Acoustic Detection of Unmanned Aerial Systems via Piezoelectric Sensor Array Fabric

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Abstract

I present a theoretical framework for passive acoustic detection of unmanned aerial systems (UAS) using a woven piezoelectric sensor array fabric capable of integrating dense arrays of acoustic sensors at densities exceeding $1000/\mathrm{cm}^2$ with embedded beamforming signal processing. I derive a master detection range equation incorporating source acoustic power, spherical spreading, atmospheric absorption (ISO 9613-1 [6]), ambient noise floor, array processing gain, and matched filter gain. For a $1\ \mathrm{m}^2$ fabric panel with $\sim 10^6$ sensor elements operating as a coherent phased array at 200 Hz, theoretical array gain reaches 60 dB. Under calm conditions (< 2 m/s wind, rural ambient 30 dBA), detection ranges of 800–2400 m are predicted for consumer quadcopters and 3–12 km for fixed-wing military UAS. Multiple draped panels separated by meters achieve aperture synthesis with sub-degree angular resolution. The sensor array fabric is a viable passive, covert counter-UAS detection layer deployable as camouflage netting, tent fabric, or vehicle covers.

Keywords: unmanned aerial systems, UAS detection, counter-UAS, passive acoustic detection, piezoelectric sensor array, phased array beamforming, acoustic propagation, drone acoustics, sensor fabric

1. Introduction

Commercially available unmanned aerial systems (UAS) and their adoption as low-cost weapons have elevated counter-UAS (C-UAS) to a tier-1 military requirement. The widespread combat deployment of the Iranian Shahed-136 series loitering munition in 2022–2024 illustrates the urgency. Passive acoustic detection offers a compelling complement to radar and electro-optical sensor suites: it emits no electromagnetic radiation (critical for emission control (EMCON) operations), operates in all weather and all lighting conditions, is immune to frequency-hopping RF jamming, and is uniquely sensitive to the rotary-wing and reciprocating-engine acoustic signatures that characterize the threat class [5].

Existing passive acoustic drone detection systems rely on discrete microphone arrays comprising 4 to 64 elements, typically spaced 0.1–1 m apart. Such arrays achieve array processing gains of 6–18 dB and report detection ranges of 100–500 m against small quadcopters under calm ambient conditions. The fundamental constraint is element count: thermodynamic and fabrication limits on discrete microphone arrays prevent scaling beyond ~ 100 elements without prohibitive cost and logistics burden.

I propose a woven or laminated textile integrating dense arrays of piezoelectric acoustic sensors at densities of $\geq 10\ \mathrm{sensors}/\mathrm{cm}^2$ up to $\geq 1000\ \mathrm{sensors}/\mathrm{cm}^2$. A $1\ \mathrm{m}^2$ panel at $1000/\mathrm{cm}^2$ density yields $N = 10^7$ sensor elements, five to six orders of magnitude beyond any fielded acoustic array. The architecture integrates beamforming signal processing directly into the fabric's processor layer, enabling real-time steered beam formation across the aperture.

I develop the full theoretical detection range framework for this technology applied to UAS detection in the sections that follow. Section 2 describes the sensor array fabric architecture and piezoelectric mechanism. Section 3 catalogues the measured acoustic signatures of consumer and military UAS platforms. Section 4 derives the atmospheric propagation model. Section 5 develops phased array processing gain formulas for the fabric geometry. Section 6 derives and numerically solves the master detection range equation. Section 7 presents comprehensive tabulated range predictions across platform, fabric configuration, and environmental conditions. Section 8 discusses practical limitations and compares against fielded systems.

2. Sensor Array Fabric Architecture

2.1 Fabric Construction

The sensor array fabric is a laminar multi-layer construction. From outer surface inward: (1) an outer cladding layer providing environmental and abrasion protection; (2) a display layer capable of rendering alphanumeric and graphical information, potentially showing real-time threat bearings; (3) a processing layer housing microprocessors, digital signal processors (DSPs), and analog conditioning electronics; (4) a communications array layer providing inter-element and external data links; (5) one or more sensor array layers (the core detection medium) comprising the piezoelectric bilayer acoustic sensor matrix; and (6) an inner cladding layer completing the laminar sandwich.

The sensor array is defined by an array of bilayer cells in which adjacent layers of $\mathrm{CaCO_3}$ (calcite) and $\mathrm{KC_4H_5O_6}$ (potassium hydrogen tartrate, potassium bitartrate, or cream of tartar) form each sensing unit. Cell lateral dimensions are specified at $\leq 300\ \mu\mathrm{m}$, with achievability to $\sim 20\ \mu\mathrm{m}$ via advanced 3D printing techniques. At the lower bound, maximum sensor densities reach

$$(1/20\mu\mathrm{m})^2 = 25{,}000/\mathrm{mm}^2 = 2.5 \times 10^9/\mathrm{m}^2$$

though the analysis here is bounded at $1000/\mathrm{cm}^2$. Array spatial configurations include rectangular (Cartesian) grids, polar/annular layouts, tiled geometries, and fully three-dimensional conformal arrays.

2.2 Piezoelectric Mechanism

Potassium hydrogen tartrate $\mathrm{KC_4H_5O_6}$ belongs to the chiral L-tartrate family and crystallizes in the monoclinic system (space group $P2_1$, point group 2), which is non-centrosymmetric and therefore inherently piezoelectric [12]. It is a chemical precursor to Rochelle salt (sodium potassium tartrate, $\mathrm{NaKC_4H_4O_6 \cdot 4H_2O}$), the first technologically exploited piezoelectric material, with piezoelectric coefficients d_{14} exceeding 100 pC/N at room temperature [11].

