Investigating the Feasibility of Innovative Technologies to Improve Air Quality Monitoring over the Medium to Long Term

Stage 1 and Stage 2 Report

Report for the Department for Environment, Food and Rural Affairs, Welsh Government, the Scottish Government and the Department of the Environment in Northern Ireland

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Contact:

Justin Lingard

Ricardo Energy & Environment

Gemini Building, Harwell, Didcot, OX11 0QR, United Kingdom

t: +44 (0) 1235 75 3306

e: justin.lingard@ricardo.com

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Author:

Justin Lingard (lead author), Tim Scarbrough, Ben Grebot, Federico Karagulian, David Sykes, Alison Loader, Brian Stacey, Paul Willis, Stephen Stratton (Ricardo Energy & Environment), Professor Margaret Bell (Newcastle University), Professor Rod Jones (University of Cambridge), Professor Paul Monks (University of Leicester)

Approved By:

Paul Willis Paul Willis

Date:

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Executive summary

Introduction to this study and its scope

Air quality monitoring data underpins national assessments of compliance with the EU Ambient Air Quality Directive (Directive 2008/50/EC) and Fourth Daughter Directive (Directive 2004/107/EC) and checks that local authorities meet national air quality objectives, as part of the Local Air Quality Management (LAQM) regime. Monitoring data can also support health impact assessment, help investigate causes of air pollution and therefore, underpin improvements in air quality.

The UK's current air quality monitoring networks comprise a range of 'fixed measurement' monitoring equipment that meets prescribed data quality objectives. Much of the equipment is relatively large and requires regular calibration, conditioning servicing and maintenance and, in some cases, dedicated enclosures with mains power. These characteristics lead to certain restrictions on the number of measuring sites, where they are located, and their spatial and temporal resolutions.

As part of Defra's on-going cycle of continuous improvement within air quality monitoring, there is a need to identify and evaluate innovative technologies that could potentially help improve the evidence base or offer improved value for public money, whilst continuing to deliver improvements in air quality. This study sought **to identify innovative air quality monitoring techniques and assess their potential ability to meet Defra's medium to long-term (10-15 years) evidence requirements for the UK's national ambient air quality monitoring**. The study also aimed to identify and assess potential risks to innovation and market barriers facing such innovative technologies. The findings of this research are based on a questionnaire consultation with a range of instrument manufacturers, equipment suppliers and research institutes involved in the development of innovative air quality monitoring technologies. The assessment has been carried out by Ricardo Energy & Environment in partnership with three nationally renowned experts[1] from the UK air quality monitoring research community.

Each innovative technology was considered against six key topics:

- Use within the UK's national and local monitoring networks;
- Maintenance of the compliance monitoring data quality objectives defined in the European Air Quality Directives;
- Provision of measurements to demonstrate fulfilment of national and local air quality objectives;
- Provision of improved data, e.g., improved spatial/temporal resolution;
- Improved access to data, analysis tools, additional observations, or the re-alignment of observations which could be of research value; and
- Reduced or limited costs over the lifespan of the monitoring technology.

Identified innovative air quality monitoring techniques and their potential ability to meet Defra's medium to long-term (10-15 years) evidence requirements

Four groups of innovative technologies were identified:

- Remote sensors located on **satellites;**
- **Remote sensors** that are either deployed aloft on aircraft or are ground based;
- **Pervasive sensors** which provide fixed point measurements, and which are characterised as being small, physically robust and deployable in locations that conventional instruments cannot due to constraints in size, weight, access to power and telemetry links; and

[1] Professor Margaret Bell, Newcastle University, Professor Rod Jones, University of Cambridge, Professor Paul Monks, University of Leicester – see section 1.1. below for details

- **Fixed-point sensors** are active and automatic analysers similar to those currently used within the UK's national air quality monitoring networks.

At this stage, looking 10-15 years into the future, it is difficult to speculate how the innovative technologies could become part of the UK air quality monitoring network and integrated with the empirical modelling approach. Stakeholders involved with these technologies may not be making this question of integration an important consideration at this stage of their development. For all of the innovative technologies identified, however, one important step would be the testing and validation against measurements from the UK's current air quality monitoring networks.

Findings specific to each of the four groups of technologies are summarised in turn below.

Satellite-borne sensors appear unlikely to *replace* the UK's monitoring networks over the next 10 to 15 years. Their spatial and temporal resolution is not expected to match current monitoring networks in this timeframe and they cannot yet meet the data quality objectives of the European air quality Directives. There are also some technical hurdles to overcome and these sensors are expensive compared to current in-use technology. However, the potential advantages that satellite-borne sensors do offer include: estimating pollutant concentrations across large areas between fixed point monitors; identifying regional sources of air pollution affecting local air quality; and providing simultaneous and continuous measurement of multiple pollutants. These advantages suggest that satellite-borne sensors could be used within the next 10-15 years to *supplement* air quality monitoring networks nationally or regionally and/or as part of the UK's empirical modelling. Outside of air quality monitoring, satellite-borne sensors could also provide an important contribution to validation and compilation of national emissions inventories.

Similarly to satellite-borne sensors, **ground-based or airborne remote sensors** typically measure pollutant concentrations along the path of a beam or column of air. This feature distinguishes them from fixed point measurements used by the UK monitoring network (and required by the European air quality Directives) and therefore limits their direct application within the current framework due to constraints imposed by data quality objectives and the lack of appropriate CEN standards. However, this feature also provides their key advantage, which is the ability to measure multiple pollutants simultaneously over large areas (when airborne) with a wide spatial scale. As such, remote sensors could be used within the next 10-15 years to supplement UK monitoring networks, but given the expense of making such measurements there would have to be a strong evidential case, at the current time, for their use". For example, there appears to be strong potential for application within the LAQM regime for remote sensors mounted on low flying aircraft to generate maps of air quality across entire cities to a spatial resolution of less than 100 metres in just a few hours. A similarly novel application is foreseen in deploying continuously scanning ground-based remote sensors to generate three dimensional maps of local air quality to investigate street canyons and hotspots. There are also technical challenges to be addressed for these sensors, including reducing the measurement uncertainty levels (currently up to ±90%). Similarly to satellite borne sensors, remote sensors could also provide an important contribution to validation and compilation of regional emissions inventories.

Of the two categories of technologies providing fixed point measurements, **pervasive sensors** are typically small, physically robust instruments requiring limited configuration, maintenance or calibration and are battery (or battery and solar) powered. These properties mean the sensors could be deployed in locations inaccessible to current measurement technologies, e.g., at height, on mobile platforms, or in remote locations without access to mains power or telemetry. Due to their small size they could be used in mobile applications (e.g. carried by vehicles, bicycles or people) to produce maps of air quality, or as personal air quality monitoring devices. Pervasive sensors may offer cost savings compared to existing conventional air quality monitoring instruments, and are more likely to offer such saving if uptake was widespread. Multiple sensors can be combined as arrays to provide networks with high spatial resolution. Sensors to measure different parameters (air quality, noise, GPS, meteorology) can be integrated in a single unit to provide supplementary information and integrate with wider research communities.

Pervasive sensors may be able to offer acceptable levels of measurement uncertainty in the future. However, they currently only comply with the data quality objectives of the European air quality Directives to provide indicative measurements rather than fixed measurements. Particulate matter measurements are acceptable for LAQM Review and Assessment but not Detailed Assessment. If the data quality objectives for fixed measurements were met then pervasive sensors could displace existing instruments to form part of the UK air quality monitoring network within the next 10-15 years. If these objectives are not met, or the guidance does not change, then these sensors could supplement the UK's air quality monitoring in the medium term (5-10 years). It is also a possibility that in-street measurements using pervasive sensors could reduce reliance of dispersion modelling for compliance assessment. However, modelling would still be required for remote areas and future scenarios. The technology also has some technical issues to resolve, including: the need for a standardised approach to sensor calibration, sensor reliability, and limits of detection (a CEN working group recently established in 2015 may address this); and limiting cross-sensitivity of nitrogen dioxide (NO_2) sensors to ozone (O_3) / oxidants.

Fixed-point sensors are active and automatic analysers similar to those currently used within the UK's national air quality monitoring networks. Three innovative active and automatic samplers were identified in this study that could potentially contribute to the UK air quality monitoring networks: micro-aethalometers measuring black carbon (BC); optical particle counters (OPC) measuring particulate matter PM_{10} and $PM_{2.5}$; direct-measurement NO_2 analysers, and Differential Ultra Violet Absorption Spectrometer (DUVAS) capable of measuring a range of gaseous pollutants. Each of the technologies has different characteristics and has different potential for application in the UK air quality monitoring networks:

- Compact micro aethalometer's robust portable design may offer BC measurements with greater spatial resolution providing human exposure data, and measurements in otherwise inaccessible locations, in addition to the existing fixed-point BC measurements from the UK air quality monitoring networks.
- OPC measure particle number and size, and could provide simultaneous estimates of $PM_{2.5}$ and PM_{10}, and in some cases meteorological data. They tend to be smaller and more portable than existing (gravimetric) particulate samplers, used in the UK's national and local air quality monitoring networks, allowing them to be used in a range of configurations offering greater spatial resolution. Current LAQM guidelines limit their use to screening and assessment studies; they would need to demonstrate equivalence before they could be used for compliance monitoring.
- Direct-measurement NO_2 analysers limit the potential for small over-estimations of NO_2 due to interferences from nitrogen compounds which affect chemiluminescent NO_X analysers currently used in the UK's national and local air quality monitoring networks. National compliance modelling relies on NO_x measurements; changing this approach would be difficult or perhaps impossible due to the complexity of atmospheric chemistry and the uncertainties in estimating primary NO_2 emissions. If this technology were to be used in UK monitoring networks, there would either need to be a change in the UK's compliance modelling approach or the technology would need to be operated alongside current NO_X analysers (i.e., at additional cost). They do not offer any improvements in spatial or temporal resolution compared to current analysers.
- DUVAS instruments can simultaneously measure a range of gaseous pollutants. If they could demonstrate equivalence, one DUVAS could potentially displace several gas analysers within the UK and local authority air quality monitoring networks, but the initial capital cost of the DUVAS may offset any cost savings. A mobile variant is available, offering the capability of providing higher spatial resolution measurements and insights to pollution micro-environments, e.g., street canyons and hotspots. These measurements could be used for detailed assessments within the LAQM regime.

Market barriers facing innovative air quality monitoring technologies

A series of high-level risks and market barriers common to most or all of the technologies have been identified. The most prominent is the extent (in time and cost) of the process to demonstrate that a measurement technique is equivalent to the reference technique. Only techniques that are the reference method or demonstrated to be equivalent can be used for compliance purposes for national and local air quality targets. Equivalence testing can only occur if there are agreed CEN standards for techniques. CEN standard methods exist for fixed point measurement techniques, but there are no standards for validating the performance of satellite and remote sensors. In the absence of suitable standards there is currently no recognised route by which these technologies can demonstrate their equivalence to the reference methods, their suitability for use in national compliance monitoring, or use within the LAQM regime.

Other barriers identified include a lack of standardised approaches for processing and validating data from some technologies, lack of or limited development funding, and the risk of lack of technology uptake. A number of potential measures to remove these market barriers have been identified for Defra to consider. However, the evidence collected suggests that developers are responding to the on-going needs of the air quality monitoring market without intervention, including demonstration of equivalence. Defra may wish to investigate measures that could enable satellite and remote sensors to be considered for use for short campaigns that gather information, or perhaps in national compliance monitoring or within the LAQM regime if this is considered useful.

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Appendices

Glossary

AOD	Aerosol Optical Depth
AQS	UK's Air Quality Strategy
AURN	UK Automatic Urban and Rural Network
BC	Black Carbon
BrO	Bromine Oxide
BS	British Standard
CEN	European Committee for Standardisation
CEN WG42	CEN Working Group 42 on gas sensors
CH_3OH	Methanol
CH_4	Methane
ClO	Chlorine Oxide
CO	Carbon Monoxide
CO2	Carbon Dioxide
CSA	CSA group - http://www.csagroup.org/
Defra	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
DG Environment	Environment Directorate-General
DOAS	Differential Optical Absorption Spectroscopy
DQO	Data Quality Objective
DUVAS	Differential Ultraviolet Absorption Spectrometer
EIONET	European Environment Information and Observation Network
ESA	European Space Agency
FDMS	Filter dynamics Measurement System
GHGI	UK Greenhouse Gas Inventory
GIS	Geographical Information Systems
GPRS	General Packet Radio Service
GPS	Global Positioning System
HCOOH	Formic acid
JRC	European Commission's Joint Research Centre
LAEI	London Atmospheric Emissions Inventory
LAQM	Local Air Quality Management
LAQM.TG09	Local Air Quality Management Technical Guidance (TG.09)
LoD	Limit of Detection
MCERTS	Monitoring Certification Scheme
NAEI	National Atmospheric Emissions Inventory

NDA	Non-disclosure Agreement
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxides (NO + NO_2)
NPPF	National Planning Policy Framework
O_3	Ozone
OPC	Optical Particle Counter
PAH	Polyaromatic Hydrocarbons
PHE	Public Health England
PM_{10}	Airborne particulate matter passing a sampling inlet with a 50% cut-off efficiency at 10 µm aerodynamic diameter and which transmits particles of below this size
$PM_{2.5}$	Airborne particulate matter passing a sampling inlet with a 50% cut-off efficiency at 2.5 µm aerodynamic diameter and which transmits particles of below this size
QA/QC	Quality Assurance/Quality Control
SO_2	Sulphur Dioxide
TEOM	Tapered Element Oscillating Microbalance
TEOM-FDMS	Filter Dynamic Measurement System-modified Tapered Element Oscillating Microbalance
TUV	Technischer Überwachungsverein
UFP	Ultrafine Particles
UNECE	United Nations Economic Commission for Europe
US EPA	United States Environmental Protection Agency
UTMC	Urban Traffic Management Control
VOC	Volatile Organic Compound

1 Introduction

1.1 This report

This report presents the findings of a study carried out on behalf of Defra and the Devolved Administrations of Scotland, Wales and Northern Ireland to investigate the feasibility of innovative technologies to improve air quality monitoring over the medium to long-term.

The study was led by Ricardo Energy & Environment in collaboration with three nationally renowned project partners from the UK research community:

- Professor Margaret Bell, Newcastle University, whose expertise covers pervasive sensing and its application in urban traffic management control (UTMC).
- Professor Rod Jones, University of Cambridge, whose expertise is in sensor technologies, including small, low cost sensors, and remotes sensing techniques.
- Professor Paul Monks, University of Leicester, whose expertise is in remote sensing techniques and satellite observations.

The project team are extremely grateful to the instrument manufacturers and distributors who engaged with this project, providing insight into forthcoming innovative technologies. Hence, the limitation of the study, are that technologies not included due to manufacturers and distributors not responding, perhaps due to commercial sensitivity or other reasons, see Section 2.6 below for details. We are also thankful to the developers and users of the technologies profiled in this report for their thoughts on potential future developments and anecdotal evidence relating to the use of some of the techniques, in their current form.

1.2 Background and context

1.2.1 Policy context

The UK Government is required to demonstrate compliance with a number of standards for air quality, at European and UK level. These include the:

- EU Directives including the Ambient Air Quality Directive (2008/50/EC)[2] and the 4th Daughter Directive (2004/107/EC)[3] which set limits for pollutant concentrations in ambient air (hereafter referred to as the "European air quality Directives").
- UK's Air Quality Strategy (AQS)[4]. The UK's Air Quality Objectives are at least as stringent as corresponding EU limit values and target values.
- United Nations Economic Commission for Europe (UNECE) Gothenburg Protocol[5] and its implementation in the EU as the National Emissions Ceilings Directive (2001/81/EC)[6]. These set limits on total annual emissions of pollutants for the UK.

The key drivers for air quality monitoring are:

- Compliance assessment against the requirements of the European air quality Directives.
- Review and assessment of local air quality to check that local authorities are meeting national air quality objectives, as part of the Local Air Quality Management regime.

[2] http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32008L0050&from=EN

[3] http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32004L0107&from=EN

[4] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69336/pb12654-air-quality-strategy-vol1-070712.pdf

[5] http://www.unece.org/env/lrtap/multi_h1.html

[6] http://ec.europa.eu/environment/air/pollutants/ceilings.htm

- Provision of evidence to support health impact assessments of specific air pollutants by, for example, Public Health England.
- Provision of data which adds value to a broad spectrum of Defra's research activities into the causes of air pollution, the development of mitigation measures and air quality policy.

The over-arching aim is to deliver improvements in air quality

1.2.2 How air quality measurements are currently used in the UK

On a national level, the UK uses a combination of monitoring and modelling data to provide the evidence base to determine its compliance with air quality limit and target values for EU air quality Directives reporting and national objectives set out in the AQS. This approach presents a number of benefits including a reduction in the cost burden for measurements, providing a more complete assessment and providing policy-relevant information for air quality management including source apportionment (linking concentrations with specific sources). The use of models for annual compliance reporting provides a consistent framework within which projections of future air quality for current and/or potential policies can be explored cost effectively. Modelling also provides support to policy development in order to identify the most cost effective ways to improve air quality and public health. National compliance modelling is carried out for Defra and the Devolved Administrations. Air quality monitoring data from the national networks is used to calibrate the modelling work whilst measurements from local authority sites, obtained under the Local Air Quality Management (LAQM) regime, are used to verify the model outputs. This approach results in mapped ambient air pollutant concentrations across the UK for up to 13 pollutants including the pollutants of most concern in terms of health burdens and statutory compliance risks, which are nitrogen dioxide (NO_2) and coarse particulate matter (PM_{10}).

Defra and the Devolved Administrations recognise the important role that local authorities have to play in helping deliver the AQS's air quality objectives and the mandatory European air quality limit values; action taken at the local level can be an effective way of tackling localised air quality problems, that could lead to an overall improvement of air quality across the UK. Under the LAQM regime, all UK local authorities are obliged to review and assess air quality in order to assess the risk of an air quality objective being exceeded. Where a risk is identified, a further Detailed Assessment must be completed to provide an accurate assessment of the likelihood of an air quality objective being exceeded at locations with relevant exposure. This is achieved through the use of quality-assured monitoring and validated modelling methods to determine current and future pollutant concentrations in areas where there is a significant risk of exceeding an air quality objective. Where necessary an air quality management area is declared and an Action Plan is devised to reduce the likelihood of a future exceedance and thereby mitigate the risk posed.

1.2.3 Current measurement methods

An evidence base must be collated to determine compliance with air quality standards and the achievement of specific objectives, whether as part of a Detailed Assessment within the LAQM regime, or to provide evidence for the national compliance assessment. Measurements of air pollutant concentrations form an important part of this. Defra, the Devolved Administrations, and local authorities use the following types of air quality monitoring methods within the UK Automatic Urban and Rural Network (AURN) and local authority LAQM networks:

Passive sampling methods, offering simple, robust cost-effective measurements, e.g., NO_2 or benzene diffusion tubes or denuders (trace gases), which provide indicative measurements suitable for screening and assessment studies. This type of monitoring requires minimal operator training and infrastructure.

Active (semi-continuous) methods are filter-based measurements of daily particulate concentrations, particulate speciation, PAH speciation, and black carbon measurements. There is a requirement for filters to be removed, conditioned and weighed on a routine basis as well as regular calibration, servicing, and maintenance of instrumentation. This type of monitoring requires minimal infrastructure, though mains power may be required.

Automatic point monitoring, e.g. on-line, near-real time gas and particulate measurements, that offer high resolution (hourly) data which can be collected automatically, but which can be expensive, requiring dedicated and skilled operatives. They require regular calibration, service, and maintenance which are a source of on-going costs. Commonly they require a dedicated enclosure (often with air conditioning) and mains power.

For many years, UK national and local air quality monitoring networks have used a hybrid approach combining a range of measures and techniques, including:

- Automatic and non-automatic samplers.
- High-resolution and time-integrated sampling.
- Measurements and modelling.

This hybrid approach offers a versatile means to assess current and future air quality on a national and local scale, and mitigates the risks associated with reliance on a single type of technique or approach.

1.2.4 Standardisation of measurement methods and demonstration of equivalence

Current monitoring practices and networks have been developed in response to European and UK legislation with the purpose of measuring, as accurately as possible, air pollutant concentrations. To ensure that the measurements taken are comparable and of a similar quality throughout the UK and Europe, European Committee for Standardisation (CEN) standards have been developed for the methods used for the measurement of air pollutants. Where air quality measurement methods, other than the reference method stated in the Directives are used, the method must undergo equivalence testing.

An “Equivalent Method” is one that conforms to the data quality objectives (DQOs) set for data capture and measurement uncertainty as described in Table 1-1. An example of this is the UK’s use of the Filter Dynamic Measurement System-modified Tapered Element Oscillating Microbalance (TEOM-FDMS) for measuring PM_{10} rather than Klein Filtergerät samplers, as stated in the Directive. Equivalence Testing must be undertaken by an approved test house, in the UK this is CSA group. The time taken for a method to demonstrate equivalence varies, for gaseous pollutants it can be less than a year, but for particulate matter it may take two or more years. The reason is that the reference method for particulate matter measures daily mean concentrations. It can therefore take a long time to gather a sufficiently large sample of daily means, for the statistical analysis necessary to demonstrate equivalence.

Table 1-1 Ambient air quality measurement CEN standards, reference methods and associated data quality objectives for five common air pollutants

Pollutant	CEN Standard	Reference measurement method	Minimum data capture (%)	Fixed measurement: uncertainty (%)	Indicative measurement: uncertainty (%)
Carbon monoxide	EN14626	Infrared spectroscopy	90	±15	±25
Nitrogen dioxide	EN14211	Chemiluminescence	90	±15	±30
Ozone	EN14625	Ultraviolet photometry	90	±15	±30
$PM_{10}/PM_{2.5}$	EN12341	Klein Filtergerät*	90	±15	±50
Sulphur dioxide	EN14212	Ultraviolet fluorescence	90	±15	±25

*: Reference equivalent PM_{10} measurement methods including TEOM-FDMS, Beta Attenuation Monitors, and Partisol (gravimetric) are used in the UK’s compliance monitoring. TEOM measurements corrected using the King’s College Volatile Correction Model (which are also reference equivalent) are also used in LAQM, but not for compliance monitoring.

The Air Quality Directive defines “Indicative Measurements” as measurements which meet DQOs that are less strict, defined in terms of the percentage uncertainty, than those required for fixed measurements. Table 1-1 lists the relevant CEN standards, associated reference and reference-equivalent methods measurement methods used within the UK AURN and LAQM networks, for five common air pollutants. Table 1-1 also lists the two main DQOs defined in the CEN Standards: (1) uncertainty, and (2) minimum data capture, for both fixed point and indicative measurements (e.g., NO_2 diffusion tubes).

Instruments based upon reference techniques require "Type Approval" – which confirms compliance with the requirements of the reference method as detailed in the appropriate CEN standard, examples of which are listed in Table 1-1. "Type Approval" provides independent verification that a technique is fit for its stated purpose, that its performance is in-line with the manufacturer's claims, and that its stated uncertainty and precision are correct. Standard methods, reference methods and equivalence testing are important. Ensuring the data quality and data capture requirements of the European air quality Directives is met is necessary for compliance as well as to maintain confidence and where different types of methods are used, the results need to be shown to be consistent and comparable.

The European air quality Directives requires mandatory fixed measurements in zones and agglomerations where the long-term objectives for ozone or the assessment thresholds for other pollutants are exceeded. It allows for information from fixed measurements to be supplemented by modelling techniques and/or indicative measurements to enable point data to be interpreted in terms of geographical distribution of concentrations. The use of supplementary techniques of assessment allows for a reduction in the required minimum number of fixed sampling points.

1.3 Aim of this study and its scope

1.3.1 Overall aims

As part of the on-going cycle of continuous improvement within air quality monitoring, there is a need to identify and evaluate innovative technologies that can help improve the evidence base whilst offering improved value for public money.

The purpose of the study was to identify innovative air quality monitoring techniques and assess their potential ability to meet Defra's medium to long-term (10-15 years) evidence requirements for the UK's national ambient air quality monitoring (as detailed above). The study was commissioned in two stages. Stage 1 aimed to identify and assess potential innovative air quality monitoring technologies. Stage 2 aimed to identify and assess potential risks to innovation and market barriers that could limit uptake of innovative technologies.

The purpose of this study was not to pick specific "winners" or to endorse technologies, but to examine the benefits and limitations of potential innovative technologies and so provide a resource mapping of potential innovative technologies to Defra's current and developing needs. Whilst reviewing which technologies could realistically fill the current processes gaps or provide step changes to future development.

