Institution: University of Hertfordshire		
Unit of Assessment: 9 – Physics		
Title of case study: Commercialisation of high-resolution, low-cost particulate matter (PM) sensors increases prevalence of and access to air quality monitoring		
Period when the underpinning research was undertaken: 2000 – 2015		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Paul Kaye	Research Professor	1974 – present
Edwin Hirst	Senior Research Fellow	1990 – present
Richard Greenaway	Senior Research Fellow	1994 – present
Period when the claimed impact occurred: September 2013 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Based on their research into the characterisation of atmospheric aerosols, University of Hertfordshire (UH) researchers developed low-cost Optical Particle Counters (OPCs) that measure airborne particulates at high resolutions. These were patented and commercialised by UK SME Alphasense Ltd; since 2015, 18,420 units have been integrated into air quality monitoring systems in 70 countries. This delivered significant economic impact: at least £53.2m in associated commercial revenues and 32 new jobs. The OPCs were used by the UN Environment Programme to map air pollution hotspots in the developing world and by World Athletics to monitor the impact of poor air quality on athletes' health and performance. They were key to the establishment of comprehensive air quality monitoring networks by city authorities for more effective regulation and stronger public health protection, including three cities in China with a combined population of 24 million. Their affordability democratised access to air quality monitoring for citizen groups in five countries.

2. Underpinning research (indicative maximum 500 words)

Accurate characterisation of atmospheric aerosols improves our understanding of how particulate matter affects air quality and the climate. However, accuracy has traditionally come at a prohibitive cost. About a decade ago, high-resolution OPC instruments, which used light-scattering technologies to count and size airborne particulates, typically cost in excess of £10,000, constraining the creation of air pollution monitoring networks capable of addressing what the World Health Organisation has defined as a 'public health emergency'.

Between 2000 and 2011, researchers in the Particle Instruments and Diagnostics Research Group, led by Kaye and funded by NERC, the UK Met Office and the US National Science Foundation [**G1-G5**], were focused on the development of complex aircraft wing-mounted cloud analysis instruments capable of the *in situ* identification, classification and sizing of atmospheric cloud particles such as ice crystals, microdroplets and mineral dust. The so-called 'SID' (Small Ice Detector) probes provided data on the abundance, size and shapes of these atmospheric particles that profoundly affect cloud radiative properties – a primary source of uncertainty in climate change modelling. Critically, to avoid affecting the particles being measured, the SID instruments had to be 'open-path' designs [**3.1**], i.e. free from mechanical obstructions such as aerosol sampling tubes onto which droplets could impinge or ice crystals shatter. The Group's aerodynamic and aerosol behaviour modelling ultimately resulted in wing-mounted instruments that used two complex optical assemblies to spatially define a 'virtual' measurement zone in free space at the nose of the instrument, and a third to determine a particle's size and shape. These instruments (SID-2 and SID-3), have since been successfully deployed by atmospheric scientists on more than 50 campaigns by the UK's FAAM research aircraft [**3.2-3.4**]. The SID-2 was the first device to successfully measure and classify high altitude atmospheric particles down to micron sizes [**3.4**].

In 2010, the Group applied the SIDs' open-path sampling principles to the design of OPCs for a ground-based sensor network to study air quality at Heathrow Airport, as part of a NERC-funded consortium led by the University of Cambridge [**G5**]. The project required a network of sensor nodes to measure gases and particulates around the airport's perimeter for a 15-month period, but at the time there was no affordable solution for monitoring particulates. The challenge was two-fold: firstly, traditional OPC designs were based on air pumps to draw in ambient aerosol. These pumps required protection from particle contamination (a frequent cause of failure) by an upstream particle filter. These filters would become blocked on a monthly basis and require manual replacement, an activity the Heathrow authorities would not accept. Secondly, conventional OPCs could suffer water damage by sampling fog droplets, not uncommon at Heathrow.