Calcite ($\mathrm{CaCO_3}$ in rhombohedral $R\bar{3}c$ symmetry) is centrosymmetric and therefore non-piezoelectric in bulk form. In the bilayer construction, it serves as a mechanical stress-concentration and acoustic coupling layer that efficiently transfers incident pressure waves to the active $\mathrm{KC_4H_5O_6}$ layer. The architecture is functionally analogous to SEBS elastomer cladding layers used in PVDF-TrFE composite acoustic fiber arrays reported by Yan et al. (2022) in *Nature* [8], where the mechanically stiff sheath concentrates stress at the piezoelectric core.

Based on Rochelle salt analogs and published data for organic piezoelectric crystals, I estimate the effective piezoelectric coefficient d_{eff} for the $\mathrm{CaCO_3/KC_4H_5O_6}$ bilayer in the range 5–30 pC/N, yielding a passive pressure sensitivity per element of approximately 0.1–5 mV/Pa for cell dimensions of 20–300 μm and typical acoustic impedance matching conditions [13]. Empirical characterization of fabricated bilayer cells is the highest-priority validation item before system deployment.

2.3 Signal Processing Subsystem

The integrated processor layer houses microprocessors, DSPs, and analog filtering electronics woven into or laminated onto the fabric structure. The signal processing pipeline proceeds as: (a) per-element analog conditioning and anti-alias filtering; (b) analog-to-digital conversion; (c) fast Fourier transform (FFT) decomposition into the frequency domain; (d) frequency-domain weighting and beamforming delay application; (e) spatial summation across the beamforming aperture; (f) bandpass, bandstop, high-pass, or low-pass filtering; and (g) output to the communications layer or display layer.

Beamforming allows the array to amplify signals arriving from a selected look-direction while attenuating signals from all other directions by an amount determined by the beam pattern sidelobe level. Frequency filtering permits matched-subband processing targeting the known spectral features of UAS signatures (blade pass frequency fundamentals and harmonics) while rejecting out-of-band wind noise and broadband environmental noise.

2.4 Military Fabric Applications

The physical form factor of the sensor array fabric enables deployment modalities unavailable to any discrete-element acoustic array system. Primary military applications include camouflage netting draped over vehicles, artillery positions, and command posts (providing both physical concealment and continuous 360° acoustic surveillance without additional logistical footprint); tent and shelter fabric incorporating detection into the shelter skin itself; vehicle drape covers carried as standard equipment that activate acoustic surveillance upon deployment; uniform fabric patches providing individual dismounted-soldier acoustic sensing; and perimeter barrier fabric serving as a passive acoustic tripwire perimeter. The display layer could render real-time threat bearing arrows directly on the fabric surface, providing eyes-on situational awareness without electronic displays or headsets.

3. Drone Acoustic Signatures

3.1 Consumer Quadcopters

Rotary-wing UAS produce acoustic signatures dominated by tonal blade-pass frequency (BPF) components and their harmonics, superimposed on broadband turbulence noise. The BPF for a rotor with N_b blades spinning at RPM rotations per minute is:

$$\mathrm{BPF} = \frac{\mathrm{RPM} \times N_b}{60} \quad [\mathrm{Hz}]$$

For a DJI Phantom II (2-blade, 239 mm diameter propeller, cruise RPM ~ 3840): $\mathrm{BPF} = (3840 \times 2)/60 = 128\,\mathrm{Hz}$. Zawodny et al. (2016) [1] measured overall sound pressure levels (OASPL) of 70–80 dBA at 1.51 m reference distance across the RPM operating range. Kloet et al. (2017) [3] report that the primary acoustic energy of multirotor UAS concentrates in the 650–2110 Hz range, with the fundamental BPF often falling in the 100–300 Hz band.

Motor phase synchronization between quadcopter arms has an important effect: when motors are synchronized at 90° phase offset, BPF components from the four rotors undergo partial cancellation, reducing the net tonal level by up to -6 dB at the BPF. Alexander and Whelchel (2019) [2] characterize the DJI Matrice 600 Pro acoustic signature across three spectral regions: tonal components below 1 kHz (BPF and harmonics), broadband turbulence noise 1–3 kHz, and high-frequency interaction noise 5–20 kHz. The EASA PR-42 standard reports a sound power level $L_{WA} = 97$ dB(A) for the DJI Matrice 350 RTK.

Table 1. Consumer multirotor UAS acoustic characteristics.

Platform	Type	N_b	RPM Range	BPF (Hz)	OASPL	Ref Dist	Source
DJI Phantom II	Quad	2	2000–5400	67–180	70–80 dBA	1.51 m	Zawodny 2016 [1]
DJI Phantom 4	Quad	2	3000–6000	100–200	72–82 dBA	1 m	Kloet 2017 [3]
DJI Matrice 600	Hex	2	3000–5000	100–167	~85 dBA	1 m	Alexander 2019 [2]
DJI Matrice 350 RTK	Quad	2	—	—	L_{WA} 97 dB(A)	—	EASA PR-42
DJI Mavic 3	Quad	2	4000–7000	133–233	~75 dBA	1 m	Estimated
Racing Quad (generic)	Quad	2–3	5000–8000	167–400	80–90 dBA	1 m	Estimated

3.2 Military Fixed-Wing UAS

Fixed-wing military UAS powered by reciprocating piston engines produce very different acoustic signatures: strong low-frequency engine harmonics (often 50–200 Hz), propeller BPF components, and combustion noise. Sedunov et al. (2019) [5] demonstrate acoustic classification of multiple UAS platforms using spectral template matching.

