NERC Scoping Study R8-H10-71

Environmental and Earth Science Using Next Generation Aerial Platforms

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Environment Research and Services

Final Report

July 2009

Environmental Research and Services

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Summary

We provide a set of recommendations showing how the Natural Environment Research Council (NERC), and its Technology theme in particular, could provide a lead in delivering UAV-based Earth and Environmental science. We then focus on 7 key science areas, and currently open questions, that have emerged in our study as best tackled using UAV-based measurement strategies.

Based on a bibliometric analysis of the peer-reviewed literature, the UK appears not to be a major innovator in the area of unmanned aerial vehicle (UAV) engineering, lagging far behind USA and China in published work. UK involvement in UAV-based Earth and environmental science has been sporadic and restricted to one-off projects/reports (fewer than 10 since this area began to be developed ca. 1995).

Most UAVs are designed for military operations; fewer than 50 platforms are ready for the commercial and scientific sectors. Nevertheless, this is a sufficient number to enable a broad range of Earth and environmental science to be accomplished in a 2-5–year timeframe, particularly if international collaborations for access to large platforms can be established promptly.

There is no one-size-fits-all solution for UAV-based science in the NERC science area. The science suggests roles for high-altitude long-endurance (HALE), medium-altitude long-endurance (MALE), small, mini- and micro-UAVs.

The NASA Global Hawk is, de facto, the world HALE facility. If access can be negotiated, this facility offers UK scientists the best and most cost-effective route to HALE-based science. In the first instance, much of the UK-led science could exploit existing UK expertise in campaign planning and modelling support, rather than payload development.

Other large UAVs (MALE and similar) are available from European and Israeli providers. These platforms are suitable for missions requiring long endurance at lower altitudes. There is an opportunity for the UK to gain a lead in the provision of these platforms in partnership with other countries.

Small UAVs provide greater payload capacity, flexibility, range, endurance, and — perhaps most importantly — stability in turbulence, than mini- and micro-UAVs. These benefits come at the cost of ease of deployment, however. Small UAVs are best accessed through a facility. There is a chance for the UK to take a lead here, by providing such a facility, perhaps in partnership with other countries.

Mini- and micro-UAVs with built-in payloads are best thought of as instruments, rather than as platforms. Although there is much to be gained from carrying these light and easily deployable instruments into remote areas, they will usually add most value when integrated into larger research platforms such as ships, (mobile) ground bases, and even manned aircraft.

The regulatory environment for UAVs is changing, but it is unlikely that European targets to enable “file-and-fly” operations for UAVs with maximum take-off weight (MToW) > 150 kg by 2013 will be met. In the interim, operations will be permitted on a case-by-case basis and will be easiest in remote environments such as the poles and the remote ocean. UAVs with dry weight < 20 kg operate in a more relaxed regulatory framework in the UK, and could be deployed immediately in less remote environments, although not in built-up areas.

We identify 7 science missions in which UAVs could outperform both satellites, ground sensor networks and manned aircraft, and which can be accomplished using existing platforms in the current regulatory framework. Those missions are: mapping of the Greenland and Antarctic ice-sheet bedrock, forest-atmosphere interactions, air-sea exchange, ocean ecology responses to climate change, aerosol direct and indirect effects, the distribution of climate-active gases, and volcanic hazards. Funding any one of these would provide impetus for a number of spin-off missions.

It is highly unlikely to be cost-effective for NERC to develop bespoke UAV platforms, except possibly micro-UAV platforms as and when they are needed.

The costs of UAV missions vary dramatically with platform. Micro-UAV missions are affordable in responsive-mode-sized grants. The costs of the Global Hawk are very heavily subsidised by NASA, and so are affordable in consortium-sized grants. Access to other large UAV platforms is of the order of £ 1M for a 1-month deployment and 100 flight hours. NERC will get much-improved value for money if it commits to several years with a given UAV provider.

Nomenclature

Below, we use these terms with the following meanings:

ANO = Aviation National Order

BAS = the British Antarctic Survey

BGS = the British Geological Survey

CAA = Civil Aviation Authority

CERES = Clouds and Earth's Radiant Energy System satellite instrument

CMOS = Complementary metal–oxide–semiconductor integrated circuit technology

COTS = Commercial, off-the-shelf

Dry weight = weight of the aircraft, including payload, but without fuel

EASA = European Aviation Safety Agency

EDA = European Defence Agency

ENAC = L'Ente Nazionale per l'Aviazione Civile (National Civil Aviation Authority of Italy)

EO = either (i) electro-optical (usually visible wavelength) sensing, or (ii) Earth Observation

EU = European Union

EUFAR = European Facility for Airborne Research

EuroCAE = European Organization for Civil Aviation Equipment

GEOSS = Global Earth Observation System of Systems

GERB = Geostationary Earth Radiation Budget satellite instrument

GMES = Global Monitoring for the Environment and Security

HALE = high-altitude (above 10 km), long-endurance (greater than 6 hours) UAV

HAP = High-altitude platform. An aerial platform designed to stay on-station at altitudes, typically above 12 km (40,000 ft), for many hours, days, or longer. Lighter-than-air platforms, with engines, are HAP platforms.

ICAO = International Civil Aviation Organisation

InSAR = Interferometric synthetic aperture radar

IR = infra-red

ISP = Integrated Signal and Processing

LALE = Low-altitude (< 3 km), long-endurance (greater than 6 hours) UAV.

Lidar = remote sensing by light detection and ranging

MALE = medium-altitude (3 – 10 km), long-endurance (greater than 6 hours) UAV.

M(O)EMS = Micro- (Opto-) Electrical and Mechanical Systems

MoU = Memorandum of Understanding

MToW = maximum take-off weight.

Next Generation (Aerial) platforms = highly autonomous, un-crewed, aerial platforms

NERC = Natural Environment Research Council

NERC science = science described in the *Next Generation Science for Planet Earth* as well as that fundable through any NERC programme

NOCS = National Oceanography Centre Southampton

NOTAM = “Notice To Airmen” (electronic bulletin of unusual activity in an area)

OTH = Over the horizon (with respect to command and control of UAVs)

Radar = remote sensing by radio-wave detection and ranging

RAN = Registro delle Costruzioni e del Registro Aeronautico Nazionale

SAR = synthetic aperture radar

SATCOM = satellite communications

TBD = To be determined

UAS = un-crewed/unmanned aircraft system. The combined system of aerial platform, ground and air control segments and, sometimes, payload. For our purposes, UAV and UAS are practically synonymous since we take it as given that to fly a particular UAV an appropriate ground segment must be in place.

UAV = un-crewed/unmanned aerial vehicle, i.e., any aerial platform capable of flight without on-board piloting. The aircraft can be fixed wing, rotary, or lighter-than-air. See below, and Table 1, for categories of UAVs used in this report.

> Mini- and micro-UAV = UAV with MTOW < 30 kg and payload capacity typically below 5 kg. May not be stabilised, unit cost typically ca. 3kEuro.
>
> Small UAV = UAV with MTOW < 150 kg and payload capacity typically below 10 kg.
>
> Large UAV = UAV with MTOW > 150 kg and payload capacity above 10 kg (typically 10s - 1000 kg)

UTLS = upper troposphere, lower stratosphere, roughly 10-25 km altitude.

VSLS = very short-lived (ozone destroying) substances

VTOL = vertical take-off and landing

Table 1. Categories of UAVs used in this report, mapped onto the categories given in the *Unmanned Aircraft Systems Global Perspective 2008/2009* (UVS International). There is a good deal of fuzziness in the categorisation of UAVs because individual platforms are optimised for different characteristics. Aviation authorities, including CAA and ENAC, use the term "small aircraft" for UAV with dry weight less than 20kg, "light UAV" for UAV with dry weight between 20 kg and 150 kg, and "UAV" for any UAV with dry weight above 150 kg. The nomenclature, in Europe at least, is likely to be regularised through deliberations of EuroCAE Working Group 73.

This report categories	UVS Int. Categories	Acronym	Range (km)	Ceiling (km)	Endurance (hours)	MToW (kg)	Civilian Example
Micro	Nano	η	<1	0.1	<1	<0.025	PD-100
	Micro	μ	<10	0.25	1	<5	SUMO
Mini	Mini	Mini	<10	0.15 – 0.3	<2	<30	Carolo T200,
Small	Low-Altitude Long Endurance	LALE	>500	3	>24	~30	Aerosonde MkIV
	Close Range	CR	10 - 30	3	2 – 4	150	Eyeview MK50
Large	Short Range	SR	30 - 70	3	3 – 6	200	Camcopter Eyeview MK150
	Medium Range	MR	70 – 200	5	6 – 10	<1500	Heron 1 Hermes 900
	Medium Range Endurance	MRE	>500	8	10 – 18	<1500	Falco
	Medium-Altitude Long Endurance	MALE	>500	14	24 – 48	>1500	Ikhana, Heron TP
	High-Altitude Long Endurance	HALE	>2000	20	24 – 48	>4000	Global Hawk
	Stratospheric	Strato	>2000	20 - 30	>48	TBD	None
Not covered	Unmanned Combat Aerial Vehicle	UCAV	~1500	10	~2	10000	--
	Lethal	Leth	300	4	3 – 4	250	--
	Low-Altitude Deep Penetration	LADP	>250	0.05 – 9	0.5 – 1	350	--
	Decoy	Dec	0 – 500	5	<4	250	--

Opening remarks

The near-term, high-level, scientific objectives of NERC are listed in the 2007-2012 strategy document *Next Generation Science for Planet Earth.* There are 50 science challenges outlined, ranging from

"Provide accurate observations of the global climate system for long-term monitoring of climate to quantify changes and to test and evaluate climate models"

through

"Explore ecosystems to discover novel biodiversity and increase knowledge of the function, distribution and abundance of biodiversity"

to

"Enable better forecasting of volcanic eruptions and management of volcanic crises by providing the necessary observations and developing more robust statistical tools for risk-analysis".

