Advanced Research + Invention Agency ARIA

Programme Thesis

Ubiquitous particle profiling: making invisible matter *matter*

v1.0

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CONTEXT

This document presents the core thesis underpinning a programme that is currently in development at ARIA. We share an early formulation and invite you to provide feedback to help us refine our thinking.

This is not a funding opportunity, but in most cases will lead to one – sign up **here** to learn about any funding opportunities derived or adapted from this programme formulation.

An ARIA programme seeks to unlock a scientific or technical capability that

+ changes the perception of what's possible or valuable
+ has the potential to catalyse massive social and economic returns
+ is unlikely to be achieved without ARIA's intervention.

PROGRAMME THESIS, SIMPLY STATED

An overview of the programme thesis, accessible & simply stated

Airborne particulate matter (PM) is one of the most important, and least well-resolved, features of the environment around us. PM shapes everything from respiratory disease and cancer risk, to cloud formation and radiative forcing, yet we are poorly equipped to characterise it outside specialist laboratory settings, where real-world scenarios cannot be fully reproduced. Low-cost sensors can tell us that particulate matter is present outdoors, but usually reduce it to coarse mass bins such as PM2.5 (<2.5μm) and PM10 (<10μm), obscuring five orders of magnitude of size variation, with substantial measurement assumptions and uncertainties. High-performance laboratory instruments can reveal rich

physical, chemical and biological information, but are expensive, fragile, suffer from restricted sampling throughput, and are difficult to deploy routinely, with appropriate spatial and temporal coverage, in the field. As a result, we often know that particles are there, but are blind to: what they are, how they are changing, where they came from, what damage they are likely to cause, or what action they should trigger.

This programme will develop the core capability needed for ubiquitous particle profiling (UPP): portable, autonomous systems that can sample air in real-time and connect particle size, shape, mixing state, and molecular species information to source attribution. We are looking for Creators from diverse backgrounds to build a shared measurement capability that can make invisible matter *matter*. We will focus on the common technical bottlenecks that cut across a wide range of applications, from industrial emissions enforcement to occupational exposure: sampling without bias or transmission loss; robust single-particle measurement across relevant size ranges with high throughput; action-relevant chemical or biological fingerprints; calibrated operation in uncontrolled environments; and analytical methods that convert complex particle signatures into trustworthy source information.

If successful, this programme will change PM from an invisible threat to a measurable and actionable feature of the world around us. We aim to catalyse improved enforcement of existing regulations, increase our understanding of the human and atmospheric consequences of PM, and as a result, shape the future global regulatory landscape which is critical to enable action.

This programme thesis is derived from the ARIA opportunity space: Adaptive Machines.

PROGRAMME THESIS, EXPLAINED

A detailed description of the programme thesis, presented for constructive feedback

Why this programme

The air around us may look transparent but it is actually a vibrant chemical and biological ecosystem. The particulate matter suspended in the air is incredibly diverse, ranging in size from <10 nm to >100 μm and being composed of more than 10^5 different chemical (including biological) compounds [1]. PM arises either by direct emissions or secondary chemical reactions in the atmosphere and can come both from natural sources, such as sea spray and pollen, cloud droplets and ice crystals, and anthropogenic sources, such as combustion and vehicle wear (Annex 1) [2,3]. Crucially, these diverse chemical constituents do not exist as isolated components but instead as highly heterogeneous internally and

externally mixed populations [4] that evolve dramatically with thermodynamic ageing and physical transport from the point of emission [5].

Human and planetary impacts of PM

The physical morphology and chemical profiles of suspended PM exert profound effects on both human biology and planetary thermodynamics (Figure 1). At the human scale, the WHO recognises air pollution as the biggest global environmental health threat in the current century [6] and the World Bank estimates premature deaths due to air pollution cost the global economy more than $225bn in lost labour income [7].

The physical diameter of PM influences its biological penetration depth and ultimate destination within the body [8], hence size has been the threshold for the majority of existing environmental regulation [9–12]. While ultrafine particles (also referred to as PM0.1, diameter < 0.1 μm) dominate on the basis of number, fine (PM2.5, diameter < 2.5 μm) and coarse (PM10, diameter < 10 μm) particles dominate in terms of mass and volume of material [13]. PM10 typically localises in the upper respiratory tract and can induce localised inflammation. PM2.5 and PM0.1 can potentially escape this initial filtration, respectively penetrating deep into the alveoli and translocating into the blood stream even crossing the blood-brain-barrier, triggering wider systemic pathologies [14–16]. Yet the focus on mass or size completely ignores the chemistry and/or biology of what is being inhaled; two particles of identical size can have completely divergent toxicologies if they contain carcinogens like benzo[a]pyrene, which elevates cancer risk (>10%)[17], or transition metals with oxidative potential, which have a stronger association with adverse respiratory health effects than other particle compositions or PM2.5 concentrations alone [18]. Hazard can depend strongly on material form: respirable crystalline silica, for example, is a recognised cause of lung cancer; silica in other forms is not [19].

At the planetary scale, this same interplay of physical size and chemical composition helps determine the role of aerosols in Earth's climate system. Particle size, composition and affinity for water, together with ambient supersaturation, govern whether particles activate as cloud condensation nuclei (CCNs), linking microscale properties to cloud reflectivity, lifetime and precipitation patterns[3,20]. Beyond these cloud-mediated effects, aerosols interact directly with radiation: scattering generally increases planetary albedo by reflecting sunlight back into space, whereas absorption converts radiation into heat, warming the surrounding atmosphere. The balance is determined by particle composition, size, shape, water uptake and mixing state: sulphates, nitrates, sea salt and many organic aerosols predominantly

scatter light, whereas black carbon strongly absorbs it, with brown carbon and mineral dust absorbing more selectively by wavelength. The IPCC estimates total anthropogenic aerosol effective radiative forcing over 1750–2019 at –1.1 Wm^{-2}, with an uncertainty range of –1.7 to –0.4 Wm^{-2}; around three-quarters of this effect arises through aerosol–cloud interactions [20]. Innovation in particle-profiling capability could better reveal sources of cooling or warming, helping turn the largest contributor to uncertainty in estimates of total historical radiative forcing[21,22] into a measurable problem. Better resolving cloud-aerosol interactions will reduce downstream uncertainties in climate impact forecasts, increasing the strength of their call to action.

