Operation of small sensor payloads on tactical sized unmanned air vehicles

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ABSTRACT

The miniaturisation of sensors has in recent years led to the ability to provide multiple sensor operations from a single Unmanned Aircraft System (UAS) platform. Multiple UAS platforms can be synchronised to link devices from separate UAS platforms thus proving a powerful capability for data collection, while opening up interesting opportunities in the way data is retrieved and used. A range of new sensors being investigated will be discussed with reference to selected case studies that have taken place. As we move into an increasingly growing, data rich environment, data management, quality and pedigree will become of increasing importance. Operations for both defence and non-defence applications will be discussed with reference to the present capability and what is required in future systems. This paper describes some of the sensors currently being evaluated. In the coming years it is expected that we will see a sharp increase in the use of small tactical sized autonomous vehicles in general and a large growth in the capability of the payloads being used.

NOMENCLATURE

ACR	Advanced Ceramics Research
AGL	above ground level
BAE	BAE Systems
BYU	Brigham Young University
CCD	charge couple device
CCN	cloud condensation nuclei counter
CIRES	Cooperative Institute for Research in Environmental Sciences
CU	University of Colorado
DARPA	Defense Advanced Research Project Agency
DHS	Department of Homeland Security
DoD	Department of Defense (US)
EM	electro-magnetic
EMG	electro-magnetic gradiometer
EO	electro-optical
GCS	ground control system
HSI	hyperspectral imaging system
IED	improvised explosive device

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iGCS	integrated ground control system
IR	infra red
JAUS	joint architecture for unmanned systems
JMPS	joint mission planning system
LAASS	low altitude airborne sensor system
MAC	Maldives Autonomous UAV Campaign
MAIS	Manta airborne imaging system
MWIR	mid wave infra-red
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NAVAIR	Naval Air Systems Command
NIR	near infra-red
NOAA	National Oceanic and Atmospheric Administration
NSCT	Naval Special Clearance Team
NSF	National Science Foundation
ONR	Office of Naval Research
ORASIS	object real time adaptive signature identification system
RF	radio frequency
RHIB	rigid hull inflatable boat
SAM	spectral angle method
SAR	synthetic aperture radar
SBIR	Small Business Innovative Research
SFOV	synthetic field of view
SIO	Scripps Institute of Oceanography
STANAG	STANdardization AGreement
UAS	unmanned air system
UAV	unmanned air vehicle
USA	United States of America
UUV	unmanned underwater vehicle
3D	three dimensional

1.0 INTRODUCTION

The purpose of most UAV flights is typically to collect data usually in the form of video or images of regions of interest. Climate and resource data have provided society with an improved prediction capability from weather to resource management. Governments rely on remote sensing for treaty verification, disaster management, weather forecasting, and resource planning. Businesses require it to improve the efficiency of their operations and consumers depend on it for everyday decisions – often without knowing the source. Over the next decade and beyond, the use of remote sensing as a primary observational tool for understanding the Earth will grow rapidly as emerging user needs push demand[1]. Airborne data collection is a large industry in itself, ranging from satellites that continuously monitor different aspects of our planet to small, single-engine piloted planes or balloons used to obtain specific information about a localised region. Unmanned air vehicles are therefore a natural platform for many of these existing sensor capabilities. The 'pilot less' nature of UAVs means that they can be designed to be small, as they do not need to be designed around the physical size of the pilot. There is an exciting vision that advanced sensor technologies will allow us to view the Earth in three dimensions at nested spatial scales, blurring the boundary between remote and in-situ information. Vast networks of sensors will bring the most remote corner of the world into our daily lives and internet geospatial portals and geographic search engines will put all of this information at our fingertips[1]. Many existing sensors that have been developed around these larger manned platforms, however, are too large to fit within the small Tier I and II class of UAVs, and there is an emerging business in the miniaturisation of sensors for these new autonomous vehicles. Within the commercial world there is already a significant effort to miniaturise electronics for more convenient personal use and these sensors (primarily higher resolution video, still imagery and solid state processors and memory) are benefitting small UAVs.

The personal entertainment industry has driven the miniaturisation of many components to the size that is readily hand-held, and very capable, high resolution imaging devices are now commercially available at a moderate price. The biomedical industry has spawned microscope attachments capable of collecting and analysing hyperspectral data in a very portable device. Similarly, the mining and exploration industries have refined several sensors for greater portability by individuals and these devices are now available for use from small UAVs.

