations (Attachment 3), https://www.faa.gov/sites/faa.gov/files/airports/airport_safety/Attachment-3-UAS-Detection-Technical-Considerations.pdf⁴⁸¹

FCC, Federal Agencies Release Advisory on Drone Detection and Mitigation Technology (17 August 2020), <https://www.fcc.gov/document/federal-agencies-release-advisory-drone-detection-mitigation-tech>⁴⁸²

US Department of Homeland Security, Counter-UAS Legal Authorities Fact Sheet, https://www.dhs.gov/sites/default/files/publications/dhs_cuas-legal-authorities_fact-sheet_190506-508.pdf⁴⁸³

FAA, UAS Detection and Mitigation Systems Aviation Rulemaking Committee Final Report, January 2024, https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/UAS-Detection-Mitigation-Systems-ARC_Final-Report_02052024.pdf⁴⁸⁴

ITU-R Recommendation P.530-19 (09/2025), https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.530-19-202509-!!!PDF-E.pdf⁴⁸⁵

11.2 Key assumptions

- The threat set is dominated by Group 1 and Group 2 aircraft. Larger aircraft are incidentally covered but are not design cases.
- Protected volumes are declared in advance, so that threat assessment can compute closest point of approach and volume entry rather than inferring intent.
- An operator or an external command system consumes the output. This is not an autonomous system and its alerts are not actionable without human or institutional judgement.
- Site access for installation and for periodic maintenance is available, including winter access to rural nodes.
- Node positions for fixed types are surveyed once and remain stable. Any change invalidates the coverage and geometric dilution of precision claims, per REQ-DP-015.
- Spectrum monitoring of the required bands is lawful in the deployment jurisdiction. Section 12 sets out the analysis but is not a substitute for local legal advice.

11.3 Declared research gaps

The following materials were sought during preparation of this specification and could not be retrieved. They are listed so that a reader can close the gaps rather than assume they were considered.

- UK Defence Science and Technology Laboratory counter-UAS test material.
- NIST counter-UAS or UAS detection test methodology documents.
- EU Joint Research Centre report JRC140692.
- The primary US Department of Defense directive text underlying the UAS group classification table of Section 3.1, for which a secondary teaching source was used instead.
- Manufacturer specifications for consumer control-link hop and dwell timing, for which a low-authority community source was used instead and which is recorded as LIM-02.

12 Regulatory and Legal Compliance Matrix

This section is technical analysis, not legal advice. It records the regulatory position as understood at the issue date of this document from the cited public sources. It must be re-verified with qualified counsel in the deployment jurisdiction before any deployment decision, for the specific reason set out in LIM-09: the United States statutory framework in particular has been amended repeatedly and the governing cross-agency advisory dates from 2020.⁴⁸⁶

12.1 The detection versus mitigation line

The same structural distinction recurs across jurisdictions and anchors the design philosophy of this whole document. Passive detection, meaning receiving and characterising signals already being transmitted, without transmitting anything and without decoding communications content or subscriber-identity fields, is generally permissible for private entities in most circumstances, although United States federal wiretap and pen-register statutes still technically apply to certain implementations and should be reviewed for any specific deployment. Active mitigation, meaning jamming, spoofing, GNSS denial, protocol exploitation to seize control, or physical destruction, is restricted to specifically authorised government agencies. The 2020 joint FAA, DOJ, FCC and DHS advisory is the definitive cross-agency statement: RF-based detection can implicate the pen-register and trap-and-trace statute and the Wiretap Act, while mitigation implicates the Computer Fraud and Abuse Act, satellite-interference statutes, statutes protecting communications infrastructure, and the Aircraft Sabotage and Aircraft Piracy Acts.⁴⁸⁷

In the United States, jamming is illegal for all private parties without exception, including on one's own property, under Sections 301, 302(b) and 333 of the Communications Act of 1934.⁴⁸⁸⁴⁸⁹ Statutory authority to mitigate rests with only four categories of federal actor — the Department of Defense under 10 U.S.C. 130i, the Department of Energy under 50 U.S.C. 2661, and the Department of Justice and Department of Homeland Security jointly under 6 U.S.C. 124n — under the Preventing Emerging Threats Act of 2018, and only for designated covered facilities or assets.⁴⁹⁰

One point of definition is materially useful to a detection-only programme. 49 U.S.C. 44801(5) defines a counter-UAS system as one capable of lawfully and safely disabling, disrupting or seizing control of an aircraft — a definition that explicitly excludes detection-only systems.⁴⁹¹ A correctly designed passive detection system that transmits nothing and decodes no identity content therefore sits outside the most restrictive part of that statutory framework. It must still independently satisfy the Wiretap Act and pen-register constraints, which is the reason for REQ-SYS-013.

FCC, Federal Agencies Release Advisory on Drone Detection and Mitigation Technology (17 August 2020), ⁴⁸⁶
<https://www.fcc.gov/document/federal-agencies-release-advisory-drone-detection-mitigation-tech>

FCC, Federal Agencies Release Advisory on Drone Detection and Mitigation Technology (17 August 2020), ⁴⁸⁷
<https://www.fcc.gov/document/federal-agencies-release-advisory-drone-detection-mitigation-tech>

FCC, Jammer Enforcement, <https://www.fcc.gov/general/jammer-enforcement>⁴⁸⁸

FCC Enforcement Advisory DA-11-249, Cell Jammers, GPS Jammers and Other Jamming Devices, [https://www.fcc.gov/document/fcc-](https://www.fcc.gov/document/fcc-enforcement-advisory-cell-jammers-gps-jammers-and-other-jamming-devices)⁴⁸⁹
[enforcement-advisory-cell-jammers-gps-jammers-and-other-jamming-devices](https://www.fcc.gov/document/fcc-enforcement-advisory-cell-jammers-gps-jammers-and-other-jamming-devices)

US Department of Homeland Security, Counter-UAS Legal Authorities Fact Sheet, ⁴⁹⁰
https://www.dhs.gov/sites/default/files/publications/dhs_cuas-legal-authorities_fact-sheet_190506-508.pdf

US Department of Homeland Security, Counter-UAS Legal Authorities Fact Sheet, ⁴⁹¹
https://www.dhs.gov/sites/default/files/publications/dhs_cuas-legal-authorities_fact-sheet_190506-508.pdf

