UAS Report

COST Action ES0802
Unmanned Aerial Systems in Atmospheric Research

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Contents

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Summary

COST Action ES0802 in a nutshell

The interdisciplinary 'Unmanned aerial systems (UAS) in Atmospheric Research' COST ES0802 project was conducted between November 2008 and May 2013. The project had been initiated in 2007 by a handful of European atmospheric scientists to coordinate ongoing and anticipated activities towards the development and application of UAS for environmental research purposes. In this report, the terms Unmanned Aerial System(s) (UAS), Remotely Piloted Aircraft(s) (RPA) and Remotely Piloted Aircraft System(s) (RPAS) are used interchangeably.

The project had two main goals. The first was to specify the attributes of cost-efficient sensor platforms for monitoring the Atmospheric Boundary Layer (ABL) and the underlying surface of the Earth. The second was to facilitate trans-boundary operations of such systems by instigating harmonisation of national rules and regulations for UAS operations. Ultimately, the Action created an exceedingly successful network of nearly 100 individuals from more than 32 institutions across 19 European countries and the US.

WORKING GROUP ACHIEVEMENTS

The Action was structured in four different working groups, each dealing with an aspect identified as being particularly important for the successful use and operation of UAS in atmospheric science.

Working Group 1 on UA systems collected information with respect to airframes, propulsion systems, battery technology and ground control stations for small to mid-size UAS. Results of Working Group 1 provided important information to other Working Groups; for example, to Working Group 2 as a guide for determining scientific payload capacity and to Working Group 3 as a guide for setting the range and endurance requirements of various systems when planning scientific missions.

Working Group 2 on UA sensors identified commercially-available sensors and also developed new sensors compatible with the size, weight and power supply limits that specifically relate to smaller platforms. In addition, they defined and proposed best practices for calibrating and operating sensors according to various atmospheric parameters.

Working Group 3 on atmospheric measurements by UAS identified currently under-sampled atmospheric phenomena particularly suitable for being addressed by UAS. They also developed and tested corresponding measurement strategies and appropriate flight missions. A joint measurement campaign, in 2011 in France, and an overview of all campaigns and available UAS datasets that will be valuable in future ABL research, were important milestones for the Group.

Last, but not least, Working Group 4 kicked off the highly-needed homogenisation of rules and regulations for future successful operations of UAS for scientific purposes. They produced an overview of the national authorities involved in the approval of UAS operations in the countries participating in the COST Action, and also issued guidelines and documents covering best practice in the responsible and safe operation of UAS by scientific groups.

INTRODUCTION TO COST

COST – the acronym for European Cooperation in Science and Technology – is the oldest and widest European intergovernmental network for cooperation in research. Established by the Ministerial Conference in November 1971, COST is presently used by the scientific communities of 36 European countries to cooperate in common research projects supported by national funds.

The funds provided by COST – less than 1% of the total value of the projects – support the COST cooperation networks (COST Actions) through which, with EUR 30 million per year, more than 30,000 European scientists are involved in research having a total value which exceeds EUR 2 billion per year. This is the financial worth of the European added value which COST achieves.

A "bottom up approach" (the initiative of launching a COST Action comes from the European scientists themselves), "à la carte participation" (only countries interested in the Action participate), "equality of access" (participation is open also to the scientific communities of countries not belonging to the European Union) and "flexible structure" (easy implementation and light management of the research initiatives) are the main characteristics of COST.

As a precursor of advanced multidisciplinary research, COST has a very important role for the realisation of the European Research Area (ERA), anticipating and complementing the activities of the Framework Programmes, constituting a "bridge" towards the scientific communities of emerging countries, increasing the mobility of researchers across Europe and fostering the establishment of "Networks of Excellence" in many key scientific domains such as: Biomedicine and Molecular Biosciences; Food and Agriculture; Forests, their Products and Services; Materials, Physical and Nanosciences; Chemistry and Molecular Sciences and Technologies; Earth System Science and Environmental Management; Information and Communication Technologies; Transport and Urban Development; Individuals, Societies, Cultures and Health. It covers basic and more applied research and also addresses issues of pre-normative nature or of societal importance.

Web: www.cost.eu

Background to the project

The Unmanned Aerial Platforms in Atmospheric Research Project

The prospect of climate change and its consequences for the environment and communities requires political and economic action to help reduce the magnitude of change, both by cutting greenhouse gas emissions and applying effective adaptation strategies to reduce the adverse effects of their impacts. However, decisions about such actions require a solid factual base, and consequently we need a better understanding of the magnitude and pace of climate change-related modifications in the atmosphere and natural ecosystems, as well as their repercussions for local populations. This requires environmental observations and monitoring at a wide range of temporal and spatial scales.

THE ADVANTAGES OF UNMANNED AERIAL SYSTEMS

While traditional in situ measurements of environmental quantities provide unsurpassed precision and reliability, their coverage in space and time remains sparse. Satellite observations offer almost permanent temporal and global observations, but being bound to satellite orbit geometry, they are somewhat inflexible as to where these observations are taken. Furthermore, they have spatial resolutions that are often insufficient for a given purpose. Unmanned Aerial Systems (UAS), namely flying platforms piloted from the ground that are commonly known as 'drones', increasingly offer versatile tools to fill the gap between on-the-ground measurements and satellite observations. Starting from modifications of simple model airplanes, scientific UAS have undergone considerable development, in recent years becoming valuable tools for atmospheric and observational monitoring. While dwarfing the defence-related UAS industry, one can nevertheless find an increasing number of aerial-platform manufacturers and more and more companies that provide miniaturised instruments of increasing complexity and sophistication that can be employed on platforms with limited payload capacity.

In comparison with manned aircraft, UAS have the advantage of being extremely versatile and flexible. They can be used in a broad spectrum of observational tasks and employed in situations unsuitable for manned aeroplanes. For instance, they can be flown at extremely low altitudes as well as in dangerous situations, such as in volcanic ash clouds or near hurricanes or tornadoes. Applications of UAS include a wide range of atmospheric measurements, but also various remote sensing observations of Earth-surface properties and processes. UAS can also be employed for operational tasks, including forest fire detection and monitoring, mapping of geographical, biological and hydrological features and resource exploration, habitat monitoring and precision farming. Automatic operation via autopilot systems delivers unsurpassed accuracy in repeat surveys. Autopilot systems also enable multi-platform operations. Flying UAS in stacked formation enables quasi-three-dimensional probing of atmospheric properties, a task that cannot be achieved to the same extent by any other platform, yet their infrastructure and runway requirements are minimal and their operation therefore cost-effective.