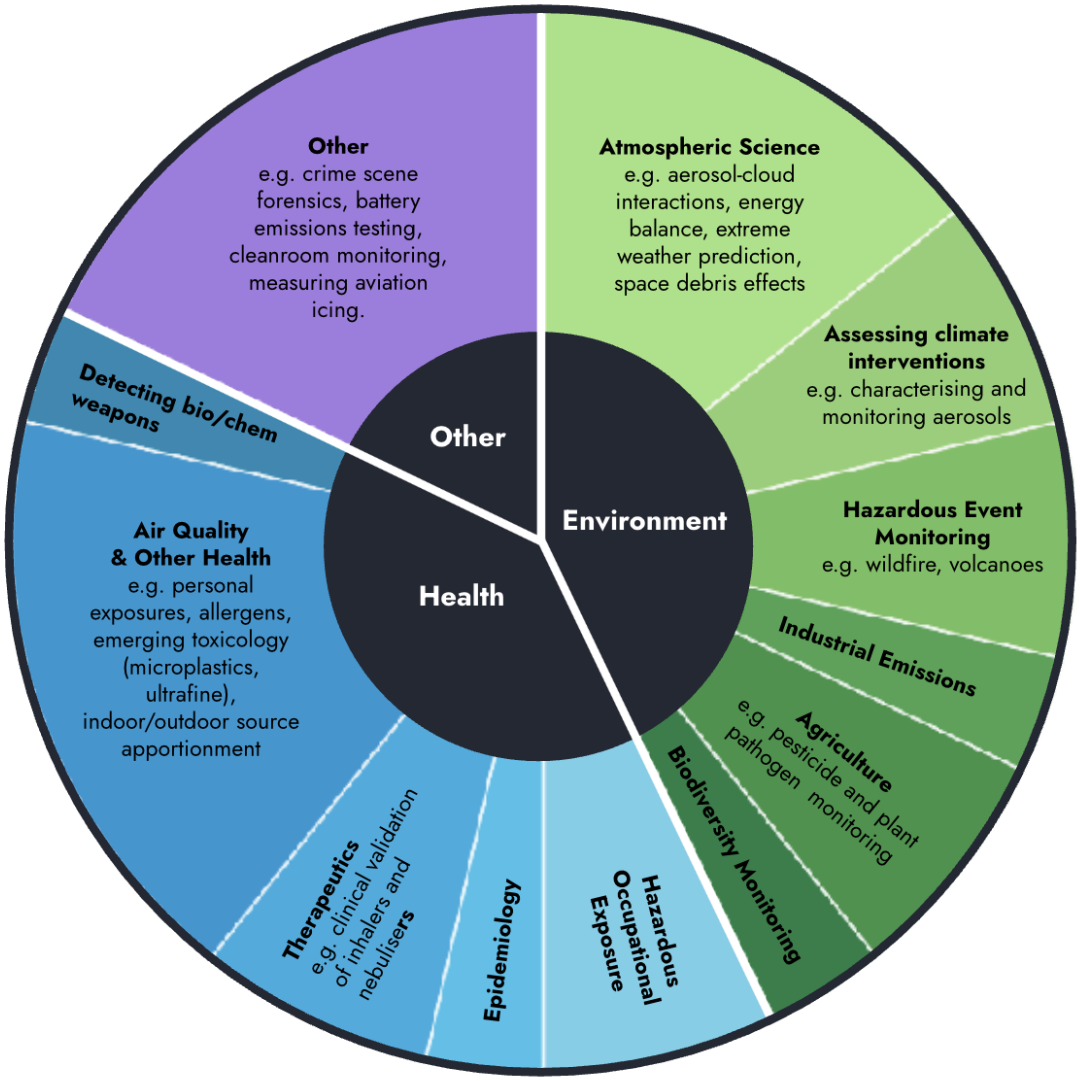


Figure 1: *Visualisation of the breadth of application areas for profiling particulate matter.*

Challenges in profiling PM

Despite the far-reaching implications of PM across human health and environmental sciences, analysis of PM properties remains a major challenge. Physically, particles span more than five orders of magnitude in size with irregular morphologies, resulting in a range of different fluid dynamic and size detection principles, from aerodynamics to optics. Their material composition comprises distinct organic, inorganic and biogenic species organised in diverse mixing states that are often semi-volatile (Figure 2, Annex 1), creating a fundamental trade-off in analytical methods between single-particle specificity, temporal resolution and molecular depth [23].

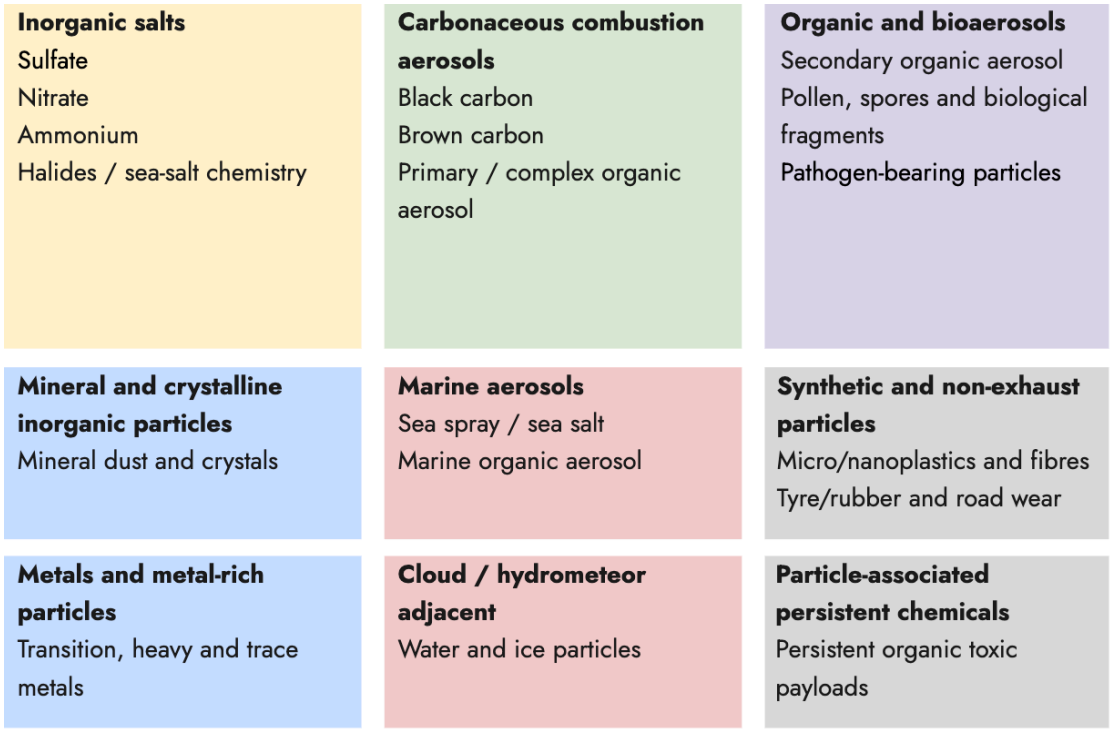


Figure 2: *Visual summary of aerosol (and aerosol-adjacent) classes and their key targets (see Annex 1 for full description).*

A wide range of instrumentation already exists for profiling PM, or more precisely, aerosols, which encompass both the suspended particles and their gas matrix. An ideal instrument would determine the size of an individual aerosol particle, its concentration in the sample, and provide a quantitative measure of its molecular constituents in real-time without sampling bias or transmission losses[13]. Systems largely diverge by capability to either profile size (Annex 2) or composition (Annex 3); few can achieve both.

Offline measurements using filters to capture PM can achieve high precision and molecular depth, but have sampling biases and sacrifice temporal resolution. Online systems for ensemble analysis tackle the temporal resolution problem but still average chemical information across the entire population of air that is sampled so are blind to mixing states. Single-particle instruments can resolve those localised mixing states that are lost in bulk methods, and evaluate aerodynamic sizes in real-time, but sacrifice detailed chemical speciation with their high energy fragmentation. There is a complementarity in the capabilities and challenges of mass spectrometry and optical methods (see Annexes 2 and 3), which brings opportunity. There are also shared system-level challenges, such as in sampling and analysis, which could be tackled by a community of technologists from multiple disciplines.

There are also huge performance-portability trade-offs. Laboratory gold-standard mass spectrometry systems are heavily reliant on ultra-high vacuum systems, precise optical alignments and often climate-controlled environments, incompatible with field needs of autonomy and robustness across environmental conditions. While some of these systems have been field deployed, for measurements from aircraft for dynamic and responsive applications, or at air quality supersites, efforts are sparse due to the limited number of instruments and the huge cost of individual campaigns. At the other end of the spectrum, highly portable low-cost nodes focus on mass approximations like derived total PM2.5 [24], but are in general blind to chemical information and lack precision, meaning the use of composition information in regulation is limited [8]. The trade-off between high grade reference instruments (rich but sparse information) and low-cost sensor networks (high coverage but limited information), is demonstrated by the YorkAirMap [25]. Widespread UPP capability would collapse this divide, making regulatory-grade particle information affordable at network scale.

What we hope to accomplish

Currently, the in-situ particle profiling landscape has a small selection of underlying technologies wrapped in proprietary vendor frameworks. This programme seeks to catalyse a radical rethink of these underlying principles, fostering the development of platform- and application-agnostic, frontier techniques to bring together disparate market needs into a unified, high-impact innovation force. We are driven by a long-term North Star, a goal beyond the programme's timescales, which we believe can be achieved by activating a community with the UPP programme.

The North Star

Our North Star is for profiling the size, shape, and molecular species of single particles to become a ubiquitous capability that can meet the needs of many end-users (as shown in Figure 1). Ubiquitous does not mean universal: we want to kick start innovation with an end-to-end, systems approach to deliver capability, not a single "perfect" instrument. Imagine a world enabled by UPP technologies:

- **Personalised health risk management is predictive, not reactive:** Real-time aerosol identification transforms pollen and airborne virus tracking to look like weather forecasts, enabling individuals with respiratory diseases or severe allergies to preemptively manage personal exposure.
- **Regulatory accountability operates at the fenceline:** Environmental enforcement shifts from coarse spatial averaging to explicit fingerprinting, separating natural and anthropogenic sources, forcing industrial facilities to immediately confront and mitigate the toxicological footprint of their boundary emissions.
- **Severe weather forecasting bridges the microscale and macroscale:** Improved particle and cloud observations constrain how models represent aerosol–cloud interactions, increasing confidence in probabilistic rainfall and flood-risk forecasts and giving authorities more time to prepare
- **The global energy budget comes into sharper focus**: Ubiquitous in-situ profiling of aerosols, cloud hydrometeors and turbulence transforms aerosol–cloud interactions from a poorly observed source of uncertainty into a measurable, model-testable system—substantially constraining aerosol forcing, strengthening Earth system models and improving confidence in climate projections.