None of the NERC grand challenges are soluble by a single measurement or modelling strategy. Instead, *integrated measurement and modelling strategies* — that test different aspects of our understanding (often, as encapsulated in models) using observations of the appropriate spatial and temporal resolution — are required. When considering the potential of Next Generation platforms for NERC science, it is important to remember that no single observation strategy can provide the answer to high-level science challenges on its own. Next Generation platforms, coupled with miniaturised instruments, offer the potential for novel observational strategies, but are not replacements for manned aircraft, satellite sensors, or ground-based observations. In what follows, the emphasis is inevitably on the potentialities of UAV-based science; knitting this into a fully integrated programme for NERC science is outside the scope of this study, but the necessity of this should, nevertheless, be borne in mind.

Within integrated research strategies there should be, of course, individual projects with tightly defined objectives, and the methodologies proposed for the project must be capable of delivering the objectives. For instance, a proposal to measure CO_2 fluxes above forest canopies using UAV-borne sensors must demonstrate that the platform can put sensors of the required technical specification into the right place for the right amount of time, delivering a data set that is complementary to those available using flux towers and using satellite. Exactly what "sensors of the required technical specification" and "the right place for the right amount of time" mean, depends on how the particular research project has been conceived; it might be one highly precise and accurate sensor carried by a single rastering UAV, or it might be many cheap but less accurate sensors, deployed on a fleet of expendable UAVs. Quantified accuracy, precision, cost, etc., would be defined within any such proposal; these details are clearly outside the scope of this study, therefore.

What, then, is within the scope of this study? An assessment of the state of readiness of next generation platforms, a brief survey of emerging technologies for the miniaturisation of airborne instruments, and a list of indicative science areas within which UAV-based projects are feasible and likely to produce high-impact science.

Input to the scoping study

We have taken input to the scoping study from a wide range of sources and in a variety of ways. At the start of the scoping study period we issued a call for input and supplied pro-forma documents for replies. We received 5 instrument returns, 5 platform returns, and 7 science returns. This rather low rate of return probably indicates reluctance to take time to fill-in forms as much as the general level of interest in UAVs and their payloads. We have also had a significant amount of email correspondence with senior scientists, platform providers and instrument teams. We have had extensive personal contact with interested parties through attendance at conferences and workshops. We have surveyed the community of new platform providers via conferences[1], the commercial literature, particularly Shephard Press' *Unmanned Vehicles* and *Unmanned Aircraft Systems: the Global Perspective 2008/2009* (Unmanned Vehicle Systems (UVS) International), backed-up by personal visits to NASA[2], IAI-Malat, Elbit, Selex Galileo, Alenia Aeronautica, and QinetiQ.

To gauge the full extent of scientific exploitation of UAVs in Earth and Environmental Science, we have undertaken a broad search of the literature, using ISI Web of Knowledge[3] (see below) and four more focused studies: a preliminary study of the legal situation, a survey of UAVs in volcanology, a survey of active instruments for deployment on UAVs, and a survey of passive instruments for deployment on UAVs. These interim studies are available from the authors on request. Our synthesis of this input forms the remainder of this report.

A bibliometric study of UAVs in Earth and Environmental Science

Although most general discussions of UAV capability include a long list of potential civilian uses — for emergency response, detection of natural hazards, coastal surveillance, telecommunications, etc. — peer-reviewed literature on the civilian exploitation of UAVs is still relatively scarce, particularly so for Earth and environmental science.

A Web of Knowledge search on "unmanned aerial vehicle" for all years yielded 976 references, of which only 22 had authors with addresses in the UK (cf. 469 papers with authors from USA, 115 from China, 48 from France, 18 from Italy, and 16 from Germany). Refining the search by Earth and environmental science categories[4] yielded 179 references, of which 6 have UK authors. The citation profile of the Earth and environmental science papers is modest, as might be expected in an emerging field; the most cited UAV paper in the NERC science area are Egger et al. (2005), which has 16 citations, and Herwitz et al. (2004), which has 10 citations. Early papers refer to "model aircraft" rather than UAVs (Konrad 1970; Harding 1989; Bennett *et al.* 1992) but are scarce and unconnected. The oldest reference to mention UAVs explicitly in Earth and environmental science is from 1995 (Hofstetter *et al.* 1995), but there is little more for the next 8 years, until many more papers begin to appear in the middle of the first decade of this century. Up to the end of 2004, topics studied include

- atmospheric science (Abrahamsson *et al.* 2003; Ma *et al.* 2004),
- fire detection (Ambrosia *et al.* 2003),
- marine-mammal surveillance (Stark *et al.* 2003),
- land-use and agricultural remote sensing (Archer *et al.* 2004; Herwitz *et al.* 2004; Johnson *et al.* 2004),
- earth surface deformation (Hensley *et al.* 2004),

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[1] The Bristol International UAV conference, March 2009 and the IRSE conference, Stresa, April 2009

[2] This visit was undertaken in June 2009 by the Technology Theme Leader and Steven Wilson of NERC.

[3] http://wok.mimas.ac.uk/

[4] Subject areas used within the search were: Meteorology & Atmospheric Sciences OR Geochemistry & Geophysics OR Instruments & Instrumentation OR Agriculture OR Oceanography OR Imaging Science & Photographic Technology OR Spectroscopy OR Forestry OR Remote Sensing OR Geography OR Plant Sciences OR Marine & Freshwater Biology OR Geology OR Mining & Mineral Processing OR Public, Environmental & Occupational Health OR Chemistry OR Biodiversity & Conservation OR Environmental Sciences & Ecology OR Zoology. The search was conducted on 11 May 2009.

- cryosphere mapping (Lawrence and Hilliard 2004), and
- pollutant detection (Cao *et al.* 2004; Pearce *et al.* 2004).

Beyond 2004, new topics proposed for UAV-based science include

- wildlife tracking (Jones *et al.* 2006),
- microgravity experiments (Kraeger 2006),
- lower atmosphere CO_2 concentrations (Watai *et al.* 2006; McGonigle *et al.* 2008),
- river channel bathymetry (Lejot *et al.* 2007),
- planetary studies (Lorenz 2008), and
- environmental radioactivity (Kurvinen *et al.* 2005; Perajarvi *et al.* 2008).

As with the number of reported UAV platforms (see below), the literature on UAVs in Earth and Environmental science is growing quasi-exponentially.

The range of Next Generation Platforms

Many designs for new aerial platforms have been presented recently, including airships, rotary wing, and fixed-wing aircraft. These new platforms are designed to fill gaps in the current fleets with respect to one or more of: ease of deployment, decreased risk, long endurance, high altitude, and autonomous operation. In the aviation industry, UAV platforms are recognised as being particularly well-suited to missions that are *dull* (i.e. repetitive and long duration operations extending beyond pilot duty-cycles), *dirty* (we set aside the moral implications of the word and consider here only contaminated environments) or *dangerous* (i.e., extreme environments). As we discuss below, the observations required for much NERC science fit this description.

The *Global Perspective 2008/2009* from UVS International, the UAV community umbrella organisation, lists 974 UAV platforms, ranging from palm-size helicopters to full-size aircraft. The number of UAV platforms is growing quasi-exponentially, with an e-folding time of about 5.5 years. However, the vast majority of these are technology demonstrators or military aircraft; for the environmental sector the number of realistic platforms is substantially reduced for all but the smallest aircraft types. The *Global Perspective 2008/2009* lists 311 civil or dual-purpose UAV platforms, of which only 41 are described as “market ready”. The only one of the six UK civil UAV platforms described as “market ready” appears no longer to be available[5]. Nevertheless, as discussed below, there are sufficient platforms available to enable a broad range of Earth and environmental science to be accomplished in a 2-5–year timeframe. To access the available platforms, international collaborations — with NASA, and probably also with Italian and/or Israeli manufacturers — will be necessary.

Alongside platforms, civil training and test facilities are required. Parc Aberporth is the UK centre for UAV testing. Both Sweden and Finland have UAV test facilities in the far north[6]. The CCUVS initiative in Canada is already running courses for the Canadian police and aims to have a fully operational civil facility for UAV training operational by 2013[7].

Since the potential for NERC-related science varies very much with platform type, we discuss individual UAV classes below. See Table 1 for the categorisation used in this report.