Additionally for many defence and scientific missions the utilisation of UAVs and the data required has been better defined and this has led to focused efforts to miniaturise sensors, or suites of sensors, for specific applications. Some of these devices generate a much greater volume of data than previous lower resolution devices and this has led to a need for on-board data storage or computers that can better control and manage the sensor utility.

The present desire for additional data as well as data from different sensors for Tier I and II type UAVs is dependant upon, and intimately related to;

1. Miniaturisation of existing sensors
2. Power management
3. Data management and communications
4. Unique attributes afforded by autonomous machines.

To facilitate the collection and rapid processing of data in future systems it will be important for the UAS to operate with an on-board processing capability. The processor should be generic in nature and interface with a range of autopilots and sensors, and should be capable of performing predetermined tasks based on the requirements that are desired.

Ideally, the on-board processor should partition tasks/commands between the auto pilot, payload and wireless link, as well as perform on-board processing (decisions based on multiple sensor data inputs, real time video stabilisation, synthetic aperture radar (SARs) and hyperspectral image processing etc.). The computer will also provide on-board data storage capability. The interfaces and formats should be standardised so that they are compliant with North Atlantic Treaty Organization (NATO) STANdardization AGreement (STANAG) 4586 / 4609, Joint Architecture for Unmanned Systems (JAUS) and Joint Mission Planning System (JMPS) and others.

This paper addresses some of the issues above that were experienced by Advanced Ceramics Research (ACR – a small business developing and manufacturing small tactical UAVs in the United States of America (USA)) in the preparation and execution of specific missions. It covers a range of sensors and sensor suites and highlights some strengths and weaknesses that were encountered. Advanced Ceramics Research was purchased by BAE Systems in June 2009.

1.1 Spectral Imaging

By using multiple spectral bands, the reflectance of objects can be better interrogated, thereby allowing discrimination of objects otherwise difficult to detect in normal reflected light. Multi-spectral and hyperspectral imaging are extremely powerful tools that have been utilised extensively for a wide range of applications. There are literally hundreds of publications on the topic every year and many proprietary, secret and open source techniques that are available by which to sort the data. Recent papers have provided quantitative measures of algal distribution and composition in the Potomac River[2], inland water quality[3] and vegetative species and infestations[4, 5]. Spectral analysis has been able to view through water and discriminate between channels and mud flats otherwise not observable to the human eye in rivers and shallow waters. Several commercial companies in the USA now offer multi-spectral analysis of crops to optimise productivity through the management of water and fertilizers as well as to identify 'infestations' which might be harmful to the crops. They have also been used for mineral exploration and for the tracking of water based contaminants from weeping domestic septic systems or agricultural run-off[6]. These cover but a few of the capabilities of this technique but highlight the specificity with which the technique can be employed.

Figure 1. Airborne mid-infrared image of a portion of an agricultural research farm: 1) citrus trees, 2) dry fallow land, 3) irrigated land, and 4) water body[10].

Most conventional airborne multispectral imaging techniques are performed at relatively high altitudes including satellites. Although very high quality optics are employed the ultimate resolution that's achieved can be relatively low (10s of metres for satellites and sub metre for lower altitude manned aircraft). Also the large viewing distance often results in the need for significant atmospheric corrections to be carried out that can be time consuming and expensive. Lower altitude aircraft would provide a higher resolution capability for many of these sensors and would avoid the need for atmospheric corrections.

Infra-red (IR) imagery in the midwave IR (MWIR – typically 1·3μm to 2·5μm) is also sensitive to water absorption and has been used to map agricultural regions and provide information for differentiating vegetation, soil, and water and for identifying management practices such as irrigation[7, 8, 9].

Airborne imagery provides useful information particularly using filtered light such as observed in Fig. 1, which shows a narrow band filtered image (1·635μm to 1·645μm) clearly identifying regions of irrigation fallow and treed lands[10].

1.2 Radio frequency (RF) sensing

The use of radio waves reflected from objects of interest, has been used since the Second World War. These technologies are currently highly developed and are used for a wide range of applications ranging from accurately tracking fast-moving objects to 3-dimensional (3D) imaging reconstruction. Synthetic Aperture Radar (SAR) compares images (reflections) taken from two different positions in space thereby allowing the reconstruction of the view from two vantage points providing details of the spatial scale. Through the comparison between images taken over a longer duration – usually days, weeks or years, the observer is able to discriminate between changes that have taken place between the data capture, known as 'change detection'. This technique has been used successfully to observe buried mines using synthetic aperture radar with change detection.