Programme goals

Towards our North Star of ubiquitous particle profiling, in 3.5 years this **programme** will drive innovation in field operable systems towards single particle analysis (not excluding ensemble approaches, if appropriate) with autonomous, robustly calibrated, real-time operation, across 5Ss (Table 1): **sampling, size, shape, species** and **source**. We have aggregated needs from diverse application spaces to develop the application-agnostic target metrics presented. We envisage a range of final form factors that are pulled towards **a variety of field use cases,** e.g. personal wearability, drone deployment, air quality ground stations, and instruments that spike against different target metrics.

Table 1: Target programme metrics compared to North Star ambition for ubiquitous capability.

Target	Initial Programme	North Star
Sampling	Appropriate ambient intake flow rate for 20:1 concentration. Demonstrate an independently validated sampling/transfer path: well characterised losses, humidity tolerance, fouling detection, and methods for autonomous calibration.	Appropriate ambient intake flow rate for >100:1 concentration and transmission efficiency of >90%. Automated isokinetic flow matching for deployment on moving platforms.
Size	Size-resolved, particle-level measurement across **10 nm to 10 µm**.	Routine profiling from ultrafine particles to microparticles: **<10 nm to >100 µm**.
Shape	Output asphericity where physically meaningful.	Trustworthy particle morphology where physically meaningful.
Species	Each final prototype should identify and quantify **at least two species from materially distinct classes** in real time. Prioritise action-relevant fingerprints over full untargeted molecular identification.	Broad species profiling across all aerosol classes with ability to deconvolve **state**, mixing and ageing.
Source attribution	Identification of **>5 pre-specified sources** with **>90% sensitivity** and **>70% specificity** against reference measurement. Result communicated to a remote user within 2 hours.	Real-time open world attribution and apportionment across all known source classes with **>95% sensitivity** and **>70% specificity** for challenges set. Edge compute outputs information that is useful, usable and used.
Endurance	**Up to 3 months unattended field operation** at the end-of-programme demonstration, with **>85% usable data uptime** and no manual recalibration.	Self-cleaning, self-calibrating sampling capability to enable **12 months + endurance without maintenance**.
Cost	Demonstrated market value and pathway to lower cost production at scale; no specific target envelope at the prototype stage.	**<£1k bill of materials** for an integrated system is achievable at global commercial scale manufacturing volumes.
Portability	Operational system contained within a portable form factor close to that suitable for the application use case. Guidance for personal wearability or drone mounting: **weight <1kg and power <10W.**	Operational system contained within a portable form factor that meets end user requirements, as defined during the UPP programme.

Guidance for ground station installation:
weight <35kg and power <150W.

Moving towards the North Star

This programme targets the broad capability of ubiquitous particle profiling, but within the programme timeframe, we are agnostic about whether this is achieved by the streamlined combination of different devices, or fully integrated within a single device. If teams propose to combine different devices, they should present a clear vision of how their approach can reach the North Star target beyond the lifetime of the programme. A further expectation is that the technology innovation delivers a capability that can easily generalise, for example, through modular implementations. One approach to achieving this is through open source dissemination. We therefore expect programme teams to participate in field demonstrations across multiple different use-cases to demonstrate generality of capability.

Long term, we believe that achieving the full spectrum of 5S capability at under £1k bill-of-materials (BOM) is vital for ubiquitous deployment. Our goal for the initial programme is to deliver field demonstrations of system capability, unconstrained by a defined BOM. Nonetheless, we expect programme teams to be able to demonstrate a pathway to future cost reduction at the manufacturing scale expected for ubiquitous deployment.

Why it's worth shooting for

A ubiquitous particle profiling capability would unlock methods to manage known air quality problems, but more importantly, enable research into unknown and emerging threats. Here we present a vision for the future within the scope of the known challenges, as well as highlighting some of the biggest research questions we'd be able to answer for future management.

A vision for a future of healthy cities

Today, urban air quality is largely managed through sparse monitoring networks, modelled averages and retrospective compliance thresholds. Cities can often tell when legal limits have been breached, or how annual PM2.5 and PM10 concentrations are changing, but they rarely know in real time what particles are made of, where they came from, how they are moving, or how to reduce exposure. If action is taken, responses are usually broad, slow and source-agnostic: traffic restrictions, clean-air zones, public alerts and long-term policy

plans, rather than precise interventions linked to specific particles, places and moments. The Environment Act 2021[11] sets out the polluter pays principle, which states that where possible, the costs of environmental damage should be borne by those causing it. But it is not possible to enforce with current source attribution methods. UPP could change that.

In port cities, the usual sources of particulate matter such as vehicles and domestic fires are joined by significant emissions from shipping activity – this can comprise up to 10% of PM2.5 particles [26]. In these kinds of cities, the full particulate matter challenge is on display (Figure 3): a dense urban core, major river crossings, freight corridors, large ports, industrial-maritime yards, coastal air and domestic burning, intersect with hospitals, schools and care homes, all within a few kilometres of each other. Like many cities, there may be a Clean Air Zone[27], but these often only target one source of emissions: older, more polluting taxis, buses, vans, coaches and HGVs. Other industries typically avoid enforcement as the burden of proof works in their favour.

Distributed, low cost particulate sensing of the type available today could, if deployed in a concerted fashion, have a huge individual impact: in response to a major plume, vulnerable residents could receive targeted alerts, hospitals could adjust ventilation, and nurseries could keep the windows closed.

But when the air around you is already laden with PM, there's only so much to be done to protect vulnerable people. Imagine instead a future where these cities can fully enforce the polluter pays principle. Where particulates are traced to the very ship or factory they came from with evidence robust enough to support regulatory investigation and legal enforcement. Where that evidence isn't just a one-time study, but ongoing tracking of compliance on a company-by-company basis. Such a transformation requires lab-grade chemical sensing on the streets, operating continuously 365 days of the year, gathering evidence that no lawyer can dispute.

Even after fully enforcing the polluter pays principle, certain weather conditions could still result in dangerous pollution levels building up from time to time near high-risk communities. But now, with the additional, real-time knowledge of how much pollution is coming from each source, the local authorities have the knowledge and evidence they need to incentivise additional, short term measures - companies that reroute freight, pause high-dust work, or reduce port idling can be rewarded: the same evidence that forces compliance can also show where rewards are due.

The outcome is cleaner air, with real human benefits - fewer unmanaged asthma and COPD crises, better protected care homes, more resilient hospitals, and visible accountability for sources that used to hide amongst the smog.

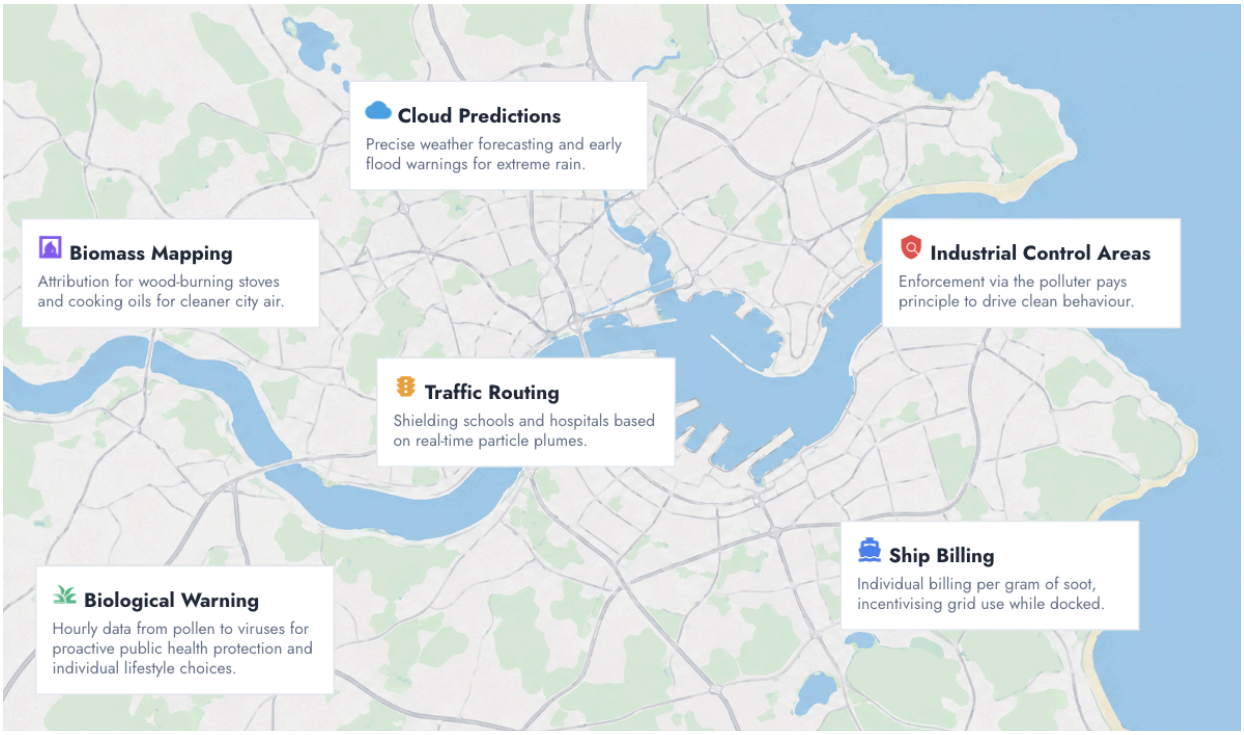


Figure 3: *Potential application impacts of a particle profiling network across a port city. Port city map is illustrative and AI generated.*