PROJECT OBJECTIVES AND APPROACH

UAS come in many shapes and sizes – from small and relatively simple, to large and hugely complex, and everything in between. Likewise, a broad range of the UAS scientific technology developers comprise non-military institutions and individuals. In November 2008, the European Science Foundation's (ESF) COST programme conferred an Environmental-Sciences award to a small interdisciplinary, international consortium for a project titled 'Unmanned Aerial Platforms in Atmospheric Research' (COST action ES0802) to bring these disparate stakeholders and resources together so that we might begin to fully exploit the potential of UAS technology. Over the duration of the project, the consortium has grown significantly and now includes more than 35 partners from 19 different countries.

The COST action ES0802 has addressed a wide spectrum of issues related to civilian UAS, and is organised into four working groups (WGs). The development of suitable UAS is critical to serve the various research tasks addressed by the consortium partners. WG1 covers all aspects of airframes, propulsion, autopilot and ground control stations, investigating available UAS platforms and operation with specific emphasis on atmospheric research capabilities. WG2 deals with specific requirements of UAS sensors: size, power consumption constraints and standardised calibration procedures. Members of WG2 focus on recommendations, based on the partners' experience and the available literature, for the employment of particular sets of sensors for various kinds of measurements. Partners in WG3 address real-world applications of UAS to solve relevant scientific issues and to develop and define optimal mission strategies for the operation of UAS. Finally, WG4 is dedicated to the crucial legal and regulatory issues related to the scientific use of UAS.

Introduction to key people

JOACHIM REUDER – CHAIR

Joachim is Professor in Experimental Meteorology and Deputy Head of Department at the Geophysical Institute at the University of Bergen, Norway. He has more than 20 years of experience in atmospheric boundary layer research, in such fields as turbulence and turbulent exchange processes, air-sea interaction, atmospheric radiation, and the effects of orography on the wind field and precipitation. In the last few years he has been working intensively on the marine atmospheric boundary layer in the context of offshore wind energy installations. In this regard, he is leading the work package on Met-Ocean measurements at the Norwegian Center for Environmentally-Friendly Energy Research NORCOWE and for the national Norwegian offshore wind energy-related infrastructure projects EFOWI and OBLO. Joachim has been Chair of the COST Action ES0802 from its inception in 2009, and will continue until its completion in 2013. He has been working on the development and application of remotely controlled and autonomous unmanned aerial systems for atmospheric boundary layer research since 2001. His group is continuously improving and operating the Small Unmanned Meteorological Observer SUMO as a 'controllable and recoverable radiosonde' for meteorological research.

PHIL ANDERSON – CO-CHAIR

Phil is head of Marine Technology at the Scottish Association for Marine Science (SAMS) in Scotland. His team develops marine and polar autonomous instrumentation including ship-launch – recovery Remotely Piloted Aircraft (RPA). Prior to joining SAMS in 2012, he spent 27 years at the British Antarctic Survey (BAS), initially as a wintering field scientist studying stratified turbulence and ending up as running the atmospheric boundary layer and polar RPA programme. He was awarded the Polar Medal in 1996 for his studies on blizzards. In the 1990s, Phil developed a number of techniques to probe the winter-time polar atmosphere, including low-power autonomous remote systems at the surface and kite, blimp and rocket instrument platforms aloft. More recently he has concentrated on the physics of coherent structures in the stable boundary layer, whilst developing the use of RPA for measuring the structure of the atmosphere near the surface. At SAMS these techniques will help understand sea-ice dynamics in the Arctic and help explain the observed dramatic reduction in summer-time sea-ice coverage.

PROFESSOR CONSTANTINOS SOUTIS – LEADER WG1

Constantinos is currently Chair in Aerospace Engineering as well as being the Director of the Aerospace Research Institute and Research Director of the Northwest Composites Centre at the University of Manchester. He has over 25 years of experience in working with composite structures and has made significant research contributions in modelling the compressive response of composite plates with open or filled holes under uniaxial, bi-axial static and fatigue loading; impact and post-impact compressive strength and crush energy absorption; multi-scale modelling of damage in orthotropic laminates under multi-axial in-plane loading; and structural health monitoring using low frequency Lamb waves and repair techniques. Some of the fracture models he has developed have been implemented in commercial computer design packages, used successfully by industry and academia. His industrial research and engineering experience includes work with the Structural Materials Centre of the Defence Evaluation & Research Agency (visiting research fellow, 1995-2001), QinetiQ (Trusted Expert, 2001-2003), Cambridge Consultants, Cytec Materials Engineering and ABB Research in Switzerland. He is the author or co-author of over 350 archived articles, which include more than 170 ISI listed journal papers and some 20 PhD students have qualified under his supervision and guidance. Professor Soutis is an Associate Editor of the *RAeS Aeronautical Journal* and the *International Journal of Structural Health Monitoring*.

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Photo credit to follow

JENS BANGE – LEADER WG2

Jens is Professor at the Centre for Applied Geo-Science at the Eberhard Karls University of Tübingen, Germany. He teaches courses in environmental physics with a focus on atmospheric turbulence, renewable energy, data analysis and measurement technology. His group consists of engineers, meteorologists, mathematicians, geo-ecologists, and physicists, which is a good reflection of the diversity of skills needed in his main research field: probing the lower troposphere (its turbulent structure and transport of energy, momentum and matter) using small unmanned research aircraft (RPA). Before he started using RPA for atmospheric research, Jens used manned research aircraft of various sizea (including the helicopter-borne turbulence probe Helipod), starting with first measurements in the nocturnal stable boundary layer in 1995. He is a founder member of the EU COST action ES0802 'UAS', and a representative of Germany (together with Burkhard Wrenger), a member of the management committee, and head of the work group 2 on atmospheric sensors sensors for RPA from the beginning of the COST action in 2009 until its end in 2013.

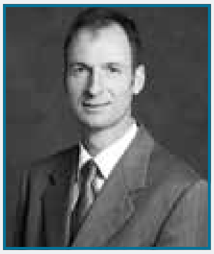
JOAN CUXART – LEADER WG3

Joan is a researcher and lecturer at the University of the Balearic Islands, in Mallorca. He has 25 years' experience in research and operations in Atmospheric Sciences. He has worked at the Spanish Meterological Agency (Barcelona and Madrid), the French Centre National de Recherches Scientifiques (Toulouse) and has also been a visiting scientist at the Oregon State University (Corvallis, USA). His first experience was on the Large-Eddy modelling of the turbulence in the Atmospheric Boundary-Layer, using the Meso-NH model and contributing to the development of its parameterisation scheme, both for clear and cloudy boundary layers. Later he became more interested in the study of the stably stratified boundary layer over complex terrain, combining experimental work and numerical modelling. He has participated in several field campaigns in Europe and the US, being much involved with RPAs in the recent years. He is the Editor of Tethys, Journal of Mediterranean Meteorology and a member of the Editorial Board of Boundary-Layer Meteorology. Joan has served as the chair of the Working Group 'High resolution atmospheric measurements using UAS' of the COST Action ES-0802.