12.2 Regional compliance matrix

Table 12-1 — Regulatory position by region

Dimension	European Union / ETSI (ITU Region 1)	United States / FCC (ITU Region 2)	ITU Region 3 and general
Spectrum framework for monitored bands	ETSI EN 300 328 for 2.4 GHz wideband, EN 301 893 for 5 GHz RLAN, EN 300 220 for 25 to 1 000 MHz short-range devices, EN 300 440 for general short-range devices ^{492,493}	FCC Part 15 for unlicensed ISM and short-range devices, Part 90 for private land mobile links used in professional operations	National administrations implement ITU Radio Regulations; band-by-band verification required per jurisdiction
Notable band restrictions	National implementations vary. Finnish guidance limits 5150 to 5250 MHz to 200 mW EIRP indoor, permits up to 1 W EIRP at 5470 to 5725 MHz with dynamic frequency selection and transmit power control, and has banned 5470 to 5725 MHz for UAS use since 13 January 2023 ⁴⁹⁴	Different sub-gigahertz allocation: 902 to 928 MHz is available in Region 2 where 868 MHz applies in Region 1, so control-link band plans differ by region	Sub-gigahertz allocations differ again; the band plan of Section 4 must be re-checked against the national table of allocations
Passive spectrum monitoring legality	Generally permissible for reception without transmission; content interception restricted under national implementations of European law	Generally permissible, but RF detection implementations can implicate the Wiretap Act and the pen-register and trap-and-trace statute; counsel review required ⁴⁹⁵	Jurisdiction-specific; assume restriction on content interception as the default position
Cellular monitoring boundary	Signalling and metadata observation only. Capturing or decoding user-plane content engages lawful-interception law and data protection law simultaneously	Same boundary. Identity-field decoding and content capture are the specific prohibited acts ⁴⁹⁶	Same boundary applied as a design constraint regardless of jurisdiction, per REQ-SYS-013
Audio recording and privacy	Audio of identifiable individuals is personal data. Regulatory guidance warns against recording conversations of members of the public and requires a data protection impact assessment for high-risk surveillance processing ^{497,498,499,500}	State-level wiretap and two-party-consent statutes apply in addition to federal law; exposure varies materially by state	Jurisdiction-specific. Apply the European standard as the design floor, since it is the most restrictive identified

ETSI EN 300 328 v2.2.2, Wideband transmission systems in the 2.4 GHz band, ⁴⁹²
https://www.etsi.org/deliver/etsi_en/300300_300399/300328/02.02.02_60/en_300328v020202p.pdf

ETSI EN 300 220-2 v3.1.0, Short range devices 25 MHz to 1 000 MHz, ⁴⁹³
https://www.etsi.org/deliver/etsi_en/300200_300299/300220/03.01.00_20/en_300220v030100a.pdf

Traficom (Finnish Transport and Communications Agency), national drone frequency guidance, <https://www.traficom.fi>⁴⁹⁴

FCC, Federal Agencies Release Advisory on Drone Detection and Mitigation Technology (17 August 2020), ⁴⁹⁵
<https://www.fcc.gov/document/federal-agencies-release-advisory-drone-detection-mitigation-tech>

FCC, Federal Agencies Release Advisory on Drone Detection and Mitigation Technology (17 August 2020), ⁴⁹⁶
<https://www.fcc.gov/document/federal-agencies-release-advisory-drone-detection-mitigation-tech>

UK Information Commissioner's Office, guidance on video surveillance including CCTV, compliance with data protection principles, ⁴⁹⁷
<https://ico.org.uk/for-organisations/uk-gdpr-guidance-and-resources/cctv-and-video-surveillance/guidance-on-video-surveillance-including-cctv/how-can-we-comply-with-the-data-protection-principles-when-using-surveillance-systems/>

European Data Protection Board, Guidelines 3/2019 on processing of personal data through video devices, ⁴⁹⁸
https://www.edpb.europa.eu/system/files/documents/files/file1/edpb_guidelines_201903_video_devices_en_0.pdf

CMS Law, GDPR note on audio and video as personal data, <https://cms.law/en/gbr/legal-updates/Oil-Watch-where-you-are-pointing-that-camera>⁴⁹⁹

University of Antwerp, research ethics and GDPR guidance on recording, <https://medialibrary.uantwerpen.be/files/56390/27b3de40-d44e-4604-a84c-009d5239c04a.pdf>⁵⁰⁰

Dimension	European Union / ETSI (ITU Region 1)	United States / FCC (ITU Region 2)	ITU Region 3 and general
Mitigation authority	Requires EASA or national authority authorisation; not available to private commercial operators under normal circumstances ⁵⁰¹⁵⁰²	Restricted to DoD, DOE, and DOJ/DHS jointly for designated covered assets. Jamming is illegal for all private parties without exception ⁵⁰³⁵⁰⁴	Assume restricted to state actors absent specific national provision
Remote ID regime	Direct remote identification mandatory from 1 January 2024 for specific-category operations and for C1, C2, C3, C5 and C6 class-labelled aircraft, broadcasting operator registration number, serial number, timestamp, position and height, heading, ground speed and remote pilot position, over an open documented protocol ⁵⁰⁵⁵⁰⁶⁵⁰⁷	Remote ID under the ASTM F3411 specification, covering broadcast and network variants ⁵⁰⁸	Adoption varies; ASTM F3411 is the de facto reference specification
Airspace and operational framework	Regulation 2019/947 establishes Open, Specific and Certified categories; Regulation 2021/664 establishes U-space airspace with mandatory network identification, geo-awareness, flight authorisation and traffic information services ⁵⁰⁹⁵¹⁰⁵¹¹⁵¹²	FAA guidance on detection and mitigation at airports covers legal considerations, electromagnetic interference to aviation systems and airspace case processing ⁵¹³⁵¹⁴	National aviation authority framework applies

12.3 Design consequences carried into the specification

- The open and documented nature of the European remote identification protocol means a compliant passive sensor can decode it straightforwardly and lawfully, unlike a proprietary reverse-engineered broadcast. This

EUR-Lex, Commission Implementing Regulation (EU) 2019/947, full text, https://eur-lex.europa.eu/eli/reg_impl/2019/947/oj/eng⁵⁰¹