1.3.2 Scope of the project

1.3.2.1 Pollutants

The air pollutants and parameters that were within the scope of this study are all those relevant to the presiding legislation and AQS listed in section 1.2.1, including:

- Oxides of nitrogen (NOx);
- Nitrogen dioxide (NO_2);
- Ozone (O_3);
- Sulphur dioxide (SO_2);
- Particulate matter ($PM_{2.5}$ and PM_{10});
- Hydrocarbons;
- Polycyclic aromatic hydrocarbons (PAHs);
- Metals covered by the 4th Daughter Directive, e.g., arsenic, nickel, cadmium, lead;

- Black carbon (BC);
- Ultrafine particles (UFP);
- Particle number; and
- Particle speciation.

1.3.2.2 Monitoring technologies

Given the range and type of air quality pollutants under consideration, there was a clear desire to identify techniques that were capable of measuring multiple pollutants simultaneously, where possible, but not to exclude techniques only capable of measuring single air quality pollutants.

The innovative technologies that were within the scope of this study were considered in four groups:

- Satellite-borne sensors.
- Remote sensing techniques, which can be deployed aloft, attached to aircraft offering air quality measurements with greater spatial resolution, and at ground-based air quality monitoring stations, offering similar levels of spatial resolution to airborne air quality measurements but at fixed locations.
- Pervasive sensors, small, compact, and physically robust devices containing electrochemical sensors which can be deployed in locations that traditional instruments cannot due to constraints in size, weight, access to power and telemetry links.
- Fixed-point sensors are active and automatic analysers similar to those currently used within the UK's national air quality monitoring networks

The focus of the work was on identifying innovative technologies capable of providing air quality measurements **not** emissions measurements. However, through the course of the work it became apparent that there were innovative technologies, e.g., satellite-borne sensors, that could serve a dual purpose (beyond the study's initial considerations) and be used to support the validation and compilation of emissions inventories on a local level, e.g., city-scale inventories such as the London Atmospheric Emissions Inventory (LAEI), and national emissions inventories, such as the National Atmospheric Emissions Inventory (NAEI) and the UK Greenhouse Gas Inventory (GHGI). These are described further in later sections of this report.

1.3.3 Key considerations that scope this study

The following six key considerations for each innovative technology formed the scope of this study:

- Use within the UK's national and local monitoring networks.
- Maintenance of the compliance monitoring DQOs defined in European air quality directives.
- Provision of measurements to demonstrate fulfilment of both national and local air quality objectives.
- Provision of improved data, e.g., improved spatial/temporal resolution.
- Improved access to data, data analysis tools, additional observations, or the re-alignment of observations which could be of research value.
- Reduced or limited costs over the lifespan of the monitoring technology.

The study assessed how and/or where innovative technologies offered improvements compared to current technologies. Within this context, it was also necessary for the study to consider the:

- Suitability of innovative technologies to supplement or displace the UK's current national monitoring networks composing of fixed point measurements which have demonstrated equivalence with the requirements of European air quality directives and fulfil the DQOs.
- Integration of innovative technologies with the UK's empirical modelling approach, which is used to demonstrate compliance with the European air quality Directives.

- Suitability of innovative technologies to provide measurements that can feed into the LAQM Review and Assessment regime and inform other users like local Health or Highways Authorities.
- Potential to offer reduced or limited costs whilst maintaining or adding value to Defra's compliance and research monitoring networks through improved spatial or temporal resolution, and/or additional observations and data.

1.4 Structure of this report

This report is structured as follows:

- Section 2 details the methodology that was used in both Stages 1 and 2 of the study and defines the terms "risks to innovation" and "market barriers".
- Section 3 summarises the assessment findings for each technology group in subsections 3.2 to 3.5 drawn from stakeholder responses, including benefits, limitations and possible measures that could be considered by Defra to overcome barriers to deployment of each technology. The assessments are based on the key considerations given in subsection 1.3.3 Subsection 3.6 provides a summary of common high level risks and barriers facing multiple technologies.
- Section 4 summarises the conclusions of this work drawing together the report's findings.

2 Methodology

2.1 Overview

The research for this study was carried out using the Delphi Technique[7,8,9]: a recognised iterative method for gathering data, and achieving a convergence of opinion, within a group. Due to the short delivery timescales of this project the Delphi Technique process was restricted to two rounds, which was considered sufficient to reach consensus on the required outputs. The methodological framework of the Delphi Technique is described below:

1) Identify the research question, which was:

   "What are the potential innovative technologies to meet Defra's medium to long-term (10-15 years) requirements for air quality monitoring?"

2) Identify relevant technologies/studies/policies.

3) Select most relevant technologies/studies/policies.

4) Chart the data.

5) Collate, summarise and report results.

6) Consult throughout the process.

The study stakeholder consultation covered both stages of the study: Stage 1 to identify potential innovative air quality monitoring technologies and Stage 2 to identify risks and barriers preventing adoption of these innovative technologies. The scoping study component of Stage 1 took the form of a questionnaire sent to stakeholders identified by the project team and is described in Section 2.3. The stakeholder responses were analysed and assessed to identify potential innovative air quality monitoring technologies and their associated benefits and limitations as described in Section 2.4.

Risks to innovation and market barriers reported by the stakeholders were collated from the responses for use in Stage 2. Based on these risks and market barriers, a series of possible measures were developed by the project team for each innovative technology that Defra (and other relevant stakeholders) could consider pursuing to reduce the risks to innovation, overcome market barriers and promote uptake of the innovative technologies. The "priority" rating for these possible measures is described in Section 2.5.

Limitations of the study approach are briefly described in Section 2.6.

2.2 Definitions of terms

The terms 'risk to innovation' and 'market barrier' are used to assess the likelihood of technologies coming to market. Risks to innovation are factors which might become a problem in the future, whereas market barriers are factors which already exist and are perceived to be impeding the progress of a new technology towards commercialisation. Examples of both are given Table 2-1.

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[7] Hilary Arksey, Lisa O'Malley. Scoping Studies: towards a methodological framework, 2005 [online]. Available at: http://www.tandfonline.com/doi/abs/10.1080/1364557032000119616#.VG4RUPmsV8E [accessed on 20/11/2014].

[8] Danialle Levac, Heather Colquhoun, Kelly O'Brien. Scoping Studies: advancing the methodology, 2010 [online]. Available at: http://www.implementationscience.com/content/pdf/1748-5908-5-69.pdf [accessed on 24/11/2014].

[9] Wanda L. Stitt-Gohdes, Tena B. Crews. The Delphi Technique: A Research Strategy for Career and Technical Education, 2004 [online]. Available at: http://scholar.lib.vt.edu/ejournals/JCTE/v20n2/pdf/stitt.pdf [accessed on 26/11/2014].

Table 2-1 Examples of risks to innovation and market barriers

Examples of "risks to innovation" include:

- Limited supply or access to a technology or knowledge.
- Restricted knowledge transfer, small knowledge base.
- Underfunding.
- Lack of market acceptance or difficulties accessing the market – if resulting from an information or awareness issue, a regulation issue or a development issue, e.g.:
  - Lack of awareness that a technique is available or suitable.
  - Insufficient information about a technique's performance, leading potential users to "stick to what they know".
  - Regulation or guidance that does not mention or cover the new technique. Potential users therefore do not know if they are allowed to use the technique, or how they should do so.

    (Lack of market demand alone is not a barrier in this context.).
- Inability to implement innovation or bring about change.

Examples of "market barriers" include:

- Physical constraints such as limitations in technological ability.
- Legislation – is legislation (UK or European) designed to encourage development?
- Requirements for the use of reference methods, the Monitoring CERTification Scheme (MCERTS) for type approval and the ongoing demonstration of equivalence.

2.3 Stakeholder consultation

2.3.1 Selecting stakeholders

The definition of an "innovative technology" was unbounded, but given the application it could be:

An instrument, sampler, sensor (active or passive), method, or system (partially or fully integrated)… *– or –* A satellite-borne sensor or measurement device… *– or –* A remote sensing technique…	…that would provide air pollutant (gaseous and/or particulate-phase) measurements.

A list of stakeholders was drawn-up by the project team that were considered to be best placed to advise on potential innovative technologies to meet Defra's medium to long-term (10-15 years) evidence requirements for national air quality monitoring. The stakeholders included:

- Air quality instrument manufacturers in the UK and overseas.
- Air quality equipment suppliers in the UK and overseas.
- Organisations involved in the development of innovative technologies, such as universities and research organisations.
- Other stakeholders, such as those with past experience of using some of the innovative technologies, e.g., as part of UTMC systems.

The list of the stakeholders that were approached is given in Table 2-2. Just under a third of those consulted provided a response to the questionnaire.

Table 2-2 Stakeholders consulted and responses (Y = Yes, N = No, NDA = non-disclosure agreement)

Stakeholder	Responded	Stakeholder	Responded	Stakeholder	Responded
Aeroqual	Y	Aerodyne	N	Kanomax	N
AethLabs	Y (requested NDA)	AFC International Inc.	N	KWJ Engineering	N
Air Monitors	Y	Amey	N	Magee	N
Alphasense	Y	Aquaria	N	Matter	N
Casella	Y	Arup	N	Metrohm	N (requested NDA)
Citytech	Y	Avanti Consulting	N	Mouchel Council	N
Digicore	Y	AVL	N	Newcastle	N
Edinburgh Council	Y	Baseline Mocon	N	Ogawa USA	N
Envirowatch	Y	Biral	N	Owlstone	N
ET	Y	Cambustion	N	Passam AG	N
Gateshead Council	Y	CEH	N	Platypustech	N
GeoTech	Y	Clairair	N	PMS	N
Leicester Council	Y	Clarity	N	Radiello	N
Ion Science	Y	Dekati	N	SGX Sensortech	N
Palas	Y	Durham Council	N	Siemens	N
Perkin Elmer	Y	Edinburgh Instruments	N	SIREM	N
Quantitech	Y	ESG	N	SKC	N
Transport for Scotland	Y	Figaro	N	Sunset Laboratories	N
Turnkey	Y	Filter Integrity	N	Transport for Greater Manchester	N
University of Leicester	Y	FIS	N	Topas	N
		Gradko	N	TRL	N
		Grimm	N	TSI	N
		Horiba	N	TZOA	N
		Imtech	N	Unitec	N
		Inmarsat	N	U-pod	N
		IVL	N	URG	N

2.3.2 Questionnaire

Having identified the key stakeholders, a questionnaire was devised to capture the evidence required for this study. An integrated questionnaire covering the requirements of Stages 1 and 2 was developed, capturing as much detailed information as possible to avoid approaching stakeholders twice. The questionnaire that was used is shown in Appendix 1.

The questionnaire aimed to identify:

- Innovative technologies for air quality monitoring that stakeholders had in development, which were likely to come to market in 10-15 years, including technical information on:
    - Measurement handling.
    - Costs – capital and on-going.
    - Flexibility of device design and practical considerations.
    - Servicing, calibration and reliability.
    - Measurement uncertainty.
    - Temporal and Spatial Resolution.
- The factors driving the development of innovative technologies.
- The perceived market barriers to their development
- How market barriers might be overcome.

The questions aimed at capturing technical information on technologies were posed to provide a better understanding of the technology in recognition of the fact that instruments and technologies are rarely chosen on the basis of one desirable parameter, but are more often a compromise between several competing factors.

The questionnaire was sent to the stakeholders via email to gather evidence of potential innovative technologies. Where possible the project team and academic partners sent the questionnaire to a specific contact in the stakeholder organisation. The consultation was conducted in January 2015.

2.4 Identifying and assessing innovative technologies from stakeholder responses

On receipt of a completed questionnaire, the innovative technology described in the stakeholder response was assessed by the project team against the criteria given in Appendix 2. This provided a risk assessment of each innovative technology. For each of the criteria assessed, the reviewer gave a numeric score of 1 to 5 denoted by the "score" row at the top of Table 2-3. The Likert scale[10] approach was used as it allowed the assessor's preferences or degree of agreement with a statement or set of statements, relating to quality, costs, likelihood, agreement, how often?, and so on, to be scored on the same numeric scale. Negative or undesirable responses or attributes were intended to be scored lowly (ones or twos), whilst positive responses or attributes to be scored highly (fours or fives). A value of three was awarded to a middle option for neutral responses, e.g., "neither agree nor disagree". This approach allowed the questionnaire responses to be assessed consistently against the same criteria. If a criteria could not be assessed, the assessor was asked to note the reason, even if the question was not applicable to the technology being assessed, just so the reason was clear.

[10] Likert Scale is a five (or seven) point scale which is used to allow the expression of agreement or disagreement with a particular statement, in this case risk assessment.

Table 2-3 Likert Scale used in the risk assessment of the innovative technology

ASSESSMENT CRITERIA	SCALE				
Score	1	2	3	4	5
Quality	Very poor	Poor	Average	Good	Very good
Costs	Very high	High	Average	Reasonably low	Very low
Likelihood	Impossible	Unlikely	Likely	Reasonably likely	Certain
Agreement	Strongly disagree	Disagree	Neither agree / disagree	Agree	Strongly agree
How often?	Very Frequent	Frequent	Average	Less than average	(Almost) Never

The responses of the project team were collated by the Ricardo Energy & Environment project manager and relayed to the academic partners who were asked to moderate the scoring and form a consensus opinion on the innovative technologies. Where several instruments of one type were assessed, e.g., pervasive sensors, an academic partner provided a single, over-arching risk assessment based on all the questionnaire responses. The academic partners used their technical knowledge and professional judgement, averaging scores where values varied by one, rounding-up or down where necessary. In instances where the difference in scores was greater, a range of scores were provided in the overall assessment. This avoided the potential for a criteria scored as 1 (poor) and 5 (very good) to be reported as 3 (average) in the overall assessment. This approach allowed identification of the most promising innovative technologies with the potential to meet Defra's medium to long-term (10-15 years) evidence requirements for national air quality monitoring.The questionnaire responses covering the remote sensing of air quality, using satellite, ground-based, and aircraft-borne sensors, were provided by the research colleagues of one of the academic partners. In this instance the questionnaire responses were assessed by another member of the project team in order to limit potential bias. The completed summary risk assessments are included in Appendix 3.

The limitations and benefits of the innovative technologies were identified from the stakeholder responses. The limitations and benefits were assessed based on the risk assessment scoring described above and against the key considerations listed in Section 1.3.3. These criteria provided a consistent approach for assessing and reporting the suitability of each innovative technology against Defra's future needs.

2.5 Identifying risks to innovation and market barriers and developing measures to address these

Stage 2 examined the perceived risks to innovation that stakeholders reported to be impeding innovation and development, and market barriers reported to be preventing uptake (or from being used to their full potential) of innovative air quality monitoring technologies. The risks to innovation and barriers were compiled from the stakeholder responses to the questionnaire sent out during Stage 1. The stakeholder responses were reviewed by project team and academic partners to capture stakeholder suggestions as to how risks to innovations and market barriers could be overcome. In some cases the project team and academic partners inferred risks to innovations and market barriers based on the stakeholder responses due to time constraints.

The project team analysed the risks to innovation and market barriers and from these developed potential measures for each innovative technology that Defra (and other relevant stakeholders) could consider pursuing over the next 10-15 years. "Measures" in this case simply means a course of action. Each proposed measure was appraised by assigning a "priority" rating, as defined in

Table 2-4, together with reasoning for the rating.

Table 2-4 Priority ratings and definitions used to categorise risks and market barriers

Priority rating	Description
High	Major risks to innovation and market barriers need to be resolved immediately (within 1-5 years) as they could severely impede innovative technologies coming to market within the next 10-15 years.
Medium	Moderate risks to innovation and market barriers need to be resolved in the medium term (within 5-10 years) and are less urgent than major risks, e.g., an adequate workaround may exist. They could impede innovative technologies coming to market within the next 10-15 years. Once major risks to innovation and market barriers are resolved these may become a higher priority but this would need to be re-assessed in time.
Low	Minor risks to innovation and market barriers, which are unlikely to the innovative technologies coming to market within the next 10-15 years and have negligible effect.

High-level risks to innovation and market barriers, common to all or most of the innovative technologies, were also identified from the stakeholder responses. These are summarised in Section 3.6.

2.6 Study methodology limitations

There were several inherent limitations associated with this study:

- Limited timescales: due to the short timescale of Stages 1 and 2 there was a limited window of opportunity to consult with stakeholders and gather evidence on innovative technologies.
- Limited evidence or response: limited evidence, or assessment of conceptual technologies, could lead to a low risk assessment score. The project team and academic partners assessed the questionnaire responses and used their professional judgement and technical knowledge to assess the risks thereby mitigating the effect of limited responses.
- Commercial confidentiality: a number of respondents remarked that they were wary of revealing commercially sensitive information when responding to the questionnaire. To avoid this some respondents did not provide detailed information, but instead provided rather broad, generalised responses, with limited detail. In two cases non-disclosure agreements (NDAs) were issued by Ricardo Energy & Environment in response to respondent's wishes.
- The study methodology did not include time to return to stakeholders to follow-up and discuss their responses. If this had been part of the study, it would have been expected to generate more insight and depth into the stakeholders' assertions and provide supporting evidence.

3 Findings

3.1 Categorisation of innovative technologies

Examination of the questionnaire responses revealed that the innovative technologies lay in four broad technological groups:

1. Satellite-borne sensors.
2. Remote sensors composed of ground-based and airborne sensors.
3. Pervasive sensors.
4. Fixed-point sensors.

Ground-based and airborne sensors belong to a class of instruments known as ‘remote sensors’, which can also include satellite-borne sensors. Stakeholder responses were received detailing applications of all three sensor types. However, considerations for satellite-borne sensors are different from ground-based and airborne sensors and are therefore considered separately (Section 3.2). Based on the similarities in the innovative technologies described in the stakeholder responses received for ground-based and airborne sensors, which use similar instruments but different deployment methods, these sensors are considered together under the umbrella heading of remote sensors in Section 0.

Ground-based sensors were differentiated from “fixed-point sensors”, as air pollutant concentrations are typically measured along the path of a beam, rather than within a fixed volume, but this is not always true as indicated by some stakeholder responses. Path measurements allow ground-based sensors to measure air pollutant concentrations over a wide spatial scale.

Pervasive sensors are discussed in Section 0 and include active and automatic samplers similar to fixed-point sensors, as detailed in Section 0. The difference between these two classes is that pervasive sensors employ electrochemical sensors, to measure gases, and optical particle counters (light scattering cells), to measure particulate matter, rather than spectroscopic methods (e.g., chemiluminescence used in NOx/NO_2 analysers) or filter sampling to measure particulate matter. They are specifically designed to be much smaller, more compact and robust, than typical fixed-point sensors. This allows them to be deployed in a range of configurations, and in remote or inaccessible locations.

Passive sampler manufacturers and suppliers in the UK and overseas indicate that they do not have any new types of passive sampler in development. Therefore, the consultation did not reveal any new passive samplers that might be relevant in the context of this study.

3.2 Satellite-borne sensors

3.2.1 Summary of findings for satellite-borne sensors

Table 3-1 presents the assessment of satellite-borne sensors against the key study considerations, detailed in Section 1.3.3, based on the stakeholder responses. Where information was provided by the project team, this is noted in the Table. A summary of limitations and benefits of satellite-borne sensors is provided at the end of the Table. The summary risk assessment for this technology, as described in Section 2.4, is given in Appendix 3.

Table 3-1 Assessment of satellite-borne sensors

Satellite-borne sensors
Will it be possible to use the innovative technology within the UK’s air quality monitoring networks in the next 10-15 years?

- **Will the innovative technology be suitable to supplement or displace the UK's air quality monitoring network?**
- **Will the innovative technology be suitable to provide measurements that can feed into the LAQM review and assessment regimes?**
- **Will the innovative technology be able to provide measurements to help fulfil national and local air quality objectives?**

It appears unlikely that satellite-borne sensors will displace the UK's air quality monitoring network in the next 10-15 years, but may provide supplemental data to UK's air quality monitoring networks. The technology has a number of technical limitations to be resolved, including (in no particular order):

- Satellite-borne sensors cannot measure through clouds in the lower troposphere, limiting their application for air quality measurements in the UK's temperate climate which is characterised by periods of cloud cover. Were they to be used air quality measurements would be unavailable when there was cloud cover, limiting the completeness of the long-term datasets.
- Currently, satellite sensors cannot measure beyond the lowest 1 km of the atmosphere due to sensor sensitivity issues and large uncertainties associated with processed data products. Therefore they are unable to provide surface air quality measurements.
- Satellite-borne sensors can provide measurements over regional and national-scales, with typical resolutions of the order of tens of kilometres. These resolutions are too coarse for use within the LAQM Review and Assessment regime, but may have value in identifying regional pollution sources which may contribute to poor local air quality. Improvements in spatial resolution are predicted for future years through the deployment of new satellite-borne sensors and are detailed later in this table.
- Surface NO_2 concentrations can be inferred, together with CO and SO_2 near large point sources and small area sources, e.g., harbours and airports, and a limited range of VOCs. Surface-level particulate concentrations, however, can only be inferred if particulates are well-mixed in the boundary layer as the signal uncertainty is likely to be lower than at altitude, but typical uncertainties in surface-level particulate concentrations are currently around 80%. Ground-level ozone measurements are challenging and strongly dependent on the sensor type (ideally limb and nadir sensors used in tandem).
- Measurement uncertainty is dependent on the sensor and the algorithm used to infer the concentration. Measurement uncertainties are considerable (see table below); greater than 30% for most pollutant species, except for CO and CO_2 for which uncertainties are 21% and 1-8%, respectively. The low percentage uncertainty associated with CO_2 satellite sensor measurements reflects the extensive work done in recent years to reduce uncertainties for measuring this important greenhouse gas, and the use of dedicated satellite sensors (i.e., specific sensors for CO and CO_2). This may indicate that with enhanced research effort on other pollutants and dedicated sensors, their measurement uncertainties could be improved. Different algorithms are used by different data providers to convert "raw" data to final "data products" (column concentration of trace gases and particulates). This can lead to inconsistencies between data products in the reported air pollutant concentrations. Verification of satellite sensor measurements can be provided by ground-based or airborne sensors to assess uncertainty[11].

Species	CO	NO_x/NO_2	O_3	Particulates	SO_2	CO_2
Typical uncertainty (%)	<21	35-60	45	80	50	1-8

- Measurement uncertainties can be reduced by combining observations from downward-looking (nadir) sensors with those from sideways-angled (limb) sensors.

There exists potential for satellite measurements to "fill the gaps" between monitoring stations, on a national and regional scale, providing supplemental data for verification purposes. An example is the use of satellite data

[11] Data sources for typical uncertainty where compiled by stakeholders from various academic studies

in determining the impact of accidental releases and natural events, e.g., earthquakes, forest fires, volcanic emissions, and regional and global-scale pollution events, on the UK's national and local air quality. Based on the current assessment, it is unlikely that satellite data will form the core measurement method used in the national compliance networks or the LAQM regime.

Will the innovative technology comply with the air quality monitoring data quality objectives (DQO) defined in ambient air quality directives (EU Directives 2008/50/EC and 2004/107/EC)?

It is unlikely that satellite-borne sensors will comply with the DQOs given in the air quality Directives. Satellite-borne sensors provide column measurements of air pollutants whereas the air quality Directives currently require fixed-point measurements. The air quality Directives would have to be amended to permit the use of satellite data for compliance reporting.

The Copernicus programme, sponsored by the European Commission, supports fundamental research for satellite data validation through the comparison of satellite measurements with fixed-point measurements. This could be an important preparatory step to enable future use of satellite data for surface measurements. Engagement with the Copernicus programme could be a first step in realising the use for satellite measurements for national and local air quality measurement as there are currently no DQO for satellite measurements.

Will the innovative technology be able to provide air quality measurements with improved spatial/temporal resolution?

One of the strengths of satellite-measurements is their increased field-of-view; they have a coarse spatial resolution offering improved spatial resolution over a wide-scale, but are incapable of providing high-resolution images on a kilometre-by-kilometre scale. The increased field of view of satellite data has the potential to compliment fixed point measurements collected by the current UK national monitoring networks and has the capability to provide data over a wide spatial range in a few measurements. The spatial resolution of current satellite measurements, e.g., 80 km x 40 km for GOME 2, 13 km x 24 km for OMI, is expected to improve within the next few years through the launch of the ESA's Sentinel 1-6 missions. These are expected to provide measurements with a resolution of 7 km x 7 km. However, finer resolution observation, e.g., 1 km x 1 km as used in national compliance maps, appears to remain beyond the 10-15 year horizon of this study.