In the area of remote sensing for exploration and mining, RF techniques are commonly used to partially penetrate the ground to provide information as to the rock type, sediment layers, density and conductivity. The electro-magnetic (EM) gradiometer measures the gradient of the EM field and is commonly used today by companies such as Fugro to explore regions of interest for mineral resources. Many of these techniques are now being transferred onto small UAVs.

As mentioned earlier in the introduction, many sensors are commercially available and operational today, but are not capable of being flown on small Tier I and Tier II size of UAVs due to weight and size limitations. This paper summarises some of the sensors being investigated and flown on the Silver Fox and Manta UAVs and describes some of the applications for which they are being investigated.

2.0 RECENT UAV DEVELOPMENTS

2.1 Infrared

Several small microbolometer IR video cameras are available on the market today. These cameras observe the 'thermal' range (typically 8μm to 12μm) and are able to discriminate between differences in temperatures. They can readily discriminate between a person's or animal's body heat and the background temperature and are often used to detect and track living things. When combined with imagery in the visible range (0·3μm to 0·75μm) they can be used very effectively to discriminate between targets of interest. The system however needs to be selected for the desired task and the typical lower resolution imagery (typically 240 × 320 pixels) can provide limited information on the 'targets' being observed. Figure 2 shows a comparison between a low and higher resolution IR video camera flown simultaneously (240 × 320 versus 480 × 640 respectively) and their ability to discriminate between details around the target.

This comparison compared a FLIR camera with a 50mm lens with a camera manufactured by I2Tech to observe roughly the same field of view. Both cameras were mounted into the Silver Fox payload as shown in Fig. 3.

Figure 2. IR video frames collected simultaneously at 1,000ft above ground level (AGL). These images clearly identify improved detail (including tyre tracks) at the higher resolution.

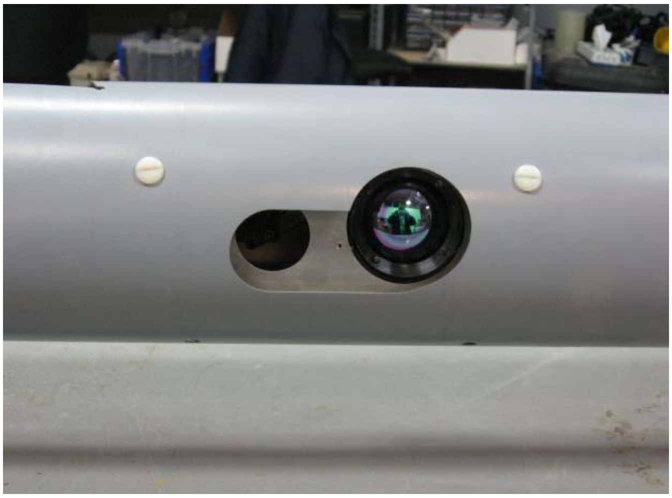

Figure 3. Camera mounts on the B4 Silver Fox UAV for the low and higher resolution IR video cameras.

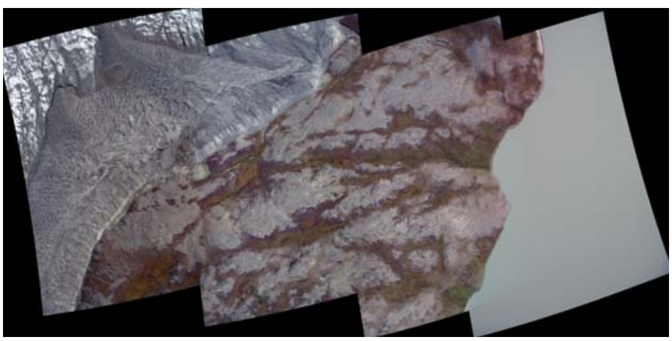

Figure 4. High resolution (4Mpixel) image mosaic from Greenland showing the transition off the ice shelf (left) to the sea (right).