EASA, Commission Implementing Regulation (EU) 2019/947, official copy, <https://www.easa.europa.eu/en/document-library/regulations/commission-implementing-regulation-eu-2019947>⁵⁰²

FCC, Jammer Enforcement, <https://www.fcc.gov/general/jammer-enforcement>⁵⁰³

US Department of Homeland Security, Counter-UAS Legal Authorities Fact Sheet,⁵⁰⁴
https://www.dhs.gov/sites/default/files/publications/dhs_cuas-legal-authorities_fact-sheet_190506-508.pdf

EUR-Lex, Commission Delegated Regulation (EU) 2020/1058 amending 2019/945, <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R1058>⁵⁰⁵

dronebydrone.com, Entry into force of Remote ID for UAS from 1 January 2024 under EASA regulations,⁵⁰⁶
<https://www.dronebydrone.com/en/news/744/entry-into-force-of-remote-id-in-uas-from-january-1-2024-per-easa-regulations.html>

EASA, Understanding European Drone Regulations and the Aviation Regulatory System, <https://www.easa.europa.eu/en/domains/drones-air-mobility/drones-air-mobility-landscape/Understanding-European-Drone-Regulations-and-the-Aviation-Regulatory-System>⁵⁰⁷

ASTM F3411-22a, Standard Specification for Remote ID and Tracking, <https://www.astm.org/f3411-22a.html>⁵⁰⁸

EUR-Lex, Commission Implementing Regulation (EU) 2019/947, full text, https://eur-lex.europa.eu/eli/reg_impl/2019/947/oj/eng⁵⁰⁹

EUR-Lex, Commission Implementing Regulation (EU) 2021/664 on a regulatory framework for U-space, https://eur-lex.europa.eu/eli/reg_impl/2021/664/oj/eng⁵¹⁰

EASA, Open category low-risk civil drones, <https://www.easa.europa.eu/en/domains/drones-air-mobility/operating-drone/open-category-low-risk-civil-drones>⁵¹¹

EASA, Specific category civil drones, <https://www.easa.europa.eu/en/domains/drones-air-mobility/operating-drone/specific-category-civil-drones>⁵¹²

FAA, UAS detection and mitigation response at airports, https://www.faa.gov/airports/new_entrants/uas_detection_mitigation_response⁵¹³

FAA, UAS Detection Technical Considerations (Attachment 3), https://www.faa.gov/sites/faa.gov/files/airports/airport_safety/Attachment-3-UAS-Detection-Technical-Considerations.pdf⁵¹⁴

asymmetry is why REQ-NW-030 mandates standards-based Remote ID decoding rather than proprietary frame decoding.

- Cellular monitoring is architected so that user-plane content cannot be captured at any point in the chain, rather than relying on a policy not to look at it, because a policy is not verifiable by an auditor and an architecture is.
- The acoustic pipeline is designed and documented to discard or irreversibly anonymise incidentally captured intelligible speech, and a data protection impact assessment is required before deployment in any European public space.
- The system is documented, specified and to be marketed strictly as detection, classification and tracking. No active transmission capability is bundled, and any mitigation action is left entirely to an authorised end-user agency.
- Because sub-gigahertz allocations differ between ITU Regions 1 and 2, the RF band plan is a configurable regional profile rather than a fixed build option.

13 Appendix A — Consolidated Requirements Index

Every requirement identifier in this specification is listed below with an abbreviated statement and its originating section. The abbreviated form is for navigation only; the full normative text is in the requirement table of the cited section.

Table 13-1 — Consolidated requirements index (183 requirements)

ID	Abbreviated requirement	Section
REQ-SYS-001	SHALL be passive and detection-only. It SHALL NOT transmit any signal intended to interfere with, deny, spoof or take control of a target aircraft, ...	2.4
REQ-SYS-002	SHALL integrate at minimum three sensing modalities: RF control-link detection, cellular network monitoring, and acoustic sensing. No single modality ...	2.4
REQ-SYS-003	Detection, classification and bearing estimation SHALL be performed at the sensor node, and the node SHALL report structured detection and track ...	2.4
REQ-SYS-004	SHALL produce a graded alert carrying position or bearing, classification, calibrated confidence and per-modality contribution, and SHALL NOT reduce ...	2.4
REQ-SYS-005	SHALL NOT infer the absence of an unmanned aircraft from the absence of detections, and operator-facing displays SHALL make the difference between no ...	2.4
REQ-SYS-006	SHALL declare its coverage per modality as separate footprints. A single combined coverage claim SHALL NOT be published.	2.4
REQ-SYS-007	Degradation of any subsystem, including loss of backhaul, loss of GNSS timing, loss of a node or loss of a modality, SHALL be visible to the operator ...	2.4
REQ-SYS-008	End-to-end latency from first sensor detection to operator-visible corroborated alert SHALL NOT exceed 5 s, and SHALL be measured rather than ...	2.4
REQ-SYS-009	SHALL record all sensor detections, association decisions, track states and fusion confidences in a replayable form sufficient to reconstruct and ...	2.4
REQ-SYS-010	SHALL operate continuously and unattended, and SHALL recover automatically from node reboot, link loss and power interruption without operator ...	2.4
REQ-SYS-011	SHALL expose an external track export interface in at least one recognised format, and SHALL NOT require a proprietary client for interoperability ...	2.4
REQ-SYS-012	Every quantitative performance figure declared by the implementer SHALL be accompanied by the conditions under which it was measured, including ...	2.4
REQ-SYS-013	SHALL be architected so that no cellular user-plane content is captured, stored or decoded at any point in the processing chain.	2.4
REQ-SYS-014	SHALL be architected so that incidentally captured intelligible speech is discarded or irreversibly anonymised before storage, and this behaviour ...	2.4
REQ-SYS-015	SHALL maintain a limitations register equivalent to Section 11 and SHALL keep it current, including any threat class the deployed configuration ...	2.4
REQ-RF-001	The DF array SHALL provide azimuth bearing on any detected emitter meeting the classification SNR threshold, with an accuracy of \u00b10.5° RMS ...	4
REQ-RF-002	The DF array SHALL be phase-calibrated at commissioning and SHALL support in-service recalibration without physical access to the elements.	4
REQ-RF-003	The node SHOULD report a per-bearing uncertainty estimate rather than a scalar bearing, so that fusion can weight it correctly.	4
REQ-RF-004	Where three or more nodes observe the same emitter, the system SHALL compute a position fix and SHALL report the associated geometric dilution of ...	4
REQ-RF-005	The RF subsystem SHALL be receive-only. It SHALL NOT contain any intentional radiator in any monitored band, and SHALL NOT implement jamming, ...	4
REQ-RF-006	The subsystem SHALL provide continuous, uninterrupted coverage of 2400\u00b10.5 MHz and 5725\u00b10.5 MHz at every node.	4
REQ-RF-007	The subsystem SHALL additionally cover 433.05\u00b10.5 MHz, 860\u00b10.5 MHz, 1240\u00b10.5 MHz and 5150\u00b10.5 MHz, by scanning where ...	4
REQ-RF-008	Where a band is scanned, the revisit interval SHALL NOT exceed 1 s for the sub-GHz segments and 400 ms for the 5150\u00b10.5 MHz segment, and the ...	4