The pumpless, open-path measurement protocol employed in the SID aircraft probes was, in principle, the ideal solution. However, the wing-mounted SID designs were far too large and expensive for use at Heathrow, so the UH Group undertook extensive optical and aerodynamic modelling of various designs. The final design, later patented worldwide in 2015 [**3.5**], was based on a unique geometry of custom-designed elliptical mirror and dual-element photodiode detectors, creating a 'virtual' particle measurement zone in free space, unencumbered by mechanical structures. It represented a breakthrough in OPC technology, offering accuracy approaching that of high-end commercial instruments but at a small fraction of the cost, weight and power requirement. Critically, its design allowed long-term unattended operation.

The OPCs were deployed at 42 locations around Heathrow, running continuously for 15 months without manual intervention, delivering 110 million particle size profiles and confirming their commercial viability as low-cost, high-quality sensors. The 'Heathrow project' demonstrated that major sources of air pollution outside the airport perimeter in fact originated from traffic emissions from central London [**3.6**]. Consequently, the commercial potential of the OPCs was recognised by Alphasense Ltd, the sensor company that had provided the pollutant gas sensors to the Heathrow project. Alphasense licensed the technology from UH in 2013 and have since funded Kaye's group to carry out further research for OPC design and performance improvement.

3. References to the research (indicative maximum of six references)

3.1 Hirst E, Kaye PH, Greenaway R, Field PR, Johnson DW. Discrimination of micrometre-sized ice and super-cooled droplets in mixed-phase cloud. Atmospheric Environment. 2001;35(1):33-47. https://doi.org/10.1016/S1352-2310(00)00377-0 (*87 citations*)
3.2 Haywood JM, Osborne S, Francis PN, Keil A, Formenti P, Andreae MO, Kaye PH. The mean physical and optical properties of regional haze dominated by biomass burning aerosol measured from the C-130 aircraft during SAFARI 2000. Journal of Geophysical Research: Atmospheres. 2003;108(D13). 8473. https://doi.org/10.1029/2002JD002226 (*260 citations*).
3.3 Field PR, Hogan RJ, Brown PRA, Illingworth AJ, Choularton TW, Kaye PH, Hirst E, Greenaway R. Simultaneous radar and aircraft observations of mixed-phase cloud at the 100m scale. Quarterly Journal of the Royal Meteorological Society. 2004;130(600):1877-1904. https://doi.org/10.1256/qj.03.102 (*44 citations*)
3.4 Cotton R, Osborne S, Ulanowski Z, Hirst E, Kaye PH, Greenaway R. The Ability of the Small Ice Detector (SID-2) to Characterize Cloud Particle and Aerosol Morphologies Obtained during Flights of the FAAM BAe-146 Research Aircraft. Journal of Atmospheric and Oceanic Technology. 2010;27(2):290-303. https://doi.org/10.1175/2009JTECHA1282.1 *(71 citations)*
3.5 Kaye PH, Hirst E, inventors; Alphasense Ltd, assignee. Second Generation Low-Cost Particle Counter. US patent 9,116,121. 2015 Aug 25. https://google.com/patents/US9116121
3.6 Jones R, Popoola OMA, Mead MI, Bright V, North R, Stewart GB, Kaye PH, Hueglin C, Mueller M, Curruthers D, Saffell J. High density air quality network at Cambridge and London Heathrow Airport: first results and interpretations. 2013. Abstract from Air Quality Monitoring New Technologies, New Possibilities, Royal Society of Chemistry, London, 11 Dec 2013.

<u>**Key underpinning grants**</u>

G1 Measurement of scattering and absorption properties of ice crystals appropriate to tropical cirrus cloud. NERC NER/T/S/2001/00203, PI: Kaye; £151,467; 2002-5.