RUNE STORVOLD – LEADER WG4

Rune is Senior Scientist at the Earth Observation Department and Head of the Unmanned Aircraft Group, at Norut in Tromsø, Norway. His background is in optics and atmospheric physics. He was involved in the US Department of Energy Atmospheric Radiation project from 1997 to 2003, and there he analysed cloud and radiation data from the North Slope of Alaska site, while working for the Geophysical Institute at the University of Alaska Fairbanks. He started at Norut in 2003 using synthetic aperture radar data for measurements of cryospheric properties and doing modelling of microwave scattering and propagation in snow and ice. In 2005 he established the Unmanned Aircraft Group at Norut, developing aircraft, sensors, and communication and control systems for airborne remote sensing using unmanned Aircraft. The focus is to develop techniques and services aimed towards both science and industry to meet the need for high resolution high quality measurements of the Arctic environment. Rune is currently co-chairing the Arctic Council Arctic Monitoring and Assessment Programs Expert Group on Unmanned Aircraft, working for increased access to the Arctic Airspace for scientific data collection using unmanned Aircraft and increased circumpolar collaboration. He has been the chair of Working Group 4 on UAS Operation in COST Action ES0802 from its start in 2009 until the end in 2013.

BURKHARD WRENGER – WEB / DATABASE MANAGER



Burkhard is Professor in Applied Computer Sciences and Vice President Teaching and Internationalization at the University of Applied Sciences Ostwestfalen-Lippe, Germany. He has 20 years' experience in the development of data acquisition systems and sensors and their integration in the fields of nano- and environmental physics. He has been Webmaster and Database master of COST Action ES0802 from the start in 2008 until the end in 2013. His main focus related to Remotely Piloted Aerial Systems is the development of suitable sensors and small rotary and fixed wing platforms for environmental monitoring in urban areas and atmospheric boundary layer research. The Atmospheric Meteorological Onboard Computer AMOC, developed jointly by his group and the University of Tübingen, is a frequently used data acquisition system within the groups of the COST Action ES0802.

MANFRED LANGE – EDITOR, FINAL REPORT

Manfred received a PhD in Geophysics from the University of Kiel, Germany in 1980. After a two-year post-doctoral fellowship at the Californian Institute of Technology in Pasadena, California, USA, he held a position as staff scientist/glaciologist at the Alfred-Wegener-Institute for Polar and Marine Research (AWI) in Bremerhaven, Germany. From 1992 to 1995, he was the Director of the Arctic Centre at the University of Lapland in Rovaniemi, Finland. Between 1995 and 2007, Manfred was appointed full Professor in Geophysics (a position he still holds) and since 1998, he has also been Director of the University of Münster's Center for Environmental Research (Germany). He is the founding Director of the Energy, Environment and Water Research Center of the Cyprus Institute in Nicosia, Cyprus (www.cyi.ac.cy) and a Professor since September 2007. As of April 2013, he is the acting Vice President for Research of the Cyprus Institute. Manfred is also the coordinator of the APAESO project (Autonomous flying Platforms for Atmospheric and Earth Surface Observation), which aims to build up an unmanned autonomous airplane facility to carry out atmospheric research and Earth observations in the Mediterranean. He has been a member of the COST Action ES0802' Coordination Group since 2009.

UAS operations near Nicosia, Cyprus © Kjell Sture Johansen

Atmospheric Boundary Layer monitoring requirements

ABL requirements workgroup

This report comes from Costas Soutis of the University of Manchester and Burkhard Wrenger of the University of Applied Sciences, Ostwestfalen-Lippe, with contributions from other Group members.

BASIC ATMOSPHERIC RESEARCH REQUIREMENTS

In Working Group 1, we focused on air chemistry, the stable boundary layer including mid-latitude and polar regions, the convective boundary layer and spatial transition situations. These scenarios give rise to specific requirements for scientific instruments and Remotely-Piloted Aircraft Systems (RPAS), in terms of maximum flight time, cruising speed, payload, flight patterns and manoeuvrability.

A tactic we employed for investigating passively degassing volcanoes was to obtain a 3D mapping of the plumes for studying their evolution over time. This requires RPAS ranges of several tens of kilometres and up to 1.5 hours' flight time with standard Geographic Positioning System (GPS) spatial resolution and accuracy. Investigating plumes from industrial installations and urban areas involves more precise GPS spatial resolution and accuracy. For both scenarios, preferred airframe configurations are blimps or multicopter rotary wing systems.

Fixed wing airframe configurations are better suited to most other scenarios. Studying the stable boundary layer and transitions demands flight times of up to 10 hours and ranges over 1,000 km. If the payload instruments weigh between one and five kilograms, only fixed wing configurations of at least 25 kilogram' Maximum Takeoff Weight (MTOW) with combustion motors are suitable. For more local campaigns, the preferred propulsion method is electric motors and Lithium polymer battery packs.

Telemetry, connected to a ground control station, enables scientists to monitor data in real time. A telemetry link is essential for beyond-line-of-sight operation.

STRUCTURAL MATERIALS

Modern composite materials combining properties of two or more constituents, such as metals, ceramics, polymers, elastomers or glass, can be designed to create a system with an innovative property profile. Such composites deliver high performance, lightweight airframes with superior strength and durability and weight savings of up to 20 per cent for wings and fuselages. Other benefits include fewer parts, complex shaping, reduced scrap, longer life and better corrosion resistance.

RPAS AERODYNAMIC, STABILITY AND CONTROL DESIGN CONSIDERATIONS

RPAS shape should be tailored to meet required performance targets at various points in the flying envelope. Designers therefore experiment with airframe configurations, some reworking early designs to offer improved flight performance using modern structural materials and propulsion systems.

Fixed wing RPAS are the most frequently used systems in complex atmospheric investigations. Unconventional configurations have been developed, such as twin fuselages with various tail control modifications and pusher engines, and for canard or three-surface solutions. Improved aerodynamic performance can be achieved via innovative flap designs or adaptive wings.