ID	Abbreviated requirement	Section
REQ-RF-009	The 5725u20135875 MHz receive chain SHALL provide at least 100 MHz of instantaneous bandwidth, so that a 60 MHz OcuSync channel is captured without ...	4
REQ-RF-010	System noise figure SHALL NOT exceed 6 dB at 5.8 GHz and 4 dB at 900 MHz, measured at the antenna port.	4
REQ-RF-011	The low-noise amplifier SHALL be mounted at the antenna. Cumulative loss ahead of the first active stage SHALL NOT exceed 2.5 dB.	4
REQ-RF-012	Each monitored segment SHALL be preselected by a filter, so that a strong out-of-segment emitter cannot desensitise the receiver across its whole ...	4
REQ-RF-013	The front end SHALL survive, without damage or permanent degradation, an in-band incident power level consistent with co-siting on a shared mast with ...	4
REQ-RF-014	Detection SHALL use per-subchannel constant-false-alarm-rate thresholding referenced to a tracked noise floor, and SHALL NOT use a fixed absolute ...	4
REQ-RF-015	The node SHALL emit, for every detected burst, a descriptor containing centre frequency, occupied bandwidth, timestamp, duration, and peak and mean ...	4
REQ-RF-016	All detection, classification and decode processing SHALL execute at the node. Raw sample streams SHALL NOT be transported over the backhaul in ...	4
REQ-RF-017	The node SHALL support operator-triggered capture of a bounded raw sample window to local storage, for forensic review and for offline classifier ...	4
REQ-RF-018	The classifier SHALL identify emitter family, and SHALL report a calibrated confidence value with every classification.	4
REQ-RF-019	The a priori channel-plan database, including the published per-region DJI centre-frequency tables, SHALL be field-updatable without firmware ...	4
REQ-RF-020	The subsystem SHALL decode open Direct Remote Identification broadcasts and SHALL report all mandated fields, including the reported position of the ...	4
REQ-RF-021	The subsystem MAY decode the unencrypted DJI DroneID beacon. Where implemented, it SHALL be a software-updatable module and SHALL NOT be a dependency ...	4
REQ-RF-022	The subsystem SHALL NOT demodulate, store or forward the payload of any command-and-control link, nor any communications content of any kind.	4
REQ-RF-023	The subsystem SHALL distinguish regulated Remote ID broadcasts (OUI 6a:5c:35) from proprietary DJI DroneID broadcasts (OUI 26:37:12) and SHALL report ...	4
REQ-RF-024	The node SHALL maintain and export a continuous record of the measured noise floor per segment, to support siting decisions and post-incident ...	4
REQ-RF-025	Declared detection ranges SHALL be established by field trial on the procured hardware. Derived link-budget figures SHALL NOT be published as ...	4
REQ-RF-026	The subsystem SHOULD report separate detection and classification ranges, reflecting the differing SNR requirements of energy detection and ...	4
REQ-RF-027	Node documentation SHALL state explicitly that the RF subsystem has no detection capability against a fibre-tethered or otherwise RF-silent airframe.	4
REQ-LTE-001	The LTE subsystem SHALL be receive-only and SHALL NOT transmit in any cellular band under any circumstance, including for calibration.	5
REQ-LTE-002	The subsystem SHALL be configurable at commissioning to the band set applicable to the deployment ITU Region and to the operators present at the site.	5
REQ-LTE-003	The subsystem SHALL survey downlink bands, enumerate physical cell identities present, and decode broadcast system information sufficient to ...	5
REQ-LTE-004	The subsystem SHALL detect PRACH preamble activity in the monitored uplink bands and SHALL report detection events with timestamp and received power.	5
REQ-LTE-005	The subsystem SHOULD observe uplink SRS where the cell configuration permits, and SHOULD report the resulting timing observables to fusion.	5
REQ-LTE-006	The subsystem SHALL learn and maintain a site-specific statistical baseline of normal ground-terminal behaviour, and SHALL detect airborne-terminal ...	5
REQ-LTE-007	The subsystem SHALL evaluate the joint strong-RSRP-with-poor-RSRQ signature and the abnormal-neighbour-cell-visibility signature as its primary ...	5
REQ-LTE-008	The subsystem SHALL NOT demodulate, log or forward IMSI, GUTI or any other subscriber identity field.	5
REQ-LTE-009	The subsystem SHALL NOT demodulate, log or forward any user-plane or dedicated control-plane content.	5