Shahed-136 / Geranium-2: Powered by the MADO MD-550 (or derivative) air-cooled two-stroke engine. The engine fires at approximately 5500–6000 RPM cruise, producing a dominant spectral peak near 1070 Hz (the first harmonic of the combustion-cylinder frequency ~ 107 Hz, i.e., cylinder fires ~ 107 Hz at cruise, 2-stroke: cylinder freq $= \mathrm{RPM}/60 = 5550/60 \approx 92.5$ Hz, harmonic stacking gives energy out to 2000 Hz). Engine modulation sidebands appear at ~ 73.5 Hz spacing. Under calm atmospheric conditions the Shahed-136 is audible at ranges exceeding 10 km.

MQ-9 Reaper: Honeywell TPE331-10GD 950 shp turboprop. Turboprop acoustic signatures are dominated by propeller BPF and broadband turbine noise. Estimated OASPL at 1 m: 100–115 dB, dominant energy 50–5000 Hz. **MQ-1 Predator:** Rotax 914F, 115 hp. Two-blade propeller, cruise RPM ~ 2200, $\mathrm{BPF} \approx 73$ Hz. **Bayraktar TB2:** Rotax 912S engine; propeller BPF ~ 71 Hz at cruise, engine cylinder frequency ~ 173 Hz (4-stroke, 4-cylinder: $f_{\mathrm{cyl}} = \mathrm{RPM}/60 \times 2 = 5200/60 \times 2 \approx 173$ Hz). **RQ-7 Shadow:** AR741 rotary engine, estimated propeller BPF 80–100 Hz.

Table 2. Military fixed-wing UAS acoustic characteristics and estimated sound power levels.

Platform	Engine Type	RPM (cruise)	Prop BPF (Hz)	Energy Band (Hz)	Est. SWL (dB)
Shahed-136	2-stroke piston	5500–6000	~183	200–2000	121
MQ-9 Reaper	Turboprop	~1100	~73	50–5000	116
MQ-1 Predator	4-stroke piston	~2200	~73	70–4000	110
Bayraktar TB2	4-stroke piston	~5200	~71	70–3000	108
RQ-7 Shadow	Rotary (AR741)	~6000	~100	100–3000	107
Hermes 900	Rotax 912S	~5500	~92	80–2000	109

3.3 Source Sound Power Level Estimation

All detection range calculations require the source sound power level L_W in dB re 1 pW. For a source measured at reference distance r_0 in the free field (no ground reflection), the sound power level is obtained from the measured SPL by:

$$L_W = \mathrm{SPL}_{\mathrm{meas}} + 20 \cdot \log_{10}(r_0) + 11 \quad [\mathrm{dB\ re\ 1\ pW}]$$

For a consumer quadcopter measured at $\mathrm{SPL} = 80$ dBA at $r_0 = 1$ m: $L_W = 80 + 0 + 11 = 91$ dB(A) re 1 pW. For the DJI Matrice 350 RTK with $L_{WA} = 97$ dB(A), the figure is directly available. For the Shahed-136, estimating $\mathrm{SPL} \approx 110$ dB at 1 m yields $L_W \approx 121$ dB. For the MQ-9 Reaper estimating $\mathrm{SPL} \approx 105$ dB at 1 m yields $L_W \approx 116$ dB. I use these values as input parameters throughout Sections 6 and 7.

4. Atmospheric Acoustic Propagation Model

4.1 Spherical Spreading Loss

For a compact acoustic source radiating into an unbounded free field, the transmission loss due to geometric spreading follows the inverse-square law. In decibel form:

$$\mathrm{TL}_{\mathrm{sph}}(r) = 20 \cdot \log_{10}\left(\frac{r}{r_0}\right) \quad [\mathrm{dB}]$$

where $r_0 = 1$ m is the reference distance, representing a 6 dB loss per doubling of range. For absolute SPL prediction from L_W, the free-field point source equation is $\mathrm{SPL}(r) = L_W - 20 \cdot \log_{10}(r) - 11$ [dB], where the 11 dB term accounts for 4π steradian solid angle ($10 \cdot \log_{10}(4\pi) = 10.99$ dB). Selected spreading loss values:

Table 3. Spherical spreading transmission loss vs. range.

Range (m)	$\mathrm{TL}_{\mathrm{sph}}$ (dB)
10	20.0
25	28.0
50	34.0
100	40.0
200	46.0
500	54.0
1000	60.0
2000	66.0
5000	74.0

4.2 Atmospheric Absorption, ISO 9613-1

Beyond geometric spreading, acoustic energy is absorbed by thermoviscous processes and molecular relaxation in atmospheric oxygen and nitrogen, as rigorously described in ISO 9613-1:1993 [6] and the supporting work of Bass et al. (1995) [7]. The absorption coefficient α [dB/km] is a strong function of frequency, temperature T, relative humidity RH, and atmospheric pressure P_a. The ISO formula involves oxygen and nitrogen relaxation frequencies f_{rO} and f_{rN}:

$$\alpha = 8.686\, f^2 \left\{ 1.84 \times 10^{-11} \left(\frac{P_r}{P_a}\right) \left(\frac{T}{T_r}\right)^{1/2} + \left(\frac{T}{T_r}\right)^{-5/2} \left[\frac{0.01275\, e^{-2239.1/T}}{f_{rO} + f^2/f_{rO}} + \frac{0.1068\, e^{-3352.0/T}}{f_{rN} + f^2/f_{rN}} \right] \right\} \quad [\mathrm{dB/km}]$$

At $T = 20^\circ\mathrm{C}$, $\mathrm{RH} = 50\%$, $P_a = 101.325$ kPa, the absorption coefficient takes the following values across the acoustic frequency range of interest. The critical insight here: low-frequency BPF components (100–300 Hz) propagate with absorption of only 0.3–0.9 dB/km, while the 4–8 kHz band suffers 27–80 dB/km. Drone fundamental frequencies are detectable at long range even when higher harmonics are severely attenuated.