Major research questions UPP could tackle

Which aerosols reach **cloud-forming** altitudes, how do their properties change during transport, and under what conditions do they activate as cloud condensation or ice-nucleating particles? When does this activation meaningfully alter cloud formation, precipitation and radiative effects? Fixed stations sample mainly at the surface and satellites infer properties remotely, leaving few co-located observations of aerosol composition, cloud hydrometeors and turbulence through the lower atmosphere. UAV-mounted UPP could provide repeated, spatially resolved vertical profiles that connect surface emissions to processes at cloud base. Unlike permanent networks, these mobile systems could be dispatched to capture short-lived events or establish baselines in poorly instrumented locations, but doing so will require representative sampling from a moving platform, robust calibration under changing conditions, and sufficient payload, power and endurance for paired measurements. Answering these questions would help constrain aerosol–cloud

interactions in Earth system models, validate satellite retrievals and support more reliable climate and rainfall-risk assessments; ultimately enabling better decisions about flood protection, water management, agriculture, and climate adaptation.

Microplastics and nanoplastics exist at the limits of today's particulate measurement capability and improved knowledge could build the basis for future regulation and management. They are now understood to move through air as well as water and food, but we lack the exposure maps needed to answer key questions: Which polymers are people actually inhaling and what systemic impacts do they have? Can airborne plastics reach reproductive organs or other sensitive tissues? Microplastics and nanoplastics have been reported in human reproductive tissues and raised plausible questions about fertility [28,29], but presence is not yet proof of harm or whether the exposure was via water, food, or air. Spatially resolved particle profiling capabilities would unlock epidemiological studies to quantify the impact of airborne polymers on human life.

At planetary scale, the uncertainty around microplastics is just as troubling. Airborne microplastics were initially thought to be a small direct radiative forcing term, yet newer modelling suggests coloured micro- and nanoplastics may absorb light strongly enough to become a non-trivial, regionally concentrated warming agent [30]. Ubiquitous particle profiling would help us build a global knowledge-base from which to understand how plastic particles from different sources meaningfully alter clouds, albedo, or local warming. To get there requires extreme portability, deploying size (<10 nm) and speciation capabilities in aircraft-mountable devices measuring vertical profiles of micro- and nanoplastics in the atmosphere, alongside quality assurance and control methods to ensure that the tools used are appropriate for concentrations relevant to the atmosphere.

Ultrafine particles expose a major blind spot in modern air-quality management. In its 2021 Global Air Quality Guidelines, the WHO set guideline levels for PM2.5 and PM10, but could not do the same for ultrafine particles (UFPs, PM0.1) because the exposure evidence base was inconsistent. Instead, they issued good-practice statements, including a direct call to "utilize emerging science and technology" to improve UFP exposure assessment for epidemiology and management [6]. Policy and monitoring are beginning to catch up: the 2024 EU Ambient Air Quality Directive [31] requires UFP monitoring at designated supersites, while the UK's Particle Concentrations and Numbers (PCN) Network [32] already measures particle number and size distributions at a small number of locations, but neither brings the evidence needed to interpret what those measurements mean for health. This programme could close the gap, helping us to understand whether short-lived

spikes of UFPs from traffic, cooking, combustion, or industry sources are biologically meaningful and whether particle number, size, composition or oxidative potential predict harm better than mass. These questions become acutely important when considering observed links between air pollution and neurodegenerative disease [33]. A particle-profiling network would turn the WHO recommendation into an actionable research platform: moving UFPs from an unregulated, poorly characterised residual category, into a measurable exposure class that can support epidemiology, intervention and eventually regulation.

Does **space debris** pose a threat to atmospheric integrity? The exponential proliferation of low Earth orbit mega-constellations has turned the space industry's traditional "design to demise" disposal paradigm into an accidental atmospheric experiment [34]. As thousands of end-of-life satellites burn up in the upper atmosphere, their ablation is projected to inject a massive, unnatural influx of metals that fundamentally alters stratospheric chemistry, already introducing an estimated 600-fold excess of aluminium, 1750-fold excess of copper, and an 8000-fold excess of germanium relative to natural cosmic meteoroid deposition [35]. If left unchecked, the long-term physical and chemical consequences of this rapidly accumulating metallic payload could damage the ozone layer, increasing human UV-B exposure and altering Earth's energy balance. By expanding UPP sensing capabilities to upper-atmosphere conditions, and combining them with next-generation high-altitude pseudo-satellites or balloons, we could capture the first direct, *in situ* observations of metallic aerosol mixing states. The resultant tracking of how anthropogenic space debris ages and activates as cloud-nucleating elements would confirm whether proactive international governance frameworks are needed.

Why it's differentiated

Breaking the silos

The present particulate profiling ecosystem is deeply siloed by application, with a huge diversity of users and needs, from workplace exposure regulators to global climate modellers. The result is a lack of centralised economic incentive to innovate, leaving the instrumentation landscape fragmented and stagnant. By treating PM profiling as a ubiquitous problem, this programme seeks to highlight the physics and engineering commonalities between end-user needs and unite disparate fields. In doing so, this programme should catalyse a new aggregated market force for real-time single particle profiling information.

Attracting frontier technologies

We target ambitious characterisation, cost and endurance capabilities to encourage a radical rethink of existing platforms and encourage the transplantation of scalable technology modalities into the aerosol science community. Low-flow particle mobility sizers and high maintenance, fluid dependent condensation particle counters (Annex 2) could benefit from recent innovations in microelectronic mechanical systems and microfluidics [36]. Dramatic reduction in physical footprints for mass spectrometry could be achieved through miniaturised vacuum pumps and improved direct sample handling, such as through application-specific sampling cartridges [37]. Alternative speciation methods based on optical shape [38] and spectroscopy [39] are also reaching a level of maturity that could enable multi-parametric integration [40] (e.g. fluorescence, photoacoustics, Raman) and extreme miniaturisation through photonic integrated circuits. The typical performance-portability trade-off can increasingly be tackled with data-driven approaches, with diffusion models valuable in deconvolving complex overlapping spectra and joint-embedding predictive architectures learning representations to simplify processing from raw data inputs to source attribution.

Systems approach

Within the ARIA programme, we encourage teams to think about the entire instrumentation chain end-to-end across the 5Ss. Shared systemic bottlenecks in sampling can be tackled, looking at new ways to transport particles from ambient atmospheres into the analytical system with minimal drift, fouling, or size-dependent transmission losses. Forcing field autonomy and rapid feedback requires the development of user-friendly operations and edge compute analytical strategies for source attribution, requiring clear use-cases and comprehensive well-validated reference libraries that are integrated and accessible. AI-driven approaches to categorise PM and for source apportionment could hold significant potential in rapidly transforming raw outputs into usable stakeholder insights.

What we expect to fund

We are looking for multidisciplinary teams who aim to push the boundaries of PM sensing through rapid instrumentation development across the 5Ss. The target instrument specifications for the programme lifetime are set out in Table 1, but all teams must envisage and develop a pathway to the long term North Star goals. Teams will build a field-ready prototype to be tested in a multi-use case demonstration at the end of the 3 years, while

performing in diverse lab-based and field-based mini demonstrations along the way to push the teams to be sector-agnostic in their designs.

Who we expect to fund

We expect to fund a diverse range of teams (or individuals) with complementary expertise, collectively pushing towards the North Star. We do not expect teams to tackle the entire problem, however, some teams may wish to do so. The programmatic nature of the funding is such that learnings across different target areas will be shared across the programme. To bring the diversity of potential teams to life, some imagined teaming examples are illustrated below. These examples are neither exhaustive nor restrictive.