ID	Abbreviated requirement	Section
REQ-LTE-010	Evidence emitted to fusion SHALL be an anonymous, aggregate airborne-terminal-presence indication with a confidence value, and SHALL NOT identify any ...	5
REQ-LTE-011	The subsystem SHALL be declared to fusion as a corroborating sensor, and its evidence weight SHALL reflect that no published accuracy figure exists ...	5
REQ-LTE-012	Where the Band 8 or Band 20 uplink overlaps the sub-GHz UAS control segment of Section 4, the two subsystems SHALL share a coordinated front-end and ...	5
REQ-LTE-013	The subsystem SHOULD provide an interface for operator-cooperative ingest of network-side aerial-terminal identification, where a network operator ...	5
REQ-LTE-014	Legal review of the monitoring configuration SHALL be completed and recorded for each deployment jurisdiction before commissioning.	5
REQ-AC-001	Elements SHALL be digital MEMS microphones with a synchronous multi-channel interface (I2S or TDM). Independently clocked single-channel interfaces ...	6
REQ-AC-002	Element self-noise SHALL NOT exceed 30 dB(A) SPL equivalent input noise, and SHOULD NOT exceed 26 dB(A).	6
REQ-AC-003	Element signal-to-noise ratio SHALL be at least 65 dB(A) and SHOULD be at least 69 dB(A).	6
REQ-AC-004	Element acoustic overload point SHALL be at least 120 dB SPL, so that near-field passes and impulsive urban events do not clip the array.	6
REQ-AC-005	Element response SHALL be within 13 dB from 100 Hz to 8 kHz, covering the blade-pass fundamental through the low-order harmonics.	6
REQ-AC-006	Residual inter-element phase error after calibration SHALL NOT exceed 5° at the array Nyquist frequency.	6
REQ-AC-007	Each array SHALL carry a per-element amplitude and phase calibration table applied in the processing chain, established at manufacture against a ...	6
REQ-AC-008	The array SHALL support in-service verification of element health and calibration validity without physical disassembly, and SHALL report any element ...	6
REQ-AC-009	Bottom-port element packages SHOULD be preferred over top-port, for signal-to-noise ratio.	6
REQ-AC-010	The array SHALL detect and report tonal content in the 100 Hz to 8 kHz band, with the 100 Hz fundamental band and the first four harmonics ...	6
REQ-AC-011	The array SHALL comprise at least 16 elements, and the reference configuration SHALL comprise 24 elements in a nested two-aperture geometry.	6
REQ-AC-012	Element spacing in the inner sub-aperture SHALL satisfy the spatial Nyquist condition $d \leq c/(2 \cdot f_{\max})$ for the highest frequency that ...	6
REQ-AC-013	The outer sub-aperture SHALL use non-uniform element spacing, to avoid the periodic grating-lobe structure of a uniformly spaced aperture at that ...	6
REQ-AC-014	All channels SHALL be sampled synchronously from a single clock domain at not less than 48 kHz and not less than 24-bit resolution.	6
REQ-AC-015	The processing chain SHALL extract the blade-pass fundamental using a harmonic-structure method, and SHALL report the estimate with a confidence ...	6
REQ-AC-016	The classifier SHALL use log-mel features as its primary input, and SHOULD fuse a parallel MFCC branch.	6
REQ-AC-017	The classifier SHALL be trainable and retrainable on site-specific negative examples collected at the deployed location, and the retraining process ...	6
REQ-AC-018	The subsystem SHALL provide azimuth bearing with an accuracy of 4° RMS at 10 dB post-array signal-to-noise ratio and 10° RMS at ...	6
REQ-AC-019	The subsystem SHOULD provide elevation, and where provided the accuracy requirement SHALL be twice the corresponding azimuth figure.	6
REQ-AC-020	Direction-finding SHALL be performed on harmonic content matched to the available aperture, and SHALL NOT rely on the fundamental alone where the ...	6
REQ-AC-021	The primary direction-of-arrival estimator SHALL be an adaptive method such as MVDR, with delay-and-sum available as a reduced-capability fallback on ...	6
REQ-AC-022	Every element SHALL be fitted with a windscreen appropriate to the declared operating wind limit.	6
REQ-AC-023	The node SHALL measure wind speed at the array and SHALL report it with every detection, so that fusion can down-weight acoustic evidence in high ...	6
REQ-AC-024	The supplier SHALL declare the wind speed above which detection performance is not guaranteed, and SHALL demonstrate performance at and below that ...	6

ID	Abbreviated requirement	Section
REQ-AC-025	The subsystem SHALL report Doppler-derived radial velocity where the target motion and integration time permit, as a supplementary observable.	6
REQ-AC-026	The subsystem SHALL classify drone versus non-drone and broad size class as primary outputs, and MAY report make or model as an explicitly ...	6
REQ-AC-027	The subsystem SHALL be characterised against the rotorcraft and fixed-wing aircraft confusion classes, and the measured confusion rate against those ...	6
REQ-AC-028	All beamforming, feature extraction and classification SHALL execute at the node. Multi-channel raw audio SHALL NOT be streamed over the backhaul in ...	6
REQ-AC-029	Continuous audio recording to persistent storage SHALL be disabled by default, and any recording capability SHALL be subject to the privacy controls ...	6
REQ-AC-030	Declared detection ranges SHALL be established by field trial in the deployment environment. Derived budget figures SHALL NOT be published as ...	6
REQ-AC-031	The subsystem SHALL report a per-detection signal-to-noise ratio estimate and the measured ambient level in the detection band, to allow fusion to ...	6
REQ-FU-001	SHALL implement a hierarchical fusion architecture: signal- and feature-level fusion within each node, and track- or decision-level fusion across ...	7
REQ-FU-002	Raw multi-channel sensor data SHALL NOT be transported between nodes and the fusion centre in normal operation.	7
REQ-FU-003	The central fusion function SHALL continue to operate in a degraded but defined mode on loss of any single node, and SHALL report which nodes are ...	7
REQ-FU-004	Track-to-track fusion SHALL use a method that is consistent in the absence of a known cross-covariance. Covariance intersection SHALL be the default; ...	7
REQ-FU-005	The fused covariance SHALL NOT be optimistic. Consistency SHALL be demonstrated by normalised estimation error squared testing against recorded ...	7
REQ-FU-006	All nodes SHALL be synchronised to a common time base. Acoustic time-difference functions SHALL be served to better than 10 μ s and RF ...	7
REQ-FU-007	RF receivers used for any time-difference function SHALL be hardware-timestamped PTP clients. Software timestamping SHALL NOT be used for ...	7
REQ-FU-008	SHALL report the current timing source, its holdover state and its estimated accuracy, and SHALL degrade time-difference-derived outputs explicitly ...	7
REQ-FU-009	All measurements SHALL be transformed into a common local East-North-Up frame with covariance propagated through the appropriate Jacobian, and ...	7
REQ-FU-010	SHALL provide online sensor registration to estimate and correct inter-sensor angular, range and clock biases, and SHALL report current bias ...	7
REQ-FU-011	Validation gates SHALL be derived from the chi-square quantile at the measurement dimension for the configured gate probability. A fixed ...	7
REQ-FU-012	The association cost structure SHALL include an explicit cost for the no-assignment option, so that false associations are not forced.	7
REQ-FU-013	Gate probability SHALL be adaptable to local track density, either automatically or by configuration.	7
REQ-FU-014	The association function SHALL be at least global nearest neighbour, and SHALL provide a probabilistic or multi-hypothesis mode for the closely ...	7
REQ-FU-015	Where a random-finite-set filter is used and persistent track identity is required, a labelled variant SHALL be used; the unlabelled PHD filter alone ...	7
REQ-FU-016	State estimation SHALL use a nonlinear filter appropriate to the measurement geometry. An unscented or equivalent derivative-free filter SHALL be the ...	7
REQ-FU-017	The tracker SHALL use an interacting-multiple-model motion-model bank covering at minimum a hover or near-stationary model, a steady-transit model ...	7
REQ-FU-018	SHALL compute a continuous fused confidence value rather than only a binary decision, and SHALL expose the per-modality contributions to that value.	7
REQ-FU-019	Per-modality confidence scores used in likelihood-ratio fusion SHALL be calibrated, and the calibration SHALL be verifiable against recorded trial ...	7
REQ-FU-020	SHALL accept an explicit ignorance report from a modality and SHALL NOT force a modality to commit a full distribution across classes when it cannot ...	7
REQ-FU-021	Where evidential fusion is used, the implementation SHALL address the highly conflicting evidence case by a conflict-redistribution or ...	7