Table 4. Atmospheric absorption coefficients at $T = 20^\circ\mathrm{C}$, $\mathrm{RH} = 50\%$ (ISO 9613-1 [6]).

Frequency (Hz)	α (dB/km)	Absorption at 1 km (dB)	Absorption at 5 km (dB)
50	0.10	0.10	0.5
100	0.28	0.28	1.4
200	0.88	0.88	4.4
500	2.08	2.08	10.4
1000	4.72	4.72	23.6
2000	10.90	10.90	54.5
4000	27.00	27.00	135.0
8000	80.00	80.00	400.0

4.3 Wind Effects and Noise Floor

Wind is the primary limiting factor for acoustic drone detection. Wind interacts with sensor elements to produce broadband noise following the Strasberg (1955) model for turbulent flow over a surface: the wind noise power spectral density scales approximately as U^6 where U is wind speed. Wind also creates acoustic refraction effects; upwind propagation encounters a negative sound speed gradient (shadow zone formation) causing 10–25 dB additional propagation loss, while downwind propagation benefits from positive refraction giving +5 to +15 dB enhancement. Wind noise floor estimates at a fabric sensor element:

Table 5. Wind noise floor vs. wind speed at fabric sensor element.

Wind Speed (m/s)	Wind Speed (kt)	Sensor Noise Floor (dB SPL)	Detection Penalty (dB)
<1	<2	~25	0 (baseline)
2	3.9	~35	~10
3	5.8	~40	~15
5	9.7	~55	~30
8	15.5	~65	~40
12	23.3	~75	~50

4.4 Ambient Noise Environments

Table 6. Ambient acoustic noise environments relevant to UAS detection.

Environment	L_N (dBA)	Typical Use Case
Very quiet rural night	20–25	Remote FOB, open desert
Rural daytime, calm	30–35	Agricultural terrain, daylight
Suburban residential	40–50	Perimeter defense, populated zone
Urban mixed use	55–70	Urban combat, vehicle traffic
Military FOB (variable)	45–65	Generator noise, vehicle activity
Active airfield perimeter	70–85	High ambient, severe limitation

4.5 Temperature, Stratification, and Ground Effects

Atmospheric temperature gradients cause acoustic ray bending (refraction). Under a normal temperature lapse rate (temperature decreasing with altitude), sound rays are refracted upward, creating a shadow zone at extended ranges. Under a temperature inversion (temperature increasing with altitude, common at night), rays are refracted downward, creating a ground-hugging duct that significantly enhances long-range propagation; a critical condition that can extend detection ranges by 3–10x. For elevated drone targets flying above 50 m AGL, direct-path ground reflections produce constructive and destructive interference patterns that depend on surface acoustic impedance; beyond 200 m range, the dominant path is direct-air and ground effects are typically below 3 dB.

5. Phased Array Processing Gain

5.1 Delay-and-Sum Beamforming

The classical delay-and-sum (DAS) beamformer steers the array toward a look direction by applying time delays τ_n to each element's signal to compensate for propagation path differences, then coherently sums [9]:

$$y(t) = \frac{1}{N}\sum_{n=1}^{N} w_n \cdot x_n(t-\tau_n)$$

where $x_n(t)$ is the n-th element's output, w_n is the amplitude taper weight (uniform taper: $w_n = 1$), and the steering delay is:

$$\tau_n = \frac{\mathbf{r}_n \cdot \hat{\mathbf{u}}}{c}$$

where $\mathbf{r}_n$ is the position vector of the n-th element, $\hat{\mathbf{u}}$ is the unit look-direction vector, and $c = 343$ m/s is the speed of sound at 20°C. For a uniform linear array (ULA) with element spacing d, the beam pattern in the far field is:

$$B(\theta) = \frac{\sin(N\pi d\sin(\theta)/\lambda)}{N\sin(\pi d\sin(\theta)/\lambda)}$$

5.2 Array Gain

Array gain G_{array} is the improvement in SNR at the beamformer output relative to a single element, assuming spatially white (incoherent) ambient noise. For N elements with unity-weight DAS beamforming [9]:

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

Mapping the sensor array fabric configurations to array gain: at $N \geq 100$ sensors (a small patch), $G \geq 20$ dB; at $N \geq 1{,}000$ sensors, $G \geq 30$ dB; at $\geq 10\ \text{sensors/cm}^2$ over a 1 m^2 panel ($N \geq 100{,}000$), $G \geq 50$ dB; at $\geq 1000\ \text{sensors/cm}^2$ over a 1 m^2 panel ($N \geq 10{,}000{,}000$), $G \geq 70$ dB theoretical. Practical gain is limited to approximately 85% of theoretical (in dB) due to inter-element correlation, fabrication non-uniformity, and calibration residuals.

Table 7. Theoretical and practical array gain vs. fabric configuration.

Fabric Size	Density (/cm²)	N sensors	Theoretical G (dB)	Practical G (dB, 85%)
10cm × 10cm	10	100	20.0	17.0
10cm × 10cm	1000	10,000	40.0	34.0
1m × 1m	10	10,000	40.0	34.0
1m × 1m	1000	1,000,000	60.0	51.0
2m × 3m	10	600,000	57.8	49.1
2m × 3m	1000	60,000,000	77.8	66.1

5.3 Spatial Aliasing and the Fabric Advantage

Spatial aliasing in a sampled aperture occurs when the inter-element spacing d exceeds the Nyquist criterion $d \leq \lambda/2 = c/(2f)$. For the fabric's maximum cell size of 300 µm, the alias-free upper frequency is:

$$f_{\text{alias}} = \frac{c}{2d} = \frac{343}{2 \times 3 \times 10^{-4}} = 571{,}667\ \text{Hz} \approx 572\ \text{kHz}$$

572 kHz is more than 70 times higher than the highest frequency of interest ($\sim$ 8 kHz). The fabric is massively oversampled spatially across the entire acoustic band, and spatial aliasing is completely eliminated. By contrast,

conventional discrete microphone arrays with 5–20 cm element spacing are spatially aliased above 850–3400 Hz, severely limiting beamforming performance at higher frequencies.

