Institution: University of Hertfordshire

Unit of Assessment: Panel B (9): Physics

Title of case study: Exploiting Spatial Light Scattering (SLS) for Particle Characterisation

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

Since 1994, the university has pioneered the development of **spatial light scattering** for the rapid detection and classification of various types of airborne particle. This ‘particle thumbprint’ technology, based on an analysis of the detailed 2-dimensional pattern of light scattered by each particle, has since found worldwide application.

Over the 2008–13 period, the technology was exploited by commercial companies and research organisations from the USA, mainland Europe, the UK and Japan in areas including military bioaerosol detection; atmospheric cloud microphysics and climate research; particle/powder process control; stack emissions monitoring; environmental pollution assessment; and, most recently, the real-time detection of hazardous airborne asbestos fibres.

2. Underpinning research (indicative maximum 500 words)

The science of particle light scattering accelerated rapidly in the slipstream of laser technological developments. Lasers provided an ideal method of illuminating whole suspensions of airborne or liquid-borne particles, with the resulting scattered light distributions being analysed at various scattering angles to determine key properties of the suspension. In comparison, the use of lasers for single particle analysis was generally restricted to simply particle counting and sizing.

The manner in which a single particle scatters light is dependent not only on its size but also on its shape and internal structure (as well as the wavelength and polarisation of the incident illumination and the medium supporting the particle). The potential existed therefore to use the pattern of light scattered by a particle as a ‘thumbprint’ by which the particle could be characterised, classified and even identified. However, it was only in the early 1990s that the high-sensitivity, high-resolution, optical detectors and low-cost computer processing power required to investigate this potential became readily available. This challenge was taken up in the mid-1990s by the Particle Instruments Research Group, part of the university’s Centre for Atmospheric and Instrumentation Research (CAIR) and has since led to technologies that have been adopted by commercial companies and research organisations worldwide (see Section 4).

The group, led by Professor Paul Kaye and including a team of postdoctoral research assistants, among them Edwin Hirst (now a staff member and active researcher), undertook their fundamental research into **spatial light scattering (SLS)** under sponsorship from the EPSRC, NERC, Leverhulme Trust, and industry (see Section 3). This resulted in the first publications in the field that fully highlighted the potential of the new technology (see, for example, Section 3, References 1–3) as well as several international patents later assigned to commercial and governmental third parties under royalty-sharing agreements.

The research itself comprised two major strands: the development of *instrument systems* that exploited optoelectronic and computing advances of the time to allow the real-time capture of particle light scattering data, and the development of *theoretical models and algorithms* to interpret these data and allow the necessary particle characterisation/identification. This theoretical work, largely undertaken by researchers Joseph Ulanowski and Evelyn Hesse, encompassed both direct and inverse scattering problems (the former being the computation of particle scattering from the knowledge of particle properties; the latter, the extraction of particle parameters such as size, shape and refractive index from scattering data). This research has since developed into the Light Scattering and Radiative Properties Research Group, a significant and active research area within CAIR.

Since the initial fundamental research into theoretical and empirical particle light scattering phenomena, the development of our research has been heavily influenced by meeting specific needs of end-user communities who required instrumentation to allow the non-destructive real-time detection and identification of various particle types. Application areas have included the detection of aerosolised warfare agents; the *in situ* measurement and characterisation of cloud particles such as droplets, ice crystals and solid aerosol that profoundly influence cloud radiative properties and ultimately global climate; the characterisation of incinerator smoke-stack emissions; the real-time monitoring of occupational aerosols associated with, for example, mining and ‘sick buildings’; clean-room monitoring; water quality monitoring; and, most recently, the detection of potentially lethal airborne asbestos fibres. Each application area has required the development of new research methodologies and techniques to achieve the desired aims (see Section 4).