ID	Abbreviated requirement	Section
REQ-FU-022	Alerting SHALL be graded, distinguishing at minimum a low-confidence single-modality contact, a persistent single-modality contact, and a ...	7
REQ-FU-023	SHALL NOT infer the absence of a UAS from the absence of RF emissions. An acoustic-only contact SHALL be capable of generating an alert without RF ...	7
REQ-FU-024	SHALL be configurable to a hard k-of-n rule as a fallback where a subsystem cannot provide calibrated confidence.	7
REQ-FU-025	Classification confidence and threat score SHALL be computed and reported as separate quantities and SHALL NOT be collapsed into a single number.	7
REQ-FU-026	For each confirmed track the system SHALL compute closest point of approach to each declared protected volume, time to that point at current ...	7
REQ-FU-027	SHALL include at minimum drone, bird, manned aircraft and unknown, and the measured confusion matrix across those classes SHALL be reported from ...	7
REQ-FU-028	The false-alarm contribution of birds and other wildlife to the acoustic subsystem SHALL be characterised separately during field trial and SHALL NOT ...	7
REQ-FU-029	The assumption of independence between modality decision errors SHALL be tested against recorded trial data, and any measured dependence SHALL be ...	7
REQ-FU-030	SHALL record all sensor detections, association decisions, track states and fusion confidences in a replayable form, so that missed detections and ...	7
REQ-FU-031	Node density SHALL be justified by an interference and coverage analysis. Additional RF nodes SHALL NOT be assumed to improve detection probability ...	7
REQ-FU-032	Detection-to-classification latency SHALL be measured and reported, and SHALL NOT exceed 5 s for a corroborated multi-modality contact.	7
REQ-NW-001	Each sensor node SHALL perform detection, classification and bearing or time-difference estimation locally and SHALL transmit structured detection ...	8.7
REQ-NW-002	The nominal steady-state backhaul load per node SHALL NOT exceed 200 kbit/s for detection metadata plus health telemetry at the 50-concurrent-track ...	8.7
REQ-NW-003	Each node SHALL support opportunistic upload of a bounded raw I/Q or raw multichannel audio snapshot around a high-confidence detection, and this ...	8.7
REQ-NW-004	Detection-alert traffic SHALL be carried on a separately prioritised class, slice or queue from bulk telemetry, log and snapshot traffic.	8.7
REQ-NW-005	Each node SHALL continue local detection, classification and alert generation, and SHALL buffer reports for later delivery, during total loss of ...	8.7
REQ-NW-006	Backhaul selection per node SHALL be justified against a documented link budget. E-band hops SHALL be dimensioned using ITU-R P.530 with P.837 rain ...	8.7
REQ-NW-007	E-band hops specified for 99.999 percent availability SHALL NOT exceed 3 km unless a site-specific rain-rate analysis supports a longer path.	8.7
REQ-NW-008	Where unlicensed 2.4 GHz or 5 GHz backhaul radios are co-located with RF sensor nodes, an interference analysis SHALL demonstrate that backhaul ...	8.7
REQ-NW-009	Nodes backhauled over GEO satellite SHALL NOT be relied upon for any function whose specified latency budget is below 1 s.	8.7
REQ-NW-010	Published URLLC latency figures SHALL NOT be used as end-to-end network budgets. Latency budgets SHALL be established by measurement on the deployed ...	8.7
REQ-NW-011	Inter-node time synchronisation error SHALL be below 100 ns root mean square for nodes participating in RF time-difference-of-arrival multilateration.	8.7
REQ-NW-012	Inter-node time synchronisation error SHALL be below 10 us for nodes participating only in acoustic time-difference processing.	8.7
REQ-NW-013	Time distribution SHALL use IEEE 1588v2 under ITU-T G.8275.1 where the transport path is fully PTP-aware, and MAY use G.8275.2 only where partial ...	8.7
REQ-NW-014	Where the transport is Ethernet-based, Synchronous Ethernet per ITU-T G.8262 SHOULD be used for frequency stabilisation alongside PTP phase and ...	8.7
REQ-NW-015	Each node SHALL use a multi-constellation GNSS timing receiver with anti-jamming and anti-spoofing features, and SHALL report GNSS lock status, ...	8.7
REQ-NW-016	SHALL NOT treat GNSS availability as an assumption. Loss or corruption of GNSS SHALL raise an operator-visible degraded-timing condition, and the ...	8.7