- **Plume tracking and harsh-environment aerosol capture.** A team rooted in volcanology and atmospheric field campaigns could bring deep expertise in sampling dynamic, high-concentration, chemically complex plumes under difficult environmental conditions. Their core technology goal might combine drone- or mast-mounted sampling, robust isokinetic inlet design, plume reconstruction, and particle-source fingerprinting. Although motivated by volcanic emissions, the same capability could translate to industrial fenceline monitoring, wildfire smoke, port emissions, construction dust, and future research into stratospheric aerosol interventions. *Example team: atmospheric scientists, drone operators, environmental regulators, and instrumentation company.*
- **Miniaturised single-particle mass spectrometry for ultrafine and other health-relevant aerosol sizes.** A team with deep expertise in mass spectrometry could attack one of the hardest programme challenges: making high-information chemical analysis instruments more portable and autonomous. Their approach might combine a new class of compact vacuum pump, lower-cost aerodynamic lensing, or enrichment to reach ultrafine particles down to ~10 nm, and edge-compute methods for targeted source attribution. The health pull could extend beyond lung deposition to systemic exposure: particles that translocate into blood, brain, placenta or other organs. *Example team: mass-spec company, aerosol physicists, microfabrication or vacuum specialists, and hospital partners exploring toxicology.*
- **Wearable or indoor optical particle profiling for personal exposure.** A team from consumer optoelectronics, photonics, computational imaging or wearable sensing could focus on the environments where people receive much of their real exposure: homes, schools, workplaces and transit. Their prototype might combine low-power optical sizing, morphology, fluorescence or Raman signatures with contextual source attribution for cooking oils, wood burning, cleaning products,

bioaerosols, workplace dusts and traffic ingress. The ambition would not be lab-grade untargeted chemistry, but a small, usable device that moves beyond PM2.5 mass towards actionable exposure fingerprints. The team could explore applications in monitoring workplace exposure together with regulatory collaborators. *Example team: optical engineers, embedded systems designers, exposure scientists, occupational-health partners and user-centred product design expertise.*

How we plan to coordinate teams

This programme will structure a tightly synchronized, multi-disciplinary cohort designed to share analytical solutions and accelerate the translation of frontier components into ruggedised field systems (Figure 4).

Multidisciplinary Co-Design Sandpits
We will actively recruit pure technologists from outside the existing communities invested in aerosol research —including microfluidics engineers, semiconductor device physicists, and consumer optoelectronic specialists—and place them into structured, collaborative sandpits alongside end-users with motivations across climate science, environmental regulation and public health. We will first host a programme discovery workshop to stress test the ideas in this thesis and build bridges between these communities. We then plan to support a series of targeted mini workshops to encourage teaming and ideation prior to solicitation. Direct interaction during project ideation is vital but should continue routinely throughout the programme to ensure that downstream usability constraints actively drive upstream hardware architecture.

The philosophy of attracting new entrants to the field will continue through to team selection, where we will index on newly formed collaborations or expansions of teams with existing track records to fill specific innovation gaps relevant to the thesis. In addition to in-person sandpit activities, we will host a virtual teaming platform to help with finding collaborators, as well as making targeted introductions at the concept paper stage of the solicitation. We envisage this programme being composed of a small pool of focused teams that engage in regular sprints / hackathons to tackle common bottlenecks.

Integrated Systems Engineering
To help creators navigate the complex systems integration needed to build an end-to-end single-particle profiling platform, we intend to onboard a partner organisation to focus on cross-cutting systems engineering and ruggedisation blueprints. The partner will explore

opportunities for common interface specifications for hardware and software that could streamline long-term integration of capabilities developed across the 5Ss. We expect long-term integration to be achieved through iterative engineering loops between the partner organisation and creator teams, leading to the assembly of robust demonstrator systems. We expect programme teams to demonstrate a clear pathway to future cost reduction and manufacturing at the scale required for *ubiquitous deployment*, ensuring that frontier prototypes transition into high-impact, real-world translation platforms.

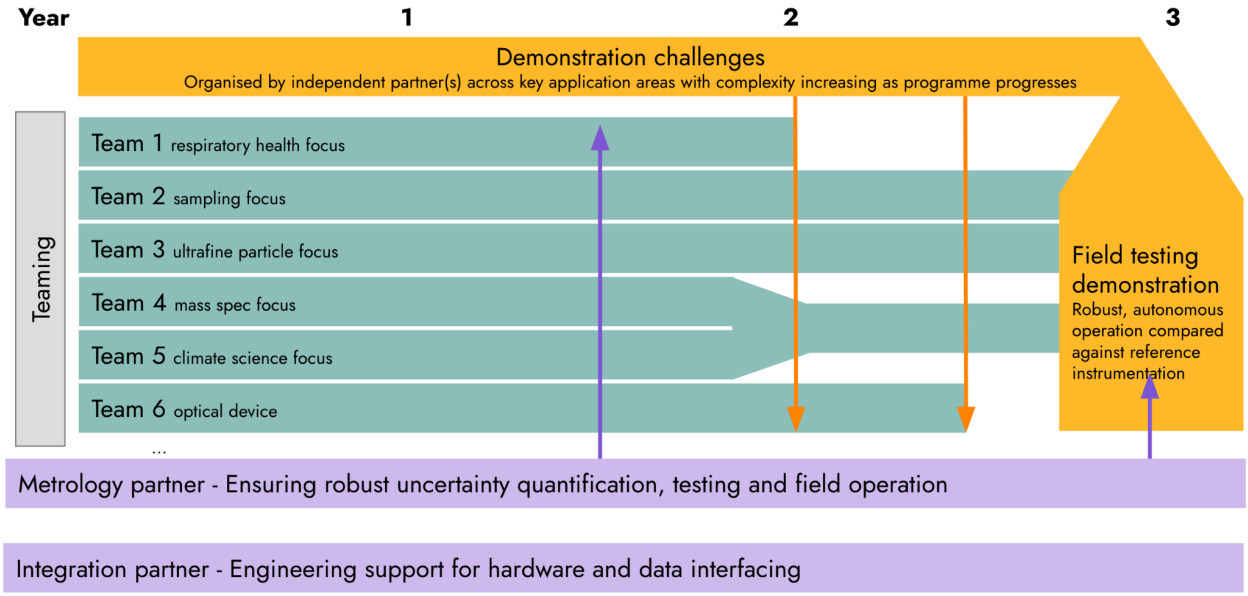


Figure 4: *Example timeline of teams' trajectories through the programme. Note that 6 teams are included as examples but we expect the overall number of teams within the programme will be larger. We expect a diversity of teams: some may have a pure technical focus and depend on the challenge partner to define use cases, others may come with a pre-defined use case or research question, but will still be expected to apply their technology across other areas. Demonstration challenges will be defined at the programme outset, may be used as stage gating to evaluate project progress, and will allow external teams to compete. It is not expected that all teams will successfully complete all challenges.*

How we plan to measure success

Creator team success

Programmatic success will be quantitatively measured against the targets set out in Table 1, alongside demonstrations set for potential end-use cases to define real-world problems.

Co-design and co-production will ensure solutions are practical, affordable and provide data for improved evidence-based decision making.

Phase 1: Benchmarked Laboratory Validation:
We plan to provide an independent metrological partner for the programme to enable lab-based testing against agreed targets set out in Table 1. The metrology partner will first work across the programme to coordinate a common testing protocol that will be used to benchmark prototypes against gold-standard reference methods using controlled aerosol mixtures in a laboratory setting at the end of year 1. They will then work alongside teams towards the final year field testing, establishing rigorous field quality assurance and control protocols and quantifying instrumental drift, humidity tolerances, and fouling signatures before any systems are deployed in field campaigns.

Phase 2: Stress testing at local field deployments:
Teams that demonstrate success in laboratory testing will progress to field testing at sites co-located with analytical reference instrumentation. The field tests will be defined and designed by the challenge partner through engagement with end-users to define the most relevant demonstrations across real sites, aerosol mixtures, and decisions, to unlock future value of the data for the UK and internationally. We anticipate that such sites might include existing urban air quality networks, occupational exposure settings, or ship-based with atmospheric profiling for cloud formation over oceans.

The demonstration challenges act as an opportunity for breaking silos, by encouraging teams to test their instruments against different application areas across human and environmental health. They also give clearly demarcated stage-gates at which the programme team may double down on those teams that demonstrate exceptional progress and/or defund teams who are not able to meet programme-wide benchmarks.

Phase 3: Final field demonstration
The final field demonstration will require an extended campaign to demonstrate endurance targets can be met. The challenge partner will coordinate logistics and define source attribution requirements, while the metrology partner will define appropriate metrics to quantify final performance. The final demo should include deep consideration of the end-user, with co-production of the demo goals to ensure that the data products are accessible and meaningful for end-user action. The goal of the final field demonstration is to attract follow-on funding and investment for successful teams.