G2 An aircraft instrument for analysing the structure of Atmospheric Aerosol and Cloud Particles. NERC NE/B506094/1, PI: Kaye; £161,719; 2004-7.
G3 Co-Development of Small Ice Detector (SID) Probe for HIAPER. US NSF/UCAR Subcontract No. S05-35616, UH PI: Kaye; US$125,000; 2004-6.
G4 Miniature Atmospheric Particle Classifier. NERC NE/H002316/1, PI: Kaye; £157,417; 2010-11
G5 High density sensor network system for air quality studies at Heathrow airport. NERC NE/I007296/1, UH PI: Kaye; £84,068; 2011-14.

4. Details of the impact (indicative maximum 750 words)

Having established itself as one of Europe's leading manufacturers of gas sensor technologies, UK-based Alphasense Ltd sought to expand into the particle monitoring field. In September 2013, the company signed a licensing agreement with UH to commercialise the patented OPC technology. Reliant on the expertise of Kaye's group in optical and laser light-scattering techniques, Alphasense commissioned UH to produce 150 OPC-N1 prototype devices and design the algorithms required to assess particulate matter (PM) and convert particle size and count data to PM_1, $PM_{2.5}$ and PM_{10} for air quality monitoring. The prototypes were sold into the UK, US and Europe as core components that could be incorporated into commercial air quality monitoring systems. Customer feedback verified that the low-cost OPC-N1 units provided PM data comparable to that from existing OPCs, which were many times more expensive.

UH's technology had opened up a market that was previously unachievable; the OPC's low cost made the sale of monitoring systems capable of measuring PM commercially viable and, unlike other OPCs on the market, it was designed for unattended operation in inaccessible locations such as rooftops and trunk roads [**5.1**]. Demand grew rapidly and Alphasense accelerated production, bringing the OPC-N2 to market in early 2015. Growth was aided by independent evaluations confirming the efficacy of the OPC's field performance, which were published in peer-reviewed journals from 2017 onwards [**5.1**]. With further research support from Kaye's group, the company released the OPC-N3 in March 2018, which, for the same price, extended the device's capabilities to pollen and spore monitoring.

Economic impact via revenues for SMEs in UK and overseas – and the wider supply chain

At the end of 2020, Alphasense had sold 18,420 OPC-N2 and OPC-N3 units at £285 each, with sales rising to an average of ~500 per month. The OPCs have generated Alphasense £5.2m in revenue from sales in 70 countries, directly creating seven jobs at the company and making a significant contribution to its business performance [**5.1**, **5.2**]. A further two FTE research roles have been created and sustained at UH through ~£100,000 a year in development funding from Alphasense. The product profit margin peaked at 64% in 2018. The company's 2019 strategic report [**5.2**] read: "*The results for the year reflect further growth in turnover of 16% … Recently developed new products* [referring to the OPCs] *continued to perform well as concerns about air quality, especially in the Far East, led to impressive demand*." Summing up the strategic importance of the OPCs, Alphasense's Technical Director said: "*Alphasense had concentrated on gas detection for 21 years but for the last seven years we have focused on developing our capability in particle monitoring, which has allowed us to cover all critical measurements in air quality at a time when air pollution has risen to the top of policy and media agendas* [**5.1**]."

The majority of Alphasense's customers over the impact period were commercial companies that manufactured and sold air quality systems and networks. Without the OPC, these products would not have come to market [**5.1**]. Thus, UH research has resulted in economic impact via the wider supply chain. Its customers range from large companies, including GRIMM Aerosol, Bosch and Thermo Fisher, to SMEs, including South Coast Science and Atmospheric Sensors Ltd in the UK and QuantAQ in the US. Other significant customers are Kunak Technologies and Libelium, both based in Spain, and Sail Hero, the largest provider of air quality systems in China. According to Alphasense's Technical Director, the OPC-N3 has allowed these companies to enter or establish a competitive advantage in a global air quality monitoring market projected to reach $6bn in 2025 [**5.1**]. Based on its own data, Alphasense reports that at least £48m in commercial revenues were generated and 25 sales, manufacturing and engineering jobs were created and sustained over the impact period through third-party sales of integrated systems [**5.1**]. As an example of how an Alphasense customer has benefitted from the OPCs, GRIMM Aerosol selected the OPC-N3 for a new range of mid-cost PM instruments after finding it outperformed competitor sensors; the company deployed the OPC-N3 in a German government-funded project to establish a smart air quality network in the city of Augsburg. Having long manufactured high-end air quality monitoring reference and validation systems, the mid-cost instrument means GRIMM has the capability to offer a fully integrated network comprising three tiers of instrumentation, increasing its market share and enabling urban authorities to widen their air quality sensor networks [**5.3**].