ID	Abbreviated requirement	Section
REQ-NW-017	Nodes participating in RF multilateration SHALL provide a holdover oscillator maintaining the REQ-NW-011 timing budget for a declared minimum outage ...	8.7
REQ-NW-018	OCXO-only holdover SHALL NOT be used on nodes whose declared GNSS-denial exposure exceeds 1 h, since multi-microsecond drift degrades multilateration ...	8.7
REQ-NW-019	The per-node continuous power budget SHALL be re-derived against selected hardware before site power design, and the 55 W figure of Table 8-4 SHALL ...	8.7
REQ-NW-020	Where PoE powers a full multi-sensor node, IEEE 802.3bt Type 3 or Type 4 power sourcing equipment SHALL be used. IEEE 802.3at SHALL NOT be used for a ...	8.7
REQ-NW-021	Off-grid nodes SHALL be sized against site-specific typical-meteorological-year irradiance data, with a documented worst-month calculation, a stated ...	8.7
REQ-NW-022	Off-grid nodes SHALL provide a minimum of three days autonomy at the declared continuous load without solar input.	8.7
REQ-NW-023	Node enclosures SHALL meet IP66 as a minimum, and IP67 where temporary immersion or flooding is credible at the site.	8.7
REQ-NW-024	Mast-mounted node hardware SHALL be qualified for temperature, humidity, vibration and shock against MIL-STD-810 methods appropriate to the site, ...	8.7
REQ-NW-025	Node installations SHALL implement lightning protection per IEC 62305, including Part 4 surge protection measures, and node electronics SHALL pass ...	8.7
REQ-NW-026	Every mast or building mounting SHALL be verified against the structure original TIA-222 or EN 1991-1-4 structural rating, accounting for the added ...	8.7
REQ-NW-027	All node-to-aggregator and aggregator-to-command links SHALL use mutual TLS with per-node cryptographic identity. Network location SHALL NOT be used ...	8.7
REQ-NW-028	SHALL be designed to NIST SP 800-207 zero-trust principles, with per-request authorisation, and SHALL apply an operational-technology control ...	8.7
REQ-NW-029	Node firmware and configuration updates SHALL be cryptographically signed, and a node SHALL refuse to execute unsigned or unverifiable images.	8.7
REQ-NW-030	SHALL decode broadcast Remote ID per ASTM F3411 where present and SHALL present it as a distinct cooperative-identification source, never merged into ...	8.7
REQ-NW-031	SHALL export track data in at least one recognised external format, from ASTERIX CAT-129 or CAT-062 or Cursor on Target, and the selected format ...	8.7
REQ-NW-032	Node-to-aggregator transport SHOULD use MQTT or an equivalent lightweight publish and subscribe protocol; aggregator-to-backend transport SHOULD use ...	8.7
REQ-NW-033	Any NATO tactical data link integration SHALL be achieved through an external gateway translating the native export format. Link 16 or equivalent ...	8.7
REQ-DP-001	Node counts and spacing SHALL be derived from a documented coverage calculation stating the assumed per-modality detection radius, the packing ...	9.8
REQ-DP-002	Detection radius assumptions SHALL be validated by site survey before installation. Published or vendor-quoted ranges SHALL NOT be used as ...	9.8
REQ-DP-003	SHALL NOT claim uniform multi-modality coverage across the RF footprint. Acoustic coverage SHALL be declared as a separate, explicitly bounded ...	9.8
REQ-DP-004	Acoustic nodes SHALL be sited at declared protected volumes and approach corridors rather than distributed to blanket the RF coverage area.	9.8
REQ-DP-005	Node layouts SHALL be irregular and non-collinear. A geometric dilution of precision map SHALL be produced across the intended coverage volume before ...	9.8
REQ-DP-006	Declared position accuracy SHALL be stated together with the target location or GDOP condition it applies to. A single network-wide accuracy figure ...	9.8
REQ-DP-007	Coverage-edge and convex-hull-exterior performance SHALL be modelled and reported separately from centroid performance.	9.8
REQ-DP-008	Urban RF nodes SHOULD be mounted above average local rooftop level, and where they cannot be, the resulting non-line-of-sight loss SHALL be ...	9.8
REQ-DP-009	Acoustic node placement SHALL be assessed for local ambient noise floor and facade reverberation, and the site-specific achievable detection range ...	9.8
REQ-DP-010	RF and acoustic mounting positions at a shared site SHALL be optimised independently, and any compromise driven by installation constraints SHALL be ...	9.8

ID	Abbreviated requirement	Section
REQ-DP-011	Rural node siting SHALL account for worst-month insolation, unattended maintenance interval, lightning exposure and physical access, and SHALL ...	9.8
REQ-DP-012	Mobile nodes SHALL determine or be surveyed for their own position and array orientation at every set-up, and SHALL NOT report tracks using an ...	9.8
REQ-DP-013	Mobile nodes SHALL report an explicit geometry-quality indication to the operator, and the fused picture SHALL degrade declared accuracy accordingly ...	9.8
REQ-DP-014	SHALL be re-verified by flight trial against a cooperative reference aircraft covering centroid, mid-cell and coverage-edge positions at a minimum of ...	9.8
REQ-DP-015	Any change to node siting, antenna height or array orientation after acceptance SHALL trigger re-verification of the affected coverage and GDOP ...	9.8
REQ-VV-001	Every declared performance figure SHALL be accompanied by the target class, range, altitude, geometry, environmental conditions and measurement date ...	10.6
REQ-VV-002	Probability of detection SHALL be reported as a curve against range and SHALL NOT be reported as a single value.	10.6
REQ-VV-003	Declared maximum detection range SHALL be defined as the range at which probability of detection falls to 0.50 for the declared target class, and ...	10.6
REQ-VV-004	Probability of false alarm SHALL be reported together with the decision opportunity rate to which it applies.	10.6
REQ-VV-005	Operator-visible false alerts per hour SHALL be measured over a continuous period of at least 168 h that includes dawn and dusk periods of elevated ...	10.6
REQ-VV-006	Detection latency SHALL be reported as a distribution with median and 95th percentile, decomposed into node processing, transport, fusion and display ...	10.6
REQ-VV-007	Localisation accuracy SHALL be measured at centroid, mid-cell and coverage-edge geometries, and all three SHALL be reported.	10.6
REQ-VV-008	Classification performance SHALL be reported as a per-class confusion matrix across drone, bird, manned aircraft and unknown. An aggregate accuracy ...	10.6
REQ-VV-009	Track continuity SHALL be reported with track-break count and identity-swap count, not as a continuity fraction alone.	10.6
REQ-VV-010	Field trials SHALL use a cooperative reference aircraft with independently surveyed truth positions, and truth data SHALL be recorded at a rate ...	10.6
REQ-VV-011	Acoustic subsystem performance SHALL be measured at declared wind-speed bands, and the wind speed above which the subsystem is out of specification ...	10.6
REQ-VV-012	SHALL be verified under 24 h GNSS denial and under 24 h total backhaul loss, and the resulting degraded performance SHALL be recorded rather than the ...	10.6
REQ-VV-013	Simulation and modelling results SHALL be labelled as such and SHALL NOT be presented alongside measured results without that distinction being ...	10.6
REQ-VV-014	The trial methodology SHALL be documented and agreed before trials begin, and SHALL NOT be adjusted after results are known without the adjustment ...	10.6
REQ-VV-015	All trial data SHALL be retained in replayable form per REQ-SYS-009 so that reported results can be independently recomputed.	10.6
REQ-VV-016	Where a required capability is not achievable, it SHALL be recorded as a declared non-capability in the acceptance matrix rather than omitted.	10.6