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[5] The MagSurvey Prion mini-UAV – see http://www.barnardmicrosystems.com/L4E_magsurvey.htm

[6] Test sites are listed in http://www.barnardmicrosystems.com/L4E_test_sites.htm

[7] http://www.ccuvs.com/

Large UAVs

NASA platforms

The only new research platforms with significant payload carrying capabilities and proven operability for long-endurance missions are the two **Global Hawk** HALE UAVs and one **Ikhana** (Predator B) MALE UAV aircraft that have been transferred to NASA[8]. There is no European equivalent to the Global Hawk, but perhaps no European equivalent is needed. Access to the Global Hawk for UK/European scientists is being negotiated in at least two ways: through a NERC-NASA MoU and through Italo-US contacts. The NASA facility may become, therefore, de facto, the global HALE facility.

Other Platforms

Alongside the USA, Israel is the leading provider of UAV platforms. The leading Israeli providers of large UAVs, IAI-Malat and Elbit, provide the **Heron** and **Hermes** series of MALE UAV, which are very well-established platforms. There are a number of European initiatives for civil MALE UAV platforms[9], the leading of which is probably the **Sky-Y/Molynx** programme of Alenia Aeronautica. The SMAT project ("Sistema Monitoraggio Avanzato del Territorio"), currently running in the Piedmont region of Italy, provides scientific access to the Sky-Y and other UAVs for a range of scientific and civil contingency applications.

High-altitude Platforms (HAPs)

The HAP concept is for very long endurance (weeks-to-months) deployment above a single location. Trading-off areal coverage against spatial resolution, HAP platforms are usually designed to operate in the stratosphere. This has the additional advantage of removing the platform from tropospheric weather systems. The **QinetiQ Zephyr** is a special case of a large(-ish) UAV, and is intended for use as a High-altitude platform (HAP). Zephyr is therefore designed to carry payloads of a few kg to altitudes of over 60,000 ft (over 18 km) for many hundreds of hours using solar power and fuel cells. The aircraft has been successfully demonstrated and continues to be developed. It is expected to be customer-ready with a further 2-3 years of development. Other HALE UAVs can be used to provide HAP functionality but, because they have endurance of tens of hours rather than tens of weeks, more than one HALE would be needed to provide continuous HAP coverage of a single location. Nevertheless, for emergency response and other time-limited HAP functions, HALE platforms would be suitable.

Several lighter-than-air HAP programmes are underway. Although test flying of these platforms has taken place and is continuing, to the best of our knowledge, none of these programmes will yield a customer-ready platform within the next 3 years unless there is a substantial investment of tens of millions of dollars. Whilst it is not impossible that this will occur in the frame of emerging commercial opportunities, such as HDTV, we consider it unlikely.

Further, although there are some interesting developments for ultra-light sensors (see p16), it is likely that most scientific remote sensing applications in the next decade will require substantial MALE and HALE platforms, capable of carrying 10s - 1000 kg payload.

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[8] http://www.nasa.gov/centers/dryden/news/Features/2007/dryden_globalhawk_audio.html

[9] See, for example, Flight International's UAV directory at http://www.flightglobal.com/directory/search.aspx?navigationid=372&aircraftcategory=uav&manufacturertype=uav

SWOT analysis for Large UAVs (including HAP) in NERC science

Particular strengths of large UAV systems are:

- Payload capacity suitable for large Earth-observation instruments and multi-instrument packages
- Autonomous flight for long distances or long duration (or both)
- Access to altitudes inaccessible to other UAV systems (i.e., above 10,000 ft or 3 km) and other piloted aircraft (i.e., the remote UTLS).

Presently, the most important weaknesses, limiting the utility of large UAVs for NERC science are:

- Limited access to platforms
- Difficulties in obtaining flight permission
- Lack of UK payloads

Large UAVs present several important opportunities for NERC science. They are the most suitable platforms for large-area Earth Observation to complement satellites (see p20) and they provide access to parts of the atmosphere — e.g. the UTLS and the Antarctic interior — that are difficult to reach otherwise. Like all UAVs, the large platforms are suitable for dull, dirty, and dangerous deployments, although it should be noted that the considerable expense of these systems means that they will not be deployed in environments posing a significant risk of loss (e.g., near-field volcanic plumes, the core of continental convection). Specific scientific targets suited to use of large UAVs are discussed below (p21).

The most important threat to large UAV operations is regulatory. For all UAVs larger than model aircraft, there are significant regulatory hurdles to operating in unrestricted/un-segregated airspace (p18, below). The regulatory framework is particularly complicated for aircraft with MToW in excess of 150 kg. Nevertheless, science missions using large UAVs have been flown (June 2009) using the Global Hawk. Permission to fly these missions is given on a case-by-case basis and depends on, inter alia, altitude of flight of the UAV, air traffic in the operations area, and population underneath the operations area.

Overall, we find that large UAVs have the potential to make a very significant impact in several aspects of NERC science. This potential can be realised most immediately through negotiated access to existing platforms. The resulting projects are as likely to use UK expertise, in mission programming and modelling support, as to use UK instruments.

Recommendation #1: fund science projects that can utilise immediate access to existing large UAVs for high-impact science.

Small UAVs

Small remote-controlled aircraft are just beginning to be exploited for Earth and environmental science. The highest impact science has been delivered by users of the **Manta B** of Advanced Ceramics (Ramanathan *et al.* 2007; Roberts *et al.* 2008). The most developed operational use of small UAVs is in Japanese rice farming[10]: over 2,000 small UAVs have been sold in this sector, with the **Yamaha Rmax II** UAV helicopter being the market leader. NASA uses the **SIERRA** platform, designed by the USA Naval Research Lab., which has a MToW of about 200 kg, ceiling of ca. 4 km (12,500 ft) and endurance of ca. 11 hours. Small UAVs can be quite substantial platforms, therefore.

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[10] La Franchi, P., "monitoring the Ranges", *Unmanned Vehicles*, **14**, 14-17, 2009

There is an EC COST Action (COST 0802 or "COST-UAS")[11] on the use of small, mini- and micro-UAVs for atmospheric research. There is already NERC input to this COST Action; Phil Anderson from BAS is the co-convener. European Union COST Actions exist to coordinate nationally-funded research on a given topic and do not provide significant research funding[12].

SWOT analysis for Small UAVs in NERC science

Particular strengths of small UAV systems are:

- Ease of deployment and, hence, deployment in remote regions, although some take-off and landing infrastructure is usually required (cf. mini-UAVs, below)
- Deployment from ships, including vertical take-off and landing (VTOL) for helicopter-based systems.
- Flight in the surface layer (i.e., at altitudes <300 m above ground-level)
- "Swarm" capability – i.e., multiple vehicles flying in formation, although using mini-UAVs for swarms of more than 3 platforms, say, may be more affordable.

Presently, the most important weaknesses, limiting the utility of small UAVs for NERC science are:

- Line-of-sight (LoS) operation (OTH operations, controlled by SATCOM, is possible but not much used)
- Low payload weight (typically < 10 kg)
- Lack of experienced pilots
- Low endurance for helicopter-based systems (typically < 3 hrs).

Generally, the greatest opportunity afforded by small UAVs is flexibility, in the same way that the ARSF Dornier is a more flexible platform than the FAAM BAe146. However, there are some potential traps for the unwary. Care must be taken when considering making alterations to the airframe. For aircraft (UAV or conventional) made of standard materials, it is not difficult to cut windows and inlets into the fuselage; for aircraft made of advanced composite materials, such modifications may require the whole airframe to be re-tested, adding significantly to costs. Because of their relative stability in flight, ease of deployment, and substantial payload capacity, small UAVs offer the best potential for recoverable flight of high-precision instruments into hazardous environments such as volcanic plumes, meteorological storms and heavy turbulence. Specific scientific targets suited to use of large UAVs are discussed below (p21).

As with large UAVs, the greatest threat to use of small UAVs for NERC science is the lack of a well developed regulatory framework. Small UAVs are generally below the MToW at which international regulation comes into force (p18), which simplifies the situation somewhat compared to large UAVs.

It is clear from the COST Action remit, and from our overview of other aspects of NERC science, that small UAVs have the potential to make a significant impact. To realise this impact quickly, projects should be devised that make use of existing civil platforms, rather than developing new platforms or waiting for military "cast-offs". A likely additional benefit of funding high-impact science projects will be to open up small UAV technology for the monitoring of natural resources, natural hazards, and biodiversity in ways which will yield important new insights over longer timescales.

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[11] http://www.cost-uas.net/

[12] http://www.cost.esf.org/about_cost

To ensure that these early-adopter projects develop into a national capability in small UAVs, a UK science centre for UAV operations should be established. This could consist of 1-3 aircraft of different types (small and mini-UAVs), but all with advanced stabilisation and high levels of autonomous operation, a general-purpose ground segment, one or more core instrument sets, and a cohort of trained operators who would probably be distributed throughout the NERC community. The centre would collaborate closely with the emerging civil facilities (e.g. Parc Aberporth) to enable flight-testing.