A special configuration, popular in RPAS design, is the V-shaped tail, which has the advantage of smaller, fewer tail control surfaces. If enhanced yaw stability is required, a lower fin may be added, creating a Y-shaped tail, which can also be used in inverse or extended to an X-shaped tail where increased surfaces are needed. Several RPAS have been designed using double vertical tails, sometimes divergent and extended with equally divergent ventral fins, also creating the appearance of an X-shaped tail.

Extension of pitch and yaw control surfaces to attain increased manoeuvrability and high stability during long flights has led to more revolutionary solutions, such as twin boom aircraft. Another revolutionary configuration is the flying wing solution, which is tailless. From an aerodynamic viewpoint, it can be regarded as the optimum, though it lacks stability. Pitch stability can be enhanced by using a double curvature aerofoil and applying a progressively diminishing angle of attack in delta wings. The outer wings act as the tail stabiliser. Pitch control is assured by using swept-back wings and elevons. Directional stability is achieved by such features as fins or winglets.

DESIGN FOR METEOROLOGICAL AND ENVIRONMENTAL MEASUREMENT

Mission profile must govern RPAS instrumentation and, therefore, payload and airframe configuration design, if optimal performance and energy consumption are to be achieved. Cruising speed and length of flight are also key requirements in airframe design.

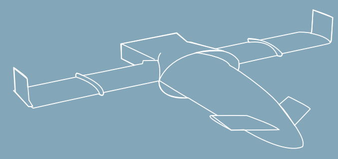
Apart from the materials used, airframe weight is strongly influenced by construction techniques. The wing is bent by gravitational and dynamic forces, during launch, landing and high angle of attack manoeuvres, and also twisted due to the cambering of the aerofoil. These forces must be carried by the structure. Basic designs are the torsion box, truss frameworks and the double spar and D-Box designs.

AVIONICS REQUIREMENTS FOR SMALL RPAS

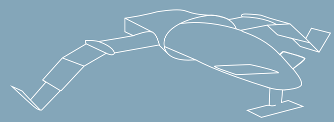
Miniaturisation of electronic hardware and sensors widens the possibilities for flight control strategies for small RPAS. Increased automation also offers new experimental setups and campaigns for fixed wing and rotary wing RPAS. However, some flight control requirements are standard irrespective of configuration: cancellation of atmospheric disturbances, attitude and flight path control and determination of the RPAS' spatial position.

An autopilot usually consists of a flight-controlling computer device and the

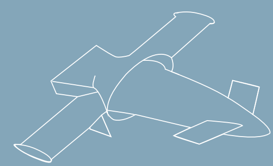
Aelius, unmanned aerial vehicle, entirely built out of composite materials (Aeroart/USFD).



AIR CONFIGURATION



ON-WATER CONFIGURATION



UNDER-WATER CONFIGURATION

sensors that measure control variables: a GPS receiver for tracking spatial positioning and velocity above ground, and gyrometers and acceleration sensors for obtaining data. The datasets are filtered to eliminate long-term drifts and achieve greater accuracy, and the resulting control signals are fed into actuator sub-devices, servos and motor controllers. Flight planning requires the setup of a list of waypoints or flight patterns for the autopilot to follow step-by-step. The next level, autonomous flights, includes detection of fixed or moving obstacles for changing the flight path accordingly, known as Sense and Avoid.

The autopilot usually provides a telemetry data interface to a ground control station. Several modem types are used, with the technology and

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AMOR multicopter by University of Applied Sciences Ostwestfalen-Lippe with vertical sensor mast required for atmoshperic boundary layer investigations. Depending on the payload, the flight time is up to 40 min.

protocol strongly depending on the mission. For short distance line-of-sight flights, Zigbee-based modems in the 2.4 GHz band are usual; for long distance flights, satellite communications are preferred. In either case, operators can obtain feedback on the aircraft's position, flight path, and fuel and battery levels.

AIRFRAMES TESTED IN THE PROJECT

Most RPAS used by the participating groups in the project are of fixed wing type with an MTOW of 0.5 to 65 kilogram and payload capacities ranging from 0.1 to 25 kilogram. The smallest, AMOR Wing XS from the Ostwestfalen-Lippe University of Applied Sciences and SUMO from the University of Bergen are Commercial Off The Shelf systems made of foam with wing-only airframe configurations and extensions. They have proven their ability to carry meteorological payloads for up to 40 minutes in hundreds of successful RPAS flights.

The larger fixed-wing RPAS, MASC from the University of Tübingen and UMARS from the Zurich University of Applied Sciences, have standard airframe composite material configurations with a V-tail (MASC) or separated V-Tail (UMARS). They have pusher propellers powered by an electric motor which allow undisturbed air flow. The largest RPAS used in the Project, the Cruiser II, has a pusher configuration.

> "Further effort is required to make these aerial systems more robust, with the ability to take off and land, day or night and in hostile – hot, cold, or wet – environments, with minimal piloting skills."

Two Groups demonstrated the ability of rotary wing systems to contribute to Atmospheric Boundary Layer investigations, if vertical profiles, hovering capability and flying only several metres above ground level are required. The Vario XLC turbine helicopter operated by Aalborg University has a MTOW of 40 kilogram including a payload of approximately 12 kilogram, making it very versatile. The AMOR multicopter, developed by the Ostwestfalen-Lippe University, is based on a composite airframe and propellers with four to eight electric motors. The payload of the four-motor version (Quadcopter) may be up to 2 kilogram. Depending on the payload and battery pack, an endurance of 40 minutes can be achieved if the payload is reduced to under 0.5 kilogram. The advantages of this configuration are flight altitudes from nearly ground level to approximately 400 m above ground, with easy handling and maintenance. Automatic take-off and landing is also possible. The downwash of the propellers gives rise to specific sensor installation configurations.

The most exotic RPAS used in the project was a Minizepp blimp operated by the University of East Anglia. This airframe allows the hovering and low velocity operation necessary for air chemistry investigation in the vicinity of degassing volcanoes.

Further effort is required to make these aerial systems more robust, with the ability to take off and land, day or night and in hostile – hot, cold, or wet – environments, with minimal piloting skills.

UAS sensors for atmospheric research

The scientific payload of remotely-piloted aircraft

This report comes from Jens Bange and Norman Wildmann of the University of Tübingen, and Burkhard Wrenger of the University of Applied Sciences, Ostwestfalen-Lippe, with contributions from other Group members.

Our working group focused on the scientific payload carried by remotely-piloted aircraft (RPA). The scientific payload of an RPA comprises, in addition to the sensors themselves, the measurement computer system, data storage, data link(s) to ground stations, and ground station and data analysis software, as well as sensor calibration routines.