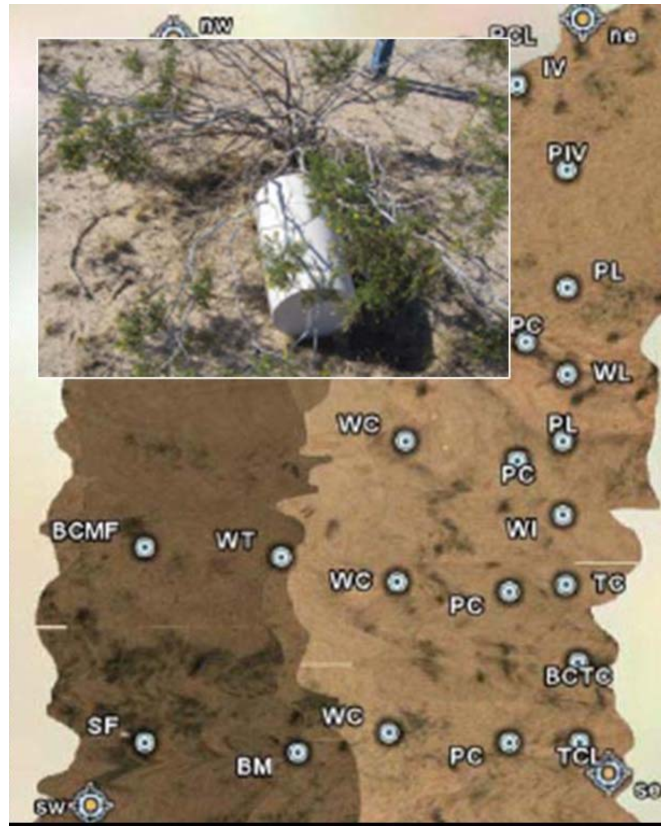

Figure 5. Georectified MAIS hyperspectral data collected in 2006 from the Manta UAV of 'simulated mines' laid out in the desert in El Centro CA. Some of the objects were buried, some camouflaged and some were partially hidden from view (insert).

2.2 High resolution visible imagery

Over the past two years the resolution of both video and still cameras available to the public has increased significantly. The quality of these systems for the most part is extremely high and with the exception of certain additional features that would be beneficial, such as hard drive data storage or the need to trigger remotely, these systems are well priced and very capable. When triggered through the autopilot, the meta-data can be collected for each of these images, allowing georectification and the generation of high resolution mosaic images such as that shown in Fig. 4. Images up to approximately 12M pixels in resolution are commonly available at very reasonable prices.

2.3 Hyperspectral imagery (HSI)

Recently a small number of manufacturers (Galileo Avionica, BAE Systems, Bodkin Design and Engineering, Headwall Photonics, NovaSol and Resonon) have started fabricating and testing hyper-spectral sensors for UAVs[12]. The last four of these manufacturers make systems primarily in the visible (0·3μm to 1·0μm) and NIR (0·9μm to 1·7μm that are small enough to be mounted onto Tier I and II type UAVs. Resonon, Bozeman, USA produce the Manta Airborne Imaging System (MAIS) that was developed for the Manta UAV and has successfully completed many data collection acquisitions over both land and water. The system weighs 5·5lbs has up to 240 spectral channels and operates between up to 200Hz. The system is a push broom imager with nearly a 10 degree field-of-view and at 1,000ft above ground level (AGL) gives a pixel size of approximately 16cm (6"). During training with Navy Special Clearance Team One (NSCT1) at El Centro Proving Grounds CA a number of 'targets' were laid out on the ground to simulate mines. The targets were plastic or metallic painted (camouflage) objects, and unexploded ordnance simulants, some buried and some obscured from view under bushes as shown in Fig. 5. Several passes over the target area were made in the Manta UAV at 1,000ft AGL and the data was collected, georectified and post-processed using the commercially available algorithm spectral angle mapper (SAM) to identify approximately 70% of the targets as shown in Fig. 5.

Parameters for SAM were based on parameters measured from some of the easily detected targets. Of the targets that were not detected however, some of them were very difficult to observe, buried under deep layers of brush or very small (small bombs stuck vertically into the soil, much smaller than the system resolution. Of the targets that were 'reasonable' everything was identified except some of the camouflage painted objects. The ORASIS program was also run by the US Navy on the same data set and did significantly better identifying the camouflage painted objects and many of the buried and covered targets although the actual data was not made available for this paper. The initial version of the 'push broom' detector required manual settings for the gain and optical focus.

Under a current program this spectrometer has been further miniaturised to be inserted and operated from the Silver Fox UAV. The spectrometer weighs 2·4lb and the on-board computer and data storage weighs approximately 2·5lb. Both components have been redesigned axially to fit within the 4·8" diameter of the UAV as shown in Fig. 6. The current spectrometer characteristics are improved over that of the MAIS and the system is fully autonomous and is operated through the autopilot.