Recommendation #2: provide a UK science centre for small UAV operations

Mini- and Micro-UAVs

Platform technology in this size range has been available for decades through the model aircraft sector, but these are usually remotely-piloted by radio-control strictly within line-of-sight. Radio-controlled model aircraft have been used for NERC-related science for decades (see results of the bibliometric study, p9, above), but only very intermittently and with only modest impact on the science. Take-up in the NERC science areas may be limited by lack of awareness of commercial products, lack of aeronautical expertise or collaborators, and cultural assumptions that NERC science requires large expensive platforms. Properly autonomous systems with in-built sensor packages and auto-piloting are only now becoming commercial-off-the-shelf (COTS). These systems have much greater range, endurance, ceiling and payload capacity than adapted model aircraft. The highest-impact NERC-related science to date has been reported using the mini-UAV (LALE) **Aerosonde** of AAI Corp (Lin 2006; Inoue *et al.* 2008; Lin and Lee 2008), which has unusually long endurance and range for this class of UAVs. A micro-UAV, **SUMO**, has also been deployed recently for meteorological measurements in the first 3500 m of the troposphere (Reuder *et al.* 2009). In the UK, McGonigle et al. report determination of CO_2 fluxes using a rotary UAV (McGonigle *et al.* 2008), BAS has successfully deployed a mini-UAV (**Carolo T200**[13]) in Antarctica to study the surface energy flux over sea ice, and Southampton University and NOCS have developed a bespoke mini-UAV for deployment and recovery from ships, such as the NERC ship RRS *Discovery*[14] . These activities appear to have proceeded largely in isolation from each other, although the recent establishment of the COST Action 802[11] may encourage connectivity. Simultaneous, independent, development of micro-UAVs within the NERC community may not disadvantage the science; because sensor and platform are often designed together, mini- and micro-UAV systems tend to be bespoke – tailored for a particular purpose. Mini- and micro-UAVs are not best suited to the establishment of a facility. Still, it is important that NERC manages its institutional risk with regard to UAVs, and unconnected developments inadvertently work against this.

The power plant used in mini-UAVs is an important consideration – both internal combustion and electric motor models are available. For small-scale engines, the output specific energy (Wh kg^{-1}) is typically higher for battery-driven electric motors than internal combustion engines, and higher still for hydrogen-powered fuel cells (Bradley *et al.* 2007). For NERC science, the most significant difference is that electric motors can operate in environments heavily polluted with aerosol or depleted in oxygen.

Take-off for mini- and micro-UAVs is very much simpler than for large UAV types. Often the aircraft are launched simply by throwing them into the air, or by use of a small catapult. There are

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[13] http://mavionics.de/index.php?option=com_content&task=view&id=10&Itemid=20&lang=en_EN

[14] http://www.uav.soton.ac.uk

several methods of landing, including snagging on a line and catching in a net. Rotary UAVs, of course, use vertical take-off and landing (VTOL). Very little, if any, ground preparation is needed for mini-/micro-UAVs, making them ideal for deployment in difficult terrain (e.g. in the middle of a forest) and from Ships. However, ship recovery using lines, nets, or VTOL becomes very difficult in stormy conditions, and these are often the conditions of most interest (see the discussion of air-sea exchange, p23, below).The solution to this offered by Southampton University/NOCS is to ditch the UAV in the sea, treat the wings and tail-plane as expendable, and recover the fuselage containing the payload. This still leaves the problem of recovery of the fuselage in heavy seas, but under those conditions, stable flight for science may not be possible in any case.

Integrating mini- and micro-UAVs into larger research infrastructure — i.e., being able to release them from ships, ground-based stations and even manned aircraft — gives the best chance for mini- and micro-UAVs to add-value to a measurement programme. For instance, the technical specification for the proposed new European icebreaker, *Aurora Borealis*, includes capacity for (un)manned VTOL aircraft. This could usefully be extended to a capacity for fixed-wing mini- or micro-UAVs. It is useful to think of the mini- and micro-UAVs with their built-in payloads as *instruments* themselves, rather than as platforms to carry a range of instruments[15]. For this to be feasible, however, the systems must be easy to operate and robust, and there should be a cohort of trained operators.

Skilled piloting is even more important for mini- and micro-UAVs than for small UAVs, because the aircraft can be adversely affected by boundary layer turbulence. For example, the windiest conditions in which the SUMO micro-UAV has flown are Force 6 strong breezes (10 – 15 m s^{-1}) (Reuder *et al.* 2009). The issue of stability of mini- and micro-UAVs to gustiness has been tackled in the UAV engineering literature only recently, and is rather under-investigated. Mini- and micro-UAVs have wing-chord Reynolds numbers[16] closer to that of birds than large passenger aircraft (Mueller and DeLaurier 2003) and so generate different around-wing flow structures than larger platforms. It may be that use of mini- and micro-class remote-controlled aircraft has not become routine in Earth and environmental science because they require very careful piloting if they are not to come down in the windy conditions that are common over large parts of the globe.

Within this class of UAV are platforms that fall under the 20-kg weight-limit for regulation by the UK aviation authorities (see p18), which makes them particularly suitable for immediate deployment in un-segregated UK airspace. Regulation is lighter because the risks associated with mini- or micro-UAVs are much smaller than for other platforms. Nevertheless, aviation authorities aim to separate mini- and micro-UAVs from other aircraft because, although these UAVs may weigh less than a large bird, the UAV typically contains high density components (e.g. battery) that are capable of causing much more damage than a bird-strike.

SWOT analysis for Mini- and Micro-UAVs in NERC science

Particular strengths of mini- and micro-UAV systems are:

- Light regulation
- Very easy deployment and, hence, deployment in difficult terrain
- Deployment from ships, including VTOL for helicopter-based systems.

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[15] We acknowledge Ed Waugh, University of Southampton, for providing this view of mini- and micro-UAVs

[16] The non-dimensional chord Reynolds number is defined as (cruise speed x mean wing-chord) / (kinematic viscosity of air) Mueller, T. J. and J. D. DeLaurier (2003). "Aerodynamics of small vehicles." Annual Review of Fluid Mechanics **35**: 89-111.

- Flight in the surface layer (<300 m)
- "Swarm" capability – i.e., multiple vehicles flying in formation
- Very low cost relative to manned aircraft
- Expendable (i.e., missions can accommodate a high rate of attrition)

Presently, the most important weaknesses, limiting the utility of mini- and micro-UAVs for NERC science are:

- Line-of-sight (LoS) operation (OTH operations, controlled by SATCOM, are possible but not much used)
- Very low endurance (ca. 3 hr), except for the LALE Aerosonde
- Very low payload weight (< 5kg)
- Lack of experienced pilots
- Narrow window of operations (susceptible to weather)

The greatest opportunities afforded by mini- and micro-UAVs are related to swarm deployment of ultra-lightweight sensors. Such sensors may not have the precision or accuracy of heavier, more complicated devices, but the pervasiveness of a swarm deployment counterbalances this. Specific scientific targets suited to use of large UAVs are discussed below (p21).

The greatest threat to successful use of mini- and micro-UAVs in NERC science is that the pace of sensor miniaturisation slows down. However, given the external drivers of space, biomedical, and military demands and internal competition in the electronics sector, we consider this a modest threat that will, at most, delay exploitation of mini- and micro-UAVs for 5-10 years.

Overall, we consider that mini- and micro-UAVs are beginning to have a substantial impact on particular aspects of NERC science. Supporting ongoing and new projects through responsive mode and underlying institutional funding is the best and simplest way to ensure the area develops. In addition, to build on the early successes and encourage further uptake across NERC science, a multi-year programme, focusing on piloting and other operational skills for mini- and micro-UAVs would be highly desirable. Such a programme could consist of summer schools on UAV technology and operations, along the lines of the GFD summer school and the NCAS climate modelling school.

Recommendation #3: Establish a programme to develop skills in mini- and micro-UAV operations.

Payloads for use on UAV platforms

In contrast to working in a "flying laboratory", such as the FAAM BAe146, where operators are constantly on-hand, instruments on UAVs must be highly autonomous. The satellite Earth Observation community has long experience in designing and manufacturing autonomous systems; other sectors of NERC science are less developed in this respect, although there is a wealth of instrument expertise throughout the NERC community. For example, the atmospheric science community is gaining experience in instrument autonomy through involvement in the MOZAIC and IAGOS programmes to mount instruments on commercial airliners.

The *Global Perspective 2008/2009* (Unmanned Vehicle Systems (UVS) International) lists 279 imaging payload packages designed for UAVs, along with a further 73 other payload packages. The preponderance of imaging payload packages is not surprising, given the widespread adoption of UAVs for military reconnaissance; the most common payloads are visible wavelength electro-optical (known as EO in the UAV community) sensors and infrared sensors. Lidars and radars, including synthetic aperture radars (SAR), are also available. Lasers are also used for range-finding and weapons guidance. Other payload packages range from meteorological dropsondes, through data links and chemical "sniffers", to fertiliser dispensers.

There has been rapid progress in radar active remote sensing in fields of interest to NERC: for example, in ice sheet sensing (Blake *et al.* 2008) and in the use of SAR (Hensley *et al.* 2004; González Partida *et al.* 2008). SAR is the only airborne and space-borne sensing technique that has high-resolution all-weather day-and-night imaging capability, useful for 2-D and 3-D mapping, environmental monitoring, retrieval of land surface parameters (Anterrieu and Khazaal 2008), characterisation of ocean and ice surfaces, and hazard and disaster monitoring. Interferometric SAR (inSAR) uses data from two or more antennae that may be on the same platform or collected in repeat passes, and gives very accurate indications of ground movement. SAR technology is miniaturising rapidly, and several variants are now light enough to be installed on UAVs (Morrison 2005; González Partida *et al.* 2008). Optical active sensing applications include laser altimetry for volcanology (Hofton *et al.* 2006), bathymetry (Hilldale and Raff 2007), submarine ecosystem sensing (Brock *et al.* 2006), forest carbon stock, and forest health studies(Andersen 2005). UAV-based active remote sensing is ready to be exploited for NERC science.