Sensors were distinguished by the meteorological variable measured (such as air humidity) instead of by the primary quantity (such as electrical capacity) or the measurement method (such as absorption). They were categorised into two classes according to application: long-term stable measurements with high absolute accuracy, and turbulence measurements with a very short response time and high resolution.

The overall goals were to avoid unnecessary multiple inquiries and to develop suitable sensors for RPA. These were achieved by the establishment of a sensor and on-board computer database, accessible, up-datable and expandable via the internet. All sensors that were studied or had been used by project members are listed in the database with parameters such as size, weight and power consumption, and absolute and relative accuracy. The database is complemented by a decision support routine that provides recommendations for sensors for a particular type of scientific mission and RPA, taking into account such factors as size and payload capacity.

RPA scientific payloads were categorised according to four classes of meteorological variables of interest, as well as according to measurement computer system: position and orientation; wind vector; thermodynamic scalars; and aerosols, clouds and radiation.

Some examples of sensors and systems that were established are outlined in the following sections.

MEASUREMENT COMPUTER SYSTEM

The study focused on various scenarios of investigations of the atmospheric boundary layer (ABL) by small RPAs with a maximum take-off weight (MTOW) of up to 65 kilogram, the development of such RPAs and the integration of sensors suitable for the application scenarios. In contrast to manned aircraft with a MTOW of several hundred kilogram, clearly there are restrictions with respect to payload dimensions and the maximum permissible weight of sensors and data acquisition (DAQ) systems. Campaigns usually have to be planned according to these constraints and missions and must therefore include a suitable selection of components. Existing and proven DAQ systems used in manned aircraft campaigns are usually not suitable for small RPAs. Consequently, the objective when planning a mission must be to achieve the optimal compromise between size, weight and performance, even if the performance of manned aircraft DAQ systems may not be mirrored.

The Airborne Meteorological On-board Computer (AMOC) system was jointly developed by the University of Applied Sciences Ostwestfalen-Lippe and the University of Tübingen in 2011. The task was to design a modular and highly versatile system which could be easily adapted and extended to meet the requirements of a vast variety of missions. Other key features of the AMOC system are: flexible ground control software for real-time monitoring; high frequency and resolution air data computations; a variety of digital interfaces for sensor integration; on-board attitude estimation by integrated inertial sensors such as accelerometers, gyroscopes and digital compasses; integrated GPS for precise time synchronisation and position information; and lastly, a

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high frequency logging service which stores precise timestamps and flight meta-data including position, time and orientation, as well as the sensor outputs, on an on-board micro secure digital flash memory card with a frequency of up to 500 Hertz.

WIND VECTOR MEASUREMENT ABOARD RPAS

Precise measurement of wind vectors using an RPA has various benefits; for example, the local wind field is important for understanding the lower atmosphere above complex terrain, especially regarding wind farming.

Turbulence is of fundamental importance for quantifying the energy budget of the Earth's surface, the interaction of the atmosphere with wind turbines or the propagation of contaminants. The turbulent wind field high above the surface can only be measured directly and with high resolution and accuracy using aircraft. Small RPAs add particularly little disturbance to the data being measured, due to their small fuselages, engines and wings. Measuring a turbulent three-dimensional wind vector is especially challenging since it requires very accurate and high resolution measurements of position, ground speed, orientation and flow angles. In addition, humidity and temperature data are required for consideration of the density fluctuations of air. The navigational part of this task can only be solved by a combination of GPS satellite data and inertia measurements. Today, the flow angles are derived from absolute pressure and pressure differences along a flow probe, usually a five-hole probe.

An airborne wind measurement system requires careful calibration due to various systemic error sources such as mounting tolerance, sensor drift and flow distortion caused by the aircraft and its aerodynamics. Using manned aircraft, most calibration has to be performed using special flight manoeuvres and highly sophisticated data analysis; the operators have to be experts in meteorology, fluid mechanics and aviation. With small RPA, the situation is made easier since a larger part of calibration can be done in wind tunnels. Calibration of an entire RPAS can be achieved in a large wind tunnel, although the effect of a running engine is still very difficult to simulate.

THERMODYNAMIC SCALARS

Thermodynamic scalars are the current temperature, humidity and pressure of an air parcel in the atmosphere. These three variables are the basic meteorological parameters used to describe thermodynamic processes. To get an idea of the thermal stratification of the atmosphere, for example, a complete set of measurements, including temperature, water vapour concentration and barometric pressure, is needed. To draw conclusions about the stability of the ABL, it is not sufficient simply to measure static temperature: all variables are required in tandem in order to gather a full picture of the thermodynamic situation.

During vertical motion, air parcels experience an adiabatic temperature change without exchanging heat with their surroundings. The lapse rate of static temperature has to be compared against the adiabatic lapse rate in order to define stability. In meteorology, the potential temperature, calculated using the barometric pressure, is introduced, which removes this effect. Water vapour content of the air, on the other hand, cannot be measured with a relative humidity sensor without knowing the temperature of the air. The more accurately each variable is measured at each point in time and space, the more precise will be the assessment of ABL evolution. Since turbulent transport is crucial to the description of thermodynamic processes in the ABL, formulating averages of temperature, humidity and pressure over a large area or a long time is insufficient. Instead, it is important to measure their turbulent fluctuations in the flow as precisely as possible. This places special additional requirements for resolution and time response characteristics of on-board sensors for RPAS.

A meteorological payload for small RPAs that was developed at the University of Braunschweig has been used in many campaigns. The sensor package consists of a thermocouple, the Vaisala HMP50 combined humidity and temperature probe and a micro-electrical mechanical system (MEMS)-based barometric pressure transducer – 144s-BARO – produced by Sensortechnics, for the thermodynamic scalars. In addition, it features a wind measurement system consisting of a flow probe developed by the University of Braunschweig and an inertial navigation system. The system is designed to be able to resolve turbulent fluctuations of variables up to 20 Hertz, excluding humidity.

Using knowledge and experience of the mini M2AV system, the University of Tübingen developed their own meteorological sensor package to be integrated into the Multi-purpose Airborne Sensor Carrier (MASC) RPAS. It consists of a thermocouple and a fine wire platinum resistance thermometer sensor for fast temperature measurement, a P14 Rapid capacitive humidity sensor from Innovative Sensor Technology AG and a 144s-BARO MEMS-based barometric pressure transducer. Like the Braunschweig system, it uses a flow probe and an inertial navigation system for wind measurement and can be used for turbulence measurement up to 20 Hertz. The system was not only installed in the own RPAS MASC, but also in the RPAS of the Andoya Rocket Range, a member organisation of the group.