Figure 6. Hyperspectral imager produced by Resonon for the Silver Fox UAV.

2.4 Other imagery devices

Under a US Army program a low light video camera was integrated into the Silver Fox UAV for night or low light conditions (dusk or dawn). The camera is made by a US manufacturer and is based on an electron multiplier (EM) CCD.

Under a NAVAIR funded program an imaging device called 'synthetic field of view' (SFOV) device was mounted onto a small UAV to provide a persistent early warning capability for facilities under threat from ballistic projectiles such as mortars and rockets. The device identifies and tracks the projectile long enough for it to determine the flight path and time of impact.

A NIR hyperspectral imaging system (viewing from 1·0μm to 1·7μm uncooled and 1·0μm to 2·5μm under cooled conditions) similar to the MAIS has been developed by Resonon for the Silver Fox UAV. It is expected that the system will have both military and non-military use in the assessment and management of crops and terrain mapping.

2.5 Electro-Magnetic Gradiometer (EMG)

In 2004 the US Navy through the Office of Naval Research (ONR) and Naval Air Systems Command (NAVAIR) funded the development of an airborne EMG for the detection of command wires used in the detonation of Improvised Explosive Devices (IEDs). Originally a hand held EMG produced by Stolar Research Corporation for the mining industry, the gradiometer was modified for use from the Silver Fox UAV. The technology is based on two components; a transmitted 'primary' wave that stimulates all conductors being illuminated and a gradiometer antenna that receives the reradiated 'secondary' field generated from the flow of current in the conductor that was generated by the initial "primary" field. Two configurations have been developed and tested.

In the first configuration the transmitting antenna was mounted onto the Silver Fox UAV while the gradiometer (receiving antenna) was towed approximately 70 feet behind the UAV as shown in Fig. 7. This configuration allows the UAV to operate remotely over a large distance. In order to allow this configuration to be towed the gradiometer was constructed using an air core in order to minimise the EMG weight.

In the second configuration the gradiometer (receiving antenna) is mounted on the Silver Fox UAV as shown in Fig. 8 and the transmitter is usually operated remotely from the ground. Both of these configurations have been tested successfully at altitudes up to approximately 250 feet AGL.

The gradiometer technology has been used to identify the position of surface command wires as well as tunnels buried deep below the surface[13]. The EMG detects the 'stimulated' field from the 'target' conductor and measures the field gradient between the two antennae (positioned at either end of the gradiometer) shown in Fig. 8. The two antenna are opposed in their electrical configuration giving rise

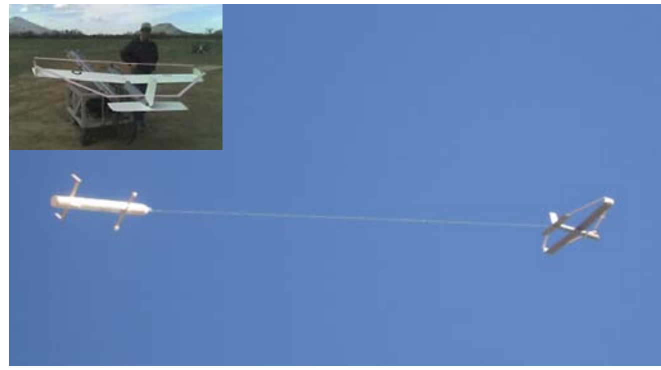

Figure 7. Configuration One – Airborne gradiometer with the Silver Fox mounted transmitter and a towed, air core gradiometer. Insert shows transmitter.

Figure 8. Configuration Two – Silver Fox mounted ferrite core gradiometer used in conjunction with a ground based or separate transmitter.