Similarly, plenty of NERC science is achievable by passive sensing and in-situ monitoring from UAVs (e.g., Berni *et al.* 2009). Hyper-spectral imaging is clearly becoming a key tool in terrestrial and marine science, although calibration of spectral signatures remains an issue. Collection of hyper-spectral imagery without supporting ground-truth-ing will be of limited value, and this could lessen the impact of this kind of earth observation over regions that are difficult to reach and so characterise. Along with developments in spectral analysis, attention has recently turned to detection of natural fluorescence, which is a sensitive indicator of plant health (Zarco-Tejada *et al.* 2009) and mineralogy. The development of extremely fast “camera-on-chip” CMOS technology may yield significant advances in instrument sensitivity and miniaturisation (El-Desouki *et al.* 2009).

Conventional cameras still have a role to play, particularly for event monitoring, and particularly when combined with other (broadband) electromagnetic sensors such as infrared. Image analysis tools may be used to increase the extraction of information from the images (Laliberte and Rango 2009). For all applications, however, images must be accurately geo-referenced (Jones *et al.* 2006). Improvements in un-cooled infrared detectors mean that sensors can become lighter and much more easily installed (Anderson *et al.* 2003).

Passive spectroscopy is likely to see a step-change in capability as MOEMS technology matures. Laser heterodyne radiometers are being developed that have much smaller footprints than current Fourier-transform spectrometers, whilst also offering narrower field-of-view and, hence, higher spatial resolution (Weidmann *et al.* 2007; Weidmann *et al.* 2007; Weidmann and Wysocki 2009). Quantum cascade lasers, integrated optics (Lambeck 2006; Zalevsky 2007; Ligler 2009) including waveguides (Wang and Lin 2007; Wang *et al.* 2007; Yamaguchi *et al.* 2009), microresonators (Jokerst *et al.* 2009), and silicon photonics (Jalali and Fathpour 2006) provide substantial potential for miniaturisation of in-situ and remote sensing infra-red spectroscopy (Charlton *et al.* 2005; Kim *et al.* 2009). Integrated signal and processing (ISP) technology (Medendorp and Lodder 2005) promises a combination of miniaturisation and rapid, on-board, signal processing that would be eminently suitable for UAV applications. However, to our knowledge, these integrated optics techniques are being taken up rather slowly by NERC-area scientists (perhaps for good technical reasons), so that it is unlikely that these techniques could form the basis of an operational UAS for Earth and environmental science within a decade.

In-situ monitoring remains the fundamental measurement strategy for atmospheric science and ocean-atmosphere-biosphere science, providing measurements of small-scale features that are important for atmospheric dynamics, atmospheric chemistry, biogeochemical fluxes, and climate forcing. Conventional, compound-specific, instruments will continue to miniaturise, using much of the same technology as for remote sensing instruments, described above. Finger-printing techniques and chemical “noses” for complicated mixtures offer a new way to sense the environment (Stlouis and Hill 1990; Rock *et al.* 2008). Such instruments already exist for the atmospheric aerosol (e.g., Murphy *et al.* 2006), but these instruments are too heavy and voluminous for any but the largest UAV platforms. However, gas-phase fingerprinting techniques have become small enough to be deployed on UAVs (Cao *et al.* 2004). A micro-fluidics system for sensing of biological aerosol has been deployed on an optionally-manned aircraft and detected low-levels of protein aerosol at heights up to 3 km (10,000 ft) (Naimushin *et al.* 2005). Although principally designed as an early-warning system for chemical-biological warfare, this sensing technology could have environmental uses in the study of airborne dispersion of spores, seeds, etc., and the detection of primary biological organic aerosol.

US scientists are leading the way, by demonstrating what can be done with existing (or easily modified) instruments and existing UAV platforms. We expect that this will stimulate interest in use of UAVs for Earth and environmental science world-wide, but particularly in the USA. Encouraging UK scientists to make similar “first steps” with UAVs will likely stimulate further developments with much bigger scientific aims and impact.

Recommendation #4: fund development of miniaturising technology for UAV-based sensing.

Regulatory Aspects of UAV deployment

UAVs are not currently regulated by a comprehensive EU legal regime. The European Defence Agency (EDA) is engaged in a technical study program to define and then act on a comprehensive political, industrial and technical road map that will enable military and civilian UAVs to begin flying through commercial airspace after 2012.This approach involves institutional and industrial players across Europe, including national governments, UAV manufacturers, the EDA itself, the European Commission and pan-European aviation organizations such as Eurocontrol and the European Aviation Safety Agency (EASA). The current position under European/International Law and the Air Law provisions of the UK and, for comparison, Italy, is as follows.

The European Law

Any aircraft that flies over the European airspace has to comply with EU laws and regulations. UAVs are considered aircrafts. EC Regulation n.1552/2002 provides that UAVs over 150 kg operating mass must comply with the EASA rules and provisions of airworthiness certification. However, UAVs which are intended for experimental use or used for State purposes are exempt. From this perspective, large (and small) UAVs are like current specialist manned research aircraft, such as the *Geophysica* of Myashishchev Design Bureau, which has been used in Europe under the rules for an experimental aircraft since 1996. Any aircraft not under EU regulation is considered to be under national regulations, so far as airworthiness certification and all related matters are concerned.

The UK Law

There is a distinction in UK law between the military and the civil regulation regimes. Military UAVs are regulated by the Ministry of Defence; civil aviation is under the CAA (Civil Aviation Authority) law provisions. In general, civil aviation in the UK complies also with the Chicago Convention of Civil Aviation of 1942 and in particular with art.8 of the Convention. Art.8 denies the possibility for an unmanned aircraft to fly over a city and its territory. In the UK, UAVs are allowed to fly in segregated airspace and they have to meet at least the same safety standards as a manned aircraft. The CAA Directorate of Airspace Policy has issued guidance on the route to certification of UAVs for operation in UK airspace: CAP 722[17]. The first edition of CAP 722 was issued in 2002, replacing preliminary guidance from 2001, and the latest edition was released in April 2009. Along with EU Regulations, UK civil UAVs are subject to the Aviation National Order (ANO) of 2005 and the Rules of the Air regulations of 2007. In the UK, any aircraft that is not military must comply with ANO regulations. However, ANO applies differently to UAVs with total dry weight under 20 kg (i.e., mini-UAVs in our terminology), and differently again to UAVs with total dry weight under 7 kg (i.e., micro-UAVs). Mini- and micro-UAVs do not have to have a certificate of airworthiness or a permit to fly issued by the CAA (CAA permission *is* required for commercial work for all aircraft weighing more than 7 kg). Larger UAVs may be exempted from certification under special circumstances. The operation of all aircraft of any weight is forbidden by the ANO to be reckless or negligent, and so likely to cause damage or injury.

The CAA position on the certification of new platforms is that they demonstrate airworthiness standards derived from, and at least as strict as, those for manned aircraft (Haddon and Whittaker 2002). Since certification is lengthy, technical, and sometimes costly, it is highly unlikely to be cost-effective for NERC to engage in development of platforms — except, possibly, of micro-UAVs, which do not require a certificate of airworthiness. Further, NERC is likely to gain most, in the medium-to-long term, by supporting use of platforms that are certified to the highest possible standards, because these are the platforms that will most easily make the transition to flight in un-segregated airspace.

A further example: Italian Law

In Italy, UAVs are considered to be aircraft. They are included under art.743 of the Navigation Code. There is a double legal regime: for military and for civil UAVs. Civil UAVs must respect EU Regulation n.1592/2002 like any other civil aircraft. UAVs must be registered to RAN (Registro delle Costruzioni e del Registro Aeronautico Nazionale). Small and light UAS (i.e., MToW <150kg) are regulated by ENAC (National Civil Aviation Authority); UAS with MToW > 150 kg are regulated by EASA, except that, if there is a scientific application, regulation is through ENAC. ENAC define “small UAVs” as those weighing less than 20 kg (approximately our mini- and micro-UAV classes), and define “light UAVs” as those weighing between 20 kg and 150 kg (our small UAV class).

In Italy, UAVs can fly within segregated airspace using a NOTAM request, and must respect the ENAC provisions and meet the security standards of the other civil aircrafts. Flights in un-segregated airspace is under evaluation; these could be possible if certain conditions can be fulfilled, e.g., if a sense-and-avoid capability is certified and installed. For flight in segregated and un-segregated airspace, certification of UAS is required. A Permit to Fly will be released after a comprehensive ENAC evaluation of the UAS performance, including evaluation of project specification, certification, and safety systems. A detailed document (“circolare”), explaining the regulations, is to be published by the end of summer 2009.

Potential Applications of Next Generation Platforms for NERC science

By their nature, UAV platforms are well suited to missions that are “dull, dirty and/or dangerous”. That is, UAVs are well-suited to sorties requiring

- Endurance beyond that allowable for a single pilot,

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[17] www.caa.co.uk/CAP722

- Repetitive flight patterns, performed precisely,
- Sorties into remote regions without alternate airports,
- Sorties close to the surface,
- Sorties into hazardous regions, including chemical and radiological hazards, and
- "Persistent awareness" — i.e., spatial and temporal resolution beyond the current capabilities of satellites, combined with endurance beyond that of conventional aircraft.