The temporal resolution of a satellite is determined by its orbit: geostationary satellites would be required for fixed measurements. Geostationary orbit satellites measure at fixed locations providing continuous measurements. On the other hand, satellites in a low earth orbit, orbiting every ~90 minutes, spend a small amount of time ('dwell time') over any given area of the earth. As a result, the measurements over a specific area, such as the UK will be restricted by this dwell time resulting in non-continuous air quality monitoring data. The project team anticipated that over the next five or more years, the simultaneous use of data from several satellites in geostationary orbit ('synchronous use') may offer the potential for continuous air quality measurements from satellite sensors such as GEMS and the planned TEMPO and Sentinel 4 missions. Synchronous use of satellites could offer data several times a day (cloud cover will likely remain a limiting factor) but it is unlikely that this could reach the hourly average measurements currently available from the UK air quality monitoring networks.

Will the innovative technology offer improved data usability, offering added research value? Will it be able to measure multiple pollutants simultaneously?

Satellite-borne sensors are an established technology capable of simultaneously measuring multiple air quality pollutants simultaneously. A wide-number of free-to-use data products are currently available offering extensive added research value, e.g., meteorology observations, sea state, land use. Stakeholders did not note any developments that would change this situation.

Satellite-borne sensors can simultaneously measure the column density, reported as molecules cm^{-2}, of a wide range of air pollutants, typically greenhouse and trace gases, including NO_2, SO_2, O_3, CO, CO_2, CH_4, CH_3OH, HCOOH, BrO, ClO. They can also provide a measure of the atmospheric aerosol loadings (in terms of the Aerosol Optical Depth, AOD) but the best results require clear skies. Approaches exist for inferring the surface particulate matter ($PM_{2.5}$) from the AOD. Gas measurements were typically provided by Differential

Optical Absorption Spectroscopy (DOAS) which uses sunlight or infrared radiation emitted from the Earth, as its light source. Satellite-borne sensors also provide standard meteorological parameters such as, temperature, barometric pressure, relative humidity, wind speed and direction.

Satellite measurements are automatically collected from satellite sensors by relevant space agencies and then distributed to different organisations which manage the pre and post-processing of the raw data (retrieved atmospheric column concentrations). Air pollutant concentrations are not measured directly but calculated using algorithms from satellite-borne sensor measurements. This process takes a few hours, during which time the "raw" data undergoes several processing steps resulting in the final data "product" – the estimated atmospheric concentration of a gas or aerosol. The age of the satellite sensor and the assumptions made in the calculation contribute to the data product's uncertainty. Each successive calculation step introduces errors and uncertainties which vary from product-to-product; uncertainties are stated by data providers. This can lead to inconsistencies in satellite air quality measurements from different providers.

Making accurate use of satellite measurements requires technical knowledge and use of scientific software requiring technically competent staff to handle the data. Open source toolkits are available to process and manage satellite data and are growing in number. Air quality measurements can be retrieved from archived data by post-processing.

The use and sharing of some satellite derived data products is limited under licencing agreements between the data provider and user, and some are free to use. Measurements can be georeferenced by incorporation into GIS based datasets allowing production of global, national and regional-scale maps.

Satellite data can provide supplemental evidence of research value for source apportionment studies and for the compilation of national emissions inventories.

What are the potential costs associated with the innovative technology?

There are considerable costs associated with the commissioning, development and deployment of satellite-sensors. The costs are commonly borne by a combination of state funding, private investment, and some data end-users. Medium to long-term planning and development of satellite sensors is required. Sensors are calibrated in the lab prior to use, in-situ maintenance and repair can be costly.

Stakeholder responses indicated that costs for satellite data were associated with data management and analysis, the development of algorithms to convert "raw" data into usable "products" of value to the end user. Other costs include data processing, licencing data products from third party data providers and data storage.

In the short to medium term, the Copernicus programme, sponsored by the European Commission, is providing a wide range of fully-funded projects to promote exploitation of satellite data over the next 20 years.

How would the output from the innovative technology be integrated with UK's empirical modelling approach which is used to demonstrate compliance with EU air quality Directives?

Stakeholder responses did not give an indication as to how satellite data could be integrated with the UK's empirical modelling approach at this time. At this stage, and looking 10-15 years ahead, it is difficult to speculate as to how the output would be integrated with UK's empirical modelling approach given current limitations, including:

- Mapped modelled concentrations of the national pollution levels are required on a 1 km x 1 km basis in order to fulfil the reporting requirements of the air quality Directives. As noted above, stakeholder responses indicated that the coarse spatial resolution of satellite data is a key limitation at the current time and finer resolution measurements were some way off.
- Preliminary validation with ground-based measurements (this could be achieved by using the current UK measurement network or ground-based sensors such as DOAS instruments as discussed in the next section) may allow satellite data to be integrated into the UK's empirical modelling approach. This approach is currently untested, though validation methods exist, and could be further developed.

How accessible are the measurements from the innovative technology to a wide range of potential end-users, e.g., Central Government, Public Health England, local authorities, local highways authorities, and the public? Can they help in the promotion of citizen science?

Some satellite datasets are freely available, e.g., those generated by NASA and Copernicus user services (http://www.copernicus-atmosphere.eu/), and can be exploited and georeferenced using open source tools by a range of end-users, including private individuals and citizen science projects, but require some technical knowledge to use. Some data satellite products require licences to use and use is restricted.

As noted above, the resolution of current satellite data is too coarse for use by local authorities and local highways authorities but it can be used to identify regional sources of air pollution that may affect local air quality.

Summary of current limitations and benefits

Limitations	*Benefits*
• Satellite measurements are limited by cloud cover, this may lead to incomplete datasets in the UK. • The large uncertainties, up to 80% in some cases, and they cannot usefully measure below 1 km means that they cannot be used to directly measure surface-level air quality. • Satellite data do not currently comply with the requirements of the European air quality Directives. European research programmes are underway to validate satellite measurements with ground-based measurements in the coming years. • Currently, post-processed satellite data may present inconsistencies due to the different methodologies used to retrieve the air quality measurements from column concentrations. • Spatial resolution of satellite data are currently too coarse (typically of the order of tens of kilometres) to be used to provide finer spatial scale data for use within the LAQM regime. • The capital costs associated with planning, developing and deploying of satellite-borne sensors, are considerable especially when considered next to other technologies.	• Satellite data have the potential to compliment fixed point measurements collected by the current UK national monitoring networks and are capable of “filling in the gaps” between monitors, on a national or regional scale. • Measurement uncertainties can be reduced by combining observations from downward-looking (nadir) sensors with those from sideways-angled (limb) sensors. • Satellite-borne sensors can simultaneously measure a wide range of air pollutants, including particulates, greenhouse and trace gases. • Air quality measurements can be retrieved from archived data by post-processing. • Higher spatial resolution data (7 km x 7 km) is expected within the next few years with the launch of the ESA’s Sentinel 1-6 missions. This data will be made available by the Copernicus programme. • Geostationary satellites may offer the potential for continuous air quality measurements - this might be achieved in the next 5 years through synchronous use of different satellite sensors such as GEMS and the planned TEMPO and Sentinel 4 missions. • In the long-term (next 10-15 years), the Copernicus programme is expected to provide fully-funded projects to help promote exploitation of satellite data. • Despite the coarse spatial resolution of satellite data, preliminary validation with ground-based measurements may allow satellite data to be integrated into the UK’s empirical modelling, though this remain untested. • Some satellite datasets are freely available and can be freely exploited and georeferenced using

	open source tools by a range of end-users, including private individuals and citizen science projects. • Satellite data could be used to compile and validate national emissions inventories. These data could be used to identify and assess emission sources, e.g., location, duration and strength. As satellite sensors can measure multiple pollutants simultaneously, the data could be used in the compilation and verification of the NAEI and the Greenhouse Gas Inventory (GHGI).

3.2.2 Potential measures to reduce the risks to innovation and market barriers associated with satellite-borne sensors

The potential measures that Defra could pursue over the next 10-15 years in order to reduce the risks to innovation and market barriers thereby promoting uptake of satellite-borne sensors are given in Table 3-2 together with priority ratings (see Appendix 3). Each proposed measure was appraised, with the reasoning provided in the respective table, and given a priority weighting as defined in Table 2 4.

Table 3-2 Satellite-borne sensors: risks to innovation, market barriers and potential measures

Risk to innovation or market barrier and rationale	Source of potential measure	Potential measure and steps to achieving potential measure. *Defra could….*	Action owner	Priority rating (low, medium, high	Ease of achieving potential measure (easy, moderate, difficult)
Satellite data cannot be used for compliance assessment purposes and data reporting to the Commission – air quality Directives do not permit the use of satellite data, this is considered to chiefly as a result uncertainty range of satellite data	Project Team	• Liaise with EC (DG ENV and JRC) to identify possible adjustments to the air quality Directives. • Engage with European Environment Information and Observation Network (EIONET) on suitable standards for satellite-borne sensor measurements. • Establish UK working group to develop proposals for DQO for satellite data. • Establish a working group to develop proposals for DQO for remote sensor data.	• UK and European commercial and research community. • Defra to lead engagement.	High	Difficult
Lack of standardised approach for processing satellite data – may lead to confusion amongst potential end-users and limit uptake.	Project Team	• Engage with UK and European partners to standardise data processing and products to convert raw data into ready-to-use data products for use in air quality applications. • Form a working group to develop standard data processing approach.	• UK and European commercial and research community • Defra to facilitate engagement	High	Moderate

Accessing satellite data – difficult for non-specialist end-users to access satellite data.	Project Team	• Engage with UK and European partners (e.g., UK Space Agency, UK Catapult Satellite Applications, ESA, and the Copernicus programme) to develop a European-wide platform to provide satellite data products to act as potential "one-stop shop" for satellite data. • Engage with UK experts to identify satellite data products of use to potential end-users. • Encourage engagement between data-providers and end-users to promote better understanding of data requirements.	• UK and European commercial and research community • Defra to facilitate engagement	Medium	Moderate
End-user understanding – end-users unfamiliar with satellite data products and unaware of what the "best" datasets are for air quality applications.	Project Team	• Consult with UK experts to identify suitable satellite products of use to air quality end-users, with the lowest uncertainty and highest spatial and temporal resolution.	• UK Catapult Satellite Applications • UK commercial and research community • Defra to facilitate engagement	Medium	Easy
Understanding of data storage needs – storing processed satellite data requires significant dedicated resources, e.g., staff, computers and data storage.	Project Team	• Develop guidance for potential end-users on satellite data management and storage.	• UK Catapult Satellite Applications • UK commercial and research community • Defra to facilitate engagement	Low	Moderate

3.3 Remote sensors

3.3.1 Summary of findings for remote sensors

Ground-based and airborne sensors are considered together in the table as stakeholders have indicated that similar instruments can be used either at fixed point locations or mounted to aircraft. Differential Optical Absorption Spectrometers (DOAS) instruments use a collimated beam of light which allows them to measure across a wide spatial extent and explains why they can be mounted to aircraft and used to derive surface-level air quality measurements.

Table 3-3 presents the assessment of remote sensors against the key study considerations, detailed in Section 1.3.3, based on the stakeholder responses. Where information was provided by the project team, this is noted in the Table. A summary of limitations and benefits of the innovative technology is provided at the end of the table. The summary risk assessment for these technologies, as described in Section 2.4, is given in Appendix 3.

Ground-based and airborne sensors are considered together in the table as stakeholders have indicated that similar instruments can be used either at fixed point locations or mounted to aircraft. Differential Optical Absorption Spectrometers (DOAS) instruments use a collimated beam of light which allows them to measure across a wide spatial extent and explains why they can be mounted to aircraft and used to derive surface-level air quality measurements.

Table 3-3 Assessment of remote sensors (ground-based and airborne)

Remote sensors (ground-based and airborne)
Will it be possible to use the innovative technology within the UK's air quality monitoring networks in the next 10-15 years? - **Will the innovative technology be suitable to supplement or displace the UK's monitoring network?** - **Will the innovative technology be suitable to provide measurements that can feed into the LAQM review and assessment regimes?** - **Will the innovative technology be able to provide measurements to help fulfil national and local air quality objectives?**
Differential Optical Absorption Spectrometers (DOAS) are not currently used in the UK's monitoring networks. They can simultaneously measure multiple gaseous air pollutants providing fixed-point or mobile, spot measurements: • DOAS instruments can be mounted to aircraft, providing spot air quality measurements. They are capable of providing high (spatial) resolution measurements (of the order of <100m) of a medium sized city (~300,000 inhabitants or ~70 km^2) to be mapped within a few hours. At the current time, the uncertainties of the air quality measurements from this research instrument are ~90%.The project team also noted that DOAS instruments can be fitted to ships allowing for the impact of ships in coastal waters and harbours to be assessed. These locations are not captured well by the UK's current measurement network, nor are they well parameterised in national emissions inventories. • Spot measurements, from aircraft, could be used to supplement measurements from the UK's national monitoring networks and continuous measurement from fixed point, ground-based instruments could form part of the UK's networks. • Ground-based DOAS instruments can continuously scan over a wide area to provide 3D air quality maps of the distribution of air pollutants over a wide extent, e.g., a town or city. Both applications would have value within the LAQM regime, allowing detailed air quality maps to be produced and emission sources to identified, as well contributing to the UK's national monitoring networks.

Will the innovative technology comply with the air quality monitoring data quality objectives (DQO) defined in ambient air quality directives (EU Directives 2008/50/EC and 2004/107/EC)?
DOAS instruments measure air pollutants along a fixed path or column and therefore do not meet the requirements of the air quality Directives which require fixed point measurements.
Will the innovative technology be able to provide air quality measurements with improved spatial/temporal resolution?
Remote sensors do not really offer improved temporal resolution, when compared to current in-use air quality monitoring techniques, but could offer improved spatial resolution. The ground-based DOAS instrument identified is capable of 360° panoramic sweeps of the lower boundary layer providing spatial and temporal variability of trace gases. Ground-based DOAS instruments have a temporal resolution of 45 minutes and a spatial resolution of ~50 m. Airborne remote sensors could provide higher spatial resolution measurements than ground-based instruments, but are dependent on good weather as poor conditions could lead to incomplete datasets. Aircraft could be grounded due to inclement weather and low cloud/fog obscuring the study area. Continuous measurements are not possible from manned aircraft due to pilot fatigue, this could be overcome through the use of unmanned aerial vehicles (UAVs), but airborne instruments could only offer spot, rather than continuous, measurements. Small aircraft have limited flight ranges, restricting the spatial extent of measurements to the local or national scale; larger aircraft have greater ranges and could be used to gather national and regional measurements. Flight altitude limits the spatial resolution; low altitude flights are required to provide high-resolution measurements which precludes the use of instruments fitted to commercial flights which cruise at heights of between 25 to 40 thousand feet.
Will the innovative technology offer improved data usability, offering added research value? Will it be able to measure multiple pollutants simultaneously?
Stakeholder responses indicated that both the DOAS instruments can simultaneously measure a range of air quality pollutants (e.g., NO, NO_2, SO_2 and O_3), VOCs and greenhouse gases, without cross interference. Currently, multiple instruments have to be used within the UK's national monitoring networks to provide the same range of measurements. Offerings of research value were also identified. Stakeholder responses indicated that ground-based remote sensors were originally developed for research purposes. These sensors have a long heritage for measuring air quality through fixed viewing geometries and are currently used to validate satellite measurements as noted above which could offer offering added research value. Data products can be georeferenced and incorporated into local and/or national mapping outputs and used to supplement UK's air quality monitoring networks. Stakeholder responses suggested that the DOAS instrument did not have a well-defined data retrieval methodology at the current time and that data processing is an intensive process requiring the use of several software packages which convert raw data into volume mixing ratios (ppb).
What are the potential costs associated with the innovative technology?
Initial and on-going maintenance costs for the DOAS instrument were not provided in the stakeholder response. The project team anticipate the cost of deployment of airborne sensors to be considerable as they typically require the use of an aircraft and trained personnel. However, such cost might be lower if unmanned technology was used, but the study found no evidence of such innovation. The stakeholder responses noted that small lightweight instrumentation can be deployed on light aircraft which has the potential to limit deployment costs. Small aircraft have limited flight ranges and could only be used to provide air quality measurements on a local or national scale. Larger aircraft have greater ranges and could be deployed on a national or regional scale.

How would the output from the innovative technology be integrated with UK's empirical modelling approach which is used to demonstrate compliance with EU air quality Directives

When considering innovative technologies, which are established but still developing, on a horizon of 10-15 years it is difficult to speculate as to how the output would be integrated with UK's empirical modelling approach given current limitations. No evidence was provided in the stakeholder response to help inform this. Further development and testing of the techniques may be required before a complete assessment can be made.

How accessible are the measurements from the innovative technology to a wide range of potential end-users, e.g., Central Government, Public Health England, local authorities, local highways authorities, and the public? Can they help in the promotion of citizen science?

Stakeholder responses indicated that remote sensors are used for research purposes and data are not accessible to the public. In the longer term, if they are developed or replaced by commercial systems, they could offer high resolution spatial data of value for local authorities and local highways authorities but further development would be required in the long-term.

Summary of current limitations and benefits

Limitations	*Benefits*
• DOAS instruments measure pollutants along a fixed path or column and therefore do not meet the requirements of the air quality Directives which require fixed point measurements. The measurement uncertainty of the research instrument identified in the stakeholder response is ~90%. • Airborne remote sensor measurements are dependent on good weather; poor conditions could lead to incomplete datasets. Airborne instruments could offer spot, rather than continuous, air quality measurements. • Stakeholder responses suggested that the DOAS instruments did not have a well-defined data retrieval methodology at the current time and that data processing is an intensive process requiring the use of several software packages which convert raw data into volume mixing ratios (ppb). • No evidence was provided in the stakeholder response but the project team expect that the cost of deployment of airborne sensors will be considerable as they typically require the use of an aircraft and trained personnel. • Stakeholder responses identified the capital cost of ground-based remote sensors to be of the order of tens of thousands of pounds. On-going maintenance costs for the DOAS instrument were not provided in the stakeholder response. • Stakeholder responses indicated that airborne sensors are currently used for research purposes and data is not accessible to the public. In the	• DOAS instruments can simultaneously measure multiple gaseous air pollutants providing fixed-point or mobile measurements. • Airborne DOAS instruments can be used to map the air quality of medium size city (~300,000 inhabitants or ~70 km^2) within a few hours, providing spot measurements. The ground-based system identified could continuously scan over a wide area to provide 3D air quality maps of the distribution of air pollutants over a wide extent, e.g., a town or city. Both applications would have value within the LAQM regime, allowing detailed air quality maps to be produced and emission sources identified, as well contributing to the UK's national monitoring networks. • DOAS instruments can provide continuous high temporal and spatial resolution measurements for a range of air quality pollutants (e.g., NO, NO_2, SO_2 and O_3), VOCs and greenhouse gases, without cross interference. Currently, multiple instruments have to be used within the UK's national monitoring networks to provide the same range of measurements. • Airborne remote sensors could provide higher spatial resolution measurements than ground-based instruments. • As with satellite measurements, airborne DOAS instruments, could be used to compile and validate local and national emissions inventories. This data could be used to identify and assess emission sources, e.g., location, duration and strength. As

longer term, if they would be developed or replaced by commercial systems, they may be able to offer high resolution spatial data of value for local authorities and other relevant authorities but further development is required. • DOAS measurements may be affected by fluctuating ambient light levels, in terms of varying light intensity and light scattering, due to changes in meteorological conditions, e.g., cloud cover, the time of day, transition from day to night. Compensation for varying ambient light levels may be required. • The size and weight of current instruments (several tens of kilograms) limits the portability of DOAS instruments.	satellite sensors can measure multiple pollutants simultaneously, the data could be used in the compilation and verification of the NAEI and GHGI. • Ground-based DOAS instruments could be used to validate satellite data and validation methodologies exist for this purpose.

3.3.2 Potential measures to reduce the risks to innovation and market barriers associated with remote sensors

The potential measures that Defra could pursue over the next 10-15 years in order to reduce the risks to innovation and market barriers thereby promoting uptake of remote sensors are given in Table 3-4. Each proposed measure was appraised, with the reasoning provided in the respective table, and given a priority weighting, as defined in Table 2 4.

Table 3-4 Remote sensors: risks to innovation, market barriers and potential measures

Risk to innovation or market barrier and rationale	Source of potential measure	Potential measure and steps to achieving potential measure. *Defra could….*	Action owner	Priority rating (low, medium, high	Ease of achieving potential measure (easy, moderate, difficult)
DOAS data cannot be used for compliance assessment purposes and data reporting to the Commission – current air quality Directives do not permit the use of remote sensors.	Project Team	• Liaise with EC (DG ENV and JRC) to identify possible adjustments to the air quality Directives to allow use of remote sensor data. • Engage with EIONET on suitable standards for remote sensor measurements. • Establish a working group to develop proposals for DQO for remote sensor data.	• UK and European commercial and research community. • Defra to lead engagement	High	Difficult
Lack of standardised approach for processing remote sensor data – may lead to confusion amongst potential end-users and limit uptake.	Project Team	• Engage with UK and European partners to form working group to develop standardised method to convert raw data into ready-to-use data products for use in air quality applications.	• UK and European commercial and research community • Defra to facilitate engagement	High	Moderate

Limited availability of data and software tools for data handling, analysis and display – data processing requires specialist software and specialist knowledge to use.	Questionnaire	• Develop guidance for potential end-users on the use and processing of remote sensor measurements. • Encourage stakeholders to make remote sensing data more widely available. • Promote knowledge sharing between UK experts and end-users. • Identify UK software developers with the capability to develop tools that would handle, analyse and display data.	• UK commercial and research community • Defra to facilitate engagement	Low	Moderate

3.4 Pervasive sensors

3.4.1 Summary of findings for pervasive sensors

Table 3-5 presents the assessment of pervasive sensors against the key study considerations, detailed in Section 1.3.3, based on the stakeholder responses. Where information was provided by the project team, this is noted in the Table. A summary of limitations and benefits of the innovative technology is provided at the end of the Table. The summary risk assessment for these technologies, as described in Section 2.4, is given in Appendix 3.

Table 3-5 Assessment of pervasive sensors

Pervasive sensors
Will it be possible to use the innovative technology within the UK's air quality monitoring networks in the next 10-15 years? - **Will the innovative technology be suitable to supplement or displace the UK's air quality monitoring network?** - **Will the innovative technology be suitable to provide measurements that can feed into the LAQM review and assessment regimes?** - **Will the innovative technology be able to provide measurements to help fulfil national and local air quality objectives?**
Stakeholder responses indicated that pervasive sensors could form part of the UK air quality monitoring network within the next 10-15 years and could supplement the UK's network in the medium term (5-10 years). The stakeholder responses indicated that measurement uncertainties are within those of indicative measurements as defined within the DQOs of the air quality Directives. Pervasive sensors capable of providing indicative measurements could be used within the LAQM regime for review and assessment purposes. Pervasive sensors can measure a range of air quality pollutants within the ranges currently measured in ambient air. They can also measure noise, meteorological conditions, position (via GPS sensors) all within one unit composed of multiple sensors. Pervasive sensors can be formed into network or arrays of sensors which can be used to provide detailed spatial air quality measurements, whilst hand-held units, and those mounted to buses, cars and bikes can be used to produce air quality maps. In the longer term (10-15 years) they could displace some of the current technologies used in the UK's air quality monitoring networks depending upon a number of factors, chiefly demonstration of compliance with the requirements of the air quality Directives. Other limitations identified in the stakeholder responses and by the project team included the need for a standardised approach to sensor calibration, sensor reliability, and limits of detection. Stakeholder responses described a range of types of pervasive sensor. Briefly, electrochemical sensors measure gases and optical particle counters (light scattering cells) measure particulate matter, thus they differ from current techniques which use spectroscopic methods (e.g., chemiluminescent NOx/NO_2 analysers) or filter sampling, used to measure particulate matter. They are typically small, compact, physically robust instruments which can be deployed in a range of configurations to give measurements at fixed locations offering features in-line with current UK air quality monitoring networks. Stakeholder responses noted that they can be deployed in traditionally inaccessible locations, e.g., at height, on mobile platforms, and in remote locations where there is no access to mains power or telemetry, providing air quality measurements in locations that are inaccessible to current measurement technologies – this was identified as a key driver in the development of this technology. Stakeholder responses reported measurement uncertainties to be ~10-20%, comparable with the requirements of indicative measurements as stated in the data quality objectives of the air quality Directives. They can provide measurements, with comparative levels of error, as time-integrated passive sampling of air pollutants, e.g., diffusion tubes used to measure NO_2, and down to a few ppb which are within the ranges currently measured in ambient air, except for NO_2 for which the limit of detection (LoD), in practice, is much higher than the other air pollutants. Limits of detection vary by air pollutant as shown below, these where provided by stakeholders in response to the questionnaires:

Air pollutant	CO	NOx/NO_2	O_3	SO_2	VOC

Conversion factor 1 ppb in µg m-3	1.145	1.88	2	2.62	--
Typical LoD ppb (top row)	~5 ppb	~40 ppb	~2 ppb	~9 ppb	10 ppb
$\mu g\ m^{-3}$ (bottom row)	~6 $\mu g\ m^{-3}$	~75 $\mu g\ m^{-3}$	~5 $\mu g\ m^{-3}$	~22 $\mu g\ m^{-3}$	--

Will the innovative technology comply with the air quality monitoring data quality objectives (DQO) defined in ambient air quality directives (EU Directives 2008/50/EC and 2004/107/EC)?