What programmatic success could achieve

You can't manage what you can't measure: By turning real-time particle profiling into a ubiquitous global infrastructure capability, UPP will unlock actionable information, decoupling anthropogenic points of origin from natural background. By providing the capability for explicit toxicological fingerprinting, we turn an invisible threat to human health into a known enemy that can be nationally regulated and locally enforced. By revealing atmospheric aerosol mixing states, we reduce microphysical cloud-condensation and radiative-forcing uncertainties that have long gridlocked climate models, giving global policy engines the confidence to accelerate global mitigation landscape. Long term, building a global inventory of PM sources and impacts will empower humanity to pro-actively avoid the unintended consequences of new classes of future pollutants that could drastically harm both human and planetary health.

ARIA Portfolio Interactions

During early discovery, overlapping interests emerged between the present thesis and several existing ARIA programmes. To maximise potential synergies, we plan to organise explicit cross-programme touch points with:

- Olfactory Perception: Feeding multi-parametric chemical and physical aerosol features directly into emerging hypersensory foundation models.
- Enduring Atmospheric Platforms: Exploring opportunity for sensing system integration into emerging platform technologies.
- Accelerated Adaptation: Mapping biogenic aerosol distributions to map ecosystem boundary shifts and acceleration of adaptation.
- Exploring Climate Cooling: Exploring drone / balloon system integration for tracking seeded cloud condensation nuclei (CCN) and marine cloud brightening microphysics.

What we do not expect to fund

Here we innovate in profiling of particulates and so we do not expect to fund technology development for the sensing of gases (including VOCs), although we recognise that these can influence the formation of secondary organic aerosols and ageing chemistry so could be of long-term interest for the programme North Star. A separate ARIA programme, Olfactory Perception, is exploring this area. We do not expect to fund development of new

platforms for delivery of the sensing technologies; for airborne platform development, see Enduring Atmospheric Platforms.

While the technologies developed in this programme would enhance the monitoring and attribution of particles in our atmosphere and stratosphere, which may prove useful for future research into climate cooling approaches, such as stratospheric aerosol injection, a target application or use case for climate interventions is not the intended focus of this programme.

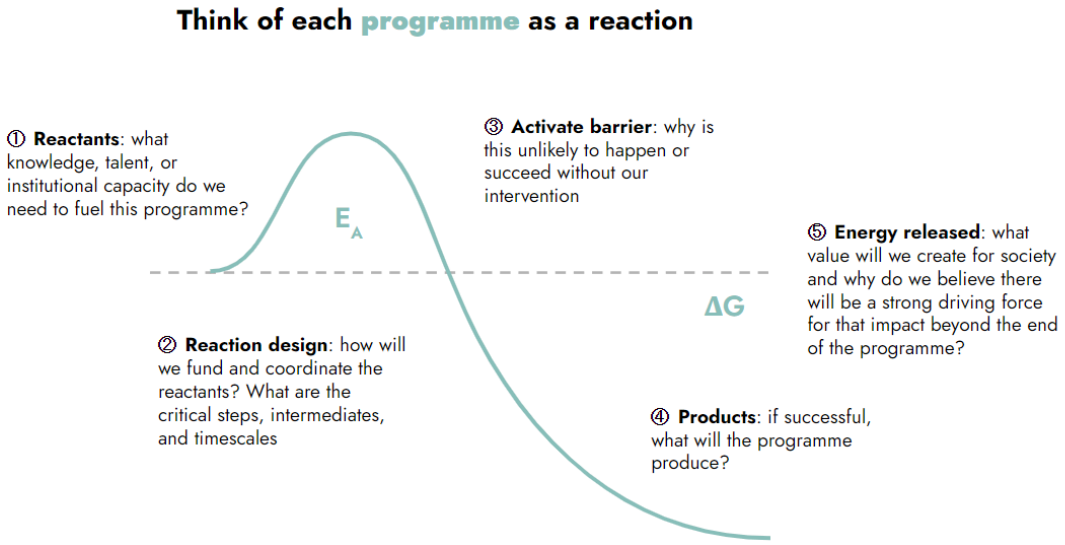
What we are still trying to figure out

The North Star and targets within this thesis represent our best guess at end-user requirements from community engagement so far. We're open to community feedback on any and all points made within the document, but are seeking specific advice on the following questions:

- Which of the size, weight, power and cost (SWaP-C) axes is the most important to index on to create a solution that is useful, usable and used?
- Where do we need single particle information and where will ensemble suffice?
- Do we build solely for gas phase or also liquid phase?
- How broad do we make the size range target? Do we encompass both nanoparticles and microparticles in the remit?
- What level of chemical speciation information is truly important for the end user compared to definitive source attribution? Should we specify an identification factor target?
- Should the programme define a specific technology capability e.g. miniaturised mass spectrometry, or allow for a diversity of technology solutions to the user defined problem?
- Do we also fund the applications-oriented science that can be delivered with the technology capability, to connect from the technology to the real-world demos?
- How do we support end-stage commercialisation of emerging technology at scale? Who would buy such a device (or devices) and what would they be willing to pay?
- Could we partner with a local authority for the final field demonstration?

PROGRAMME THESIS, REACTION DIAGRAM SUMMARY

We can metaphorically think of an ARIA programme as a chemical reaction. We present a simple reaction diagram to summarise the key elements of the imagined programme.



Ubiquitous particle profiling (UPP)

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① Strong national talent pool in atmospheric and health sciences in the UK. Regulatory drivers are increasing. Recent innovations in vacuum pumps, microfluidics and optoelectronics support new ideation on sampling handling and processing.

② We will fund a programme that bridges the gap from high performance reference technologies to distributed portable sensing by unifying the technology needs across a range of sectors.

③ Fragmentation of the existing ecosystem means end user needs are often disconnected from frontier technology innovations in both instrumentation and automation. Coordinated efforts need standardisation that is rarely funded within existing streams.

④ A ubiquitous particle profiling capability to analyse morphology and chemistry of the invisible particulate matter that exists all around us, unlocking new monitoring capabilities for everything from personal health exposures to evolving cloud dynamics.

⑤ A capability that meets needs across a range of sectors fuelling a new commercial market and enabling research that will seed future regulation, driving and self-propagating a need for further innovation in the technology to serve the created market.

ENGAGE

Our next step is to launch a funding opportunity derived or adapted from this programme formulation. Click here to register your interest, or to provide feedback that can help improve this programme thesis.

Annex 1: Summary of aerosol targets, their properties and importance for profiling

Class	Aerosol target	Examples / species	Size / application ranges	Main sources	Impacts	Why profiling matters
Inorganic salts	**Sulphate**	Sulphate salts; sulphuric acid aerosol	<0.02 μm nucleation; 0.02-0.1 μm Aitken/ultrafine; 0.1-1 μm accumulation; PM2.5/PM10 depending on ageing and source.	Primary marine and volcanic emissions; secondary oxidation of SO2 and other sulphur gases; coal/power; deliberate aerosol interventions as adjacent context	Climate cooling via scattering; CCN; acid deposition; PM2.5 respiratory impacts	Composition and size determine hygroscopicity, CCN activation and whether particles are natural, industrial or intervention-relevant
	Nitrate	Sodium nitrate; ammonium nitrate	Primarily 0.1-1 μm accumulation and >1 μm coarse fractions; relevant to PM2.5 and PM10.	Secondary NOx chemistry; traffic/combustion; agriculture via ammonia chemistry	Climate cooling; CCN; eutrophication; respiratory impacts as PM2.5 component	Speciation connects generic PM mass to precursor chemistry, source class and actionability
	Ammonium	Ammonium sulphate; ammonium nitrate	Typically 0.1-1 μm accumulation mode; mainly PM2.5-relevant.	Agriculture, livestock and fertilisers; biomass burning and controlled burns	Fine PM burden; respiratory disease; affects particle water uptake and phase	Links agricultural sources to fine PM and changes aerosol hygroscopicity; hard to interpret from size alone
	Halides / sea-salt chemistry	NaCl; chloride; bromide; iodide	0.1-1 μm accumulation and >1 μm coarse sea-salt/halide particles; relevant to PM2.5 and PM10.	Sea spray; volcanic emissions; lake beds	CCN; halogen/ozone chemistry; respiratory irritation	Fresh versus aged chloride chemistry helps separate marine background, volcanic inputs and cloud chemistry