5.4 Beamwidth and Angular Resolution, Single Panel

The -3 dB beamwidth of a ULA with element spacing d, N elements (total aperture $L = N \cdot d$) steered to broadside is approximately [9]:

$$\theta_{3\text{dB}} \approx \frac{0.886\,\lambda}{L} \quad [\text{radians}]$$

where L is the physical aperture length. For a 1 m panel, $L = 1\,\text{m}$, $\lambda = c/f = 343/f$:

Table 8. Single-panel -3 dB beamwidth vs. frequency and aperture length.

Frequency (Hz)	λ **(m)**	$L = 1\text{m}$: $\theta_{3\text{dB}}$ **(deg)**	$L = 2\text{m}$: $\theta_{3\text{dB}}$ **(deg)**	$L = 5\text{m}$: $\theta_{3\text{dB}}$ **(deg)**
100	3.430	174.1	87.1	34.8
200	1.715	87.1	43.5	17.4
500	0.686	34.8	17.4	7.0
1000	0.343	17.4	8.7	3.5
2000	0.172	8.7	4.4	1.7
4000	0.086	4.4	2.2	0.9

5.5 Distributed Aperture, Multiple Draped Panels

When multiple fabric panels are deployed separated by a baseline distance D, they form a sparse aperture whose angular resolution is determined by D rather than the individual panel dimensions. For coherent combination (requiring timing synchronization to better than $\tau_{\text{jitter}} < 25$ μs and position knowledge to $< \lambda/10$), the angular resolution approaches:

$$\theta_{\text{res}} \approx \frac{\lambda}{D} \quad [\text{radians}]$$

For incoherent combination (relaxed synchronization requirements), K panels contribute an additional $G_{\text{dist}} = 10 \cdot \log_{10}(K)$ dB in SNR improvement through non-coherent averaging, though angular resolution does not improve beyond the single-panel beamwidth.

Table 9. Distributed aperture angular resolution (degrees) vs. frequency and baseline separation D.

Frequency (Hz)	λ **(m)**	$D = 5\text{m}$ **(deg)**	$D = 10\text{m}$ **(deg)**	$D = 25\text{m}$ **(deg)**	$D = 50\text{m}$ **(deg)**	$D = 100\text{m}$ **(deg)**
200	1.715	19.65	9.83	3.93	1.97	0.98
500	0.686	7.86	3.93	1.57	0.79	0.39
1000	0.343	3.93	1.97	0.79	0.39	0.20
2000	0.172	1.97	0.98	0.39	0.20	0.10
4000	0.086	0.98	0.49	0.20	0.10	0.05

5.6 Matched Filter and Spectral Processing Gain

When the drone's spectral signature (BPF fundamental plus harmonics) is known a priori, a matched filter or coherent integration bank can be applied. The time-bandwidth product gain is:

$$G_{\mathrm{MF}} = 10 \cdot \log_{10}(B \cdot T) \quad [\mathrm{dB}]$$

where B is the signal bandwidth containing the tonal features (Hz) and T is the coherent integration time (seconds). For a UAS with BPF at 128 Hz and 5 harmonics spanning a 200 Hz band: $G_{\mathrm{MF}}(T = 1\mathrm{s}) = 10 \cdot \log_{10}(200) = 23.0$ dB; $G_{\mathrm{MF}}(T = 10\mathrm{s}) = 10 \cdot \log_{10}(2000) = 33.0$ dB. The matched filter requires a database of target spectral templates, consistent with the frequency-selective processing architecture of the fabric's signal processing layer.

Detection threshold is set by CFAR (constant false alarm rate) processing: for $P_{fa} = 10^{-6}$, $P_d = 0.9$, the required SNR at the detector input is $\mathrm{SNR}_{\mathrm{det}} \approx 13.0$ dB (Rayleigh fading model); for $P_{fa} = 10^{-8}$, $P_d = 0.95$: $\mathrm{SNR}_{\mathrm{det}} \approx 16.5$ dB.

6. Master Detection Range Equation

6.1 General SNR at Receiver

The signal-to-noise ratio at the output of the beamformer-matched-filter processing chain, at range r from the target, is:

$$\mathrm{SNR}(r) = L_W - \mathrm{TL}(r) - L_{\mathrm{atm}}(r) - L_N + G_{\mathrm{array}} + G_{\mathrm{MF}} + G_{\mathrm{dist}} \quad [\mathrm{dB}]$$

where the terms are defined as:

Symbol	Definition
L_W	Source sound power level [dB re 1 pW]
$\mathrm{TL}(r)$	Spherical spreading loss: $20 \cdot \log_{10}(r) + 11$ [dB]
$L_{\mathrm{atm}}(r)$	Atmospheric absorption: $\alpha \cdot r/1000$ [dB], α in dB/km
L_N	Ambient noise power in detection bandwidth [dB SPL]
G_{array}	Practical array gain: $10 \cdot \log_{10}(N_{\mathrm{eff}})$ [dB]
G_{MF}	Matched filter / coherent integration gain: $10 \cdot \log_{10}(B \cdot T)$ [dB]
G_{dist}	Incoherent multi-panel gain: $10 \cdot \log_{10}(K)$ [dB]

6.2 Detection Criterion

Detection occurs when $\mathrm{SNR}(r) \geq \mathrm{SNR}_{\mathrm{det}}$. The CFAR detection threshold is set by the operational requirements: $P_{fa} = 10^{-6}$, $P_d = 0.9$ yields $\mathrm{SNR}_{\mathrm{det}} = 13.0$ dB; $P_{fa} = 10^{-8}$, $P_d = 0.95$ yields $\mathrm{SNR}_{\mathrm{det}} = 16.5$ dB. All computed ranges below use $\mathrm{SNR}_{\mathrm{det}} = 13.0$ dB unless otherwise noted.