Stakeholder responses indicated that pervasive sensors are currently only compliant with the data quality objectives of the European air quality Directives for indicative measurements and further work will be required over the next 10-15 years.

A new CEN working group (WG42) was established in 2015 to develop standards for assessing the performance of pervasive *ga*s sensors (the name of the WG seems to indicate that it will be exclusively looking at *gas* sensors *not* particulate sensors). Stakeholder responses recognised there was no standardised approach for calibrating pervasive sensors but this requirement may be resolved by the formation of WG42.

Pervasive sensors measure particulate matter by means of optical particle counters (light scattering cells) and do not provide gravimetric measurements required by the air quality Directives. Under LAQM guidance measurements from optical particle counters are only acceptable for review and assessment purposes but not detailed assessment. Stakeholder responses were unclear as to whether this issue had been considered or how it was being addressed.

Will the innovative technology be able to provide air quality measurements with improved spatial / temporal resolution?

Pervasive sensors can provide improved spatial resolution and temporal resolution air quality measurements relative to current, in-use analysers.

Pervasive sensors are designed to be formed into sensor arrays, networks providing high spatial resolution (typically 80 m to 1500 m) air quality measurements. Measurements from high-density arrays could provide insights within micro-environments delivering improved source apportionment, helping to identify hot-spots and causes of air pollution, providing evidence to design solutions, take action and evaluate impacts. Applications include UTMC[12] and low emissions bus initiatives. The project team noted that detailed in-street measurements from pervasive sensors would also reduce reliance on generalised dispersion modelling.

Stakeholder responses noted that the design of devices allows them to be easily portable or wearable – key drivers in the development of this innovative technology. Hand-held devices, and devices mounted to buses, cars and bikes can be used to produce air quality maps of background and roadside air quality pollutants. Sensor location can be georeferenced through the use of GPS and incorporated into local and/or national mapping outputs and easily presented on-line.

Stakeholder responses indicated that temporal resolutions of a minute could be achieved with some types of sensor, no indication was given as to how the temporal resolution might change in future.

Will the innovative technology offer improved data usability, offering added research value? Will it be able to measure multiple pollutants simultaneously?

The project team noted that pervasive NO_2 sensors display cross-sensitivity to O_3 / oxidants which can lead to poor or erroneous NO_2 measurements.

Stakeholder responses stated that pervasive sensors can simultaneously measure a range of air quality pollutants. Electrochemical sensors measure gases and optical particle counters (light scattering cells) measure particulate matter. Additional sensors can be added, offering added research value, allowing meteorological conditions, noise, position (via GPS sensors) to be measured all within one unit.

[12] Urban Traffic Management Control systems are computerised systems used improve the flow of traffic in towns and cities and are designed to link communications between various components of traffic management, such as traffic signal control, air quality monitoring, car park management and bus priority.

The supplemental meteorological observations provided by pervasive sensors could enhance the research value of the UK's air quality monitoring networks, providing free-to-user meteorological data, in addition to that provided by other organisations, e.g., the Met Office, without adding significantly to the cost burden of monitoring. Likewise, noise measurements would offer added value and would be of interest to local authorities, local highways agencies, health professional, members of the public, and community groups.

As noted above, hand-held devices, and devices mounted to buses, cars and bikes can be used to produce air quality maps of background and roadside air quality pollutants providing supplemental data, in addition to those from the UK's air quality monitoring network.

One current area of application, highlighted in the stakeholder response and by the project team, was the use of pervasive sensors to form high density in-street networks, with UTMC systems. The data from pervasive sensor-UTMC systems could be used by local authorities and highways agencies to maximise road network potential to create a more robust and intelligent system that can be used to meet current and future management requirements, helping to reduce vehicle-emissions and improve local air quality.

What are the potential costs associated with the innovative technology?

Stakeholder responses stated that the capital costs for pervasive sensors range from a few £thousand for single pollutant devices up to £tens of thousands for fully integrated, multi-species sensors, capable of providing additional data, e.g., meteorological observations, noise. Devices can be tailored to customer's specific needs. Data links and database management account for infrastructure costs. Sensors need to be replaced at 3 to 12 month intervals, depending on manufacturer, adding to on-going recurrent costs which are be proportional to the size of the deployment. No indication was given of future costs though uptake may drive costs down.

Stakeholder responses indicated that instruments are designed to be “hot-swappable”, i.e., one unit is replaced with another, rather than been serviced or calibrated in-situ. This approach requires a small number of units need to be purchased and held in reserve and is concurrent with established practice. Additional costs are associated with data processing and analysis costs are dependent on the service provider and approach used. Only indicative costs were provided in the questionnaire responses but tend to be lower, per unit than for conventional instruments.

How would the output from the innovative technology be integrated with UK's empirical modelling approach which is used to demonstrate compliance with EU air quality Directives

Stakeholder responses did not give any indication of the potential for integrating measurements from pervasive sensors with the UK's empirical. The project team did not perceive any problem that would prevent the integration of pervasive sensor data with UK's empirical modelling approach though the data would have to be validated as with all new technologies. Integration of gas measurements could prove more straightforward than particulate measurements as pervasive sensors infer particulate mass from light scattering cells rather than gravimetric measurements.

How accessible are the measurements from the innovative technology to a wide range of potential end-users, e.g., Central Government, Public Health England, local authorities, local highways authorities, and the public? Can they help in the promotion of citizen science?

Measurements form pervasive sensors could potentially be made available to a wide range of end-users (all of those listed above), and help promote of citizen science projects, but at the current time there are no publically accessible datasets.

Stakeholder responses noted additional costs for data links and database management. As noted above, pervasive sensors can be combined with UTMC systems, allowing local authorities and highways authorities to maximise road network potential to create more robust and intelligent system that can be used to meet current and future management requirements, helping to reduce vehicle-emissions and improve local air quality. Simultaneous noise measurements and meteorological observations could be used for noise mapping and providing data that would help in the analysis of air quality measurements.

Stakeholder responses noted that pervasive sensors could be worn as personal air quality monitoring devices for use in citizen science projects and for mapping air quality. This data could be used for health assessments by health authorities and Public Health England, and to advise cyclists or a pedestrians on the best routes to minimise exposure to poor air quality.

Summary of current limitations and benefits

Limitations	*Benefits*
• Stakeholder responses indicated that the measurement uncertainty of pervasive sensors is adequate to provide indicative measurements as defined under the DQOs of the air quality Directives and thus cannot be used for compliance measurement. • Pervasive NO_2 sensors display cross-sensitivity to O_3 / oxidants which can lead to poor or erroneous NO_2 measurements. LoD for NO_2 sensors is ~40 ppb (~75 µg m^{-3}) in practice and towards the upper end of ambient concentrations. • Stakeholder responses recognised there was no standardised approach for calibrating pervasive sensors. A new CEN working group (WG42) was established in 2015 to develop standards for assessing the performance of gas sensors which help resolve this issue within the next 5-10 years. • Stakeholder responses indicated that sensors need to be replaced every 3-12 months, depending on device. • On-going costs of sensor replacement, data links and database management add to infrastructure costs.	• Pervasive sensors are designed to be small, compact, and physically robust, capable of measuring one or more air quality pollutants simultaneously via electrochemical cells (gases) or optical particle counters (particulate measurements). • Air quality sensing capabilities can be augmented by the addition of a range of other devices to the sensor in order to provide noise, meteorological observations, and positional data via GPS. The sensors can be deployed in a range of configurations giving fixed-point measurements, in locations which are considered inaccessible to current instruments, mobile devices, which can be mounted on vehicles, and could be carried or worn. • Pervasive sensors can generate air quality measurements and supplemental data which could be of value to a range of end-users and researchers. Pervasive sensor measurements could be used within the UK national monitoring networks and local authority networks. Sensors could be built-up into high density measurement networks, used to study air quality in remote locations and urban microenvironments, providing insights into in-street sources and pollution "hot-spots". Combination with UTMC systems allows local authorities and highways authorities to maximise road network potential to create more robust and intelligent system that can be used to meet current and future management requirements, helping to reduce vehicle-emissions and improve local air quality, and map noise pollution. Pervasive sensors could be worn as personal air quality monitoring devices for use in citizen science projects and for mapping air quality. This data could be used for health assessments by health authorities and Public Health England, and to advise cyclists or a pedestrians on the best routes to minimise exposure to poor air quality. • Sensor LoDs are sufficiently low to allow air quality pollutant concentrations encountered in ambient air to be measured now and in the future. • Pervasive sensors are designed to require limited maintenance and to be calibration-free during their lifetime.

3.4.2 Potential measures to reduce the risks to innovation and market barriers associated with pervasive sensors

The potential measures that Defra could pursue over the next 10-15 years in order to reduce the risks to innovation and market barriers thereby promoting uptake of pervasive sensors are given in Table 3-6. Each proposed measure was appraised, with the reasoning provided in the respective table, and given a priority weighting, as defined in Table 2 4.

Table 3-6 Pervasive sensors: risks to innovation, market barriers and potential measures

Risk to innovation or market barrier and rationale	Source of potential measure	Potential measure and steps to chieving potential measure. *Defra could….*	Action owner	Priority rating (low, medium, high	Ease of achieving potential measure (easy, moderate, difficult)
Pervasive sensors data cannot be used for compliance assessment purposes and data reporting to the Commission	Project Team	• Establish UK working group to develop proposals for compliance assessment & data reporting DQO for pervasive sensors	• UK commercial and research community commercial and research community. • Defra to lead engagement	High	Difficult
Lack of standardised approach for calibrating and testing pervasive sensors or demonstrating equivalence – may lead to confusion amongst potential end-users and limit uptake.	Questionnaire	• Engage with the recently established WG42 on *gas* sensors. • Develop standard testing and evaluation protocols for gas sensors focusing on assessing the performance of (1) sensors within a batch, and (2) sensors in different devices.	• UK commercial and research community • Defra to facilitate	High	Moderate
		• Expand remit of WG42 to cover particle sensors, or encourage formation of new WG to look into this issue. • Develop a standardised approach for inferring particulate loadings from particle number counts.			Difficult

Lack of a peer reviewed performance assessment of pervasive sensors – a robust assessment may provide credibility promoting greater uptake.	Project Team	• Undertake a peer-reviewed evaluation of the technology, and data collected to date, e.g., from field measurements and manufacturer testing, or a combination of the two. • Report on findings.	• UK commercial and research community • Defra to facilitate	High	Moderate
Only one company produces NO_2 sensors capable of measuring ambient concentrations – reliance on one producer may stifle innovation and present a risk to other developers, and end-users, if the technology changes, or the manufacturer withdraws the product from the market.	Project Team	• Engage with UK experts and sensor developers to identify whether an alternative producer/supplier of NO_2 sensors capable of measuring ambient concentrations exists.	• Market driven, no further intervention required by Defra	Low	Difficult

3.5 Fixed-point sensors

3.5.1 Summary of findings for fixed-point sensors

Table 3-7 presents the assessment of fixed-point sensors against the key study considerations, detailed in Section 1.3.3, based on the stakeholder responses. Where information was provided by the project team, this is noted in the Table. A summary of limitations and benefits of the innovative technology is provided at the end of the Table. The summary risk assessment for these technologies, as described in Section 2.4, is given in Appendix 3.

Table 3-7 Assessment of fixed-point sensors

Fixed-point sensors
Will it be possible to use the innovative technology within the UK's air quality monitoring networks in the next 10-15 years? - **Will the innovative technology be suitable to supplement or displace the UK's air quality monitoring network?** - **Will the innovative technology be suitable to provide measurements that can feed into the LAQM review and assessment regimes?** - **Will the innovative technology be able to provide measurements to help fulfil national and local air quality objectives?**
Three different instrument type of instrument were identified in the stakeholder responses which could form a part of the UK's air quality monitoring networks in the next 10-15 years. • Micro Aethalometer Aethalometers are currently used within the UK's air quality monitoring network to measure ambient black carbon (BC, soot) loadings, but there is no statutory requirement to measure BC at the current time – the measurements are used for research purposes to identify particulate matter sources. The stakeholder responses reported on the development of a micro aethalometer for personal BC exposure monitoring. The device's compact design and low weight could permit its use in a more flexible manner than conventional aethalometers. The sensor was reportedly self-calibrating with a limit of detection of 50 ng m^{-3}, comparable with current, in-use aethalometers. No information was provided on the device's accuracy and precision, but this could be established by comparison against aethalometers in-use in the UK's national air quality monitoring networks. • OPC Stakeholder responses noted the development of Optical Particle Counters (OPC) capable of measuring particle size (diameter) and number as they pass through a collimated beam of light. These can be used to produce portable and physically robust sensors, with low power requirements. Measurements can be scaled to infer particulate mass but no formalised method exists. There is no statutory requirement to measure particle number at the current time and OPC can only be used in screening assessments within the LAQM regime. • Direct-measurement NO_2 analyser Stakeholder responses identified the development of two direct-measurement NO_2 analysers using spectroscopic methods, as opposed to chemiluminescence NOx analysers, the current reference method, which are used in the UK's national and local air quality monitoring networks. NO_2 measurements from chemiluminescent NOx analysers can suffer from inference from other nitrogen compounds, e.g., particulate phase nitrate (pNO_{3-}), peroxyacetyl nitrate (PAN), and nitric acid (HNO_3) which could cause small over-estimates, possibly of the order of a few µg m^{-3}, of NO_2 concentrations, though the effect has not been fully quantified in the UK. The project team noted that the photolytic conversion of NO_2 is poor. Type and equivalence testing would be required in the next 2-5 years to demonstrate this technology's potential for use for compliance monitoring. If developers are able to demonstrate equivalence with the current reference method these sensors could supplement and/or displace chemiluminescent NOx analysers in the UK's air quality monitoring network within the medium term (5-10 years). They could also provide measurements that can feed into the LAQM regime. Sole reliance on direct-measurement NO_2 analysers could have implications for the UK's empirical modelling

approach, that requires NOx measurements, and which it uses to demonstrate compliance with EU air quality directives.

Stakeholder responses reported that direct-measurement NO_2 analysers are the same size, have similar outputs as current NOx instruments, requiring a temperature controlled environment. Accuracy and precision are claimed to be 0.5% of reading above 5 ppb for one of the devices which, the project team noted, was better than current NOx chemiluminescence analysers. The instrument would require calibration and the measurements would have to be scaled and ratified but no further information was provided, so the project team concluded that a similar QA/QC would need to be employed as currently used for chemiluminescent analysers.

- DUVAS

Differential Ultra Violet Absorption Spectrometer (DUVAS) are a novel development offering fixed-point or mobile measurements, providing improved spatial resolution of air quality pollutants, e.g., within street canyons and pollution hotspots. Such measurements may have value within the LAQM review and assessment regime.

DUVAS instruments have detection limits of the order of a few ppbs, ideal for ambient air quality measurement of gaseous pollutants in the UK, with a reported measurement uncertainty of ±3%. They can simultaneously measure a range of gases (as detailed later) and could be capable of providing fixed point measurements that could supplement or displace methods in-use in the UK air quality monitoring or local authority networks.

Will the innovative technology comply with the air quality monitoring data quality objectives (DQO) defined in ambient air quality directives (EU Directives 2008/50/EC and 2004/107/EC)?

- Micro Aethalometer

There is no statutory requirement to measure BC, though his may change in the next 10-15 years.

- OPC

Currently particulates are measured gravimetrically and there is no statutory requirement to measure particle numbers, though this may change in the next 10-15 years.

- Direct-measurement NO_2 analyser

Pending equivalence testing, which could take two to five years, there could be potential to use direct-measurement NO_2 analysers within the UK's national and local air quality monitoring networks.

- DUVAS

The stakeholder response did not indicate whether the DUVAS instruments are capable of demonstrating compliance with the requirements of the DQOs as given in the air quality Directives but it is believed that it has not undergone equivalence testing.

Will the innovative technology be able to provide air quality measurements with improved spatial/temporal resolution?

- Micro Aethalometer

Stakeholder responses indicated that micro aethalometers had a temporal resolution of 1 Hz (one measurement per second) and could offer higher resolution measurements. As a personal monitor it will be small enough to be carried or worn, and combined with GPS data, could provide detailed BC maps. The sensor could also be used in locations inaccessible to conventional aethalometers.

- OPC

Stakeholder responses indicated that OPC had a temporal resolution of 1 Hz and could offer higher resolution measurements. Some OPC are sufficiently small to be used as personal monitors which, combined with GPS data, could provide detailed particle number. The sensor could also be used in locations inaccessible to conventional gravimetric particulate instruments.

- Direct-measurement NO_2 analyser

Stakeholder responses indicated that the spatial and temporal resolution of direct-measurement NO_2 analyser was similar to those of conventional current in-use analysers.

- DUVAS

A mobile variant of this device is offered which could offer improved spatial resolution but the stakeholder responses did not give indicate whether this could offer improved temporal resolution.

Will the innovative technology offer improved data usability, offering added research value? Will it be able to measure multiple pollutants simultaneously?

- Micro Aethalometer

Micro aethalometer measurements could be combined with GPS data to provide detailed BC maps which could be used to assess personal exposure and air pollution “hotspots”.

- OPC

OPC are capable of measuring $PM_{2.5}$ and PM_{10} simultaneously with one sensor, particle counts would provide an additional research data stream. Measurements could be combined with GPS data to provide detailed particle number concentration maps which could be used to assess personal exposure and air pollution “hotspots”.

- Direct-measurement NO_2 analyser

Direct-measurement NO_2 analyser could be used to help understand the effect of nitrogen compounds on NO_2 measurements from chemiluminescent NOx analysers and the implications for exceedances.

- DUVAS

DUVAS instruments can simultaneously measure a range of air quality pollutants (e.g., NO, NO_2, SO_2 and O_3), VOCs and greenhouse gases, without cross interference. Currently, multiple instruments have to be used within the UK’s national monitoring networks to provide the same range of measurements. Offerings of research value were also identified.

DUVAS instruments are calibrated with known gases of known concentration in order to provide the instrument response which is written to file. Retrospective measurements can be obtained by calibrating the instrument at a later date and using this information to retrieve air quality measurements of air pollutant not originally measured, from archived data. This can be used to “fill-in gaps” in time series data or study air pollutants not considered at the time of the original measurements offering further research value, especially in terms of trend analysis.

What are the potential costs associated with the innovative technology?

Stakeholder responses provided limited cost information for fixed-point sensors**.**

- Micro Aethalometer

The stakeholder responses showed that the capital cost of such samplers would be in the region of £thousands. On-going maintenance costs would be in the region of £hundreds per year.

- OPC

The stakeholder responses revealed that the capital costs of OPC are quite variable, ranging from £thousands to £tens of thousands but on-going costs would be relatively low as no consumables would be required. OPC do not generally require temperature-controlled cabinets and their consumption of electricity is relatively low in comparison to more conventional instrumentation. As OPC can simultaneously measure PM_{10} and $PM_{2.5}$, combining two instruments into one may provide cost benefits.

- Direct-measurement NO_2 analyser

No information was provided regarding the capital cost and ongoing costs of direct-measurement NO_2 analysers but the project team concluded that maintenance costs would be similar to those for current chemiluminescence NOx analysers.

- DUVAS

Stakeholder responses indicated that the capital cost of a DUVAS was of the order of tens of £thousands – the cost is dependent on the range of species measured by the instrument. The cost of consumables for the DUVAS instrument are reportedly very low; on-going costs are associated with UV lamp replacement and re-calibration at a cost of several £hundred every 3-4 months.

No indication of how costs may change in the future were given in the stakeholder responses.

How would the output from the innovative technology be integrated with UK's empirical modelling approach which is used to demonstrate compliance with EU air quality Directives

- Micro Aethalometer

There is no statutory requirement to measure or model BC, though his may change in the next 10-15 years.

- OPC

There is no statutory requirement to measure or model particle numbers, though his may change in the next 10-15 years.

- Direct-measurement NO_2 analyser

The current UK compliance modelling uses NOx, not NO_2, measurements. The project team stated that uncertainties over the primary NO_2 fraction of NOx emissions in inventories and the complexity of the atmospheric chemistry would make modelling based on NO_2 measurements alone difficult, or potentially impossible. If direct-measurement NO_2 analysers were used, a change in the UK's national modelling approach would be required and current chemiluminescent NOx analysers would also have to remain in-place.

- DUVAS

No evidence was provided in the stakeholder response. Further development and testing of the techniques may be required before a complete assessment can be made

How accessible are the measurements from the innovative technology to a wide range of potential end-users, e.g., Central Government, Public Health England, local authorities, local highways authorities, and the public? Can they help in the promotion of citizen science?

Stakeholder response gave no indication as to the accessibility of the measurements from all three technologies except that measurements from all three technologies can be streamed assuming there is a suitable datalink (GPRS modem or internet) available.

OPC and micro-aethalometer measurements could be used to assess human exposure to particle number and BC, respectively. These would be of value in health impact assessment studies for use by organisations such as Public Health England, as well as local authorities and local highways authorities.

Stakeholder responses indicated that commercial DUVAS instruments are available but not in use the UK's local and national air quality monitoring networks. Data could be directly stream data to the cloud for use by potential end-users. High resolution spatial data could be of value for local authorities and local highways authorities.

Use of the data from all four instruments in citizen science applications was not identified in the stakeholder responses which may indicate it has not been considered.

Summary of current limitations and benefits

Limitations	*Benefits*
• Micro aethalometers and direct-measurement NO_2 analysers can only measure single air pollutants. • OPC can only be used as screening tools within the LAQM regime. • Stakeholder responses indicated that direct-measurement NO_2 analysers need to undergo type and equivalence testing, which could take 2-5 years to demonstrate, before they are suitable for use in compliance monitoring. • Direct-measurement NO_2 analysers would require similar levels of servicing and calibration when compared to chemiluminescent NOx analysers.	• OPC could measure $PM_{2.5}$ and PM_{10} simultaneously, particle counts would provide an additional research data stream. • Micro aethalometers and OPC require little on-going calibration, apart from annual calibration and servicing. • Micro aethalometers and OPC can offer high resolution (1 Hz) measurements, when compared to conventional samplers. They are portable, providing measurements in locations inaccessible to conventional measurements. • OPC and micro-aethalometer measurements could be used to assess human exposure to particle number and BC, respectively.

• Photolytic conversion of NO_2 is poor in direct-measurement NO_2 analysers. • If direct-measurement NO_2 analysers were used a change in the UK's national modelling approach would be required, due to uncertainties over the primary NO_2 fraction of NOx emissions, and current chemiluminescent NOx analysers would also have to remain in-place offering little cost benefit. • DUVAS instrument are commercially available but relatively new and unproven. Validation and characterisation of this technique would be required. • The stakeholder responses did not indicate whether the DUVAS is capable of demonstrating compliance with the requirements of the data quality objectives as given in the air quality Directives. They are not in use the UK's local and national air quality monitoring networks and therefore there is no data available. Data could be streamed directly to the cloud and made available for a range of end-users. • Cost implications of micro aethalometers and OPC unclear from stakeholder responses. Direct-measurement NO_2 analysers likely to be similar to chemiluminescent NOx analysers. DUVAS instruments could potentially replace multiple gas analysers but initial capital costs are significant and may offset any cost savings offered by combining several instrument into one.	• Direct-measurement NO_2 analysers limit the potential for small over-estimation of NO_2 due to interferences from nitrogen compounds which affect chemiluminescent NO_X analysers currently used in the UK's national air quality monitoring networks. They could help develop our understanding of interferences due to nitrogen compounds which affect chemiluminescent NOx analysers • DUVAS instruments can simultaneously measure multiple gaseous air pollutants providing fixed-point or mobile measurements, with a reported measurement uncertainty of ±3%. • DUVAS instruments can provide continuous high temporal and spatial resolution measurements for a range of air quality pollutants (e.g., NO, NO_2, SO_2 and O_3), VOCs and greenhouse gases, without cross interference. Currently, multiple instruments have to be used within the UK's national monitoring networks to provide the same range of measurements. • Retrospective measurements can be obtained from DUVAS data by calibrating the instrument at a later date and using this information to retrieve air quality measurements of air pollutants not originally measured, from archived data. This can be used to "fill-in gaps" in time series data or study air pollutants not considered at the time of the original measurements offering further research value. • The cost of consumables for the DUVAS instrument are reportedly very low; on-going costs are associated with UV lamp replacement and re-calibration at a cost of several £hundred every 3-4 months. • Measurements from all four technologies can be streamed assuming there is a suitable datalink (GPRS modem or internet) available.