Carbonaceous combustion aerosols	**Black carbon**	Soot/elemental carbon	Fresh soot often <0.1 μm; aged/coated particles commonly 0.1-1 μm; PM0.1/PM2.5-relevant.	Diesel and traffic; shipping; domestic heating; fossil fuel, biofuel and biomass combustion	Strong climate warming via absorption; snow/ice albedo reduction; cardiovascular and respiratory disease; carcinogenic co-pollutants	Coating, size and mixing state change forcing and toxicity; source fingerprints support fenceline accountability
	Brown carbon	Light-absorbing organic aerosol; humic-like substances; PAHs and pyrolysis tracers	Fresh biomass-burning particles often ~0.1-0.4 μm; aged particles 0.1-1 μm; PM2.5-relevant.	Biomass and biofuel combustion; wood burning; cooking; traffic; some natural humic-like substances	UV/visible absorption; warming; respiratory impacts	Optical absorption plus molecular markers can distinguish wood smoke, cooking and traffic from generic PM mass
	Primary / complex organic aerosol	Cooking aerosol; lubricating oil; organic fragments; primary organic aerosol	Aitken/ultrafine 0.02-0.1 μm and accumulation 0.1-1 μm; PM0.1/PM2.5-relevant.	Combustion, cooking, traffic, industrial/domestic activities and ecosystems	Scattering/absorption; CCN; toxic organics; PM2.5 health effects	Source-specific fingerprints matter more than bulk OA; single-particle mixing state and ageing are central to the thesis
Organic and bioaerosols	**Secondary organic aerosol**	Biogenic SOA; anthropogenic SOA; urban smog products; brown carbon	Nucleation <0.02 μm, Aitken 0.02-0.1 μm and accumulation 0.1-1 μm; PM0.1/PM2.5-relevant.	Particle-phase products from VOC oxidation from ecosystems, traffic, industry and solvents, biomass burning	CCN; climate uncertainty; visibility reduction; respiratory effects	Particle-phase products and ageing determine impacts

	Pollen, spores and biological fragments	Pollen; fungal spores; algae; lichen; biological debris	Mostly coarse 1-100 µm; fragments may enter the 0.1-2.5 µm fine fraction; PM10/inhalable-relevant.	Terrestrial and marine biosphere; mechanical fracturing; wind-driven dispersal	Allergy and asthma; CCN/INP; ecosystem signals; respiratory impacts	Morphology plus biological/chemical cues turn generic PM into actionable allergy, ecosystem and exposure forecasts
	Pathogen-bearing particles	Bacteria; viruses; respiratory droplets; aerosolised fragments	Approx. 0.01 to >10 µm depending on organism and carrier droplet; spans PM0.1, PM2.5 and PM10.	Exhaled breath; infected individuals; livestock; wastewater; healthcare and indoor settings	Infection-risk conditions; respiratory and cardiovascular effects; potential long-range transport	Need source/risk signatures and carrier context, not just particle count; species identification to avoid overclaiming definitive live pathogen ID
Mineral and crystalline inorganic particles	**Mineral dust and crystals**	Quartz; silicates; calcium carbonate; iron oxides; asbestos; ceramics	Mostly coarse >1 µm and super-coarse >10 µm; smaller fraction 0.1-2.5 µm; PM10 and larger inhalable-relevant.	Wind erosion; soil resuspension; construction; cement; volcanics; agriculture	INP; scattering/absorption; silicosis and respiratory disease; nutrient transport	Morphology and mineralogy separate natural dust from construction, asbestos and industrial sources
Metals and metal-rich particles	**Transition, heavy and trace metals**	Fe; Cu; Zn; Mn; Ni; V; Pb; Cd; Cr	Often 0.1-1 µm accumulation and >1 µm coarse modes; PM2.5/PM10 depending on source.	Brake wear; exhaust; shipping/fuel oil; industrial emissions; mining; waste	Oxidative potential; neurological, cardiovascular and respiratory toxicity; source accountability	Elemental fingerprints are central to fenceline attribution; PM mass misses toxic potency
Marine aerosols	**Sea spray / sea salt**	NaCl-rich particles; hydrated sea-salt particles (note	Accumulation 0.1-1 µm and coarse >1 µm sea-salt droplets/particles; PM2.5/PM10-relevant.	Bubble bursting, wave breaking and coastal wind	Major CCN source; climate cooling/cloud albedo; coastal	Separates natural marine background from port, road and industrial emissions; humidity

		overlap with halides)			respiratory irritation	stress-tests sampling
	Marine organic aerosol	Marine POA and SOA; biological organics; marine gels and fragments	Aitken 0.02-0.1 µm and accumulation 0.1-1 µm; PM0.1/PM2.5-relevant.	Biologically active ocean regions emitted with sea spray	CCN/INP; marine cloud formation; ecosystem signals	Strengthens coastal/cloud demonstrations and links marine biology to aerosol-cloud effects
Cloud / hydrometeor adjacent	**Water and ice particles**	Cloud droplets; ice crystals; fog; mist	Cloud/fog droplets typically ~1-100 µm; ice crystals can exceed 10 µm; adjacent to PM rather than standard PM2.5/PM10.	Condensation/freezing on CCN/INP	Cloud albedo; precipitation; hydrological cycle; aqueous-phase chemistry	Paired aerosol–hydrometeor profiling links CCN/INP properties to droplet and ice formation, precipitation and radiative effects, enabling validation of satellite retrievals and cloud models.
Synthetic and non-exhaust particles	**Micro/nanoplastics and fibres**	Polyethylene; polypropylene; textile fibres; plastic fragments	Nanoplastics <0.1 µm; submicron particles 0.1-1 µm; microplastics/fibres commonly >1 µm; PM10/inhalable-relevant.	Degradation of plastic waste/products; textiles; industrial emissions; indoor sources	Inflammation; tissue translocation; endocrine/toxicity concerns; vector for pollutants	Emerging contaminant where size, polymer type and source attribution are unresolved
	Tyre/rubber and road wear	Tyre wear particles; rubber fragments; 6PPD-quinone-associated particles; road dust	Accumulation 0.1-1 µm plus coarse >1 µm road-wear particles; PM2.5/PM10-relevant.	Tyre wear; road abrasion; resuspension	Respiratory irritation; toxicity; aquatic impacts	Source-specific fingerprints support traffic interventions beyond exhaust metrics

Particle-associated persistent chemicals	**Persistent organic toxic payloads**	PAHs; PFAS-bearing particles; pesticides; plasticisers	Size depends on carrier aerosol; commonly associated with PM0.1, PM2.5 or PM10 fractions.	Combustion; industrial/agricultural use; consumer products; waste	Carcinogenicity; endocrine disruption; chronic toxicity	Treat as payloads on aerosols, not always aerosol classes; profiling needs carrier, chemistry and source together

Annex 2: A non-exhaustive summary table of available sizing instrumentation

Note that all specifications are approximate for the class of instrument rather than a reflection of the performance of the linked commercial solutions, which are provided solely as examples, not as product recommendations.

Instrument Class, Cost and Example	**Size Detection Range**	**Sizing Vector Strengths and Weaknesses**	**SWaP and Speed**
Electrical Low Pressure Impactor (ELPI) [41] £75k-95k+ e.g. Dekati ELPI+	6 nm – 10 µm	Electrical charging and inertial impaction: Mobility-dependent charging followed by low-pressure cascade inertial impaction onto multi-stage electrometers. Can perform chemical analysis afterwards.	Low portability: Benchtop unit (25kg+) with high power footprint (~300W) that requires a strong vacuum pump Fast: Sub-second response times.
Scanning Mobility Particle Sizer (SMPS) [42] £40-70k e.g. TSI SMPS	10 nm – 1 µm	Electrical mobility: Typically a high voltage differential mobility analyser (DMA) provides physical size selection for input to a downstream detector (often a CPC). Charging probabilities decrease rapidly below 30nm.	Low/medium portability: Needs a radioactive or X-ray bipolar charge neutralizer and a high power source. Slow: 1-to-5 minute scan times make it blind to sub-second plume dynamics and vibration sensitivity can limit vehicle deployment.
Aerodynamic Particle Sizer (APS) [43] £30k e.g. TSI 3321	500 nm - 20 µm	Time-of-flight acceleration: Accelerates particle through a nozzle and uses inertial lag to determine aerodynamic diameter based on time taken to cross two laser beams. Accounts for particle shape and density so immune to refractive index variations.	Medium portability: Typically <10kg requiring 100W power. Fast: Second response times.