Once operational, of course, one would expect that UAVs would fly more conventional sorties too, monitoring and surveying. UAVs can also play an important role in the development of space instruments, in which there is generally a stage-posting from proof-of-concept (laboratory studies) to early science results (using (un)manned aircraft) to satellites.

Clearly much "dull, dirty and dangerous" observational work is part of the NERC science remit — monitoring of ice sheets and volcanoes, to name two obvious examples — and the utility of UAVs for Earth and environmental science is becoming widely recognised. At the European level, the introduction of UAVs into the European research aircraft fleet was discussed at a special EUFAR[18] meeting on the topic, at Forschungszentrum Jülich, 29-30 April 2009. Key UAV characteristics discussed at that meeting were high altitude and long endurance. EUFAR is already coordinating the use of mini- and micro-UAVs to some extent, through one of its Working Groups, and connections with COST Action 0802. We are not aware of any plans for a European UAV facility; there is a chance for the UK to take a lead here, perhaps in partnership with other countries.

NERC science areas with at least a 10-year horizon and a role for UAVs include:

- Ice-sheet dynamics
- Boundary-layer fluid dynamics and thermodynamics
- Large-scale characterisation of the composition and fluid dynamics of the free troposphere and UTLS
- Forest carbon dynamics
- Plant and animal biodiversity
- Hazard detection and mitigation
- Volcanology and other surface processes

Through all of the above, a UAV-based programme could contribute to Climate science, contemporary Earth System Science, Natural Hazards, and Environmental Pollution and Human Health. However, the UAV-based science that could contribute to each of these is different: there is no one-size-fits-all solution to UAV-based science in the NERC science area.

Satellite vs. UAVs

Satellite sensors for Earth observation can be divided broadly into two classes based on their spectral resolution: low resolution sensors and medium resolution (multispectral) sensors. Low resolution instruments are generally on board constellations of satellites and so can provide high repetition rates and wide spatial coverage (low spatial resolution); multi-spectral instruments provide higher spatial and spectral resolution but at a lower repetition rate. Many Earth observing satellites are near, or beyond, their design lifetime (Birdsey *et al.* 2009) — e.g. ASTER on Terra, Hyperion on EO1. In order to maintain continuity, the main international space agencies are designing and realizing new missions (e.g. the NASA HyspIRI mission, ASI cosmo-skymed, and the GMES Sentinel series) improving repetition time and sensor performance.

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[18] The European Facility for Airborne Research, http://www.eufar.net/

Much of the European effort in Earth observation from space is going into the GMES programme[19]. GMES has its own specially commissioned series of satellites (Sentinels 1 – 5), but also acts as an umbrella to coordinate exploitation of other European or nationally-funded satellite programmes and nationally-funded programmes of in-situ measurements. The space component of GMES constitutes one of the major European contributions to the international Global Earth Observation System of Systems (GEOSS).

GMES consists of three observing components – land, ocean, and atmosphere — which support three horizontal strands: emergency, security, and climate change. Although GMES has an explicit focus on delivering high value-added products to users, all the observing components are relevant more broadly for NERC science, as are the horizontal emergency and climate change strands. There is strong UK involvement throughout GMES: for instance, the Rutherford Appleton Laboratory, the UK Met Office and the Universities of Edinburgh, Southampton, Leicester and Swansea are all involved in delivering the Sentinel 3 satellite products.

NERC is also a major funder of ESA's Earth Observation Envelope Programme[20], which includes the Earth Explorer missions, research missions dedicated to studying specific aspects of our environment. The Explorer missions include Cryosat and EarthCare, both of which have a UK science lead. The NERC National Centre for Earth Observation (NCEO) will be a focus of scientific exploitation of the Explorer missions and GMES in the UK. UAV-based science would have to complement, rather than compete with, GMES products.

One role for UAVs is as stop-gaps between satellite missions, for example in hazard monitoring. A recent assessment of satellite capability for volcanology found gaps emerging in the coverage of passive spectral sensors that are useful for detection of volcanic ash and upper level clouds (Dean et al. 2007). There may be, therefore, a useful role for UAVs, in providing passive spectral monitoring (perhaps coupled with radar active sensing) for the highest risk volcanoes.

Payload miniaturisation makes deployment in space *and* deployment on UAVs easier. **Cubesat** is an exciting paradigm for cheap, lightweight, satellites, produced outside the space agencies, which aims to utilise the availability of very small payloads (Rausch *et al.* 2000; Toorian *et al.* 2008). Cubesat instruments for space weather, ionospheric and geo-magnetic studies have been developed (Waydo *et al.* 2002; Gregorio *et al.* 2003; Swenson *et al.* 2007). Because these and other so-called pico-satellites are cheap and easy to deploy, it has been suggested that they are stored and rapidly deployed for event monitoring (Schmidt and Schilling 2008). However, UAV technology probably has the advantage for this kind of mission because of even easier deployment, the ability to stay on-station, and the higher spatial resolution of imagery that is achievable from low altitude.

Nano-satellites are bigger than pico-satellites, and usually require support from government agencies in their development. They are, however, powerful drivers for new technology that is then worked up into full-sized satellites, or developed into operational nano-satellites. For example, M(O)EMS technology has already been tested in space in the student-based SAPHIRE nano-satellite (Swartwout *et al.* 2008).

Potential near-term projects involving Next Generation Platforms

We list below some significant open science questions that could be addressed by UAV-based measurements in the next 3-5 years. The items are provided broadly in order of our assessment of the potential for scientific impact of a UAV-based programme.

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[19] http://www.gmes.info/index.php and http://www.esa.int/esaLP/SEMRRI0DU8E_LPgmes_0.html

[20] http://www.esa.int/esaMI/Technology/SEMMR5WPXPF_0.html

Ice sheet and bedrock mapping

Rationale: Ice sheets contribute to all temporal scales of climate change, from contemporary global warming to the ice age cycles (Lemke *et al.* 2007). The behaviour of ice sheets under contemporary climate change is uncertain; what had previously been assumed to be a slowly changing process now appears from measurements to show rapid changes that have serious implications for projections of sea-level. The flow of ice sheets to the sea is restrained by friction with the underlying bedrock. Sub-glacial water also plays an important role in determining ice sheet flow. A lack of data on what is beneath the ice sheet surface is a major uncertainty in ice sheet modelling. Providing data on basal topography and sub-glacial water requires radio echo-sounding using ice-penetrating radar. The limited range and endurance of overland and manned aircraft missions means that continental-scale bedrock maps for Antarctica must be pieced together (Lythe *et al.* 2001) and are still rather incomplete[21].

Related goals: It is useful to accompany radio echo sounding (ice-penetrating radar) with laser altimetry, geomagnetic surveying, and gravity surveying[22] in order to provide additional characterisation of the ice sheet and the underlying geology.

Methodology: MALE UAVs have the range and endurance to cover all of Antarctica and Greenland ice sheets and could be deployed over regions that are particularly hazardous for manned flight because of lack of alternate airports. Some care is needed when mounting the radar on the UAV to avoid (or benefit from) radio-wave reflection by the wings and fuselage. The CReSIS programme to develop a UAV for bedrock mapping is underway in the USA (Donovan 2007) and has proposed a platform (Donovan 2006) that is similar to the FALCO from Selex Galileo. A rather large UAV (payload capacity > 150 kg, perhaps) would be required to carry a complete suite of radar, lidar, geomagnetic and gravity sensors.

Overall assessment: This is high-priority science that is accomplishable with existing civil UAV technology and is not constrained severely by permission to fly.

Forest responses to climate change

Rationale: Global climate and terrestrial ecology are intimately connected through energy, carbon, and water fluxes (Denman *et al.* 2007), forest responses to climate being modulated by nutrient availability. Aerosol and reactive gas fluxes provide a subtle additional set of feedbacks. Direct measurements of fluxes are limited to a few instrumented towers and a small number of airborne campaigns. Previous measurements have not combined atmospheric flux measurements with measurements of canopy parameters that are key to informing the next generation of dynamic vegetation models (Purves and Pacala 2008). Satellite missions provide constraining global observations, but with limited horizontal resolution and very limited vertical resolution with the result that the satellite flux observations become confounded by atmospheric transport processes. Particularly useful next steps for understanding short-term forest responses to climate are (i) widespread “snapshot” flux observations in under-sampled ecosystems, and (ii) extensions of tower measurements by long-range sorties in currently sampled ecosystems (e.g. the Amazon).

Related goals: Flux sensing could be readily and usefully combined with remote sensing of land-use, to corroborate satellite-derived rates of land-use change. The canopy remote sensing could

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[21] See, for instance, the BEDMAP2 programme web pages at http://www.antarctica.ac.uk/bas_research/our_research/az/bedmap2/index.php

[22] See, for instance, the ICECAP home page http://www.geos.ed.ac.uk/research/ICECAP

provide data for studies of plant biodiversity that could be extended to other remote locations requiring high resolution imagery to resolve variations in plant functional type.