6.3 Master Equation, Maximum Detection Range

Setting $\mathrm{SNR}(R_{\mathrm{max}}) = \mathrm{SNR}_{\mathrm{det}}$ and substituting the propagation terms yields the master detection range equation:

$$20 \cdot \log_{10}(R_{\mathrm{max}}) + \frac{\alpha \cdot R_{\mathrm{max}}}{1000} = L_W - 11 - L_N + G_{\mathrm{array}} + G_{\mathrm{MF}} + G_{\mathrm{dist}} - \mathrm{SNR}_{\mathrm{det}}$$

A transcendental equation in R_{max} because R appears in both the logarithmic term (from geometric spreading) and the linear term (from atmospheric absorption). No closed-form solution exists; I solve it numerically using Brent's method (`scipy.optimize.brentq`). Defining the **Excess Signal Budget**:

$$\Phi = L_W - 11 - L_N + G_{\text{array}} + G_{\text{MF}} + G_{\text{dist}} - \text{SNR}_{\text{det}} \quad [\text{dB}]$$

the master equation reduces to:

$$\boxed{20 \cdot \log_{10}(R_{\max}) + \frac{\alpha \cdot R_{\max}}{1000} = \Phi}$$

6.4 Worked Numerical Examples

Example 1: DJI Phantom-class quadcopter, $1\ \text{m}^2$ fabric panel ($1000/\text{cm}^2$), calm rural, $T = 1$ s integration

$L_W = 91$ dB (from OASPL 80 dBA at 1 m). $\alpha = 0.88$ dB/km at 200 Hz (ISO 9613-1, $T = 20^\circ$C, RH $= 50\%$). $L_N = 30$ dBA (rural calm). $N = 10^6$ sensors, practical $G_{\text{array}} = \min(0.85 \times 10 \cdot \log_{10}(10^6),\ 50) = 50.0$ dB. $G_{\text{MF}} = 10 \cdot \log_{10}(200 \times 1) = 23.0$ dB. $G_{\text{dist}} = 10 \cdot \log_{10}(1) = 0$ dB (single panel). $\text{SNR}_{\text{det}} = 13.0$ dB.

$$\Phi = 110.0 \text{ dB}$$

Solve: $20 \cdot \log_{10}(R) + 0.00088 \cdot R = 110.0$

$$R_{\max} = 25{,}042 \text{ m} \quad (25.04 \text{ km},\ 15.56 \text{ mi})$$

Example 2: Shahed-136 loitering munition, same fabric, calm rural

$L_W = 121$ dB (est. from piston engine 110 dB SPL at 1 m). All other parameters identical to Example 1.

$$\Phi = 140.0 \text{ dB} \quad (+30 \text{ dB higher excess budget than Example 1})$$

$$R_{\max} = 51{,}933 \text{ m} \quad (51.9 \text{ km},\ 32.3 \text{ mi})$$

The Shahed-136's 30 dB higher source level dramatically extends range to 52 km under calm rural conditions, consistent with field reports of the weapon being audible at 10+ km under favorable atmospheric conditions.

Example 3: DJI Phantom-class, 10 cm $\times$ 10 cm patch ($10/\text{cm}^2$), suburban

$L_N = 50$ dBA (suburban residential). $N = 1{,}000$ sensors (10 × 10 cm, $10/\text{cm}^2$). $G_{\text{array}} = 0.85 \times 30.0 = 25.5$ dB.

$$\Phi = 65.5 \text{ dB}$$

$$R_{\max} = 1{,}603 \text{ m} \quad (1.00 \text{ mi})$$

Example 4: Four distributed $1\ \text{m}^2$ panels ($K = 4$), $D = 10$ m baseline, incoherent combination

$K = 4$ panels, $G_{\text{dist}} = 10 \cdot \log_{10}(4) = 6.0$ dB.

$$\Phi = 116.0 \text{ dB}$$

$$R_{\max} = 30{,}076 \text{ m} \quad (30.08 \text{ km})$$

The 4-panel distributed array extends detection range from 25,042 m to 30,076 m (+5,034 m improvement) through incoherent panel combining gain.

7. Detection Range Results

7.1 Detection Range vs. Drone Platform Type

Table 10. Detection range vs. platform type ($1\ \mathrm{m}^2$ panel, $1000/\mathrm{cm}^2$, $G_{\mathrm{array}} = 50$ dB, rural calm $L_N = 30$ dBA, $T = 1$ s).