Condensation Particle Counter (CPC) £10k-25k e.g. Cambustion 5210	2.5 nm – 3 µm	Heterogeneous nucleation growth: Incoming particles pass through a supersaturated vapour that condenses and grows them into macroscopic droplets for number concentration analysis with a laser scattering counter. Susceptible to errors at high concentrations.	Medium portability: Typically 5-10kg but low-SWaP versions exist (<1kg, ~12W). Requires a continuous liquid consumable supply (although pulsed CPCs have lower consumption). Fast: Sub-second response times.
Portable Aerosol Mobility Spectrometer (PAMS) £12k-£20k e.g. Kanomax PAMS	10nm - 855 nm	Electrical mobility: Miniature cylindrical DMA operates at low flow rates but can experience high loss due to deposition on tube walls.	High portability: Light (4.5kg) low power platform, at the expense of sizing resolution compared to reference SPMS. Slow: 1 minute scan times.
Optical Particle Counter (OPC) £10k-30k e.g. Palas Fidas, Handix POPS (portable)	180 nm – 20 µm	Light scattering: Single particle scattering intensity measured from a focused sample flow. Blind to ultrafine particles due to Rayleigh scattering drop-off and accuracy relies on refractive index assumptions. Susceptible to errors at high concentrations. Can perform chemical downstream analysis afterwards.	High Portability: Exceptionally light (<1 kg), low power (<5 W) versions available. Fast: Sub-second response times.
Ultra-Low-Cost Mass Nodes £250-500 e.g. Alphasense OPC-N3, Plantower PurpleAir	300 nm – 10 µm+	Light scattering as with OPC. Output prone to drift with relative humidity and changing aerosol compositions (which alter the assumed refractive index). Cheapest instruments sacrifice on particle focusing and optical alignment, relying on regression analysis to extrapolate mass values.	Very High Portability: Tiny (<100g) and low power (<1W). Fast: Second response times.

Annex 3: A non-exhaustive summary table of available composition instrumentation

Note that all specifications are approximate for the class of instrument rather than a reflection of the performance of the linked commercial solutions, which are provided solely as examples, not as product recommendations.

Instrument Class, Cost and Example	**Size Detection Range & Sizing Vector**	**Chemical / Biological Speciation Strengths and Weaknesses**	**SWaP and Speed**
Laser Desorption / Ionisation Single Particle MS [44] £250k+ E.g. ATOFMS, LAAPTOF	40 nm – 3 µm Vector: Aerodynamic or optical sizing triggers a downstream ablation laser.	Single-step laser desorption/ionisation (LDI) provides real-time characterisation of individual particle composition, resolving single-particle mixing states (internal vs. external mixing) across both refractory cores (e.g., soot, dust, metals) and non-refractory species. The particle detection efficiency drops rapidly below 100nm due to limited light scattering; matrix effects limit species identification.	Low portability: Weighs >150 kg, consumes >500 W. Requires heavy turbomolecular pumps maintaining ultra-high vacuums ($<10^{-5}$ mbar). Slow: Less than 10 particles per second.
Thermal Vaporisation MS [45,46] £250k+ e.g. HR-ToF-AMS.	40 nm – 1 µm Vector: Aerodynamic lens focusing onto a heated tungsten surface.	Two-step thermal evaporation and electron ionisation. Provides high precision quantitative mass concentrations for bulk non-refractory organics, nitrate, sulfate, ammonium and chloride. Measures ensemble populations so cannot resolve single particle mixing states. The approach is completely blind to refractory cores (black carbon, dust, sea salt).	Portability as above. Mini-AMS and ACSM instruments have begun to improve portability. Medium speed: Bulk ensemble profiling.

Research Two-Laser Single Particle MS [47–49] £400k+ e.g. NOAA PALMS-MG, PNNL SPLAT	10 nm – 3 µm Vector: Ultra-precise aerodynamic inlet lens for improved performance under 100nm.	Two-step desorption and photoionisation separates evaporation from ionisation. Collects positive/negative mass spectra simultaneously, with potential for quantitative core-shell particle chemistry of both refractory and non-refractory components and native single particle tracking of physical morphology due to two-laser system, including density, asphericity and shape. Complex research grade system requires specialists to operate. High energy ionisation means fragmentation of long-chain complex organic isomers making isomers with the same mass formula unresolvable.	Medium portability: Custom-engineered aircraft racks for the standard SPLAT (400kg, 3.5kW) with a more portable version available at 225kg and 920W. Medium speed: Characterises up to 100 particles per second.
Ambient Organic MS [50,51] £300-600k+ e.g. FIGAERO-CIMS / EESI-ToF-MS	75 nm – 1 µm Vector: Time-gated inlets directly extract ambient particulate bulk into a gas or solvent spray.	Soft chemical (CIMS) or solvent (EESI) ionisation preserve intact molecular structures without fragmentation, important for secondary organic aerosols (SOAs) and bioaerosols. Real-time tracking of thousands of organic compounds. The approach provides bulk information so is blind to single particle mixing states. Also blind to refractory cores.	Low portability: Requires a large climate-controlled laboratory with high power (~3kW). EESI requires continuous, precise microfluidic flows of volatile charging solvents and gases. Speed varies: FIGAERO slower as requires mechanical actuation between gas sampling and particle analysis. EESI can achieve online operation.
Aerosol Extinction / Single-scattering Albedo [52] £40k-80k+ e.g. NOAA Albedometer, Aerodyne CAPS	50 nm – 2.5 µm Bulk analysis	Performs optical extinction quantification using a high-finesse optical cavity paired with an integrating sphere or acoustic resonator to directly calculate single scattering albedo. Useful for any species with strong absorption, including black/brown carbon, mineral dust and bioaerosols.	Medium portability: Benchtop size systems of 20kg and <200W power draw. Fast: Real-time outputs.

		The approach provides bulk information on optical spectra so cannot output specific chemistry. Prone to sampling losses for coarse fractions.	
Specialised: X-ray Fluorescence (XRF) for Metals £80k-150k e.g. SCI Xact 625i	Bulk analysis in PM1, 2.5 or 10 bins Vector: Selective inlet directs flow onto a moving filter tape over a gated time window.	Uses non-destructive energy dispersive X-ray fluorescence to quantify up to 67 elements, specifically targets catalytic transition metals (Fe, Cu, Zn, Mn) and heavy contaminants. Blind to organic / biogenic molecules, black carbon and light elements (Z<13) as well as single particle mixing states.	Low portability: Large systems (>75kg) with high power requirements (1kW) Slow: Time-averaged integration on filters.
Specialised: Advanced Bioaerosol Spectrometers £70k-130k e.g. Swisens Poleno-Jupiter, PLAIR Rapid-E+	300 nm – 300 µm Vector: Uses flow cytometry and angular polarised scattering.	Capture fluorescence spectral information alongside particle imaging data, used together in machine learning classification with high accuracy for pollen and spores. Limited by non-biological fluorescent pollutants and blind below 500nm. Optimised for ambient conditions rather than plumes.	Low to medium portability: Large systems (>130kg) with high power requirements (~750W), slightly smaller / lower power versions exist. Fast: real-time spectral analysis of 100s - 1000s of particles per minute
Specialised: Wideband Integrated Bioaerosol Sensor [53,54] £50k+ e.g. WIBS-5	500 nm – 30 µm Vector: Elastic light scattering triggers laser-induced fluorescence analysis.	Dual-wavelength UV excitation (e.g., 280 nm & 370 nm) maps emission spectra to resolve contributions from amino acids (tryptophan, tyrosine) and coenzymes (NADH, flavins). Real-time proxy for distinguishing bacteria, pollen and mold. Provides coarse biological information as fluorescence bands are broad and overlapping; cannot reliably distinguish live vs. dead pathogens or confirm true species identity. Limited by non-biological fluorescent pollutants and blind below 500nm.	Medium portability: Field grade weatherproof systems (~12.5kg,100W) Fast: up to 20,000 particles/sec.

Specialised: Single Particle Soot Spectrometer [55] £60k-90k e.g. DMT SP2-S	70 nm – 1 µm Vector: Laser-induced incandescence inside an intracavity laser beam. Simultaneous multi-angle light scattering to determine the thickness of coatings surrounding the core.	Heats soot particles to their boiling point (~4000 K), measuring the thermal incandescence and peak temperature to calculate the absolute mass of pure black carbon per single particle. Blind to all non-absorbing mass fractions and the composition of the coating.	Medium Portability: Flight-qualified for large research aircraft (~12 kg, ~200 W). Fast: up to 25,000 particles per second.
Specialised: Photoacoustic Soot Spectrometer £25k-40k e.g. DMT PAX	50 nm – 1 µm Vector:	Uses photoacoustic effect to quantify black carbon mass absorption and distinguish from brown carbon across discrete wavelengths. The approach provides bulk information so is blind to single particle states. Blind to all non-absorbing mass fractions and the composition of the coating.	Medium portability: Field-deployable units exist (~12kg) that use stable power lines. Slow: Time averaged response over bulk sample over seconds

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