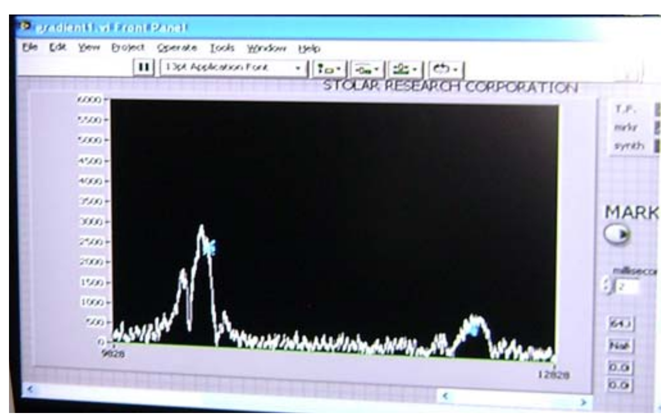

Figure 9. Typical EMG signal response when the gradiometer passes directly over an IED detonation wire or underground tunnel.

to an increase in the cumulative current as the gradiometer comes close to a conductor, but dropping close to zero when directly overhead the conductor. This gives rise to a characteristic M shaped response for the cumulative field as illustrated from the white trace in Fig. 9, when the sensor detects a conductor. The peak-to-peak distance in the gradient signature is also a characteristic of the

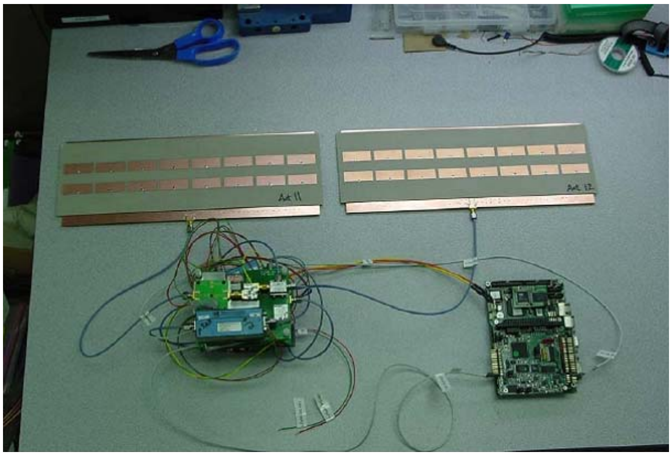

Figure 10. Antenna, RF stack and data storage device produced by BYU, operated by CU, flown by ACR.

conductor distance from the gradiometer. In the raw signal data the signal phase (green) and level of synchronisation (red) are also measured. Under an existing programme being funded by the US Navy (NAVAIR) and the US Department of Homeland Security (DHS) this technology is being evaluated for the detection of buried tunnels along the border. Signal detection is being automated through the use of detection algorithms and linked to the user interface (iGCS).

2.6 Magnetometer

In support of the US Defense Advanced Research Project Agency (DARPA) funded Low Altitude Airborne Sensor System (LAASS) a Quasar magnetometer was integrated into the Manta UAV and used in the detection of underground facilities. The aircraft initially produced a high background noise but following modification and shielding, the noise was reduced considerably allowing the magnetometer to be used effectively.

2.7 Synthetic Aperture Radar (SAR)

In May of 2005 Brigham Young University (David Young at BYU), Utah, built a lightweight microSAR unit under contract from the University of Colorado. The antenna, RF stack and data storage weighs less than 2lbs and is shown laid out in Fig. 10.

Data is written directly to the CompactFlash Card at a rate of 0·67MB per second, this gives about 25 minutes of collection time for a 1GB disk. Power requirements are 1·1 to 1·5A at 18VDC. The radar has eight range/velocity settings that can be changed manually. These range from a slow velocity of 18m/s which at a height of approximately 344m would provide a swath 1,024m wide, to a maximum velocity of 385ms^{-1} which at an altitude of 16m would provide a swath of just 9m. The radar works at a frequency between 5,520MHz and 5,600MHz. The SARs has been integrated onto the Silver Fox UAV and flown both in the United States and in Greenland.

3.0 CASE STUDIES

There have been a number of Silver Fox and Manta UAVs missions where specific data sets were collected in addition to the standard low resolution electro-optical (EO) and infra-red (IR) video. While the EO and IR video has been transmitted in real time to the integrated ground control station (iGCS), these additional sensors have logged data on-board and processed post flight. The following summarises data that was collected during:

1. Littoral surveillance mission with the US Navy
2. Tunnel detection demonstration funded by NAVAIR
3. Airborne pollution data collected in the Maldives during an expedition funded by National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), Scripps Institute of Oceanography (SIO) and the G.Unger Vetlesen Foundation.
4. Greenland expedition funded by Cooperative Institute for Research in Environmental Sciences (CIRES) and NOAA

3.1 Hyperspectral littoral surveillance

Between 8 and 10 May 2006 UAVs took part in a military exercise called Howler which was staged to demonstrate the collaborative use of underwater unmanned vehicles (UUVs) and UAVs from an offshore vessel for the purpose of littoral mine clearance. Standard mine clearance procedures for Naval Special Clearance Team One (NSCT1) had in the past used the combined efforts of divers and mammals to identify and clear mines, but this new direction was steered towards engaging autonomous vehicles that could carry out this task. During the exercise the Silver Fox and Manta UAVs worked together and shared data through a common operator interface with other autonomous vehicles.