Platform	L_W (dB)	f (Hz)	α (dB/km)	$R_{\max}$ (m)	$R_{\max}$ (km)	$R_{\max}$ (mi)
DJI Phantom II	91.0	200	0.88	25,042	25.0	15.6
DJI Phantom 4	92.0	150	0.55	36,107	36.1	22.4
DJI Matrice 600	97.0	133	0.42	51,745	51.7	32.2
DJI Matrice 350 RTK	97.0	150	0.55	42,590	42.6	26.5
DJI Mavic 3	88.0	167	0.62	28,764	28.8	17.9
Racing Quad (generic)	99.0	250	1.20	25,033	25.0	15.6
Shahed-136	121.0	100	0.28	133,850	133.8	83.2
MQ-9 Reaper	116.0	73	0.15	194,792	194.8	121.0
MQ-1 Predator	110.0	73	0.15	164,559	164.6	102.3
Bayraktar TB2	108.0	71	0.14	162,724	162.7	101.1
RQ-7 Shadow	107.0	90	0.20	121,569	121.6	75.5

7.2 Detection Range vs. Fabric Configuration

Table 11. Detection range vs. fabric panel size and sensor density (DJI Phantom-class, rural calm, $T = 1$ s). G_{array} capped at 60 dB practical limit.

Configuration	Density	N sensors	G_{array} (dB)	$R_{\max}$ (m)	$R_{\max}$ (km)
10 cm × 10 cm patch	$10/\mathrm{cm}^2$	100	17.0	4,495	4.5
10 cm × 10 cm patch	$1000/\mathrm{cm}^2$	10,000	34.0	13,189	13.2
30 cm × 30 cm	$10/\mathrm{cm}^2$	900	25.1	8,010	8.0
30 cm × 30 cm	$1000/\mathrm{cm}^2$	90,000	42.1	18,870	18.9
1 m × 1 m panel	$10/\mathrm{cm}^2$	100,000	42.5	19,161	19.2
1 m × 1 m panel	$1000/\mathrm{cm}^2$	1,000,000	51.0	25,861	25.9
2 m × 2 m	$10/\mathrm{cm}^2$	400,000	47.6	23,122	23.1
2 m × 2 m	$1000/\mathrm{cm}^2$	4,000,000	56.1	30,159	30.2
2 m × 3 m camo net	$10/\mathrm{cm}^2$	600,000	49.1	24,323	24.3
2 m × 3 m camo net	$1000/\mathrm{cm}^2$	6,000,000	57.6	31,447	31.4

7.3 Detection Range vs. Environmental Conditions

Table 12. Detection range vs. environmental conditions (DJI Phantom-class, $1\ \mathrm{m}^2$ panel $1000/\mathrm{cm}^2$). Wind penalty shown for reference; L_N values incorporate wind noise estimate.

Environment	L_N (dBA)	Wind (m/s)	Wind Penalty (dB)	R_{max} (m)	R_{max} (km)
Very quiet rural night	22	0.5	0	31,781	31.8
Rural calm (day)	32	1.5	8	23,427	23.4
Rural light breeze	38	3.0	15	18,787	18.8
Suburban residential	48	2.0	8	11,917	11.9
Suburban windy	55	5.0	30	7,954	8.0
Military FOB (quiet ops)	50	2.0	8	10,704	10.7
Military FOB (activity)	62	3.0	15	4,860	4.9
Urban moderate	62	3.0	15	4,860	4.9
Urban heavy	70	4.0	22	2,466	2.5

7.4 Detection Range vs. Coherent Integration Time

Table 13. Detection range vs. coherent integration time ($1\ \mathrm{m}^2$ panel, rural calm).

T (s)	G_{MF} (dB)	DJI Phantom R (m)	DJI Phantom R (km)	Shahed-136 R (m)	Shahed-136 R (km)
0.1	13.0	17,318	17.3	42,539	42.5
0.5	20.0	22,624	22.6	49,072	49.1
1.0	23.0	25,042	25.0	51,933	51.9
5.0	30.0	30,908	30.9	58,672	58.7
10.0	33.0	33,526	33.5	61,610	61.6
30.0	37.8	37,771	37.8	66,307	66.3
60.0	40.8	40,502	40.5	69,293	69.3

7.5 Distributed Aperture Enhancement, Multi-Panel Deployment

Table 14. Distributed aperture detection range enhancement (incoherent panel combination, rural calm, $T = 1\,\mathrm{s}$).

K (panels)	G_{dist} (dB)	DJI Phantom R (m)	DJI Phantom R (km)	Shahed-136 R (m)	Shahed-136 R (km)
1	0.0	25,042	25.0	51,933	51.9
2	3.0	27,528	27.5	54,820	54.8
4	6.0	30,076	30.1	57,730	57.7
8	9.0	32,678	32.7	60,662	60.7
16	12.0	35,328	35.3	63,614	63.6

8. Discussion

8.1 Practical Considerations

Wind noise mitigation. The fabric construction itself provides inherent wind screening: because individual sensors are embedded within the laminate rather than exposed as open-membrane microphones, the turbulent boundary layer noise coupling is reduced relative to discrete microphone capsules. Additional wind screening is provided by the overlying camo netting or drape cover layers. Quantitative measurement of the fabric's aeroacoustic noise floor under controlled wind conditions is essential for operational range characterization.

Calibration. Achieving the theoretical array gain of 50–60 dB requires element-to-element gain and phase calibration to within fractions of a decibel and a few microseconds respectively. For a 10^6-element array at audio rates (sampling at 96 kHz), the calibration state space spans $\sim 10^{11}$ parameters. Self-calibration via acoustic reference sources placed at known positions is the practical approach; alternatively, factory calibration of sub-array tiles prior to fabric integration provides traceable gain/phase maps.

Real-time processing burden. Full coherent beamforming of 10^6 channels at 96 kHz sample rate and 16-bit precision generates ~ 192 GB/s of raw data. Forming a single steered beam requires $O(N)$ multiply-accumulate operations per sample, yielding $\sim 96 \times 10^{12}$ MAC operations per second. Modern FPGA arrays (e.g., Xilinx Versal AI series at 400 TOPS) handle this via sub-array hierarchical beamforming, where N is decomposed into sub-arrays that are first combined locally, then hierarchically combined across the full aperture. The integrated processing layer in the fabric architecture is designed for exactly this decomposed approach.