3.5.2 Potential measures to reduce the risks to innovation and market barriers associated with fixed-point sensors

All the technologies identified were under-development and close to the market or in-use. Most needed to undergo equivalence and/or type testing, where appropriate, before they could achieve wider acceptance. There are established routes for equivalence and type testing of air quality monitoring sensors in the UK. Other potential measures that Defra could pursue over the next 10-15 years in order to reduce the risks to innovation and market barriers thereby promoting uptake of fixed-point sensors are given in Table 3-6. Each proposed measure was appraised, with the reasoning provided in the respective table, and given a priority weighting, as defined in Table 2 4.

Table 3-8 Fixed-point sensors: risks to innovation, market barriers and potential measures

Risk to innovation or market barrier and rationale	Source of potential measure	Potential measure and steps to achieving potential measure. *Defra could….*	Action owner	Priority rating (low, medium, high	Ease of achieving potential measure (easy, moderate, difficult)
Lack of standardised approach for converting particle number counts into particulate mass loadings – may limit uptake of OPC amongst end-users.	Project Team	• Develop a standardised approach for inferring particulate loadings from particle number counts.	• UK and European commercial and research community. • Defra to lead engagement.	High	Difficult

3.6 High level risks to innovation and market barriers and potential responses

3.6.1 Overview

Four high-level risks and barriers to innovation, affecting some or all of the technologies, were identified or inferred from stakeholders' responses to the questionnaire:

- **Lack of standardised approaches** for:
  - Processing raw satellite data into final data products
  - Validating the performance of satellite-borne sensors
  - Validating the performance of remote sensors
  - Validating the performance of pervasive sensors
  - Inferring particulate loadings from particle number counts

  These were identified in Table 3-2, Table 3-4, Table 3-6, and Table 3-8.
- **Equivalence testing** was identified as a barrier and is necessary for non-reference techniques so developers of innovative technologies can demonstrate their instrument's measurement robustness and its ability to comply with national and EU measurement standards such as the DQOs stated in the air quality Directives. Completing this process can often take 1-2 years for gas analysers and up to 5 years for particulate matter instruments (due to the time taken to gather sufficient statistically significant data to demonstrate equivalence). Stakeholders report that completing this process can be a significant time and

cost burden (although completing this process provides the developer with access to a new market).

- **Lack of access to development funding** was identified as a barrier by developers of all the identified technologies. Calls for increased development funding can be expected as greater external funding makes developer's commercial offerings more profitable and reduces the financial risk to the developer and their investors. Comprehensive understanding of the true scale of this barrier is difficult as it requires knowledge of the true development costs for a technology which is not widely available.
- The barrier of **limited uptake amongst potential end users** was inferred by the project team from the stakeholder responses. There is a need to raise awareness about innovative technologies and to publicise their benefits, but there needs to be separation between raising market awareness for technologies amongst potential end-users to drive uptake and potentially free marketing for developers' instruments, which could be met from developers' own budgets. Technology developers also have a role to play as uptake of their innovative technologies will be limited if they are not able to demonstrate that they are "fit for purpose", i.e., they are not capable of providing measurements which can demonstrate equivalence with the DQOs given in the air quality Directives. It is up to developers, not regulators, to ensure that they meet this short-coming if they wish to promote uptake amongst potential end-users. It is important, as noted above, that the process of equivalence testing does not act as a barrier.

Each of these risks to innovation and market barriers are described in the following subsections.

3.6.2 Development of Standardised Approaches for Innovative Technologies

CEN standard methods exist for fixed-point measurement techniques. In the absence of suitable standard approaches or methods, data from satellite-borne sensors, remote sensors and pervasive sensors cannot demonstrate their equivalence with reference methods, their suitability for use in compliance monitoring, or for use within the LAQM regime. If innovative technologies cannot demonstrate consistency and comparability with conventional techniques that is required by end-users, this may impede uptake.

Potential measures to overcome the market barrier and the risk to innovation

For satellite-based sensor and remote sensors techniques, there are no plans, at present, to establish CEN working groups. If the Government wished to encourage the development of these technologies, Defra could consider exploring European interest in the use of these innovative techniques for air quality monitoring. It could take a number of years to generate sufficient momentum amongst interested parties within Europe and to engage with the Commission. Development of an appropriate standard may take time and it is unlikely that there could be much progress in under ten years.

As of May 2015 a new CEN Working Group, WG42, has been established to develop standards for assessing the performance of pervasive (gas) sensors. The aspiration is that a set of standards could be in place within five or so years The WG42 has a remit to formulate a protocol for testing and performance evaluation of pervasive sensors. As pervasive sensors measure a wide range of air pollutants it will be important to ensure that any standard is comprehensive (i.e., technically appropriate for all) and cost effective.

Defra have started to engage with EIONET on suitable standards for satellite-borne sensor measurements. It would also be helpful to explore European interest in the use of satellite measurements for air quality, and how legislative pathways might need to be adapted to accommodate the use of these measurements.

Defra and the Commission could consider whether similar Working Groups would benefit other innovative technologies.

3.6.3 Equivalence testing

There is perceived to be insufficient flexibility within the current monitoring regime preventing acceptance of new technologies for the purpose of compliance assessment. This is perceived by stakeholders to lead to an increase in development costs. This is an EU issue that affects UK compliance monitoring. The relationship between LAQM monitoring and national compliance monitoring is more readily under the UK's control and therefore offers some potential scope for change. Defra could consider how to introduce flexibility into the regime without potentially "watering down" standards and still ensuring compliance with the European air quality Directives.

Potential measures to overcome the market barrier and the risk to innovation

In order to overcome the market barrier posed by the legislative framework, the following potential measures could be considered by Defra:

- Consult with stakeholders to identify where improvements to the equivalence testing process could be made.
- Consult with the European Commission / Environment Agency as to the potential to streamline and/or tier the equivalence testing process in order to make it less onerous without compromising standards of the regime.
- Explore options (e.g., with technology developers and the Environment Agency) to make the equivalence testing process more responsive so it can be adapted to assess innovative technologies as they come to market. Stakeholder perception is that there is lack of flexibility in the testing and monitoring regime for innovative techniques.
- Recognise that there are different potential markets for different sensors, with a key differentiation being whether sensors could be used for compliance assessment, indicative or other purposes. Or if they have other end-users for whom the legislative framework is not a market barrier.

3.6.4 Lack of access to development funding

Lack of access to development funding was identified as a barrier by some stakeholders, but without fuller and more detailed disclosure by stakeholders it is difficult to assess the veracity of such claims, developers' awareness of access to funding streams or the extent to which it is posing a risk to innovation or a market barrier.

Potential funding streams exist within Innovate UK for two of the innovative technologies considered in this report and may be able to offer support:

- Satellite-borne sensors and satellite data products for air quality monitoring fall within space applications supported by the Space Applications Catapult[13].
- Pervasive sensors for air quality monitoring fall within the electronics, sensors and photonics theme area of Innovate UK.

Defra do not provide funding *per se*, but hold research competitions in response to specific evidence or research needs. Small grants are also offered to local authorities through the LAQM regime and is focused towards delivering specific measures to improve local air quality.

Potential measures to overcome the market barrier and the risk to innovation

It could be helpful to identify the linkages between innovative technologies and priority areas identified by Innovate UK and Defra's "One Monitoring Strategy". This could include the direct and co-benefits offered, e.g., the use of remote sensing techniques (satellites and aircraft-borne sensors) to provide air quality monitoring data and precision farming data, both of which could be of value to Defra.

To broaden their income base, innovators may wish to consider the development of end-user applications that could deliver income in addition to sensor sales, once the innovative technology comes to market.

3.6.5 Limited uptake amongst potential end users

There appeared to be a concern that due to a lack of awareness of innovative techniques and what they can offer there could be poor uptake of such technologies across:

- Air quality professionals, e.g., researchers, consultants, local authorities and policy makers, who may be confused as to whether innovative technologies can be used for equivalence

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[13] https://sa.catapult.org.uk/programmes

monitoring under the LAQM regime (as none of the technologies are currently accepted under the Directives)

- Health professionals, e.g., local health authorities and national bodies such as Public Health England, looking to assess the impact of air pollution on human health.
- Highways agencies (local and national) who are concerned with assessing the impact of transport emissions on air quality.
- Members of the general public involved in volunteer monitoring or citizen science projects, who want to assess air quality in and around their home, place of work, or along their route to work to better inform their lifestyle choices or who to limit the impact of poor air quality on pre-existing health conditions, e.g., asthma, which may be exacerbated by poor air quality.

This could result in potential end-users sticking with familiar techniques, though it is a manufacturer's obligation to market new technology . Further assessment would be required to better understand whether this is a valid concern.

Potential measures to overcome the market barrier and the risk to innovation

Engagement between innovators and potential end users, such as marketing days or other opportunities where users and innovators can explore new ideas and air quality monitoring options could help to promote innovative technologies. In order to promote the uptake of satellite data, the UK Satellite Applications Catapult could be encouraged to establish linkages and a knowledge transfer program amongst the UK's "space-users community", composed of SMEs, non-space companies, and other potential end-users, including local authorities. This could help promote business opportunities and applications for the UK space industry. Defra are consulting with the EU Centres of Excellence to bring about this change at the European-level but this information, and the opportunity this represents, needs to be cascaded down to potential end users to encourage uptake in the next 10-15 years.

For all innovative technologies Defra could consider the following potential measures:

- As current regulations and practices may be inadvertently creating resistance to change, Defra could consider updating LAQM TG.09 (published in 2009) to identify where innovative technologies can be used within the LAQM regime and how it could be adapted to allow their use (as the LAQM regime is used to drive national measures). As with possibly examining changes to the equivalence testing regime, it is important to understand the role the LAQM regime could play for promoting uptake amongst potential end users. Other strategic documents and initiatives that could help raise awareness of innovative technologies and drive uptake amongst potential end-users include updates to the National Planning Policy Framework (NPPF) document[14], Public Health England's programme "Empowering the public and use of open source datasets and citizen science", the Department for Transport's Local Travel Plans (DfT-LTP), and Sniffer in Scotland.
- Defra could encourage the creation of a portal, or consider creating a portal (e.g., as an add-on to UK-AIR), for sharing air quality data from innovative technologies in the public domain, in particular pervasive sensors, and other environmental/social data to encourage engagement, particularly with the public and citizen science projects. The Devolved Administrations, city and local councils could consider providing similar resources on their air quality webpages. This would be consistent with Defra's strategy to open up more (air quality) data to the public. Technology developers could contribute by providing on-line resources to their users allowing them to share their air quality measurements. These could allow end-users, for example community scientists, to upload, share and map their air quality measurements, such as ones taken during their daily commute to-and-from work. This approach could provide lifestyle applications and allow people to plan their daily commute to limit exposure to poor air quality. It would be important to understand what benefits and risks such an approach would offer to Defra and potential end users. Examples include the US

[14] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/6077/2116950.pdf

EPA's air sensor toolbox for citizen scientists: http://www.epa.gov/heasd/airsensortoolbox/ and the My Environment page: www.epa.gov/enviro/myenviro.

3.6.6 Functioning of the market and whether intervention is needed

The stakeholder responses provided limited evidence but innovative technologies are under development that could serve Defra's need for improved air quality monitoring over the next 10-15 years. The evidence indicates that developers are responding to the on-going needs of the air quality monitoring market without intervention, including:

- Development of satellite-borne sensors to measure air quality pollutants, though near-surface measurements remain elusive and there are technical limitations which must be overcome.
- Development of electrochemical detectors and pervasive sensors for air quality monitoring, particularly in traditionally inaccessible locations.
- Development of miniaturised devices such as the micro-aethalometer which can be used in exposure studies.
- Development of devices such as the DUVAS instrument that are capable of providing fixed-point measurements of multiple air quality pollutants.
- Establishment of a CEN WG42 on *gas* sensors to formulate a standardised assessment protocol for pervasive technologies.

Direct intervention by Defra is not required but there are potential supporting measures that Defra could consider in order to engage and assist in developing innovative technologies further and so sustain innovation and drive uptake over the next 10-15 years.

4 Conclusions

A number of innovative technologies have been identified, many of which appear to have the potential to supplement the UK's air quality monitoring networks nationally or locally within the next 10 to 15 years in demonstrating fulfilment of national or local air quality objectives. Some technologies also have the potential to replace some of the monitoring instruments currently used in the networks in this timeframe.

Many appear to offer novel applications that have the potential to provide improved data (especially spatial resolution – e.g., city-wide air quality maps of measurements), improved access to data, and completely new approaches to using air quality data, for example as air quality monitors carried on the person. Several of the technologies also offer co-benefits beyond air quality monitoring – whether as validation of national/regional emission inventories, or the provision of low cost meteorology data. Insufficient cost information has been provided to assess all technologies, but what has been gathered indicates that some of the technologies have the potential to offer cost savings compared to existing monitoring network instrumentation, often due to their smaller size and reduced operating costs.

Most technologies have technical issues – such as a need for improving uncertainty levels or defining common calibration methods – that will need to be addressed. For all the innovative technologies examined, one important step prior to adoption would be testing and validation against measurements from the UK's current air quality monitoring networks.

There are four market barriers common to most or all of the technologies. Firstly, in order to be considered for application under the European air quality Directives, standards (CEN standards) need to be in place for the technologies. Once standards are in place, the second most prominent barrier is obtaining acceptance to be used to demonstrate compliance with the air quality Directives. This means achieving data quality objectives and gaining certification under MCERTS that demonstrates their equivalence to reference measurement techniques. Some technologies are more advanced than others in this respect than others. Satellite and remote sensors do not yet have agreed CEN standards for validating their performance; contrastingly one of the active and automatic sampling instruments identified in this report is already undergoing MCERTS process. Without being demonstrated to be equivalent, the technologies' market potential will be limited to providing indicative measurements, i.e., under LAQM limited to Screening and Assessment. However, even without acceptance for use under the European air quality Directives, some technologies may still have potential to be used by local or national highways and health authorities for assessment purposes, or used to support citizen science initiatives.

Other barriers identified include lack of, or limited, development funding, and the risk of lack of technology uptake. A number of potential measures to remove these market barriers have been identified for Defra to consider. The evidence collected, however, suggests that developers are responding to the on-going needs of the air quality monitoring market without intervention.

Appendices

Appendix 1 - Stage 1 – Questionnaire

Consultation between the project team and academic partners was used to identify innovative technologies that could be included in the study. A list of companies and organisations involved in the development of the innovative technologies was drawn-up. These companies and organisations were contacted and sent the questionnaire below in order to capture information on the extent and types of innovative technology in development. The questionnaire was composed of eleven broad questions to reflect the range of innovative technologies under consideration, e.g., sensors, instruments, systems, and remote sensing techniques, and the range of pollutants under consideration. Under each question were a series of bullet points, these were intended to provide a guide as to the type of information required in the response and were not intended to be prescriptive.

As the longer term aim of this task is better understand the barriers to innovative technologies that exist and how they could be overcome, the respondents were asked to provide this information when responding to the questionnaire. Their responses reflected the challenges they faced. This information was requested at this stage in order to limit the burden to industry posed by responding to multiple short questionnaires.

	Question	Response	Notes
1	**Respondent details** Please give: • Name • Position • Contact address • Contact telephone number • Email address		An "innovative technology" can be: 1) An instrument, sampler (active or passive), sensor, method, or system (partially or fully integrated). 2) A satellite measurement. 3) A remote sensing technique that will provide air pollutant (gaseous and/or particulate-phase) measurements.
2	**Innovative Technology** What innovative technologies do you have in development that will come to market within the next 10-15 years? Provide an overview of potential technologies giving their: • Name(s) • Expected release date • Pollutant(s) measured • Description of the general concept(s) • Intended use • Stage of development • Ability to measure other parameters of interest, e.g., temp, RH, noise, other air pollutants (e.g., NO2, PM10, and so on)?		• In describing the general concept, please describe the measurement principle, e.g., solid-state chemical sensor, filter sampling, UV Chemiluminescence. • For passive samplers state type, e.g. radial, tube-type, badge type, other. • For satellite/remote sensing technique please specify the location of the sensor, e.g., ground, space or airborne. • For satellite-borne sensors specify if they are orbital or geostationary.
3	**Rational and Motivation**		• A "smart city" is a city which functions in a sustainable and intelligent way, by integrating all its infrastructures and services into a cohesive whole and using

	What is driving the development of the innovative technology? Drivers can be: • Improved portability and miniaturisation. • Better temporal or spatial resolution. • Higher precision. • Improved detection limit. • Development of integrated system – if so what type. • Sensor-sensor, sensor-satellite. • Integration with a "Smart Cities" platform. • Monitoring to deliver multiple objectives, e.g., simultaneous measurement of several pollutants. • Provision of demand responsive platform, e.g., an Urban Traffic Management system. • Introduction of citizen science or community observations. • Disruptive technology. • Global/regional coverage and continuous monitoring. • Satellite measurements ready-to-use data on short-time scale.		intelligent devices for monitoring and control, to ensure sustainability and efficiency. • "Citizen Science" or "Community Observations" research is conducted, in whole or in part, by amateur or non-professional scientists. Examples include the Met Offices World of Weather initiative (WoW) - http://www.metoffice.gov.uk/wow • Disruptive technologies are those which change the whole framework of a market.
4	**Perceived barriers to market** For innovative technologies, state the current barriers Examples of possible barriers include: • Funding/investment/cost (capital/development). • Technological restrictions – software and hardware. • Insufficient/poor skill base. • Prohibitive market conditions/unfair competition/trade barriers. • Limited research. • Problems integrating software into current systems. • Data handling/management. • Legislative regime.		• Barriers can be device specific, such as the need for further development, reliability, cost, and the requirement for staff training. They can also include the requirement for type approval and participation in equivalence trails. • For systems, technological integration may pose a barrier. • Data pre-processing may be required in the case of remote sensing instruments. Data handling is important for high resolution measurements. The integration of new technology into existing or familiar systems may cause problems. Market conditions also play a role. Monopolies, restrictive practices, market competition, or poor understanding of a technology, or what it provides, can also act as barriers.
5	**How can these barriers be overcome** What would be required to overcome the barriers associated with development of the innovative technology Methods for overcoming barriers include: • Grants, governments funding, preferential loans, crowd funding. • Sponsorship for equipment. • Partnerships within industry or education or with government. • R and D goals. • Investment in staff. • Investment in technology.		

	• Outsourcing technology or software development. • Changes in legislation. • Data elaboration and management. • Easy and open access to software tools. • Access to data reporting portals for ad-hoc measurements.		
6	**How will the measurements be handled** Will the innovative technology provide a direct reading or will the measurements require post-processing. How will the measurements be passed to the potential end user? If high resolution or detailed measurements are generated, or if extensive post-processing is required, detail how this will be handled: • Database. • Cloud storage and processing. • Telemetry system Delay between the real-time measurement/pre-processing and final processed measurement.		• e.g., raw voltage measurements from sensors passed to database. Measurements determined by algorithm. System requires network link to remote server.
7	**Costs** Estimated costs associated with the deployment of the innovative technology to provide measurements? Provide a brief description of potential costs broken down by: • Development costs • Capital costs • Installation costs • Recurrent or maintenance costs • Analytical costs • Data processing costs • Infrastructure costs • Training costs		
8	**Flexibility of device and practical considerations** Current air quality measurement networks are based on extensive use of fixed point measurement. There is a perceived need for greater flexibility in the future. What are the practical constraints associated with your device? Practical constraints include: • Format, size and weight • Need for mains power		• e.g., rack mounted, handheld • e.g., mains power, batteries, low voltage power supply (state voltage), PV array, wind turbine • In the UK "access to mains power" means access to a 13 amp, 240 V rated supply. Though the rating of mains power varies from country-to-country, the practical limitations are the same

	• Components that constitute a risk to health, e.g., the use of radioactive sources or potentially toxic compounds • The need for appropriate shelter/housing • Limited working temperature range • Limited/no measurements due to specific meteorological conditions, e.g., rain or cloud: • Appropriate limit of detection for pollutants(s) measured • e.g., unknown or unfamiliar data structure for end user		
9	**Servicing, calibration and reliability** Service and reliability are decision critical factors in choosing an innovative technology. They add to on-going costs, whilst device reliability can limit data capture, and have wider implications, such as on resource usage. Will the design ensure? Ease of calibration - can the technology be re-calibrated? Parts can be cleaned, re-used or recycled/refurbished at minimal cost/impact to measurements and the environment? What will be the Intended service schedule? Intended replacement schedule?		• For satellite and remote sensing measurements the limit of detection can also be expressed as the total column concentration.
10	**Measurement uncertainty** State the expected limit of detection, accuracy, precision (state % error), and bias. Consider: • Whether the innovative technology will be intended for precision or indicative measurement (state perceived error and bias) • For integrated systems, breakdown by component, if possible) • For satellite measurements, state the altitude (state minimum) at which measurements become usable) • For satellite measurements, state the altitude (state minimum) at which measurements become sensitive) • For satellite and remote sensing measurements state the expected limit of detection estimated according to common concentration units used in air pollution monitoring (DU, ppm, ppb, ppt, molecules cm^{-3}, $\mu g\ m^{-3}$, and so on)		
11	**Instrument resolution** What is the innovative technology's temporal and spatial resolution? • Define the intended spatial resolution.		

	• Define the intended temporal resolution. • Specify the pixel area (km x km) associated with each datum (for a central latitude and longitude). • Specify the elapsed time between spectra acquisition. • State how many times the sensor scan a specific area/region on the earth surface.		

Appendix 2 - Stage 1 – Risk assessment criteria

The risks associated with the potential innovative technologies were identified by scoring the questionnaire responses against the criteria below. The limitations identified are summarised in Section 2.6.

Each criteria was scored against a Likert-type scale. Depending on the criteria under consideration slightly different scales were used – the scale used is indicated by the blue text in parentheses. For example, in the case of the first criteria "Measures a range of pollutants simultaneously" the questionnaire response was scored against the "Quality" scale.