Methodology: Instruments for the in-situ measurement of heat and carbon fluxes by eddy correlation are available for all UAV sizes, including mini- and micro-UAVs (e.g., Watai *et al.* 2006; McGonigle *et al.* 2008). Important explanatory parameters of ecosystem functioning, such as tree stress, can be measured using hyperspectral and fluorescence imaging (Zarco-Tejada *et al.* 2009). As for air-sea exchange, discussed below, there is merit in using several UAV-based observing strategies. Swarms of Mini- or micro-UAVs, fitted with in-situ flux probes or a spectrally-resolved imaging camera, would provide snapshots of key parameters in under-sampled regions. Using a larger UAV fitted with a suite of sensors — in-situ trace gas sensors, hyperspectral imager, SAR, and canopy lidar, say — would provide a tower-like capability for use in inaccessible areas and to link towers across an ecosystem.

Overall assessment: This is a key uncertainty in ecology, and one that is central to understanding the global carbon cycle, which could be addressed in new ways with current civil UAV technology.

Air-sea exchange

Rationale: transfer across the air-sea interface is of fundamental importance to the global carbon cycle (Denman *et al.* 2007),but is also a key factor in other biogeochemical cycles, including sulphur, halocarbons and mercury. There is considerable uncertainty in parameterisations of air-sea exchange, particularly at high wind speeds (Denman *et al.* 2007, section 7.3.4.1) and also as a result of confounding factors such as variable fetch, wave-wave interactions, the occurrence of films on the sea surface, and the dynamics of the overlying atmospheric boundary layer (Glover *et al.* 2007).

Related goals: Marine aerosol production is a closely related process that is important to climate through direct and indirect aerosol forcing. Remote sensing of for air-sea exchange could be combined with remote sensing of ocean colour, addressing the ocean productivity aspects of the global carbon cycle.

Methodology: Direct measurements of fluxes require observation of the concentration difference across the interface, which is technically challenging, particularly in the presence of sea-surface films. A combination of ship-borne and airborne measurements is required, which argues for use of either a ship-deployable micro-UAV or a MALE. Initial observations of atmospheric winds (Van den Kroonenberg *et al.* 2008) and flux estimates for CO_2 (Watai *et al.* 2006) have been made. Existing UAV active and passive remote sensing capabilities could provide sea state (by lidar/radar) and whitecap fraction (by EO sensing). There is merit in using a variety of observational strategies. Micro-UAVs may be able to provide individual parameters over relatively short ranges, but could be used in swarms and combined with ship measurements. A highly-instrumented MALE UAV, flying in the atmospheric surface layer, could provide direct flux measurements by eddy correlation as well as remote sensing of relevant parameters such as white-cap fraction, over much larger distances.

Overall assessment: This is a key uncertainty in Earth and environmental science, and one that is central to understanding the global carbon cycle, which could be addressed in new ways with current civil UAV technology.

Ocean ecology responses to climate change

Rationale: The productivity of the upper ocean is a central component of the global carbon cycle (Denman *et al.* 2007), and is important for the abundance of important food resources[23]. Key indicators of ocean productivity are observable from space through analysis of sea spectral reflectance (ocean colour), but atmospheric absorption and cloud masking are difficult to handle. Aircraft observations offer the metre-scale and sub-diurnal resolutions required to investigate the processes affecting particulate organic carbon, phytoplankton carbon biomass, calcite concentration and phytoplankton functional types (e.g., Churnside and Wilson 2008). Persistent observation is particularly important in regions with large concentration gradients, such as coastal regions (Henson and Thomas 2007).

Related goals: Studies in this area could connect to air-sea flux studies with relative ease. Knowledge of phytoplankton and algal functional types is important if progress is to be made on quantifying natural halocarbon (VSLS) emissions, which are important in tropospheric and stratospheric chemistry.

Methodology: The principal measurements are hyperspectral and fluorescence passive sensing of the upper ocean with simultaneous characterisation of atmospheric absorption. Active sensing of sub-surface ecology (e.g., Brock *et al.* 2006) would add value. Mini- or micro-UAVs deployed from ship could carry hyperspectral sensors of the required precision, and would be especially beneficial if operated in shifts to provide continuous observation. Larger, long-endurance, UAVs (MALEs) provide an alternative strategy that would be optimal for multi-objective campaigns requiring heavier payloads.

Overall assessment: This is an important topic, which has suffered from a lack of observing platforms with the “persistent observation” capability offered by UAVs. There may be some restrictions on UAV-based science in this area until UAV operations in un-segregated airspace are regularised but, with suitable choice of test sites, progress could begin to be made now.

Direct and indirect aerosol forcing of climate

Rationale: Direct and indirect aerosol interactions with climate provide a negative forcing on climate (i.e., cooling) but the size of this forcing is highly uncertain (Forster *et al.* 2007). The potential for UAV-based studies to provide useful measurements of radiative transfer through aerosol layers and clouds has been demonstrated (Ramanathan *et al.* 2007) but there are still many more sophisticated payloads and flight patterns that could be employed. Specifically, radiative transfer through Arctic stratus — i.e., synoptic-scale dynamics in the Arctic— and the impact of aerosol on this, is an attractive target with significant potential to improve climate modelling. Studies of direct radiative fluxes by desert dust in source regions, such as the Bodele depression, would also yield important new data.

Related goals: Studies of the interaction of aerosol plumes and cloud decks benefit from knowledge of boundary layer dynamics so additional atmospheric state parameters should be measured whenever possible.

Methodology: Using more comprehensive radiometer payloads to Ramanathan et al. (2007), a swarm of mini-UAVs could provide simultaneous measurements of aerosol, cloud and radiation parameters through the atmospheric column. Combining radiometers with in-situ and remote

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[23] See notes on the Coastal Theme of the Integrated Global Observing Strategy, at http://ioc.unesco.org/igospartners/coastal.htm

sensing aerosol instruments would maximise information. For desert sorties, ease of operation is an important consideration; micro-UAVs could be carried to the source regions, for instance.

Overall assessment: UAV campaigns in the Arctic, over the remote ocean, or in desert regions have the potential to make an immediate and lasting impact on our understanding of aerosol/cloud interactions and, hence, climate science.

Atmospheric pathways and the distribution of climate-active gases

Rationale: It is important to understand the spatial distributions of trace gases – especially those that are radiatively active, such as ozone and water vapour (Forster *et al.* 2007), and those for which certain transport pathways determine subsequent chemistry (e.g., VSLS entering the stratosphere) (Vaughan *et al.* 2008). The upper troposphere – lower stratosphere (UTLS) is a particularly important region in which atmospheric pathways must be understood. Because the UTLS is a cold region between the warm underlying surface and space, radiatively active gases, particles, and clouds in the UTLS can efficiently absorb upwelling infra-red radiation but re-emit little. Clouds in the UTLS can also efficiently reflect solar radiation. This reflection will be particularly important above the (dark) oceans and forests, and also above those areas where a veil of light-absorbing aerosol particles exists, such as large parts of SE Asia, S America and Africa. However, there are substantial uncertainties in the radiative transfer through the UTLS, particularly in: (i) short-wave transfer through cirrus, (ii) infra-red (continuum) absorption by water vapour, and (iii) advective and convective transport determining the distributions of ozone, water vapour, and cirrus.

Related goals: long-endurance sorties in the remote atmosphere would yield statistical and fractal information on the fundamental fluid dynamics of the atmosphere and its impact on atmospheric chemistry and climate (Tuck 2008). Chemistry observations through diurnal cycles would allow the testing of model chemical schemes — the field corroboration of stratospheric ozone destruction rates, for example.

Methodology: Of the operational UAVs, only HALEs can reach the UTLS. These, equipped with payload to measure state parameters and chemistry, offer the potential for observations of the UTLS over much longer distances and over multiple diurnal cycles. Radiative transfer studies would require formation flying with another (MALE) UAV or manned aircraft.

Overall assessment: The UAV capability is available to make immediate and significant progress in understanding the distribution of radiatively active components of the UTLS.

Short-term magma dynamics, plume evolution, eruption precursors.

Rationale: the chemical composition of volcano plumes can signal eruption hazard (Aiuppa *et al.* 2007), as can motion of the volcanic edifice and thermal anomalies on the surface (Pieri and Abrams 2005). Since no single measure is a sufficiently strong predictor of the likelihood of eruption, multi-parameter models are sometimes used to support decision-making (e.g., Aspinall *et al.* 2006). Such empirical models are "data hungry" and greatly benefit from measurements with sub-daily and metre-scale horizontal resolution.

Related goals: monitoring volcanic plume composition aids assessment of the climate impact of volcanic eruptions.

Methodology: Airborne measurement of plume composition and surface motion provides the best combination of spatial and temporal resolution, but is expensive and risky. Removing the pilot, by use of a UAV, substantially reduces the risk. In-situ sensing of a volcano plume and below-plume remote sensing, using a rotary-wing micro-UAV, have already been reported (McGonigle *et al.* 2008). For longer endurance, and stability in adverse weather, use of fixed-wing small UAVs is being developed, but ease of deployment is inevitably sacrificed. Remote-sensing payloads combining SAR, M(O)EMS-based spectroscopy, and hyperspectral imaging are being developed.

Overall assessment: Volcanoes are already providing a good proving ground for UAV technology, because the advantage of using unmanned vehicles is clear, and because the airspace above them is often segregated.