Supporting the establishment of air quality monitoring networks in major cities to address the health impacts of air pollution and better inform citizens

In June 2014 the UN Environment Assembly, the world's highest-level decision-making body on the environment, adopted a resolution to 'strengthen the role of the UN Environment Programme (UNEP) in promoting air quality'. In September 2015, UNEP unveiled a low-cost air quality monitoring device in September 2015, which the UN said could '*revolutionise air quality measurement in developing countries and help prevent deaths from air pollution that claim seven million lives each year*' [**5.4**]. The incorporation of Alphasense's OPC, based on UH's research and patented technology, allowed the device to measure harmful particulate matter; its low cost ensured the device's viability [**5.4**]. UNEP's Executive Director said its device cost $1,500 per unit, allowing governments to establish countrywide networks of monitoring stations for $150,000 - $200,000 – less than the cost of just a single monitoring station ($250,000) at that time [**5.4**]. UNEP published the blueprint for its UNEP Air Quality Monitoring Unit, specifying the use of the OPC-N2, '*as a global public good*' to '*enable governments and organisations to purchase, assemble or fabricate the units themselves*' [**5.4**]. UNEP launched the Unit in Nairobi to map the city's air pollution hotspots before deploying the system in 30 cities in developing countries [**5.4**].

City authorities around the world are using Alphasense's OPCs via the purchase of integrated air quality monitoring systems, in which the OPC-N3 is necessary to measure PM data [**5.1**]. As an example, Chinese SME Shenzhen Cambri Environmental Technology purchased ~800 OPCs from Alphasense, integrated them into their own air quality monitoring instruments and supplied them to city authorities in three Chinese cities (Shenzhen, pop. 12.5m; Dongguan, pop. 8.25m; Rizhao, pop. 2.8m) for measuring hyperlocal air quality [**5.5**]. Through the OPCs, environmental protection bureaus at these municipal governments can identify key sources of particulate emissions and enforce regulation where appropriate, e.g. if a factory is breaching emissions limits or operating without a license [**5.5**]. Shenzen Cambri reports that the availability of the OPCs has facilitated the rapid growth of the company; since its formation in 2018 it has created 25 jobs [**5.5**].

In the US, Massachusetts-based start-up QuantAQ, a spin out from MIT, uses the OPC-N3 in its integrated air quality monitoring system Modulair™-PM [**5.6**]. Example use cases [**5.6**] include monitoring indoor air quality in Georgia Institute of Technology's classrooms during the Covid-19 pandemic to guide decisions around the resumption of in-person teaching. The Modulair is being used at several airports (e.g. Boston Logan International Airport) to measure emissions and their impact on local communities; citizen-led activist groups are collaborating on these projects. The US National Park Service is using it to monitor the impact of wildfires on air quality.

Facilitating UN-World Athletics collaboration to raise global awareness of air pollution, protect athletes' health and study the impact of poor air quality on athletic performance