ASSESSMENT CRITERIA	SCALE				
Score	1	2	3	4	5
Quality	Very poor	Poor	Average	Good	Very good
Costs	Very high	High	Average	Reasonably low	Very low
Likelihood	Impossible	Unlikely	Likely	Reasonably likely	Certain
Agreement	Strongly disagree	Disagree	Neither agree / disagree	Agree	Strongly agree
How often?	Very Frequent	Frequent	Average	Less than average	(Almost) Never

Risk being assessed	Comment	Criteria	Score	Comments	Notes
Requirement for further measurements/modelling	Multiple instruments required	Measures a range of pollutants simultaneously (Quality)			
	Further measurements/modelling required to provide supporting data	Measures a range of non-AQ parameters (Quality)			Does device makes multiple measurements of air pollutants and environmental parameters,

									e.g., temperature, humidity, noise.
Market readiness	Innovative technology far from market. More work required	Market readiness (Market readiness)							e.g., Have remote sensing data been already converted into a concentration measurement fit for use?
	Very early stage of development. Long lead-in time	Time to market (Time to market)							e.g., first year of development, one year from market, mature technology at market - available for 20 years
		PERCEIVED BARRIERS TO MARKET						**Comments**	**Notes**
Barriers, type, ease with which they can be overcome	A large number of barriers may prevent development of the innovative technology	Many barriers to market (Score as quality, i.e. 1 = many, 5 = very few or none)							
	The barriers are not well understood and maybe difficult to overcome	Barriers are well defined (Agreement)							
	Barriers penetrable, but with assistance	Barriers require intervention to overcome (Score as quality i.e. 1 = most intervention needed, 5 = least intervention needed)							
	Barriers impenetrable. Innovative technology unlikely to come to market	Barriers **can** be overcome with appropriate intervention (Score as likelihood)							
		HOW WILL THE MEASUREMENTS BE HANDLED?						**Comments**	**Notes**
Ease of (re)processing	Technology exists	Raw measurements can be easily (re)processed (Quality/Agreement)							
Loss/inability to capture raw readings prevents reanalysis, if required	Can revert to original, raw readings	Raw measurements can be accessed (Quality/Agreement)							
Timely processing of measurements for use/reporting		Raw data can converted to measurements *quickly* (Quality/Agreement)							

Risk of revision/re-calculation maybe necessary if the algorithm is improved. May jeopardise evidence base/compliance reporting	May require licencing	Processing of raw measurements requires use of proprietary algorithm - e.g., to correct drift (Quality)		
Loss of evidence base	Capturing/integrating data may be troublesome	Data can be streamed (Quality/Agreement)		
		Measurements can be easily integrated (Quality/Agreement)		
		COST	**Comments**	**Notes**
Capital costs may be burdensome		The instrument capital costs (Costs)		
Installation costs may be burdensome		The installation costs (Costs)		
May add to on-going costs		The maintenance costs (Costs)		
May add to on-going costs		The analytical costs (Costs)		
		FLEXIBILITY OF DEVICE & PRACTICAL CONSIDERATIONS	**Comments**	**Notes**
Innovative technology fit-for-purpose and can be easily deployed in the field	Difficult to handle	Lightweight (Quality/Agreement)		
	Difficult to handle	Compact (Quality/Agreement)		
		Easily installed (Quality/Agreement)		Requires (no) specialist housing or infrastructure. Satellites need to be deployed in space.
		Robust (Quality/Agreement)		Temperature range, wet weather tolerance, humidity

Exposure increases risk of injury, increases morbidity/mortality	Technology poses a threat to human health (rate by Quality scale i.e. 1 = greatest threat, 5 = least threat).							State the risks for instruments/samplers/methods/systems that use radioactive sources, glass parts, toxic or irritating reagents
Will limit data coverage	Measurements impeded by meteorological conditions (rate by Quality scale, i.e. most affected = V Poor, least affected = V Good)							Some remote sensing techniques and satellite-based techniques cannot provide measurements under certain conditions, e.g., cloud
	SERVICING, CALIBRATION & RELIABILITY						**Comments**	**Notes**
Difficult to calibrate. May impact on measurement quality/reliability	Can be calibrated in-situ (Quality)							
Instrument off-line frequently. May impact on measurement quality/reliability & data coverage	Frequency of calibration ('How Often')							
Instrument off-line frequently. May impact on measurement quality/reliability & data coverage	Maintenance interval ('How Often')							
	Frequency of replacing active sensor/detector ('How Often')							
	MEASUREMENT UNCERTAINTY						**Comments**	**Notes**
Concentrations of CO and SO_2 are now at level just above the limit of detection of most current analysers. Consultation is currently underway on the removal of reporting requirements for benzene, 1,3-butadiene, carbon monoxide, lead (termed "obsolete pollutants")	Limit of detection is appropriate based on current concentrations							

		Limit of detection is appropriate based on perceived future concentrations							
	Pollutant dependent	Accuracy sufficient for indicative measurements (see table)							(as defined under the Directive - see table)
	Pollutant dependent	Precision sufficient for indicative measurements (see table)							(as defined under the Directive - see table)
	Pollutant dependent	Accuracy sufficient for fixed point measurements (see table)							(as defined under the Directive - see table)
	Pollutant dependent	Precision sufficient for fixed point measurements (see table)							(as defined under the Directive - see table)
	Risk of revision/re-calculation. May jeopardise evidence base/compliance reporting	Measurement uncertainties are well-characterised							
		INSTRUMENT RESOLUTION						**Comments**	**Notes**
Poor/limited spatial resolution.		Good spatial resolution - allows measurements to be collected from over a wide area (Quality)							
Poor/limited temporal resolution.	Dependent on application/pollutant measured	Offers good temporal resolution (Quality)							

Summary assessment:

		For conceptual technologies assess the likelihood of innovative technology coming to market (Likelihood)							
	Maintains the status quo	Is considered to be a "*game changer*" (Agreement)							

Is a disruptive technology (Agreement)							
Can be coupled with other innovative technologies, i.e., sensor-sensor, sensor-satellite, sensor-remote sensing technique (Likelihood)							

Appendix 3 - Stage 1 – Risk assessment of innovative technologies

This section summarises the risk assessment scoring and questionnaire responses for each innovative technology.

Satellite-borne sensors

Table A3-1 shows the risk assessment scoring for satellite-borne sensors based on the criteria laid-out in Appendix 2. And the narrative after the table provides the scoring rationale.

Table A3-1 Satellite-borne sensor risk assessment scoring.

						Comments
Measures a range of pollutants simultaneously (Quality)					5	
Measures a range of non-AQ parameters (Quality)				4		
Market readiness				4		Processed data are not always available to the end-user.
Time to market					5	
PERCEIVED BARRIERS TO MARKET						
Many barriers to market (Score as quality, i.e. 1 = many, 5 = very few or none)			3			
Barriers are well defined (Agreement)			3			Some processed data can only be obtained through research institutes and private businesses, whilst other datasets are freely available, but require technical expertise to process and interpret.
Few measures required to overcome barriers (Score as agreement, i.e., 1 = strongly disagree, 5 = strongly agree)		2				
Barriers **can** be overcome with appropriate intervention (Score as likelihood)			3			Processed data needs to be made more fully available.
HOW WILL THE MEASUREMENTS BE HANDLED?						
Raw measurements can be easily (re)processed (Quality/Agreement)	1					
Raw measurements can be accessed (Quality/Agreement)		2				
Raw data can converted to measurements *quickly* (Quality/Agreement)	1					
Processing of raw measurements requires use of proprietary algorithm - e.g., to correct drift (Quality)					5	
Data can be streamed (Quality/Agreement)					5	
Measurements can be easily integrated (Quality/Agreement)				4		
COSTS						
Instrument capital costs (Costs)	1					
Installation costs (Costs)	1					
Maintenance costs (Costs)	1					

Analytical costs (Costs)	1					
FLEXIBILITY OF DEVICE DESIGN & PRACTICAL CONSIDERATIONS						
Lightweight (Quality/Agreement)						NA
Compact (Quality/Agreement)						NA
Easily installed (Quality/Agreement)						NA
Robust (Quality/Agreement)					5	
Technology poses a threat to human health (rate by Quality scale i.e. 1 = greatest threat, 5 = least threat).					5	
Measurements impeded by meteorological conditions (rate by Quality scale, i.e. most affected = V Poor, least affected = V Good)		2				
SERVICING, CALIBRATION & RELIABILITY						
Can be calibrated in-situ (Quality)					5	Calibration is done before the instrument is launched in the space.
Frequency of calibration ('How Often')					5	
Maintenance interval ('How Often')					5	
Frequency of Replacing Active sensor/detector ('How Often')				4		Operational lifetime of sensor = 5-8 years.
MEASUREMENT UNCERTAINTY						
Limit of detection is appropriate based on current concentrations				4		
Limit of detection is appropriate based on perceived future concentrations				4		
Accuracy sufficient for indicative measurements		2	3			Uncertainties vary from species-to-species and are typically 50-80%, but can be as high as 100%.
Precision sufficient for indicative measurements		2	3			
Accuracy sufficient for fixed point measurements	1	2				
Precision sufficient for fixed point measurements	1	2				
Measurement uncertainties are well-characterised				4		
TEMPORAL AND SPATIAL RESOLUTION						
Good spatial resolution - allows measurements to be collected from over a wide area		2				Coarse spatial resolution, allowing large areas of study, but at low resolution
Offers good temporal resolution						
SUMMARY						
For conceptual technologies assess the likelihood of innovative technology coming to market (Likelihood)					5	
Is considered to be a "*game changer*" (Agreement)					5	
Is a disruptive technology (Agreement)					5	
Can be coupled with other innovative technologies, i.e., sensor-sensor, sensor-satellite, sensor-remote sensing technique					5	

Overview

Satellite-borne sensors are capable of measuring the column density, reported as molecules cm^{-2}, of multiple air pollutants and trace gases, including NO_2, SO_2, O_3, CO, CO_2, CH_4, CH_3OH, HCOOH, BrO, ClO. They can also provide a measure of the atmospheric aerosol loadings (in terms of the Aerosol Optical Depth, AOD) and approaches exist for inferring the surface particulate matter ($PM_{2.5}$) from the AOD. Gas measurements are typically provided by Differential Optical Absorption Spectroscopy (DOAS) which use sunlight as their light source or by using the Infrared radiation emitted from the Earth. Satellite-borne sensors can also provide standard meteorological parameters, e.g., temperature, barometric pressure, relative humidity, wind speed and direction.

Surface NO_2 concentrations can be readily inferred, together with CO, SO_2 near large sources, and a limited range of VOCs. Surface-level particulate concentrations can be inferred if well-mixed in the boundary layer and if skies are clear. However, measurement of ground-level ozone is challenging. The provision of continuous monitoring depends on the type of orbit the satellite is using. Satellite in a low earth orbit which orbits the earth every 90 minutes will only spend a small amount of time ('dwell time') over any given area of the globe. As a result, the measurements over a specific area, such as the UK will be restricted by this dwell time resulting in non-continuous measurements of air pollutant concentrations. Conversely, a satellite in a geostationary orbit over the UK and Europe will be able to make continuous measurements of pollutant concentrations. Satellites in both types of orbit can be used.

Satellite-borne sensors are an established technology which has been used extensively to develop our knowledge and understanding of atmospheric chemistry and physics. Currently they provide supplemental evidence that can be used to solve exceptional events such as earthquakes, natural fires, volcanic emissions which can contribute to the atmospheric air quality on regional and global scale.

Measurement handling

Measurements are automatically collected from satellite sensor by the relevant space agency and then distributed to different organisations, which manage the pre and post-processing of the raw data. Pre-processed and post-processed data (retrieved atmospheric column concentrations) can be available after a few hours. Making accurate use of satellite measurements requires specialist knowledge and the use of scientific software packages such as IDL, MatLab, or FORTRAN which requires staff training and development time. These considerations are reflected in the low scoring.

The use and sharing of some satellite derived data products is limited under licencing agreements with between data provider and user. Measurements can be georeferenced by incorporation into GIS based datasets which allows global, national and regional-scale maps to be produced. Satellite data products are widely available and can be accessed hence satellite-borne sensors score fours and fives.

Costs

The costs of data analysis associated with satellite-borne sensors are of the order of several millions of pounds. The Copernicus program sponsored by the European Commission is providing a wide range of funded projects to exploit satellite data from the next 20 years. This is reflected in the low risk assessment score of one throughout. Costs are associated with:

- Data provision – development of routines to convert "raw" data into usable "products" of value to the end user.
- Storage and computation costs Flexibility of device design and practical considerations.

Flexibility of device design and practical considerations

The majority of satellites are downward-looking (nadir) and provide pollutant concentrations in the column between the sensor and the Earth's surface. Therefore satellite-borne sensors cannot provide ground level point concentrations. One of the most recognised technical limitation when looking at satellite data from optical sensors, is the cloud-coverage in the lower troposphere. This has implications in the completeness of the data recorded over a given time-period.

There is significant risk associated with the deployment of satellite-borne sensors. There are cases when satellite-borne sensors have failed to work as intended or malfunctioned. In such instances the satellite programme related to a specific remote sensor is suspended with a consequent interruption of the data flow and therefore, to data processing.

Measurement uncertainty

Different algorithms are used by different data providers to convert “raw” data to final “data products” (column concentration of trace gases and particulates) which might often lead to inconsistencies and uncertainties in reported air pollutant concentrations. Table A3-2 provides indicative percentage uncertainties for common air pollutants.

Table A3-2 Typical levels of uncertainty associated with satellite-borne sensors

Species	Typical uncertainty (%)
CO	<21
NOx/NO_2	35-60
O_3	45
Particles	80
SO_2	50
CO_2	1-8
NH_3	35-70

The percentage uncertainty depends on the sensor and the algorithm used to infer the concentration, Measurement uncertainties are considerable and greater than 30% for most species, and are up to 100% in some cases, except for CO and CO_2 that are about 21% and 1-8%, respectively The low percentage uncertainty associated with CO_2 satellite sensor measurements reflects the extensive work done in recent years to reduce uncertainties for measuring this important greenhouse gas.

Temporal and Spatial Resolution

The spatial resolution is poor and quite coarse, of the order of kilometres, thus a risk score of two was awarded. The spatial resolution can vary from sensor-to-sensor, for example: 80 km x 40 km for GOME 2 compared to 13 km x 24 km for OMI. In the next 5 years, ESA’s next generation satellite-borne sensors, e.g., Sentinel 1-6, will offer a much higher (finer) spatial resolution, of the order of 7 km x 7 km. The temporal resolution of a satellite is determined by its orbit: geostationary orbit satellites measure at fixed locations and could provide continuous measurements.

Integration with the UK air quality monitoring regime

There remain fundamental limitations to measuring surface-level air pollution from space which means that in the short to medium-term satellite-borne sensors will not displace surface measurements. Satellite measurements can be used to provide supplemental supporting evidence. Consequently, they can only provide supporting measurements for verification purposes. Were measurements from satellite-borne sensors to be used for compliance reporting there would be an onus on the user to demonstrate compliance with the data quality objectives stated in the air quality Directives.

How or where will this technology provide opportunities for improvement compared to the current technology?

The strength of satellite measurements, when compared to surface measurements, is the extent of spatial coverage of multiple air pollutants. Satellite data provide complementary information to measurements collected from fixed point monitoring collected at the surface by “filling the gaps” between monitors, on a national or regional scale.

Summary of limitations

There remain fundamental limitations to measuring surface pollution from space: satellite-borne sensors can only measure air pollutants (gases and aerosols) down to the lowest 500 m of the atmosphere and therefore they cannot provide surface measurements of air pollutants. Surface NO_2 concentrations can be readily inferred, together with CO, SO_2 near large sources, and a limited range of VOCs. Surface-level particulate concentrations can be inferred if well-mixed in the boundary layer and if skies are clear. However, measurement of ground-level ozone is challenging. The provision of continuous monitoring depends on the satellite orbit: a satellite in a low earth orbit will result in non-continuous measurements of air pollutant concentrations, whilst a satellite in geostationary orbit over the UK and Europe will be able to make continuous measurements of pollutant concentrations.

The coarse spatial resolution of satellite observations, of the order of several to tens of kilometres, is a further limitation. By comparison, mapped modelled concentrations of the national pollution climate are currently provided on a 1 km^2 square basis in order to fulfil the reporting requirements of the air quality Directives. These are used for demonstrating national compliance and within the LAQM regime, where they tend to be supplemented with more detailed local information from models and measurements.

Measurements are automatically collected from satellite sensor by the relevant space agency and then distributed to different organisations which manage the pre and post-processing of the raw data. As data providers are likely to use different algorithms to convert raw data to final data products there can be inconsistencies between similar data products, i.e., of the same air pollutant. This can be overcome if data are provided by a single gateway, such as the Copernicus user services (https://www.gmes-atmosphere.eu/).

Air pollutant concentrations are inferred from algorithms (known relationships) and can have large uncertainties, but this can vary from product-to-product. In the short to medium-term satellite-borne sensors will not displace surface measurements. Consequently, they can only provide supplemental supporting evidence at the current time.

Ground-based remote sensors

Table A3-3 shows the risk assessment scoring for DOAS instrument based on the criteria laid-out in Appendix 2.

TableA3-3 DOAS sensor risk assessment scoring

						Comments
Measures a range of pollutants simultaneously (Quality)					5	
Measures a range of non-AQ parameters (Quality)			3			
Market readiness				4		
Time to market				4		
PERCEIVED BARRIERS TO MARKET						
Many barriers to market (Score as quality, i.e. 1 = many, 5 = very few or none)			3			
Barriers are well defined (Agreement)				4		
Few measures required to overcome barriers (Score as agreement, i.e., 1 = strongly disagree, 5 = strongly agree)				4		
Barriers **can** be overcome with appropriate intervention (Score as likelihood)					5	
HOW WILL THE MEASUREMENTS BE HANDLED?						
Raw measurements can be easily (re)processed (Quality/Agreement)		2				

Raw measurements can be accessed (Quality/Agreement)		2				
Raw data can converted to measurements *quickly* (Quality/Agreement)		2				
Processing of raw measurements requires use of proprietary algorithm - e.g., to correct drift (Quality)			3			
Data can be streamed (Quality/Agreement)						Unknown
Measurements can be easily integrated (Quality/Agreement)		2				
COSTS						
Instrument capital costs (Costs)				4		
Installation costs (Costs)						Unknown
Maintenance costs (Costs)			3			Unknown
Analytical costs (Costs)					5	Unknown
FLEXIBILITY OF DEVICE DESIGN & PRACTICAL CONSIDERATIONS						
Lightweight (Quality/Agreement)		2				
Compact (Quality/Agreement)		2				
Easily installed (Quality/Agreement)		2				
Robust (Quality/Agreement)		2				
Technology poses a threat to human health (rate by Quality scale i.e. 1 = greatest threat, 5 = least threat).					5	
Measurements impeded by meteorological conditions (rate by Quality scale, i.e. most affected = V Poor, least affected = V Good)			3		5	Depends on whether design or measurements compensate for variation in natural light levels
SERVICING, CALIBRATION & RELIABILITY						
Can be calibrated in-situ (Quality)						Unknown
Frequency of calibration ('How Often')						Unknown
Maintenance interval ('How Often')						Unknown
Frequency of Replacing Active sensor/detector ('How Often')						Unknown
MEASUREMENT UNCERTAINTY						
Limit of detection is appropriate based on current concentrations			3			
Limit of detection is appropriate based on perceived future concentrations			3			Maybe
Accuracy sufficient for indicative measurements			3			Maybe
Precision sufficient for indicative measurements			3			Maybe
Accuracy sufficient for fixed point measurements						Unknown
Precision sufficient for fixed point measurements						Unknown
Measurement uncertainties are well-characterised						Unknown
TEMPORAL AND SPATIAL RESOLUTION						
Good spatial resolution - allows measurements to be collected from over a wide area					5	
Offers good temporal resolution			3			
SUMMARY						
For conceptual technologies assess the likelihood of innovative technology coming to market (Likelihood)				4		
Is considered to be a "*game changer*" (Agreement)				4		

Is a disruptive technology (Agreement)			3			
Can be coupled with other innovative technologies, i.e., sensor-sensor, sensor-satellite, sensor-remote sensing technique				4		

Overview

Ground-based remote sensors are similar to those used as satellite-borne sensors, performing measurement from the bottom-up rather than from the top-down and measure air pollutant concentrations within a column or path, rather than at a fixed point. They measure multiple gaseous air pollutants, e.g., NO_2, SO_2, O_3 and the atmospheric aerosol loading.

The DOAS instrument identified in the stakeholder response used a rotating sensor to produce 360 degree panoramic sweeps of the lower boundary layer providing spatial and temporal variability of NO_2. Table A3-3 gives the risk assessment scoring for ground-based sensors based on the criteria laid-out in Appendix 2.

Measurement handling

The questionnaire responses stated that the raw measurements need to be processed to provide the final data "product", i.e., measurements of the concentrations of air pollutants. Once the instrument's spectral response has been determined in respect to a calibration gas of known concentration, raw data can be interrogated retrospectively and concentrations of other gaseous pollutants can be recovered, even if they were not initially required – this is a useful feature allowing historical measurements to be recovered. As the instrument did not have well-defined data retrieval pathway it scored two out of five.

Costs

No information was provided in the questionnaire response on the costs associated with the purchase or operational costs of the DOAS system.

Flexibility of device design and practical considerations

Ground-based remote sensing has a long heritage in fixed viewing geometries and has been used to evaluate satellite measurements. Stakeholder responses noted that DOAS instruments can sited on a mobile platform which can be used to extend the range of the measurements. Instruments weigh tens of kilograms and only likely to be moderately portable and it was awarded scores of two.

Natural light levels can affect DOAS readings as sunlight is used as light source. Consideration must be given on how to deal with the consequences of (sun) light attenuation under changing climatic conditions, i.e., as light levels change from clear sunny conditions, to cloudy and overcast. Similar consideration needs to be given to handling the variation in daylight throughout the day and inter-seasonal differences. As the questionnaire response did not indicate whether this had been taken into account, or was an issue, a score of 3 was awarded which could rise to 5 if this has been considered and fully accounted for in the instrument's design or the processing of the measurements.

Servicing, calibration and reliability

No information was provided in the questionnaire response on the servicing, calibration and reliability of the DOAS system.

Measurement uncertainty

No information was provided in the questionnaire response as to the accuracy, precision or uncertainty associated with the DOAS instrument.

Temporal and Spatial Resolution

The DOAS can measure a range of air quality pollutants across a wide spatial extent, and scored 5, though the temporal resolution of the instrument was expected to be equivalent to current, in-use techniques, thus a score of 3.

Integration with the UK air quality monitoring regime

The air quality Directives require air pollutants to be measured at a fixed point rather than along a path, which limits the use of the DOAS.

How or where will this technology provide opportunities for improvement compared to the current technology?

Stakeholder responses indicated that DOAS instruments may be able to provide measurements of a range of gaseous air pollutants, e.g., NO, NO_2, SO_2 and O_3, with no cross sensitivity, across a greater spatial extent than current measurements. They could provide an assessment of the spatial and temporal variability of national and local pollution climates. The next section details the use of this technology to provide airborne sensors which could increase their spatial resolution.

Summary of limitations

DOAS instruments measure along a path, rather than at a fixed point, and are not compliant with the requirements of the air quality Directives. The costs associated with DOAS instruments are substantial, but they have the potential to displace several instruments with one, and the on-going costs are low. This may reduce the cost burden in the longer term.

Airborne sensors

Table A3-4 shows the risk assessment scoring for airborne sensors based on the criteria laid-out in Appendix 2.

Table A3-4 Airborne sensor risk assessment scoring

						Comments
Measures a range of pollutants simultaneously (Quality)				4		
Measures a range of non-AQ parameters (Quality)			3			
Market readiness	1					Research instrument
Time to market						Unknown
PERCEIVED BARRIERS TO MARKET						
Many barriers to market (Score as quality, i.e. 1 = many, 5 = very few or none)		2				Further development required
Barriers are well defined (Agreement)				4		
Few measures required to overcome barriers (Score as agreement, i.e., 1 = strongly disagree, 5 = strongly agree)			3			
Barriers <u>can</u> be overcome with appropriate intervention (Score as likelihood)				4		
HOW WILL THE MEASUREMENTS BE HANDLED?						
Raw measurements can be easily (re)processed (Quality/Agreement)	1					Procedure not fully developed and is run on an ad-hoc basis
Raw measurements can be accessed (Quality/Agreement)			3			
Raw data can converted to measurements *quickly* (Quality/Agreement)	1					Procedure not fully developed and is run on an ad-hoc basis
Processing of raw measurements requires use of proprietary algorithm - e.g., to correct drift (Quality)		2				
Data can be streamed (Quality/Agreement)				4		
Measurements can be easily integrated (Quality/Agreement)			3			

COSTS						
Instrument capital costs (Costs)						Unknown
Installation costs (Costs)						Unknown
Maintenance costs (Costs)						Unknown
Analytical costs (Costs)						Unknown
FLEXIBILITY OF DEVICE DESIGN & PRACTICAL CONSIDERATIONS						
Lightweight (Quality/Agreement)			3			
Compact (Quality/Agreement)			3			
Easily installed (Quality/Agreement)						Unknown
Robust (Quality/Agreement)						Unknown
Technology poses a threat to human health (rate by Quality scale i.e. 1 = greatest threat, 5 = least threat).					5	
Measurements impeded by meteorological conditions (rate by Quality scale, i.e. most affected = V Poor, least affected = V Good)		2				Aircraft flights can be impeded by bad weather
SERVICING, CALIBRATION & RELIABILITY						
Can be calibrated in-situ (Quality)	1					Pre-flight calibration required
Frequency of calibration ('How Often')			3			
Maintenance interval ('How Often')				4		
Frequency of Replacing Active sensor/detector ('How Often')				4		
MEASUREMENT UNCERTAINTY						
Limit of detection is appropriate based on current concentrations						Not applicable
Limit of detection is appropriate based on perceived future concentrations						Not applicable
Accuracy sufficient for indicative measurements		2				
Precision sufficient for indicative measurements		2				
Accuracy sufficient for fixed point measurements						
Precision sufficient for fixed point measurements						
Measurement uncertainties are well-characterised					5	
TEMPORAL AND SPATIAL RESOLUTION						
Good spatial resolution - allows measurements to be collected from over a wide area					5	
Offers good temporal resolution					5	
SUMMARY						
For conceptual technologies assess the likelihood of innovative technology coming to market (Likelihood)		2				
Is considered to be a "*game changer*" (Agreement)			3			
Is a disruptive technology (Agreement)		2				
Can be coupled with other innovative technologies, i.e., sensor-sensor, sensor-satellite, sensor-remote sensing technique			3			

Overview

Airborne remote sensors use similar technologies to those used in satellite-borne sensors and ground-based sensors. Sensors are deployed via aircraft, balloons and unmanned aerial vehicles

(UAVs) and allows the measurement of air pollutants close to the earth's surface over large spatial scale. Compared to satellite remote sensing, airborne-based sensors have a higher spatial resolution and can measure to <100m. Airborne remote sensors can measure multiple air pollutants, e.g., NO_2, SO_2, O_3 and the atmospheric aerosol loading. Table A3-5 gives the risk assessment scoring for satellite-borne sensors based on the criteria laid-out in Appendix 2. The instrument assessed in this instance was a proof-of-concept research instrument. Consequently risk assessment scores were quite low when compared to other instruments or technologies assessed here. The scores for more established and tested instruments would be expected to be higher, but would have to be assessed on a case-by-case basis.