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

– *The top three publications are indicated by* **

Publications

1. Light Scattering from Non-spherical Airborne Particles: Experimental and Theoretical Comparisons. Hirst, E., Kaye, P.H. and Guppy, J.R. *Applied Optics*, 33, 30, 7180–7186, 1994. <http://dx.doi.org/10.1364/AO.33.007180> **

2. A Real-time Monitoring System for Airborne Particle Shape and Size Analysis. Kaye, P.H., Alexander-Buckley, K., Hirst, E., Saunders S. and Clark, J.M. *Journal of Geophysical Research (Atmospheres),* 101, D14, 19215–19221; 1996. <http://dx.doi.org/10.1029/96JD00228>

3. Spatial Light Scattering as a Means of Characterising and Classifying Non-spherical Particles. Kaye, P.H. *Measurement Science and Technology*, 9, 2, 141–149, 1998. <http://dx.doi.org/10.1088/0957-0233/9/2/002>

4. Simultaneous light scattering and intrinsic fluorescence measurement for the classification of airborne particles. Kaye, P.H., Barton, J.E., Hirst, E. and Clark, J.M. *Applied Optics*, 39, 21, 3738-3745, 2000. doi: 10.1364/AO.39.003738 **

5. Discrimination of Micrometre-sized Ice and Super-cooled Droplets in Mixed-phase Cloud. Hirst, E., Kaye P.H., Greenaway, R.S., Field, P. and Johnson, D.W. *Atmospheric Environment* **35**, 1, 33–47, 2001. <http://dx.doi.org/10.1016/S1352-2310(00)00377-0>. This paper described the world’s first instrument capable of the real-time discrimination of cloud ice particles and droplets down to 1um in size. **

Patents

Method and Apparatus for the Real-time Characterization of Particles Suspended within a Fluid Medium. Inventors: Kaye, P.H. and Hirst, E., US Patent 6,198,110 B1, Mar 6, 2001 (assigned to Secretary of State for Defence). This was one of a family of patents assigned to the MoD that were based on UH’s spatial light scattering research. (Documents available on request.)

Key Research Awards

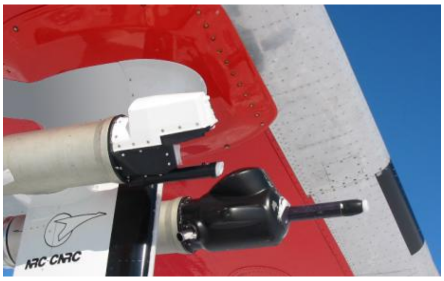
EPSRC	LINK TAPM GR/J56462	£225,988	Hazardous particle detection	1993–1996
MoD	2161/003	£182,780	Airborne Particle Characterisation	1993–1996
Biral Ltd	B1010	£98,144	Portable particle analyser	1993–1996
EPSRC	GR/K60770	£69,987	Hazardous fibre detection	1995–1998
Leverhulme Trust	SRF-12	£39,000	Asbestos and light scattering	1996–1998

EPSRC	GR/L33375	£86,100	Particle shape characterisation	1997–2000
NERC-UKMO (3 awards)	GST 021333 NER/T/S/2000/00976 NE/B506094/1	£113,199 £146,107 £161,719	Small Ice Detector (SID1, 2 and 3) instrument developments	1996–2007
EPSRC	GR/R14149/01	£148,563	Water-borne particle classification	2001–2004
DTI/ PCME Ltd	Teaching Company 4331	£102,560	Optical stack emissions monitoring	2003–2005
EU FP7	ALERT Project	£545,000	Airborne Asbestos detector	2009–2012

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

The dissemination in the early to mid-1990s of our pioneering research results on particle light scattering triggered a succession of approaches from external organisations and commercial companies. In all of the examples given below (occurring 2008–13), the organisations made the initial contact with us, each facing specific particle detection and characterisation challenges and seeking to know if our technologies could tackle them. This 'user-driven' influence has remained at the core of our research strategy and underpins the effectiveness and impact of our work in these wider end-user communities.

1. Developed from research funded by NERC and the Met Office, our Small Ice Detector (SID) probes (right), are now part of the instrument provision on the UK's FAAM (Facility for Airborne Atmospheric Measurement) research aircraft, the primary vehicle for airborne atmospheric research by the Met Office and all UK universities. Deployed in over 30 national and international atmospheric research campaigns since 2008, SID probes have provided cloud physicists for the first time with detailed *in situ* data concerning the sizes, shapes, and concentrations of small ice crystals (sub-20um) and droplets which often co-exist in clouds. This information is critical in allowing Met Office and other climate researchers to more accurately model cloud radiative properties, which the Intergovernmental Panel on Climate Change (IPCC) acknowledges is the greatest source of uncertainty in climate change prediction.