High resolution atmospheric measurements

Sampling the atmosphere

This report comes from Dr Joan Cuxart, University of the Balearic Islands, ES, the Chair of WG3. Other key personnel from WG3 include Dr Roland von Glasow, Dr Phil Anderson, Professor Joachim Reuder and Dr Bruno Neininger.

Measuring above the ground has always been a challenge for atmospheric scientists. Releasing balloons into the upper atmosphere is costly and delivers only a single observation instance; operating tethered balloons linked to the ground by a cable is very manpower-intensive but covers a limited area; remote sensing is more convenient, but often lacks precision and vertical resolution, and necessitates validation data.

Unmanned Aerial Systems (UAS) offer a new way of sampling the atmosphere. They are relatively low-cost systems that can be operated remotely from the ground and flown along pre-programmed routes for research analysis or operational purposes. Classical meteorological variables, such as temperature, moisture, wind and the concentration of some atmospheric gases can be measured, provided that the weight of the measurement devices can be lifted by the UAS. We dealt with UAS that are relatively small, mostly below 10 kilogram, with payloads up to a few kilograms.

At the start of our review in 2008, very few UAS were available for geosciences research, most being still in prototype form. At the time, some glider and small platforms were being tested. Today, there are more devices available – UAS are becoming the norm for meteorological experimentation – in a variety of sizes and with a variety of instruments, though some are still developing.

Since the legal restrictions for operating a UAS are still not well developed and it is customarily required that remotely-piloted aircraft are flown under visual control, combining research activities with manned aircraft operations is an attractive option. Strong collaborations with the small manned aircraft operator community are in progress to facilitate exchange of technology and methodologies and to find mutual operating scenarios.

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PLATFORMS AND PAYLOADS

The current platforms are of three kinds: glider-like, small aircraft and multicopters.

- Glider-like UAS typically have wingspans of 2-3 m, weigh several kilograms and can carry payloads of a few kilograms. They can fly for about an hour, in wind conditions below 15 m per second, and are intended for measurements, including gas and aerosol concentrations and turbulence quantities at different altitudes

- Small aircraft are usually under 1 m in both length and wingspan, can carry very small payloads of less than appr. one kilogram and are well-suited for vertical profiling and for transecting at constant height over small areas

- Finally, multicopters are also small and intended to operate in the lower 200 m of the atmosphere. Profiling, transecting and staying in a certain location for a while, they can carry a slightly heavier payload than the small aircraft

Instruments have to be light and small, precise and with a fast response time, which implies a need for continuous instrumentation development.

ABL PROCESS CAMPAIGNS

UAS provide a very convenient tool for sampling key processes, allowing a focus on a singular event that involves continuous distributed measurements, such as spatial and temporal transitions, at more frequent time and space intervals. During the current project, a number of field experiments took place, especially at high altitudes and in Europe.

The atmospheric boundary layer (ABL) is continuously influenced by contact with the surface: it is usually in a turbulent state and responds very quickly to changes in surface conditions. This renders the ABL very difficult to characterise experimentally and to model numerically. Complete knowledge of surface conditions and their time variations is required and, even so, a turbulent flow can only be described statistically, due to the aleatory nature of individual eddies. More data about the ABL is required to lower degrees of uncertainty and thus provide better estimations of the physical processes taking place. In mid-latitude Europe, UAS were used to study low-level winds in complex terrain, including varying topographies and heterogeneous land use patterns. During the experiments, the convective and nocturnal boundary layers together with their transition regimes were probed. Large, well-coordinated campaigns took place in France, Germany and Spain and many local experiments were carried out by individual teams at local scales. At mid-latitudes, experiments concentrated on surface heterogeneity, the evening transition period, terrain-induced low level flows and on monitoring nocturnal surface thermal inversions.

The harsh conditions of Antarctica, Iceland and Svalbard in Norway tested the limits of device operation, including the shorter life of batteries in cold conditions, and, more notably, those of the human ground teams. Experiments here focused on profiling combined with numerical modelling.

ATMOSPHERIC CHEMISTRY

The study of atmospheric chemistry via UAS is currently undergoing intensive development. Lighter sensors are emerging for mounting on larger UAS, and one such combination is under test at the moment. This platform is expected to be especially advantageous for studying distinct plumes, such as those from biomass burning, industrial point sources and volcanoes, to achieve a longer sampling time within the plume through slower speeds and/ or greater UAS endurance compared with manned aircraft. It also offers the potential of extended sampling times in stationary plumes.

Key measurements, along with meteorological variables, would be those of trace gases, aerosol and cloud particles and their turbulent (vertical) fluxes. Target gases include ozone, nitric oxide, nitrogen dioxide, sulphur dioxide, hypochlorite, hypobromite, hypoiodite, Volatile Organic Compounds, carbon monoxide and

carbon dioxide. Aerosol parameters include size distribution, water, total particulate matter, black carbon and filter samples for later chemical analysis.

The ability to simultaneously take, using different UAS, three-dimensional measurements of the concentrations of gases, aerosol particles and cloud parameters, as well as of trace gas/particle fluxes, is another important aspect, since the spatial scale of a number of features of interest in atmospheric chemistry is very small.

WIND POWER

Generation of energy from renewable sources is a key factor for the sustainable future of mankind. There is intense activity worldwide to install wind farms and make them optimally efficient for a given terrain, including offshore and elevated inland areas.

UAS can contribute to wind power development directly, by providing wind profiles and time/space variability of wind fields in candidate areas for wind farm installation. Sampling the turbulent wake downwind of windmills allows definition of how windmills should be spatially distributed within a wind farm, to minimise interference with downwind turbines. UAS measurements also provide data for initialisation and validation of very high resolution computational fluid dynamics simulations of wind farms, a standard procedure in the design of such installations. Several tests of UAS were carried out in wind parks in Denmark.

NUMERICAL MODELLING

UAS provide more representative data than point measurements because they fly over heterogeneous surfaces and provide average values and estimations of spatial variability. Whereas a surface station provides data at a constant rate, a UAS records data only when it is flying. Compared with satellite fields which provide estimations only, a UAS can sample directly in the flow, and at a finer horizontal resolution.

These advantages imply that a systematic use of UAS will be distinctly beneficial for verification purposes in operational models. Currently, verification is essentially only conducted for test cases and simulations for selected research campaigns. It is of proven value, since it allows inspection of three-dimensional complex structures, such as breeze systems.