Measurement handling

Data processing reflects the current mode of operation and measurements tend to processed in an ad-hoc fashion as measurements tend to be made for discrete measurement campaigns. In the case of the DOAS instrument reported on in the questionnaire, the instrument natively measures spectral intensity. A lengthy chain of calculations is required to turn these values into the more commonly used volume mixing ratios (ppb). The data therefore requires significant processing and a variety of software to achieve. The ad-hoc data processing is reflected in the low scores in Table A3-4.

Costs

No information was provided on costs, though they are expected to be considerable given the requirement for an aircraft for deployment, as well as the development of sensor. The questionnaire response noted that small, lightweight instrumentation can be deployed in light aircraft which limits the deployment costs. Small aircraft however have a limited range and are only capable of measurements on a local or regional scale. Larger aircraft with greater ranges would be required to map on a national scale.

Flexibility of device design and practical considerations

As research instruments, airborne sensors tend to be deployed for discrete measurement campaigns therefore the longer term operational capacity of the instrument is uncertain. As aircraft and UAVs need to refuelled and re-staffed, due to pilot fatigue, they cannot operate continuously, unless mounted to a static tethered balloon. Measurements could be impeded by meteorological conditions due to cloud cover, aircraft and UAVs may be grounded by inclement weather conditions, hence a score of two.

Servicing, calibration and reliability

No information was provided in the response on the servicing schedule, calibration interval or reliability of airborne sensors.

Measurement uncertainty

The accuracy and precision of the DOAS-based research instrument reported on in the questionnaire had not been assessed. The uncertainty of the measurements was reported to be 90%, thus the low scores in Table A3-4. The questionnaire responses did not give a guide as to how the instrument performed compared to other similar, airborne sensors.

Temporal and Spatial Resolution

Spatial resolution is altitude dependent but considered to be the strength of this technique hence a score of five was awarded. The questionnaire response reported that the DOAS-based instrument was capable of resolving to less than 100 m. This resolution would be sufficient for national compliance purposes and may offer some value to the LAQM regime.

Integration with the UK air quality monitoring regime

Measurements from airborne sensors are not used routinely within the UK air quality monitoring regime. Currently they can only provide supporting information for verification purposes. Further development work would be required to integrate these measurements into the current regime – the extent of the work required would be dependent on the technology used. In this instance, where a

DOAS instrument is being used to measure ground-level air pollutant concentration from the air, the same limitation applies as noted above: The air quality Directives require air pollutants to be measured at a fixed point rather than along a path. Furthermore, the airborne sensor would need to demonstrate that it is capable of achieving the data quality objectives stated in the air quality Directive for each air pollutant measured.

How or where will this technology provide opportunities for improvement compared to the current technology?

Provide good spatial and temporal resolution: the technology presents the ability to map the pollution climate of a medium sized city (~300,000 inhabitants or 70 km^2) within a few hours. As with satellite measurements airborne sensors are capable of "filling the gaps" between fixed point monitoring collected at the surface, on a local or regional scale, within a single shot.

Summary of limitations

The airborne sensor assessed was a proof-of-concept research DOAS instrument. Putting aside the system limitations and the large uncertainty quoted at 90%, the same limitations apply as outlined in above section for ground-based sensors.

Pervasive sensors

Table A3-5 shows the risk assessment scoring for pervasive sensors based on the criteria laid-out in Appendix 2.

Table A3-5 Pervasive sensor risk assessment scoring

						Comments
Measures a range of pollutants simultaneously (Quality)					5	Multi species, gas + PM Already available.
Measures a range of non-AQ parameters (Quality)					5	Readily combined with e.g. meteorological measurements, noise.
Market readiness				4	5	Close to market and already being marketed.
Time to market				4	5	Both already available and close to market. (Gas and PM)
PERCEIVED BARRIERS TO MARKET						
Many barriers to market (Score as quality, i.e. 1 = many, 5 = very few or none)			3			Sensor performance/validation, cultural and legislative resistance.
Barriers are well defined (Agreement)					5	Clearly defined.
Few measures required to overcome barriers (Score as agreement, i.e., 1 = strongly disagree, 5 = strongly agree)			3			Intervention required to encourage field trials/validation.
Barriers <u>**can**</u> be overcome with appropriate intervention (Score as likelihood)					5	High level of confidence
HOW WILL THE MEASUREMENTS BE HANDLED?						
Raw measurements can be easily (re)processed (Quality/Agreement)					5	
Raw measurements can be accessed (Quality/Agreement)					5	
Raw data can converted to measurements *quickly* (Quality/Agreement)					5	

Processing of raw measurements requires use of proprietary algorithm - e.g., to correct drift (Quality)					5	Meaning proprietary algorithms ARE required.
Data can be streamed (Quality/Agreement)					5	
Measurements can be easily integrated (Quality/Agreement)					5	
COSTS						
Instrument capital costs (Costs)			3	4	5	Low c.f. conventional reference instruments, higher that diffusion tubes. Some of the more expensive multi-pollutant devices have costs equivalent to current in-use analysers
Installation costs (Costs)				4	5	Low c.f. conventional reference instruments, higher that diffusion tubes
Maintenance costs (Costs)					5	Low c.f. conventional reference instruments, higher that diffusion tubes
Analytical costs (Costs)					5	If it means e.g. costs for diffusion tube analysis, there are ~ none
FLEXIBILITY OF DEVICE DESIGN & PRACTICAL CONSIDERATIONS						
Lightweight (Quality/Agreement)					5	
Compact (Quality/Agreement)					5	
Easily installed (Quality/Agreement)				4	5	Self-contained. May require mains power, hence more infrastructure needed
Robust (Quality/Agreement)				4	5	
Technology poses a threat to human health (rate by Quality scale i.e. 1 = greatest threat, 5 = least threat).					5	Benign (unless someone eats them).
Measurements impeded by meteorological conditions (rate by Quality scale, i.e. most affected = V Poor, least affected = V Good)				4		Temperature/RH effects can cause problems.
SERVICING, CALIBRATION & RELIABILITY						
Can be calibrated in-situ (Quality)				4	5	Non-invasive calibration algorithms are in development.
Frequency of calibration ('How Often')					5	A cross network calibration algorithm would be applied continuously
Maintenance interval ('How Often')				4	5	Battery lifetimes are 1-2 years for some motes. Needs confirmation.
Frequency of Replacing Active sensor/detector ('How Often')				4	5	The aim is for 1-2 years. Needs confirmation.
MEASUREMENT UNCERTAINTY						
Limit of detection is appropriate based on current concentrations			3	4	5	Species dependent (e.g., SO_2 in most of Western Europe is below detection limit). CO is probably more

						sensitive than standard reference instruments.
Limit of detection is appropriate based on perceived future concentrations						Unknown
Accuracy sufficient for indicative measurements					5	Generic statement
Precision sufficient for indicative measurements					5	
Accuracy sufficient for fixed point measurements				4		
Precision sufficient for fixed point measurements				4		
Measurement uncertainties are well-characterised			3	4	5	Species dependent
TEMPORAL AND SPATIAL RESOLUTION						
Good spatial resolution - allows measurements to be collected from over a wide area					5	Readily deployable
Offers good temporal resolution					5	<30s time resolution achievable by many sensor, others ~ 5 mins.
SUMMARY						
For conceptual technologies assess the likelihood of innovative technology coming to market (Likelihood)					5	Sensor technologies are imminent.
Is considered to be a "*game changer*" (Agreement)					5	In terms of spatial coverage.
Is a disruptive technology (Agreement)					5	In terms of low cost solution. Could be used in parallel.
Can be coupled with other innovative technologies, i.e., sensor-sensor, sensor-satellite, sensor-remote sensing technique					5	See above. Could be part of a wider information content based assimilation system

Overview

The study engaged with a number of stakeholders involved in the development of pervasive sensors. These included Envirowatch (eMote), Geotech (AQMesh), University of Leicester (Pollution Observing Device, POD), SensAir (mobile pod) and Turnkey. Alphasense, a sensor manufacturer also provided a questionnaire response. A range of anecdotal evidence based on user experience was also gathered form those within the UTMC community (Edinburgh, Gateshead and Leicester Councils and Transport for Scotland) who have used these devices. Pervasive sensors are active and automatic samplers but are differentiated from fixed-point sensors as they employ electrochemical sensors to measure gases and optical particle counters (light scattering cells) to measure particulate matter, rather than spectroscopic methods (e.g., chemiluminescence used in NOx/NO_2 analysers) or filter sampling to measure particulate matter. The common features of pervasive sensors include:

- Provision of multiple measurements: air pollutants (gases and particulate matter), noise, meteorological conditions, position (via GPS) with one unit (multiple sensors)
- Non-intrusive and robust design
- Deployable in arrays to provide good spatial coverage
- Easily commissioned and configuration-free
- Networked, wireless communication
- Self-powered, e.g., solar powered, or battery-powered, though can be mains powered
- Require limited maintenance
- Accurate, calibration-free and have lifetime reliability.

The questionnaire responses showed pervasive sensors can measure a range of different air pollutants, e.g., NOx, NO_2, CO, ozone, SO_2, as well as other inorganic and organic gases, including VOCs. The integration of light scattering cells (such as in the AQMesh or SensAir pod) permits the measurement of the number concentration of airborne particulate matter. Table A3-6 gives the risk assessment scoring for pervasive sensor based on the criteria laid-out in Appendix 2. It is based on an assessment of all the questionnaire responses.

Measurement handling

Pervasive sensors scored highly in terms of data handling. The questionnaire responses showed that high-resolution, raw voltage measurements are typically passed to a database and converted, via an algorithm to measurements. The conversion of raw voltage readings to air pollutant measurements occurs through the use of proprietary. As the raw voltages are recorded they can be re-processed if required.

The questionnaire responses revealed that GSM modems and Wi-Fi connections are used to allow date streaming. In high density areas the ZigBee[15] protocol can be used to save on SIM costs. The academic partners also noted that limitations in the spatial range can be overcome by incorporating GPRS (rather than peer-to-peer communications systems such as ZigBee) to provide independent data transfer. This requires access to mains power.

Costs

The questionnaire responses indicate that in addition to the capital cost of purchasing the instrument there are on-going recurrent costs associated with the replacement of the sensors and the detector cells. The capital costs for pervasive sensors range from a few £k up to tens of thousands of pounds for fully integrated, multi-species sensors, which would also be capable of providing meteorological observations. The cost of pervasive sensors is dependent on the scope of the end-users ambition, and multi-pollutant devices would cost more, making them comparable with current, in-use analysers, thus less attractive as an option. As one of their chief benefits (see below) is their being used as nodes and giving increased spatial resolution; hence such additional cost may also detract from this use.

The questionnaire responses also revealed that the replacement interval can vary, ranging from 3 to 12 months, depending on manufacturer. The recurrent costs were reported to be proportional to the size of the deployment. The questionnaires showed that instruments were designed to be "hot-swappable", i.e., one unit is replaced with another, rather than been serviced or calibrated in-situ. Therefore a small number of units need to be purchased and held in reserve. This is concurrent with established practice. The questionnaires also showed that data processing and analysis costs were dependent on the service provider and approach used. Only indicative costs were provided in the questionnaire responses but tend to be lower, per unit than for conventional instruments, hence the high scores in Table A3-6.

Flexibility of device design and practical considerations

Pervasive sensors are specifically designed to be deployed in a diverse range of locations, such as remote areas, or at height, where it is not possible to deploy traditional instrumentation, such as those to provide fixed point measurement. Therefore they score highly in this respect – fours and fives. The questionnaire responses indicated this was a key driver in the development of the technology. Several questionnaire responses highlighted that their small size allows them to be mounted on vehicles or carried by individuals allowing high-spatial resolution measurements to be made. In response to this, several questionnaire responses highlighted that pervasive sensors are often solar-powered allowing them to be deployed in remote locations. The academic partners, drawing on their own experience, noted that in the UK's temperate climate where cloud cover can limit the number of hours of solar radiation, and deep canyons in the built environment are cast in shadow, back-up power from batteries are needed to supplement solar rechargeable batteries when mains power is not available.

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[15] http://zigbee.org/ accessed 9th February 2015.

Continuous, un-interrupted measurements are necessary to maintain high levels of data capture. The questionnaire responses also noted that inlet design was important in order to prevent blockages that occur due to the ingress of insects and particulate matter which can reduce sample flow and limit data capture. The questionnaire responses also indicated that the cooling of sensors was a significant issue with ozone sensors.

Servicing, calibration and reliability

The academic partners and the questionnaire responses recognised that there was no standardised or formalised approach for calibrating the sensors. One suggested approach from the questionnaire was the cross-referencing measurements from within a network to determine correlations and to identify outliers. One questionnaire respondent reported that they had operated for "22 months without recalibration", but stated the need for "[sic] algorithms to correct the readings as the sensors drifted in an understood way". An inherent feature of the design of pervasive sensors is the low maintenance interval, though for some devices this is still an aspiration, but overall they scored highly. Anecdotal evidence showed that there remain concerns as to the inter-sensor repeatability and performance.

Measurement uncertainty

The academic partners indicated that pervasive sensors are capable of providing a comparative measurements, in terms of error, as time-integrated passive sampling (e.g., diffusion tubes) of air pollutants (such as NO_2). This is reflected in the comments in Table A3-5. One of the questionnaire respondents noted that the measurement error of pervasive sensors was of the order of 10-20%. This is sufficient to provide indicative measurements, reflected by a score of five, but slightly lower than the requirements for fixed point measurements, reflected by a score of four. The questionnaire responses went on to comment that errors were due to the sensor performance and could be controlled through good design. The questionnaire responses indicated that sensors can provide measurements of gaseous air pollutants down to a few ppb, though the limits of detection vary dependent by air pollutant as shown in Table A3-6. This is reflected by the range of scores awarded: three to five. In interpreting Table A3-6 it should be noted that nationally CO concentration are below the air quality Directive limit value of 10 mg m^{-3}. SO_2 concentrations have fallen well below the daily mean LV of 125 µg m^{-3} due to the decline of heavy industry since the 1970s and tend to of the order of a few µg m^{-3} in areas where there is no significant local source such as power generation or heavy industry.

Table A3-6 Typical LoDs (in ppb and µg m^{-3}) for pervasive sensors by air pollutant

Air pollutant	1 ppb in µg m^{-3}	Typical LoD	
CO	1.145	~5 ppb	~6 µg m^{-3}
NOx/NO_2	1.88	~40 ppb	~75 µg m^{-3}
O_3	2	~2 ppb	~5 µg m^{-3}
SO_2	2.62	~9 ppb	~22 µg m^{-3}
VOC	--	10 ppb	--

One issue that was not captured in the questionnaire responses, but which was noted by the project team, was the cross-sensitivity of NO_2 sensors to O_3 which lead to poor or erroneous NO_2 measurements.

Temporal and Spatial Resolution

The academic partners noted that arrays of multiple sensors can be arranged in a network – individual sensors are termed "nodes" – to provide a high level of spatial (typically 80 m to 1500 m) and temporal resolution, typically <1 minute. Both criteria were rated five in Table A3-6.

Integration with the UK air quality monitoring regime

The academic partners and the questionnaire noted that further effort is required to make measurements from pervasive sensors defensible for Defra's evidential and compliance needs. Pervasive sensors provide fixed point measurements but need to show that they are capable of demonstrating equivalence with the requirements with the data quality objectives stated in the air quality Directives for each gaseous and particulate matter air pollutants. This is relevant for all pollutants, but especially so for particulate matter, which is measured gravimetrically in accordance to the directive: Particulate matter measured by optical particle counters (light scattering cells) within pervasive sensors will remain an indicative measure of the atmospheric loading unless equivalence can demonstrated. There was little indication in the questionnaire responses that this was underway.

How or where will this technology provide opportunities for improvement compared to the current technology?

One of the key advantages of pervasive sensors inferred from the questionnaire responses and through discussion with the academic partners is the provision of high temporal and spatial resolution measurements, particularly within micro-environments such as streets. Current air pollutant measurements are fixed point measurements. The physical attributes (e.g., size, shape, mass) of pervasive sensors, allows them to be mounted in a wider range of locations when compared to traditional fixed point analysers. This allows them to be used to produce a more comprehensive picture of the pollution climate.

The questionnaire responses and the academic partners highlighted several situations within LAQM monitoring where they could provide opportunities for improvement compared to the current technology:

- Measurements from sensor arrays within street micro-environments provide improved source apportionment of air pollutants. This can help elucidate the cause of air pollution and provide evidence to design solutions, take action and evaluate impact. Such application areas include traffic management, low emissions bus initiatives, and so on.
- Pervasive sensors can be combined with UTMC systems attempt to maximise road network potential to create a more robust and intelligent system that can be used to meet current and future management requirements. The desired outcome is to reduce vehicle-emissions and improve local air quality. This can be achieved through re-routing vehicles, lowering speed limits, taking advantage of the natural ventilation of the built environment by queue relocation using UTMC depending on the forecasted meteorological conditions, or introduce travel demand management (e.g., mode shift, bus corridors, cycle incentives).
- Replacement of time-integrated passive sampling (e.g., diffusion tubes) of air pollutants (such as NO_2) with comparable levels of error.
- Limit the reliance on generalised dispersion modelling to represent the in-street dispersion of air pollutants. Currently dispersion modelling relies on national fleet characteristics to estimate emissions, using prevailing meteorological condition data and theoretical description of built environment that governs dispersion rather than measurement of the concentrations resulting from actual emissions, meteorological conditions and the actual geometry of the built environment.
- Devices can be mounted on motor vehicles and driven around road networks. The measurements can be used to map roadside air pollutant concentrations. Likewise they can be carried by individuals and used to construct maps of roadside or background air pollutant concentrations.

The questionnaire responses indicated that meteorological parameters are measured by pervasive sensors: relative humidity measurements are required to correct readings. The academic partners indicated that the supplemental meteorological observations would enhance the evidential (research) value of compliance monitoring data. They would fulfil an on-going need for free-to-user meteorological data, in addition to that provided by the Met Office, without adding significantly to the cost burden of monitoring.

Summary of benefits & limitations

The key benefits of pervasive sensors is they are capable of providing indicative measurements on high temporal and spatial scales. They are small, lightweight and compact and provide a flexible measurement platform which can be deployed in locations that cannot be accessed by current fixed-point measurement instrument. The key limitation, at the current time, is the lack of equivalence testing. In the short-term, this situation is compounded by the lack of an appropriate standard.

Fixed-point sensors

Micro-aethalometer

Table A3-7 shows the risk assessment scoring for micro-aethalometer based on the criteria laid-out in Appendix 2.

Table A3-7 Micro-aethalometer risk assessment scoring

						Comments
Measures a range of pollutants simultaneously (Quality)			3	4		
Measures a range of non-AQ parameters (Quality)	1					
Market readiness			3			
Time to market			3			2017-2020
PERCEIVED BARRIERS TO MARKET						
Many barriers to market (Score as quality, i.e. 1 = many, 5 = very few or none)			3			Cost of gaining certification and ease of gaining funding.
Barriers are well defined (Agreement)					5	
Few measures required to overcome barriers (Score as agreement, i.e., 1 = strongly disagree, 5 = strongly agree)			3			
Barriers **can** be overcome with appropriate intervention (Score as likelihood)				4		
HOW WILL THE MEASUREMENTS BE HANDLED?						
Raw measurements can be easily (re)processed (Quality/Agreement)				4	5	
Raw measurements can be accessed (Quality/Agreement)				4	5	
Raw data can converted to measurements *quickly* (Quality/Agreement)				4	5	
Processing of raw measurements requires use of proprietary algorithm - e.g., to correct drift (Quality)			3		5	
Data can be streamed (Quality/Agreement)				4	5	
Measurements can be easily integrated (Quality/Agreement)					5	
COSTS						
Instrument capital costs (Costs)			3			
Installation costs (Costs)				4		
Maintenance costs (Costs)				4		
Analytical costs (Costs)					5	
FLEXIBILITY OF DEVICE DESIGN & PRACTICAL CONSIDERATIONS						
Lightweight (Quality/Agreement)					5	

Compact (Quality/Agreement)					5	
Easily installed (Quality/Agreement)				4	5	
Robust (Quality/Agreement)					5	
Technology poses a threat to human health (rate by Quality scale i.e. 1 = greatest threat, 5 = least threat).					5	
Measurements impeded by meteorological conditions (rate by Quality scale, i.e. most affected = V Poor, least affected = V Good)						No information provided.
SERVICING, CALIBRATION & RELIABILITY						
Can be calibrated in-situ (Quality)					5	
Frequency of calibration ('How Often')				4		
Maintenance interval ('How Often')				4		
Frequency of Replacing Active sensor/detector ('How Often')						Unknown
MEASUREMENT UNCERTAINTY						
Limit of detection is appropriate based on current concentrations				4		Down to 50 ng m^{-3} for BC
Limit of detection is appropriate based on perceived future concentrations					5	
Accuracy sufficient for indicative measurements						No standard for BC
Precision sufficient for indicative measurements						No standard for BC
Accuracy sufficient for fixed point measurements						No standard for BC
Precision sufficient for fixed point measurements						No standard for BC
Measurement uncertainties are well-characterised						No standard for BC
TEMPORAL AND SPATIAL RESOLUTION						
Good spatial resolution - allows measurements to be collected from over a wide area					5	Could be widely adopted technology and thus give great spatial resolution
Offers good temporal resolution					5	1 Hz resolution.
SUMMARY						
For conceptual technologies assess the likelihood of innovative technology coming to market (Likelihood)			3			
Is considered to be a "*game changer*" (Agreement)				4		This has a great deal of potential as a device - especially given social networking and being wearable - might not be disruptive.
Is a disruptive technology (Agreement)			3			
Can be coupled with other innovative technologies, i.e., sensor-sensor, sensor-satellite, sensor-remote sensing technique			3			Portability/size of sampler will enable quick and easy deployment. Although the capital cost of the units may be a limiting factor for multiple node monitoring.

OPC

Table A3-8 shows the risk assessment scoring for the optical particle counter (OPC) based on the criteria laid-out in Appendix 2.