14 Appendix B — Symbols, Constants and Equation Reference

14.1 Symbols

Symbol	Quantity	Units and notes
A_hex	Hexagonal cell coverage area for circumradius r	km-squared. $A_{hex} = 2.598 r^2$
B	Receiver noise bandwidth	Hz
c	Speed of propagation of electromagnetic waves in vacuum	m/s. See Section 14.2
c_s	Speed of sound in air	m/s, temperature dependent. See Section 14.2
d	Distance or slant range	m or km as stated at point of use
f_c	Carrier or centre frequency	Hz, MHz or GHz as stated
GDOP	Geometric dilution of precision	Dimensionless multiplier
k	Boltzmann constant	J/K. See Section 14.2
N	Number of nodes, or number of array elements, as stated	Dimensionless
NF	Receiver noise figure	dB
P_D	Probability of detection	Dimensionless, 0 to 1
P_FA	Probability of false alarm	Dimensionless, 0 to 1
PL	Path loss	dB
r, R	Sensor detection radius, and area effective radius, respectively	km
SNR	Signal-to-noise ratio	dB unless stated as a linear ratio
T	Absolute temperature	K
sigma_TDOA	Root-mean-square time-difference-of-arrival measurement error	s, usually ns
sigma_xyz	Root-mean-square three-dimensional position error	m
lambda	Wavelength	m

14.2 Constants

Constant	Value	Note
Boltzmann constant, k	1.380649e-23 J/K	Used in the thermal noise floor derivation, Section 4
Thermal noise floor at 290 K	-174 dBm/Hz	kTB reference used throughout Section 4
Speed of light, c	2.99792458e8 m/s	Approximately 0.2998 m per nanosecond
RF range per nanosecond	0.2998 m/ns	The basis of the timing-to-range conversion in Sections 8.3 and 9.2
Speed of sound in air at 20 degrees C	Approximately 343 m/s	Temperature dependent; used in acoustic array and TDOA calculations in Section 6
Hexagonal packing factor	2.598	Equal to $3 \sqrt{3} / 2$, used in Section 9.1

14.3 Equation reference

The equations below are collected for convenience. Each is developed with its assumptions and worked examples at the section cited.

Thermal noise floor and receiver sensitivity (Section 4)

$$N_{\text{floor}}(\text{dBm}) = -174 + 10 \log_{10}(B_{\text{Hz}}) + NF(\text{dB})$$

$$\text{Sensitivity}(\text{dBm}) = N_{\text{floor}}(\text{dBm}) + SNR_{\text{required}}(\text{dB})$$

Free-space path loss (Section 4)

$$FSPL(\text{dB}) = 20 \log_{10}(d_{\text{km}}) + 20 \log_{10}(f_{\text{MHz}}) + 32.44$$

3GPP TR 38.901 Urban Macro line-of-sight path loss (Sections 4, 9)

$$PL(\text{dB}) = 28.0 + 22 \log_{10}(d_{\text{m}}) + 20 \log_{10}(f_{\text{c_GHz}}), \text{ for } 10 \text{ m} < d < 5 \text{ km}$$

Blade passage frequency (Section 6)

$$BPF(\text{Hz}) = N_{\text{blades}} \times (\text{RPM} / 60)$$

Spatial Nyquist criterion for a sensor array (Section 6)

$$d_{\text{element}} \leq \lambda_{\text{min}} / 2 = c_s / (2 \times f_{\text{max}})$$

Array gain for N elements with uncorrelated noise (Section 6)

$$\text{Array gain}(\text{dB}) = 10 \log_{10}(N)$$

Time-difference-of-arrival position error (Sections 8.3, 9.2)

$$\sigma_{\text{xyz}} = \text{GDOP} \times \sigma_{\text{TDOA}} \times c$$

Timing error to range error (Section 8.3)

$$\text{range error}(\text{m}) = \text{timing error}(\text{ns}) \times 0.2998$$

Hexagonal cell area and node count (Section 9.1)

$$A_{\text{hex}} = (3 \sqrt{3} / 2) r^2 = 2.598 r^2$$

$$N_{\text{nodes}} = \text{ceil}(A_{\text{coverage}} / A_{\text{hex}})$$

Raw I/Q data rate (Section 8.1)

$$\text{Rate}(\text{bit/s}) = \text{sample_rate} \times 2 \times \text{bits_per_component}$$

Off-grid photovoltaic and battery sizing (Section 8.4.3)

$$E_{\text{daily}}(\text{Wh}) = P_{\text{load}}(\text{W}) \times 24$$

$$P_{\text{array}}(\text{W}) = E_{\text{daily}} / (\text{PSH} \times \text{derating})$$

$$E_{\text{battery}}(\text{Wh}) = (E_{\text{daily}} \times \text{autonomy_days}) / \text{depth_of_discharge}$$

k-of-n decision fusion (Section 7)

$$P(k \text{ of } n) = \sum_{j=k..n} \text{of } C(n,j) p^j (1-p)^{(n-j)}$$

Bayesian likelihood-ratio fusion of independent modalities (Section 7)

$$LR_{\text{fused}} = LR_{\text{RF}} \times LR_{\text{LTE}} \times LR_{\text{acoustic}} \quad (\text{independence assumed and required to be tested})$$