The utility of UAS data for initialisation of models is also clear. Tests using these data in assimilation packages for observational nudging have shown their positive impact in producing more accurate weather forecasts, revealing the potential of UAS in numerical weather prediction.

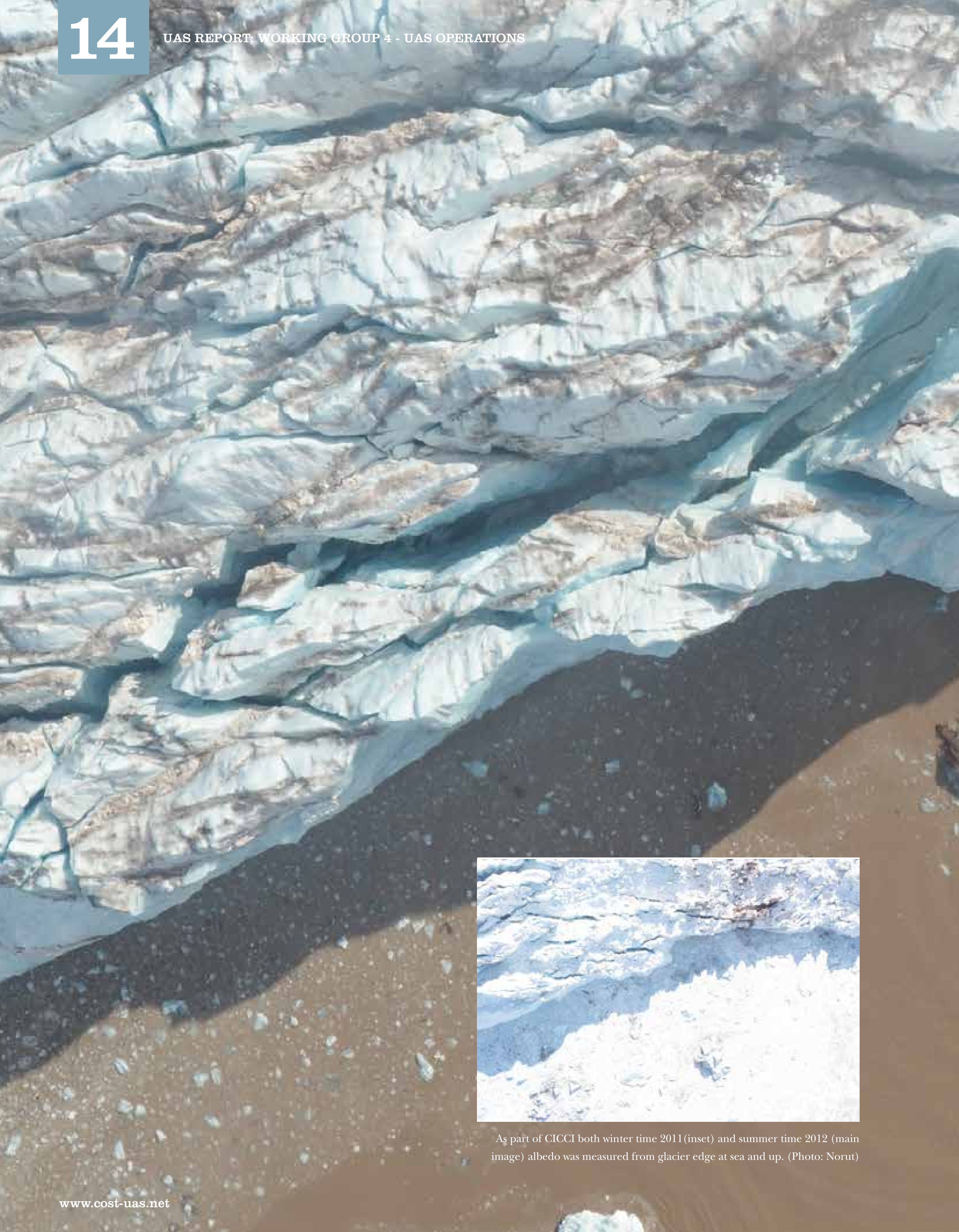
THE FUTURE

Ideally, UAS should complement classical methods, such as free or tethered balloon soundings or remote sensing devices; there should be good information at ground level, and a tower with instrumentation, as well as manned aircraft. Under such conditions, UAS can provide high spatial and temporal resolution profiling and transecting in the ABL.

Joint operation of several UAS and manned aircraft is a challenge that will certainly be addressed in the coming years. But first, the rules of operation must be clarified.

There are still improvements required in terms of reliability for UAS to become as trusted as manned meteorological aircraft. This is currently progressing through the development of more automated flight, takeoff and landing procedures. Increasing autonomy depends largely on power sources – such factors should be central to the planning of scientific missions.

As UAS become more reliable, moving from prototypes to fully user-orientated tools, they will become standard in experimental research. We also foresee that UAS will be operated routinely for initialisation and validation of operational numerical models in selected locations; there is already mounting interest in such applications from national weather services.



As part of CICCI both winter time 2011 (inset) and summer time 2012 (main image) albedo was measured from glacier edge at sea and up. (Photo: Norut)

Unmanned Aerial Systems Operation

Operational problem area

This report comes from Rune Storvold, a Senior Scientist at the Earth Observation Department and Head of the Unmanned Aircraft Group, at Norut in Tromsø, Norway, with contributions from other Group members.

Though UAS pose great research opportunities, they also pose challenges. Scientists have just started using UAS to collect data for their research and most research groups have little operational experience from manned aviation. However, the fundamental problem is that UAS do not fulfil the requirements set by national and international regulations for airworthiness: there is no pilot on board to see and steer the aircraft so it will avoid collision with other aircraft. Most platforms are built using parts from the remote control model airplane market, so not certified; and finally, since the UAS consists of a cockpit on the ground with a wireless link to the flying plane, it cannot be certified as there are no existing certification standards.

To address these issues, the International Civil Aviation Organisation (ICAO), the Joint Authorities for Rulemaking on Unmanned Systems and the European Organisation for Civil Aviation Equipment have established working groups with experts to develop regulations, standards and recommendations for best practice

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UAS operators. As manned aviation regulation has gained comprehensive experience related to operation and the handling of accidents over the last 100 years, the integration of unmanned aircraft into the regulations is taking time.The roadmap produced by ICAO for full and complete inclusion of UAS in international aviation regulation estimates that this will be in place by 2028. Until then, UAS regulations will be phased in gradually and at different speeds from country to country.