2. Following the SID probes' success, we received research contracts from leading meteorological organisations worldwide to develop and build similar spatial light scattering instruments to meet specific requirements for *in situ* detection and characterisation of microscopic ice crystals in both high-altitude atmospheric cloud and laboratory cloud-simulation environments. Since 2008, our instruments have been used by:

   (i) **US National Center for Atmospheric Research (NCAR):** Advanced SID2 probe for use on 'HIAPER' (High-performance Instrumented Airborne Platform for Environmental Research) aircraft. The resulting data has been used to reduce uncertainties and improve accuracy in NCAR climate prediction models. (Two contracts totalling US$145,000.)

   (ii) **Colorado State University/NASA:** A laboratory PPD (Particle Phase Discriminator) instrument (based on SID technology) for use in their cloud simulation chamber deployed in both ground and NASA aircraft-borne ice-cloud studies, enhancing understanding of cloud ice nucleation processes and the effects of, for example, anthropogenic aerosols on these processes. (Contract value US$68,000.)

   (iii) **Institute for Meteorology and Climate Research**, Karlsruhe, Germany: Europe's largest cloud microphysics facility. A high-resolution SID3 light spatial scattering instrument to provide data on ice nucleation and growth processes, in turn feeding into improved models for cloud behaviour, cloud albedo, and hence climate warming/cooling. (Contract value €140,654.)

(iv) **Leibniz Institute for Tropospheric Research** (Leibniz Institut für Troposphären-forschung (IfT)), Leipzig, Germany. A combined SLS and backscatter depolarisation instrument for use on the Leipzig Aerosol and Cloud Interaction Simulator, again providing data to modellers on ice nucleation processes. (Contract value €134,800.)

(v) **Institute for Meteorology and Climate Research**, Karlsruhe, Germany. An enhanced laboratory Particle Phase Discriminator, PPD2, for laboratory and airborne (inboard) investigations into, for example, the effects of bioaerosol on cloud icing, a major unknown in cloud formation and lifetime. (Contract value €76,890.)

3. **BIRAL Ltd** (Portishead, Bristol). Since the late 1990s, this major aerosol instrumentation provider to military and civilian markets has been manufacturing its 'Verotect' military generic biological aerosol detectors and, latterly, 'Aspect' and 'AFS' (Aerosol Fluorescence Analyser) civilian particles analysis instruments. All three incorporate particle light scattering technologies funded by Dstl, developed by the Particle Instruments Research Group, and subsequently licensed to BIRAL, which continues to market them internationally.

4. **CASELLA CEL Ltd** (Bedfordshire). From 2000 to 2003 we transferred our light scatter technology to this multinational environmental monitoring company by designing a novel wide-band (10nm–10um) particulate pollution monitor, the first of its kind developed in Europe.

5. **PCME Ltd** (Cambridgeshire). In the early 2000s PCME, a European leader in stack emissions monitoring, was acutely aware that its market position was threatened, as its product range, based on electrostatic measurement techniques, was not sensitive enough for new European and US Waste Incineration Standards EN-13284-2/EN-14181 and PS-11. From 2003 to 2006, we exploited our laser light scattering expertise in designing a class-leading light scattering monitor, the first to meet the new Standards and which continues to be sold as the company's successful PCME QAL 181 'Proscatter' instrument.

6. **SELECT GROUP Ltd** (Devon). In 2008, the spatial light scattering methodology we had pioneered and patented (GB2333835) a decade earlier for airborne asbestos detection was selected as the core technology in an EU FP7 SME capabilities project entitled 'ALERT'. This product development project, ranked 9th of 3,500 applications, involved Select Group and several end-user Europe-wide trade bodies such as the Thermal Insulation Contractors and the European Demolition associations, together representing most of Europe's 2.4 million construction sector SMEs. Over three years, the Particle Instruments Research Group developed the world's first real-time portable detector for airborne asbestos fibres, now being brought to market by Select Group to significantly reduce the annual worldwide 100,000+ death toll attributed to occupational asbestos exposure (International Labour Organisation) and reduced the associated US$528 billion (WHO/ILO, 2007) compensation costs.

7. **ALPHASENSE Ltd** (Essex). In early 2013, the university agreed an exclusive worldwide licence with Alphasense to exploit low-cost light scattering particle sensor technology previously provided to the Met Office for volcanic ash detection. Alphasense is now taking this device into mass production.

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

The names and contact details of individuals and organisations who can verify representative aspects of the impact described in section 4 above have been supplied separately.