Table A3-8 Optical particle counter risk assessment scoring

						Comments
Measures a range of pollutants simultaneously (Quality)				4		Can count particles between 0.18 µm to 18 µm and convert to mass concentrations. >100 size bins can be defined.
Measures a range of non-AQ parameters (Quality)			3	4		Meteorological measurements can be added.
Market readiness				4	5	Currently available
Time to market				4	5	Currently available
PERCEIVED BARRIERS TO MARKET						
Many barriers to market (Score as quality, i.e. 1 = many, 5 = very few or none)				4		Currently undergoing equivalence testing.
Barriers are well defined (Agreement)				4	5	
Few measures required to overcome barriers (Score as agreement, i.e., 1 = strongly disagree, 5 = strongly agree)				4	5	
Barriers <u>**can**</u> be overcome with appropriate intervention (Score as likelihood)				4	5	
HOW WILL THE MEASUREMENTS BE HANDLED?						
Raw measurements can be easily (re)processed (Quality/Agreement)				4	5	Possible correction factor depending on outcome of equivalence testing.
Raw measurements can be accessed (Quality/Agreement)				4	5	Measurements as recorded by sampler.
Raw data can converted to measurements *quickly* (Quality/Agreement)				4	5	
Processing of raw measurements requires use of proprietary algorithm - e.g., to correct drift (Quality)			3		5	
Data can be streamed (Quality/Agreement)				4	5	Samplers have the required outputs for use with the latest logging/telemetry systems or built-in telemetry.
Measurements can be easily integrated (Quality/Agreement)					5	
COSTS						
Instrument capital costs (Costs)			3	4		Between thousands to 10s of thousands.
Installation costs (Costs)					5	
Maintenance costs (Costs)					5	
Analytical costs (Costs)					5	
FLEXIBILITY OF DEVICE DESIGN & PRACTICAL CONSIDERATIONS						

Lightweight (Quality/Agreement)			3	4		
Compact (Quality/Agreement)				4		
Easily installed (Quality/Agreement)				4		
Robust (Quality/Agreement)				4		
Technology poses a threat to human health (rate by Quality scale i.e. 1 = greatest threat, 5 = least threat).					5	
Measurements impeded by meteorological conditions (rate by Quality scale, i.e. most affected = V Poor, least affected = V Good)				4		Smart-heated inlets used.
SERVICING, CALIBRATION & RELIABILITY						
Can be calibrated in-situ (Quality)					5	
Frequency of calibration ('How Often')					5	
Maintenance interval ('How Often')			3		5	
Frequency of Replacing Active sensor/detector ('How Often')						Unknown
MEASUREMENT UNCERTAINTY						
Limit of detection is appropriate based on current concentrations				4		
Limit of detection is appropriate based on perceived future concentrations				4		
Accuracy sufficient for indicative measurements						Not suitable under TG.09
Precision sufficient for indicative measurements						Not suitable under TG.09
Accuracy sufficient for fixed point measurements						Demonstration of equivalence required
Precision sufficient for fixed point measurements						Demonstration of equivalence required
Measurement uncertainties are well-characterised			3			
TEMPORAL AND SPATIAL RESOLUTION						
Good spatial resolution - allows measurements to be collected from over a wide area			3	4		Cost would be a limiting factor for the more expensive samplers but the low-cost samplers could be deployed at multiple locations.
Offers good temporal resolution				4		Up to 1 minute resolution.
SUMMARY						
For conceptual technologies assess the likelihood of innovative technology coming to market (Likelihood)				4	5	Some are already available
Is considered to be a "*game changer*" (Agreement)			3		5	Depending on outcome of equivalence tests.
Is a disruptive technology (Agreement)			3	4		Could potentially replace other less agile instruments.
Can be coupled with other innovative technologies, i.e., sensor-sensor, sensor-satellite, sensor-remote sensing technique		2	3			

Direct measurement NO_2 analyser

Table A3-9 shows the risk assessment scoring for direct-measurement NO_2 analyser based on the criteria laid-out in Appendix 2.

Table A3-9 Direct-measurement NO_2 analyser risk assessment

						Comments
Measures a range of pollutants simultaneously (Quality)	1					NO_2 only
Measures a range of non-AQ parameters (Quality)						Unknown
Market readiness					5	Available now
Time to market					5	
PERCEIVED BARRIERS TO MARKET						
Many barriers to market (Score as quality, i.e. 1 = many, 5 = very few or none)		2				
Barriers are well defined (Agreement)				4		
Few measures required to overcome barriers (Score as agreement, i.e., 1 = strongly disagree, 5 = strongly agree)		2				
Barriers **can** be overcome with appropriate intervention (Score as likelihood)				4		
HOW WILL THE MEASUREMENTS BE HANDLED?						
Raw measurements can be easily (re)processed (Quality/Agreement)			3			Calibrations and scaling required.
Raw measurements can be accessed (Quality/Agreement)					5	
Raw data can converted to measurements *quickly* (Quality/Agreement)			3			Data ratification needed.
Processing of raw measurements requires use of proprietary algorithm - e.g., to correct drift (Quality)					5	
Data can be streamed (Quality/Agreement)					5	
Measurements can be easily integrated (Quality/Agreement)					5	
COSTS						
Instrument capital costs (Costs)						Unknown
Installation costs (Costs)						Unknown
Maintenance costs (Costs)						Unknown
Analytical costs (Costs)					5	Not required.
FLEXIBILITY OF DEVICE DESIGN & PRACTICAL CONSIDERATIONS						
Lightweight (Quality/Agreement)			3			Similar to current analysers
Compact (Quality/Agreement)			3			
Easily installed (Quality/Agreement)			3			
Robust (Quality/Agreement)			3			
Technology poses a threat to human health (rate by Quality scale i.e. 1 = greatest threat, 5 = least threat).				4		
Measurements impeded by meteorological conditions (rate by Quality scale, i.e. most affected = V Poor, least affected = V Good)					5	
SERVICING, CALIBRATION & RELIABILITY						

	1	2	3	4	5	
Can be calibrated in-situ (Quality)				4		Requires calibration system and gas.
Frequency of calibration ('How Often')			3			
Maintenance interval ('How Often')			3			
Frequency of Replacing Active sensor/detector ('How Often')						Unknown
MEASUREMENT UNCERTAINTY						
Limit of detection is appropriate based on current concentrations					5	
Limit of detection is appropriate based on perceived future concentrations					5	
Accuracy sufficient for indicative measurements					5	Assumed
Precision sufficient for indicative measurements					5	Assumed
Accuracy sufficient for fixed point measurements						
Precision sufficient for fixed point measurements						
Measurement uncertainties are well-characterised						No data
TEMPORAL AND SPATIAL RESOLUTION						
Good spatial resolution - allows measurements to be collected from over a wide area			3			Similar to what is currently achieved
Offers good temporal resolution				4		Up to 1 minute.
SUMMARY						
For conceptual technologies assess the likelihood of innovative technology coming to market (Likelihood)				4		
Is considered to be a "*game changer*" (Agreement)			3			
Is a disruptive technology (Agreement)			3			
Can be coupled with other innovative technologies, i.e., sensor-sensor, sensor-satellite, sensor-remote sensing technique				4		

DUVAS

Table A3-10 shows the risk assessment scoring for the DUVAS instrument based on the criteria laid-out in Appendix 2.

Table A3-10 DUVAS sensor risk assessment scoring

	1	2	3	4	5	**Comments**
Measures a range of pollutants simultaneously (Quality)					5	
Measures a range of non-AQ parameters (Quality)			3			
Market readiness				4		
Time to market				4		
PERCEIVED BARRIERS TO MARKET						
Many barriers to market (Score as quality, i.e. 1 = many, 5 = very few or none)				4		
Barriers are well defined (Agreement)				4		
Few measures required to overcome barriers (Score as agreement, i.e., 1 = strongly disagree, 5 = strongly agree)				4		
Barriers **can** be overcome with appropriate intervention (Score as likelihood)				4		
HOW WILL THE MEASUREMENTS BE HANDLED?						

Raw measurements can be easily (re)processed (Quality/Agreement)					5	
Raw measurements can be accessed (Quality/Agreement)					5	
Raw data can converted to measurements *quickly* (Quality/Agreement)					5	
Processing of raw measurements requires use of proprietary algorithm - e.g., to correct drift (Quality)					5	No
Data can be streamed (Quality/Agreement)					5	Yes
Measurements can be easily integrated (Quality/Agreement)					5	Yes
COSTS						
Instrument capital costs (Costs)			3			Commensurate with other instruments
Installation costs (Costs)			3			
Maintenance costs (Costs)			3			Low compared to capital cost
Analytical costs (Costs)					5	None
FLEXIBILITY OF DEVICE DESIGN & PRACTICAL CONSIDERATIONS						
Lightweight (Quality/Agreement)			3			No heavier than current equipment
Compact (Quality/Agreement)			3			No larger than current equipment
Easily installed (Quality/Agreement)				4		
Robust (Quality/Agreement)				4		Designed to be portable
Technology poses a threat to human health (rate by Quality scale i.e. 1 = greatest threat, 5 = least threat).					5	No
Measurements impeded by meteorological conditions (rate by Quality scale, i.e. most affected = V Poor, least affected = V Good)					5	Designed to work under all conditions
SERVICING, CALIBRATION & RELIABILITY						
Can be calibrated in-situ (Quality)					5	
Frequency of calibration ('How Often')					5	Low drift
Maintenance interval ('How Often')					5	Lamp needs replacing every 6 months
Frequency of Replacing Active sensor/detector ('How Often')					5	
MEASUREMENT UNCERTAINTY						
Limit of detection is appropriate based on current concentrations				4		As good as current equipment
Limit of detection is appropriate based on perceived future concentrations				4		
Accuracy sufficient for indicative measurements						NA
Precision sufficient for indicative measurements						NA
Accuracy sufficient for fixed point measurements				4		Yes
Precision sufficient for fixed point measurements				4		Yes
Measurement uncertainties are well-characterised				4		Yes
TEMPORAL AND SPATIAL RESOLUTION						
Good spatial resolution - allows measurements to be collected from over a wide area			3		5	But could rise to a 5 if fitted to a mobile platform

Offers good temporal resolution					5	
SUMMARY						
For conceptual technologies assess the likelihood of innovative technology coming to market (Likelihood)						NA
Is considered to be a "*game changer*" (Agreement)				4		
Is a disruptive technology (Agreement)				4		Replaces many less agile instruments with more speciation
Can be coupled with other innovative technologies, i.e., sensor-sensor, sensor-satellite, sensor-remote sensing technique					5	

Overview

The study engaged with a number of stakeholders involved in the development of active and automatic samplers capable of providing fixed point measurements. The measurement methods identified fall into four instrument types:

- Aethalometer
- Optical Particle Counters (OPC)
- Direct-measurement NO_2 analyser
- Differential Ultra Violet Absorption Spectrometer (DUVAS).

Micro Aethalometer

Aethalometers are currently used within the national air quality network to provide a measure of the ambient black carbon (BC, soot) loading. There is no statutory requirement to measure BC, rather its value is in informing research into the sources of particulate matter. The questionnaire was provided by a stakeholder developing a micro Aethalometer. Its intended use would be to allow personal exposure to BC to be measured, but its compact design and low weight would also permit it to be used in a more flexible manner than traditional fixed point instruments. As the instrument is still in development the main barrier to further adoption is demonstrating equivalence with current in-use instruments and achieving certification. Table A3-8 summarises the risk assessment scoring for the micro Aethalometer based on the criteria laid-out in Appendix 2.

OPC

Responses were also received from stakeholders developing OPC samplers. OPC samplers measure the size (diameter) and number of particles as they pass through a beam of light. Particle number is determined by counting the pulses of scattered light reaching the detector. The intensity of the scattered light related is used to infer size of the particle passing through the light beam. Table A3-9 summarises the risk assessment scoring for OPC analysers using the criteria laid-out in Appendix 2. The Table summarises the questionnaire responses.

Direct-measurement NO_2 analysers

Two Direct-measurement NO_2 analysers were identified in the questionnaire responses. These analysers use an alternative technique to the current reference method chemiluminescence NOx analyser used in the national networks for compliance monitoring and local authority review and assessment. Current, in-use NOx analysers convert NO_2 to NO (nitric oxide). By characterising the conversion efficiency it is possible to infer the NO_2. The two direct measure analysers use a spectroscopic technique to provide a direct measure of NO_2. Table A3-10 summarises the risk assessment scoring for the direct measure NO_2 analysers using the criteria laid-out in Appendix 2. The table also summarises the questionnaire responses.

DUVAS

The DUVAS instrument is a double closed-ended beam device with some similarities to the DOAS instrument described previously in that it uses a collimated beam of UV light, rather than sunlight. Air pollutant concentrations are derived from column concentrations, but unlike the DOAS the column is contained within the body of the instrument which means it is capable of providing fixed-point measurements. The questionnaire response noted that it could measure multiple air pollutants, e.g., NO_2, SO_2 and O_3, as well as organic and inorganic gaseous compounds, with no cross sensitivity between gases. The DUVAS can be sited on a mobile platform, e.g., the roof of a vehicle, to provide measurements of the pollution climate within a street canyon. Table A3-10 gives the risk assessment scoring for ground-based sensors based on the criteria laid-out in Appendix 2.

Measurement handling

Micro Aethalometer

The questionnaire responses stated that the proprietary software would be required to process the measurements therefore scoring a three, but mostly fours. The project team noted that as with current in-use BC instruments further data processing may be required to reduce noise in the data and/or to adjust for non-linear responses due to the effect of filter loading. Once the instrument performance was characterised and understood, it may be possible to derive an algorithm based approach for compensating for instrument noise and/or filter loading which would improve the scores to fives.

OPC

The questionnaire responses indicate that the OPC samplers require no post-processing other than to investigate any erroneous data, e.g., noisy data or data spikes. Data are stored using an internal logger and can be disseminated to cloud-based systems using additional or internal telemetry/logging systems. The project team identified that a correction factor might need to be applied to data dependant on the outcome of equivalence testing. Once equivalence was demonstrated this would not limit the equipment’s use for compliance assessment. The scores awarded were mostly fours to fives.

Direct-measurement NO_2 analysers

The questionnaire responses indicated that measurements would be stored on an internal logger and can be disseminated to cloud-based systems using additional or internal telemetry/logging systems. The project team identified that data would need to be scaled using calibration data. The instrument would require calibration and the measurements would have to be scaled and ratified and in this respect the instrument scored threes, as this was typical, but elsewhere scored more highly (five).

DUVAS

The questionnaire responses stated that the raw measurements need to be processed to provide the final data “product”, i.e., measurements of the concentrations of air pollutants. Once the instrument’s spectral response has been determined in respect to a calibration gas of known concentration, raw data can be interrogated retrospectively and concentrations of other gaseous pollutants can be recovered, even if they were not initially required – this is a useful feature allowing historical measurements to be recovered.

Costs

Micro Aethalometer

The questionnaire responses showed that the capital cost of such samplers would be in the region of thousands of pounds, which is fairly typical and reflected by a score of three. On-going maintenance costs would be in the region of hundreds of pounds per year, and low when compared to in-use gas and particulate analysers and there are no associated analytical costs, resulting in scores of four and five, respectively.

OPC

The questionnaire responses revealed that the capital costs of OPC were quite variable, ranging from thousands of pounds to tens of thousands of pounds, which are fairly typical resulting in score of three, possibly four. However, on-going costs are likely to be relatively low as no consumables would be required leading to high scores of five. OPC do not generally require temperature-controlled cabinets and their consumption of electricity is relatively low in comparison to more conventional instrumentation. The manufacture believes that electricity costs for the site operator can be reduced from the order of £1k per annum to the region of £hundreds per annum – this money could be used to offset the capital cost.

Direct-measurement NO_2 analysers

No information was provided regarding the capital cost and ongoing costs of these instruments. The project team concluded the maintenance costs would be similar to those for current chemiluminescence analysers. No scores were awarded.

DUVAS

The questionnaire response for the DUVAS noted that the cost was to be of the order of tens of thousands of pounds depending on configuration and are therefore fairly average, hence scores of three, or thereabouts. The DUVAS is not expected to have any additional analytical costs, hence a score of five. On-going maintenance costs were reportedly considerably lower, of the order of hundreds of pounds as the DUVAS instrument has few consumables.

Flexibility of device design and practical considerations

Micro Aethalometer

The questionnaire response state that the Aethalometer sampler in development will have internet connectivity through 3G/4G or Wi-Fi. This removes the need for additional telemetry system. The scores awarded for the criteria assessed were average (threes).

OPC

The questionnaire responses stated that instruments we designed to be small and compact and thus can be deployed in a range of configurations, e.g., on lamp posts, without the need for specialist housing leading to above average scores of around four. One instrument manufacturer offered add-on sensors (at extra cost) to enable the measurement of ambient temperature, barometric pressure, and relative humidity, thus increasing the scope of measurements provided. The size range of the instruments identified in the questionnaire responses allows $PM_{2.5}$ and PM_{10} to be measured simultaneously with one instrument. It should be noted however that the reported mass fraction is measured directly, but inferred from the particle size distribution. Such measurements are permissible from screening and assessment purposes within the LAQM regime but not for detailed assessment or national compliance monitoring.

Direct-measurement NO_2 analysers

The questionnaire responses indicated that the analysers will be the same size, have similar outputs as current NOx instruments, and will require a temperature controlled environment. This is reflected by scores of three in the risk assessment.

DUVAS

Stakeholder responses noted that DUVAS instruments are offered as fixed-point or mobile devices. Mobile devices incorporate rechargeable batteries offering upto 4 hours of measurements extending the spatial range of the instrument. The instrument weighs tens of kilograms and is only moderately portable. As a commercial instrument, the design and form of the DUVAS is optimised hence its scores were reasonably high. DUVAS instruments can operate under all meteorological conditions and scored five.

Servicing, calibration and reliability

Micro Aethalometer

Scores of four and a five were awarded as the manufacture stated that the instrument would need to be calibrated on-site annually. The Aethalometer can carry-out self-calibrations using integrated dust generators. No details were provided regarding reliability.

OPC

The manufacturer stated the instrument can be service bi-annually or annually, resulting in scores of 3 or 5 respectively. Calibration is in-situ for which a score of five was awarded. No details were provided regarding reliability.

Direct-measurement NO_2 analysers

No information was provided however, the project team concluded that a similar QA/QC would need to be employed as currently is for chemiluminescence analysers. This would include regular calibrations (every 2-4 weeks) using an on-site gas calibration system and a 6-monthly maintenance schedule leading to scores of three. No information was provided regarding the instrument's reliability.

DUVAS

The DUVAS instrument has few consumables, lamp replacement is advised every 6 months of continuous operation. The instruments require infrequent calibration (every few months) with zero air and specific gases but were reported not to exhibit large drifts over time. Mirrors need to be replaced every year or two. The instrument exhibits no cross sensitivity between gases and can operate under all meteorological conditions. The DUVAS received scores of five.

Measurement uncertainty

Micro Aethalometer

The questionnaire responses show that the limit of detection of Aethalometer are in the region of 50 ng m^{-3} which was deemed to be sufficient for future concentrations. No information was provided regarding the accuracy and precision of the instruments. There are no performance standards for Aethalometers therefore this criteria could not be assessed.

OPC

The questionnaire indicated that the limit of detection of the OPC instruments was <1 µg m^{-3}. The project team concluded that the instrument would have to demonstrate equivalence were this method to be used for particulate compliance monitoring. OPC measurements are sufficient as a screening tool within the LAQM regime, but not detailed assessments, which rely on gravimetric methods.

Direct-measurement NO_2 analysers

The instrument supplier stated that the accuracy and precision (claimed to be 0.5% of reading above 5 ppb for the Cavity Attenuated Phase Shift (CAPS) spectroscopy technique) of the direct measure NO_2 analysers was better than current NOx chemiluminescence analysers. The instrument has been certified to meet the requirements of US EPA Federal Equivalent Method (EQNA-0514-212) and has therefore demonstrated equivalence in the US for monitoring NO_2 in ambient air. It is TUV certified and is undergoing MCERTS certification. Its equivalence against the data quality objective of the EU air quality Directive remains untested. The technical experts also noted that the photolytic conversion of NO_2 is not good. Based on this evidence the instrument was assessed to be capable of providing indicative measurements and awarded five, though no points were awarded in respect of its ability to provide fixed point measurements as this has not been assessed.

DUVAS

The DUVAS reportedly had detection limits of single ppb or better for most compounds and its accuracy was quoted at ±3% of the reading, hence scores of four. As these are quoted by the manufacturer/supplier these would have to be assessed further against current, in-use techniques.

Temporal and Spatial Resolution

Micro Aethalometer

The questionnaire response indicated that the Aethalometer had a temporal resolution of 1 Hz. As a personal monitor it will be small enough to be worn, and combined with GPS data, could provide high spatial resolution BC measurements. These aspects resulted in a score of five.

OPC

It was reported that the OPC are capable of providing particle number counts every 1-2 seconds. These counts can be averaged to provide the particle ($PM_{2.5}$ and PM_{10}) mass concentration every minute or so. In terms of temporal resolution the OPC scored a four. The portability, and hence the spatial resolution, of the OPC assessed varied; some were more portable than others, scoring four as they weren't specifically designed for ease of portability, but were more lightweight and robust, whilst others were intended to be rack-mounted, resulting in a score of three.

Direct-measurement NO_2 analysers

Spatial and temporal resolution would be similar to what is achieved within the current compliance and LAQM networks thus a scores of three and four, respectively.

DUVAS

The spatial resolution of DUVAS instruments is expected to be similar to current in-use techniques thus it was awarded a score of 3, rising to 5 if fitted on a mobile platform in order to extend its range, thereby offering greater spatial resolution. The stakeholder response did not offer information on the instrument's temporal resolution but it is expected to be similar to current in-use instrument, hence it was awarded a score of 3.

Integration with the UK air quality monitoring regime

Micro Aethalometer

The UK Black Carbon network is not a compliance network – its measurements inform PM_{10} and $PM_{2.5}$ source apportionment research. The project team noted that the micro Aethalometer could be used within the current national Black Carbon network following calibration against the Aethalometers within the network. Its portability means that it could also be used in exposure studies.

OPC

OPC samplers are used for PM_{10} screening and assessment studies within the LAQM regime. The questionnaire responses indicated that OPC manufacturers are keen to demonstrate equivalence which would offer the potential for OPC samplers to be used within the UK compliance network.

Direct-measurement NO_2 analysers

Pending equivalence testing, there is a potential to use direct-measurement NO_2 analysers within the compliance network. The current UK compliance modelling uses NOx measurements not NO_2. As a result, a change in Defra's approach to modelling NO_2 concentrations in the UK may be required or the current NOx analysers would simply have to remain in-place. This would offer no cost advantage.

DUVAS

The stakeholder response did not indicate whether the instrument has not undergone equivalence testing and without this, and further field testing, it is unclear what would be required to integrate it with the UK's air quality monitoring regime, but it offers (untested) potential.

How or where will this technology provide opportunities for improvement compared to the current technology?

Micro Aethalometer

The micro Aethalometer could expand the UK Black Carbon network's measurement capability. Their small size and portability mean that they can be used in a flexible way, either to make measurements at fixed locations, or to provide more detailed information at locations which are inaccessible to current instruments (which are too large and/or heavy, or require mains power). The size of micro Aethalometer enables its use in studying human exposure.

OPC

OPC can simultaneously measure PM_{10} and $PM_{2.5}$. Combining two instruments into one may provide cost benefits. Their small size and portability mean that it can be used in a flexible way, either to make measurements at fixed locations, or to provide more detailed information at locations which are inaccessible to current instrumentation as they are too large and/or heavy, or require mains power where there is none.

Direct-measurement NO_2 analysers

Direct-measurement NO_2 analysers instruments provide a direct, rather than inferred, measure of NO_2, but the technical experts noted that the photolytic conversion of NO_2 was not good. The project team reported that the inference of NO_2 concentrations from NOx measurements may lead to a small over-estimate of NO_2 concentrations, possibly of the order of 1-2 µg m^{-3} due to interferences from other nitrogen compounds, e.g., particulate phase nitrate (pNO_3^-), peroxyacetyl nitrate (PAN), and nitric acid (HNO_3), but there effects have not been fully quantified in the UK.

DUVAS

Stakeholder responses indicated that DUVAS instruments may be able to provide measurements of a range of gaseous air pollutants with no cross sensitivity. The costs associated with the instruments are substantial, but it has the potential to displace several instruments with one, and the on-going costs are reportedly low, which may help reduce the cost burden in the longer term. Once the instrument's spectral response has been determined in respect to a calibration gas of known concentration, raw data can be interrogated retrospectively and concentrations of other gaseous pollutants can be recovered, even if they were not initially required – this is a useful feature allowing historical measurements to be recovered.

Summary of limitations

Three types of instrument were assessed:

- Micro Aethalometer
- Optical Particle Counter (OPC)
- Direct-measurement NO_2 analyser
- Differential Ultra Violet Absorption Spectrometer (DUVAS).

The limitation common to all the technologies identified was that none had undergone equivalence testing and therefore could not be used for compliance monitoring. Time and resources would be required to demonstrate equivalence. Only the DUVAS is capable of measuring multiple (gaseous) air pollutants, whilst the micro aethalometer and direct-measurement NO_2 analyser can only measure single pollutants. A further advantage of the DUVAS instrument is that raw data can be interrogated retrospectively and gas concentrations recovered, even if they were not initially required. OPC measure particle numbers optically, and can, in some cases, measure the PM_{10} and $PM_{2.5}$ size fractions simultaneously. Their key limitation is that they do not directly measure the particulate (PM_{10} or $PM_{2.5}$) mass concentration, rather it is inferred from the particle size distribution and an assumed particle density.

The Gemini Building
Fermi Avenue
Harwell
Didcot
Oxfordshire
OX11 0QR
United Kingdom

t: +44 (0)1235 753000
e: enquiry@ricardo.com

ee.ricardo.com