Today, most countries allow visual line of sight (VLOS) operations where the UAS operate below 120 m and within 500 m of the pilot on the ground over non-populated areas for approved operators – requirements differ from country to country. For Beyond VLOS (BVLOS) operations, most countries treat applications on a case-by-case basis. Access to these kinds of operations is limited and many countries will not approve them unless they take place in areas without other air traffic, known as segregated airspace. Depending on the area and country, to establish a segregated airspace can take months, and usually requires that the activity has benefits for society that outweigh the disadvantages caused to other airspace users.

WORKING GROUP APPROACH

The Operations Working Group focused on four key areas:

- Education required for scientists on current rules and regulations pertaining to the operation of UAS and the permits needed
- Demonstration of how to calculate and assess the risks involved in UAS operations and the mitigation methods that might reduce those risks
- Gaining an overview of the regulations in the different member countries participating in the present COST project
- Helping participating scientists to obtain permission to operate UAS in scientific campaigns, drawing on experiences from operations gained by other consortium members and offering advice on procedures, applications and safety assessments


Launch of a UAS by means of a catapult system.

The Working Group organised small workshops at project meetings where best practice and safety measures were discussed. During the workshops, experiences were shared in relation to both general and particular planned and past operations. The Group also staged a Summer School for Masters and PhD students at Andenes in Norway, where the students were able to plan and execute actual UAS operations.

PILOT CAMPAIGNS

The Group was involved in planning two major campaigns which took place during the Project – the Boundary Layer Late Afternoon Sunset Turbulence (BLLAST) and the Coordinate Investigation on Climate Cryosphere Interaction (CICCI) campaigns. Both BLLAST and CICCI were large international campaigns utilising UAS, manned aircraft, balloons and ground-based instruments. They took place in late spring and the summer of 2011. The campaigns posed operational challenges in coordinating simultaneous multiple UAS flights. Moreover, it was necessary to coordinate manned and unmanned flights without increasing the risks either to personnel on the ground or other airspace users. Even though the campaigns were performed by different groups, the operations were discussed within the Working Group and a common approach to aircraft management and safety procedures was adopted and approved by the French authorities for the BLLAST campaign and by the Norwegian Authorities for the CICCI campaign. Both campaigns were therefore completed very successfully both from the operational and the scientific point of view.

The way forward

ISARRA: expanding the network for the future

The SUMO aircraft, a small but versatile platform for basic atmospheric measurements.

COST action ES0802 had a predefined duration of four years and so officially ended in May 2013, but joint work on UAS, now correctly termed Remotely Piloted Aircraft Systems (RPAS), will continue. There is a strong desire among the consortium not only to proceed with our successful and fruitful collaboration, but also to attract new members and extend our active network. In particular, the active RPAS community in the US will be invited to link up with us.

To provide a platform for further discussions, a new group was formed in the summer of 2012: the International Society for Atmospheric Research using Remotely Piloted Aircraft (ISARRA). It should be noted that ISARRA has explicitly expanded the scope of platforms under consideration beyond that of the COST Action by also including manned aerial vehicles. This is in response to a growing recognition that there is significant potential for synergies in complementary research with both manned research aircraft and unmanned platforms.

ISARRA is a non-profit organisation that functions as a forum for any researchers, institutions and small businesses interested in one or more of the many aspects of the use of RPAS in atmospheric and earth science. A group of volunteer researchers who were largely involved in the COST Action are the organisers and membership can be obtained free of charge by registering on ISARRA's website at www.isarra.org.

BRINGING TOGETHER A WIDER COMMUNITY

Current members come from numerous branches of science and RPAS-related fields. They cover various activities, from aircraft operators to RPAS researchers. The main purpose of ISARRA is to facilitate the exchange of knowledge and expertise within the area of atmospheric and earth sciences involving unmanned or remotely piloted aircraft, while providing an extensive network of interested parties.

An additional extension of scope beyond that of the COST Action lies in the fact that ISARRA brings together the atmospheric sciences community and the Earth-observation/remote sensing community. There is a growing number of aerial platforms that are being used to serve both communities, thereby addressing various challenges and opportunities common to both user groups. The integration of sensors probing atmospheric properties and Earth-surface characteristics in a single manned or unmanned aircraft delivers particular benefits. Two examples of such opportunities for joint measurements are outlined as follows: assessing changes in vegetation cover through detailed imaging in parallel with measuring the variations of trace gas and/or radiative fluxes over terrestrial surfaces; and taking measurements of sea-surface temperatures through infrared imaging and quantifying sea-salt aerosol emissions through simultaneous aerosol sampling.

STIMULATING DEBATE

The subject areas that ISARRA currently covers are detailed below, but there are many exciting topics that we hope to additionally explore and discuss within the ISARRA community in the future:

- Boundary layer meteorology
- Arctic- and Antarctic operations
- Campaigns and data analysis
- Wind power meteorology, in particular wake effects
- Mediterranean earth sciences
- Multi-rotor craft for atmospheric observations
- Single rotor craft
- Joint manned and unmanned missions

Examples of the topics we currently plan to explore and discuss soon are:

- The advantages or disadvantages of employing ‘swarms’ of small and flexible aerial platforms, in order to simultaneously cover larger spatial scales for specific investigations
- The usefulness of ever-more-complex multi-sensor platforms that are costly and risk-prone versus simpler, less costly platforms that may be used successively with varying sensors at the same study site
- Strategies for adapting platforms originally designed for research missions so that they can serve as operational and monitoring platforms

The main form of interaction between ISARRA members, apart from web-based discussion groups and fora, is an annual conference to bring together the various international communities of platform operators, instrument developers and scientists using manned and unmanned platforms for specific scientific investigations. The first ISARRA conference took place in Palma de Mallorca, Spain on 18-20 February 2013, as the culmination of COST Action ES0802. The next ISARRA conference is in preparation for the 26-28 May, 2014, in Aalborg, Denmark.

While COST Action ES0802 has come to an end, research and development on unmanned aerial systems and their increasing use for atmospheric investigations and Earth observations will continue. This has been the main motivation to found the International Society for Atmospheric Research using Remotely piloted Aircraft (ISARRA). ISARRA will provide a valuable basis for the exchange of ideas and concepts related to UAS science. It will preserve COST Action ES0802’s legacy by providing useful information on UAS platforms and adequate instrumentation on ISARRA’s website www.isarra.org and may lead to new and exciting cooperative research projects among its members.

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- Preliminary Design Department, Flight Sciences Directorate, Engineering Division, **Israel Aerospace Industries**, Israel (http://www.iai.co.il/22031-en/Homepage.aspx)
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ADDITIONAL INFORMATION

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