In May 2018, World Athletics (then IAAF) announced a five-year partnership with UNEP to install air quality monitoring systems at all of its 1,000 outdoor athletics tracks. The collaboration aims to study the correlation between poor air quality and athletic performance; to identify the best times for events to be held based on pollution levels; and to create greater global awareness of the wider importance of air quality monitoring. The IAAF awarded the contract for the provision of the air quality monitoring devices to Spain's Kunak Technologies, a key customer of Alphasense. The first stadium air quality monitor (using the OPC-N3 to measure particulate matter) was installed in Monaco in September 2018, providing real-time, publicly available data. Monitors were then installed over an 18-month period in Addis Ababa, Sydney, Mexico City and Yokohama [**5.7**]. On launching the programme, the director of UNEP's Global Environmental Monitoring System Unit said: *"The IAAF partnership provides practical insight into the use of low-cost sensors, so it can be the first step to build capacity at city-level networks, bringing together science for policy; using evidence-based air quality assessments to develop better urban policies* [**5.7**]." Air quality monitoring has since become a central element of World Athletics' *Sustainability Strategy*, which pledges carbon neutrality by 2030. In August 2020 Kunak's system captured air quality data along the Tokyo Olympic marathon course in Sapporo, a year ahead of the scheduled race itself [**5.7**].

Democratising access to air quality monitoring devices for civic activism on pollution

The low cost of OPC technology has helped open up air monitoring to citizen-led science projects designed to empower communities and pressure governments to act on air quality. US-based Safecast describes itself as a global volunteer-centred citizen science project working to empower people with data about their environments. Twenty of the organisation's *Solarcast* air quality sensors, incorporating an Alphasense OPC-N2, were deployed around Los Angeles in September 2017 [**5.8**]. Three months later, when Southern California experienced serious forest fires, Safecast moved a number of these sensors "*to help give people an idea of what they might be breathing and where to go to avoid increased exposure*". The Arvin Air Quality Project is a citizen science project run by the Central California Environmental Justice Network across the city of Arvin which has some of the worst air pollution levels in the country. Having purchased air quality sensors from LA-based technology company Valarm, which were built around the Alphasense OPC-N2, the project deployed sensors across Arvin and real-time data was published on a dedicated website [**5.8**]. From 2018, the Open-Seneca initiative deployed citizen science networks of low-cost air quality sensors (using Alphasense OPCs) in Cambridge, Buenos Aires and Mendoza, Nairobi and Belo Horizonte. Local stakeholders have taken ownership of the sensor networks for long-term sustainability [**5.8**].

5. Sources to corroborate the impact (indicative maximum of 10 references)

5.1 Corroborating statement from the Chief Technical Officer of Alphasense Ltd.
5.2 Annual report and financial statements for year ended 31 March 2019, Alphasense Ltd (via Companies House): https://beta.companieshouse.gov.uk/company/03264282/filing-history
5.3 Corroborating statement from the Vice President of GRIMM Aerosol.
5.4 Articles on the UNEP website corroborating the impact of UH's patented technology. Launch of the air quality monitoring unit: https://news.un.org/en/story/2015/09/507692-un-environment-agency-unveils-low-cost-device-air-quality-monitoring
Inclusion of Alphasense's OPC-N2 in the technical spec:
https://uneplive.unep.org/media/docs/news_ticker/Air_Quality_Leaflet_Letter_size.pdf;
https://uneplive.unep.org/media/docs/home/WB.pdf
5.5 Corroborating statement from the founder of Shenzhen Cambri Environmental Technology.
5.6 Corroborating statement from the CEO and co-founder of QuantAQ.
5.7 Articles on the World Athletics website corroborating the impact of UH's patented technology: **a.** Initiative: https://www.worldathletics.org/news/press-release/air-quality-monitor-stadium-monaco; **b.** Link between Alphasense OPC-N3 and Kunak Air A10:
https://airqualitynews.com/2020/02/28/air-quality-in-cities-and-the-vital-role-of-monitoring/
c. Use of Alphasense technology for PM monitoring ahead of the Olympic marathon in Japan:
https://www.worldathletics.org/news/press-releases/heat-air-quality-conditions-sapporo-tokyo-oly
5.8 Articles corroborating the link between Alphasense OPCs and citizen science networks: Solarcast in Los Angeles: https://safecast.org/2017/09/solarcast-deployment-los-angeles/; Arvin Air Quality Project: https://www.valarm.net/blog/air-quality-iot-sensors/; Open-Seneca: see **5.7b**.