Other science targets

Animal biodiversity

There is a need to assess, on large spatial scales, the sensitivity of wildlife to habitat disturbance and climate change. For animals weighing less than about 300 g, the need for light antennae can limit the ability to track animals over long distances (Wikelski *et al.* 2007). UAVs have been used to track animals directly using aerial photography (Thome and Thome 2000; Jones *et al.* 2006); we are not aware of UAVs being used as "tall masts" to bounce radio signals beyond line of sight, but this would be an obvious application of a current military use of UAVs. There is global coverage for large animal tracking from space through the ARGOS system[24], and a drive to provide a similar facility for small animals (Wikelski *et al.* 2007). This would reduce the requirement for UAV-based systems.

Atmospheric surface layer dynamics

The lowest part of the atmospheric boundary layer above the canopy in complex terrain and urban areas, called the roughness sublayer or constant-flux layer, is under-sampled and models insufficiently validated (Arnfield 2003). Detailed studies of the structure of the atmospheric surface layer (altitudes ≤ 100 m) become much easier using helicopters (e.g., Avissar *et al.* 2009) and, we expect, would become even easier when the pilot is removed (i.e., rotary-wing UAVs). In fact, in the UK, UAVs with dry weight below 20 kg are usually restricted by CAP 722 to fly no higher than 130 m (400 ft)[25]. UAVs offer considerable opportunities to validate surface-layer theories and, hence improve models of pollutant dispersion, numerical weather prediction, and global climate. These studies are a natural extension of those described above, looking at forest-atmosphere interactions and air-sea exchange. Studies of the urban surface layer, perhaps the grandest challenge in this area, will have to wait until UAV flight in un-segregated airspace is regularised and, even then, flight permission may prove difficult to get.

Land-use change

Land-use change contributes to climate change (Denman *et al.* 2007, section 7.2), can reduce wildlife ranges, and can exacerbate natural hazards. High-resolution observation of land-use change can inform models of the dynamics of these processes. Areas of particular interest are cities (urbanisation) and the remote forests (deforestation). It is also important to monitor associated changes in plant biodiversity and landslides/gully formation. These studies are a natural extension of that on forest dynamics, described above.

Diurnal cycles of chemistry and convection.

Because much atmospheric chemistry is driven by photolysis to produce free radicals, there are significant variations in the abundance of short-lived compounds over the course of a day in all parts of the atmosphere. The limited altitude resolution of satellite measurements, and the orbital constraints that pin measurements to a particular local time, make it difficult to study diurnal cycles

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[24] See www.argosinc.com

[25] See CAP722, para 2.2.2.5. CAP722 is available at www.caa.co.uk/CAP722

away from the Earth's surface. Similar constraints limit our ability to observe, through diurnal cycles of convection, those parameters not observable by radar. For example, it was not possible to follow the chemical and cloud microphysical evolution of the convective outflow from the Hector storm system for more than a few hours (Vaughan *et al.* 2008), and investigations of mesoscale convective systems in the west African monsoon were similarly curtailed in the SCOUT-O3-AMMA deployment. HALE UAVs offer the possibility to study chemistry and microphysics through whole diurnal cycles, in a natural extension of the missions described to study atmospheric pathways, above.

Multi-day Earth radiation budget

Measurements of the Earth's radiation budget are usually carried out by satellite instruments such as CERES (Wielicki *et al.* 1996) and GERB (Harries *et al.* 2005). These satellite missions can constrain the global energy budget well (Trenberth *et al.* 2009). To diagnose climate model processes, three-dimensional energy and moisture budgets are informative (Trenberth and Smith 2009), and validating these requires measurements within, as well as at the top of, the atmosphere. Airborne measurements of spectrally resolved flux divergences in the short- and long-wave, including cloud and aerosol impacts, can be made. These are particularly useful in remote, climate sensitive, regions (e.g. polar regions). Measuring over several diurnal cycles allows information to be retrieved about short-wave reflectance and diurnal cycles in the long-wave, which are difficult to get from space. HALE and MALE UAVs provide excellent platforms for such studies, which, until spectrometers can be successfully miniaturised, require significant payloads.

Indicative Costs for UAV missions

A detailed cost analysis for the operation of UAVs has been carried out by Moiré Inc. for NASA[26]. Much of this analysis is relevant for NERC. All science flying is inherently inefficient compared to the rest of the aviation sector, because flight patterns and payloads are re-designed between each mission. Large UAVs are currently more expensive than comparable conventional aircraft to purchase and operate, and likely to remain so for the foreseeable future. However, HALE and MALE UAVs provide much longer endurance than equivalent manned aircraft, and this is what is driving their take-up for science. To fund scientific access to large UAVs, agencies such as NASA and NERC will get improved value-for-money if the agency commits to several years with a given provider.

The cost estimates below, for all but mini- and micro-UAVs, are based on access to platforms through agencies, such as NASA, or directly, via the platform manufacturers. Note that providing regular access to a platform would require a NERC facility for access. Without such a structure, there will be expensive "reinventing of the wheel" as individual research groups negotiate access and set up mission logistics, and elevated costs as providers seek to re-coup costs within short-term contracts.

HALE missions

The NASA Global Hawks are the de facto international HALE science platforms. Scientific access to a Global Hawk depends on the nature of any agreement that could be reached between NERC and NASA. NASA is interested to promote international cooperation with regard to the scientific use of the Global Hawk. Therefore, it should be possible to reach an agreement for very favourable

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[26] Cost & Business Model Analysis for Civilian UAV Missions, Moiré Incorporated: June 8, 2004. Available at http://www.moireinc.com/resources/documents/MoireUAVBusinessModels.pdf

prices for the access to the Global Hawk: rates perhaps as low as a few thousand dollars per flight hour. These are not the full costs of running the Global Hawk programme[26], and this should be borne in mind when comparing with access to other UAVs.

MALE and other large-scale UAV missions

In order to get a gross idea of costs, we requested from platform providers[27] indicative quotations for the following hypothetical scientific missions: thunderstorm microphysics and chemistry, terrestrial carbon cycle, volcanic hazard, ice-sheet bedrock mapping, and ocean carbon cycle. These projects were chosen to provide a broad range of platform requirements. The thunderstorm microphysics and chemistry mission was specified to require a MALE aircraft (ceiling 45,000 ft, endurance 12 hours, payload > 300 kg) deployed for 1 month (70 flight hours). The terrestrial carbon cycle mission was specified to require a smaller platform, but still with endurance (ceiling 4000 ft, endurance >24 hours, payload > 100 kg) deployed for 1 month (120 flight hours). The volcanic hazard mission was specified to require one small/mini-UAV (ceiling < 20,000 ft, endurance < 8 hours, payload < 60 kg) or a swarm of mini-/micro-UAVs, each carrying a different part of the payload (i.e., SAR, lidar, interferometer, and in-situ gas sensor), deployed for 10 days (100 flight hours). For the ocean carbon cycle mission the key platform specification was prolonged flight at 100 ft in severe weather. For the bedrock mapping mission, the key platform requirement was deployment of a large antenna array and operation over very long distances. For the purposes of the exercise, we assume that permission to fly is granted for all the hypothetical missions.

All platform providers confirmed that the hypothetical missions were achievable using existing platforms. The amount of pricing information varied greatly between providers. IAI-Malat informed us that their pricing is commercially sensitive information, and were not willing to deliver a price for leasing of their products until they were engaged in a more formal bid process. Elbit also indicated that it is quite difficult to provide costs, but did state that for missions of one month and several tens of flight hours, funding of ca. £ 0.5M would be totally insufficient; funding of probably one order of magnitude higher would be needed.

Alenia Aeronautica estimated costs around £ 0.9 M (1M Euro) for most missions. The volcanology mission was estimated to be cheaper, at ca. £ 0.4 M (0.5 M Euro). All missions were assumed to use the Sky-Y vehicle, except the thunderstorm study, which required the Molynx vehicle. These costs correspond roughly to a little below $10/flight-hour/lb-payload, which is about half the “full costs” estimated by Moiré for Global Hawk missions[26], but significantly above the indicative subsidised cost of ca. $1.50/flight-hour/lb-payload.

Mini- and Micro-UAV missions

For mini- and micro-UAVs, purchase-costs are usually well below those of conventional aircraft, and are typically a few thousand pounds. For example, the cost of one unit of the SUMO micro-UAV meteorological sensor was ca. £1,000 (1,200 Euro) (Reuder *et al.* 2009), McGonigle et al. (2008) report a cost for their UAV of £ 1,200 ($2,000), but this is without payload, autopilot, ash filters and other components that would be required to make the complete UAS. Schiebel recently reported costs for their Camcopter platform of £ 300 (350 Euro) per flight hour[28]. Phil Anderson of BAS reported initial costs of £ 40-50,000 (50-60 kEuro) for the Carolo T200 system he used, but

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[27] Alenia Aeronautica, Selex Galileo, IAI-Malat, and Elbit

[28] Reported at the Bristol International UAV conference, March 2009.

added that there can be substantial additional costs if a platform needs to be modified for a particular application[29].

Operational costs for mini- and micro-UAVs are often a small fraction of the total costs of the field study (i.e., much smaller than the costs of maintaining the researchers in the field).

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[29] Reported in answer to questions at the STN meeting on UAVs, London, February 2009.

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