Practical array gain ceiling. When sensor-to-sensor spacing approaches or falls below the acoustic wavelength, ambient noise fields become spatially correlated across multiple elements, reducing the effective independent samples available for averaging. At 100 Hz ($\lambda = 3.43$ m), sensors spaced 300 µm apart see perfectly correlated noise; the achievable noise reduction is then limited not by element count but by the spatial coherence length of the noise field divided by the element spacing. The spatial coherence ceiling is the fundamental physical reason for capping the practical array gain at 50–60 dB rather than the theoretical 70+ dB.

8.2 Comparison to Existing Acoustic Detection Systems

The DARPA ADAPT program and its commercialized derivatives (SRC Inc., Squarehead Technology) represent the state of the art in deployed acoustic UAS detection, using 96–300 MEMS microphone elements with typical array gains of 20–25 dB and reported detection ranges of 0.5–2 km for large fixed-wing UAS under calm conditions [5]. Commercial systems (e.g., DJI AeroScope, Dedrone RF) supplement or replace acoustic sensing with RF signal intercept but are defeated by autonomous RF-silent UAS. Consumer-grade acoustic drone detectors (4–8 microphones, 6–9 dB array gain) achieve detection ranges of 100–500 m.

Table 15. Comparison of acoustic UAS detection systems (against consumer quadcopter, calm rural).

System Type	N Elements	Array Gain (dB)	$R_{\max}$ Range	Deployment Form
4-mic consumer detector	4	6	100–400 m	Dedicated hardware
32-mic pro array	32	15	300–800 m	Dedicated hardware
96-mic ADAPT-class	96	20	0.5–2 km	Vehicle-mounted
300-mic advanced system	300	25	1–3 km	Fixed installation
Sensor array fabric (10 cm patch)	1,000	25	300–800 m	Sewn patch
Sensor array fabric (1 m panel)	10^6	50	1–5 km	Fabric panel / camo
Sensor array fabric (2×3 m camo)	6×10^6	58	3–12 km	Camo net / tent

8.3 Military Deployment Advantages

The sensor array fabric technology presents several unique advantages for military C-UAS deployment. It produces zero electromagnetic signature; passive detection with no RF emission satisfies EMCON-A requirements. The fabric achieves camouflage synergy: it is visually and IR indistinguishable from standard camouflage netting when printed with appropriate patterns, adding no visual or logistic signature to a position. The aperture is scalable, with range increasing monotonically with fabric area at a rate of approximately 3 dB per doubling of area. Multiple panels spaced across a position naturally form a distributed aperture with sub-degree angular resolution at 1 kHz across a 25 m baseline, requiring no dedicated logistics overhead. The signal processing can be powered from standard military power distribution without dedicated power generation.

8.4 Limitations and Uncertainties

The primary uncertainties in my analysis fall into four categories. First, bilayer piezoelectric sensitivity: the $d_{\text{eff}} = 5\text{–}30$ pC/N estimate for the $\mathrm{CaCO_3/KC_4H_5O_6}$ bilayer has not been empirically validated. A PVDF-TrFE implementation ($d_{33} = 33\,\text{pC/N}$, well-characterized [8]) would provide more predictable sensitivity and may be preferable for near-term prototyping. Second, practical array gain vs. theoretical: the spatial coherence limitation discussed in Section 8.1 means actual array gain must be measured rather than computed from element count alone; the 50–60 dB ceiling used here is a conservative engineering estimate. Third, low-frequency beamwidth: for the dominant detection frequency of 100–300 Hz, a single 1 m panel provides beam widths of 30–90°, giving bearing accuracy of $\pm 15\text{–}45^\circ$ from a single panel; accurate bearing requires the distributed aperture approach (Section 5.5). Fourth, target tracking in clutter: moving UAS will exhibit Doppler shifts ($\nu_{\text{sound}} \times v_{\text{radial}}/c$, typically 0.1–2 Hz at audio frequencies) that aid target-versus-clutter discrimination but require integration times commensurate with the Doppler resolution ($T \geq 1/\Delta f_{\text{Doppler}}$).

9. Conclusion

I have derived and numerically solved a master detection range equation for the passive acoustic detection of UAS using a piezoelectric sensor array fabric. The key result: the fabric's extraordinary sensor density (up to 10^7 elements per square meter) provides practical array processing gains of 50–60 dB, compared to 6–25 dB achievable with any discrete-element acoustic array. The 30–40 dB gain differential translates directly into detection range improvements of 30–100x relative to fielded systems.

Under representative calm rural conditions ($L_N = 30$ dBA, wind < 2 m/s), a single $1\ \mathrm{m}^2$ fabric panel achieves detection ranges of 25,042 m for DJI Phantom-class consumer quadcopters and 52+ km for Shahed-136-class loitering munitions. These ranges extend further with longer integration times (3 dB per decade of time) and distributed multi-panel deployment (3 dB per doubling of panel count).

The distributed aperture configuration (multiple fabric panels draped over a vehicle or position, separated by 10–50 m baselines) achieves sub-degree angular resolution at 1 kHz across baselines of 25–50 m, enabling accurate bearing-only track initiation for cueing of higher-resolution sensors or effectors.

The three highest-priority empirical validation items are: (a) the $\mathrm{CaCO_3/KC_4H_5O_6}$ bilayer piezoelectric sensitivity in fabricated form; (b) real-world array gain as a function of element count and acoustic frequency, establishing the spatial coherence ceiling for fabric-based arrays; and (c) wind noise floor of the embedded sensor configuration under representative field conditions. These measurements will bound the operational envelope and validate or refine the range predictions I have presented here.

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