During the exercise the hyperspectral imaging device mounted in the Manta UAV was launched from the top deck of the US Navy's 'Stiletto' experimental vessel and flown over predetermined regions of the near shore littoral zone. For the purpose of this exercise the levels of gain and focus of the camera were set manually but a revised version is currently available that allows these variables to be changed in real-time through an interface with the autopilot. The data was stored on the UAV and post processed using ORASIS. Figure 11 shows a number of georectified sweeps that were carried out over the region of interest (identified in the image by the acronyms LFOS, RFOS, RF and LF) superimposed over a Google land image. The surf zone is shown on the right of the image just out of view. The water was not clear and varied from approximately 5m to 20m in depth. Following analysis, the processed data successfully identified the position of submerged objects as shown in Fig. 11. These objects were approximately six pixels in diameter (approximately 1m with a 16cm pixel size) and resembled spherical mines floating in the water column. The processed data also allowed the

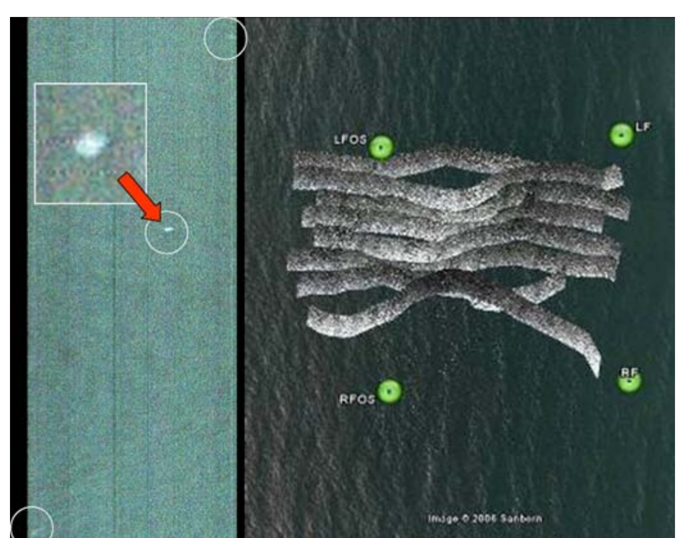

Figure 11. Georectified hyperspectral sensor sweeps over a littoral zone showing processed data that allowed identification of spherical mine-like objects.

sea bottom to be seen in places and the position of kelp beds to be determined. The reflection of the sun off the water was significant and appeared to saturate the image contrast but this effect was successfully removed during processing.

3.2 EMG tunnel detection

The first successful demonstration of the UAV mounted EMG was carried out during a short flight in December 2004 under a US Navy funded Small Business Innovative Research (SBIR) program. These first successful flights led to additional support through a Phase II SBIR from NAVAIR that allowed significant improvements to the technology and detection technique to be undertaken. Seven more development spirals were flown starting in March 2005 and system improvements continued through 2005 into 2006 that enabled a tunnel detection demonstration in August 2006. During the tunnel detection demonstration the gradiometer was mounted directly onto the UAV and a ground-based transmitter was used to stimulate the tunnel. Several flights over the area of interest showed that the detection technology could repeatedly locate the position of a known smuggler's tunnel between the United States and Mexico in Douglas, AZ, setting another UAV industry milestone[13].

For the purpose of the demonstration the UAV was flown along the border at a height of approximately 100ft AGL and approximately 40knts. The tunnel was approximately 40ft below the surface of the road. The technology has been further improved and continues to be funded by NAVAIR and DHS with the goal of developing a fielded capability for border surveillance and tunnel detection.

3.3 Maldives autonomous UAV campaign

As discussed previously[14], in March 2006 a UAV campaign was launched from the Maldives by Dr V. Ramanathan from the Scripps Institute of Oceanography (SIO), to study how human beings are polluting the atmosphere and their impact on the climate, including global warming[15]. During this extensive campaign data was collected which better characterised the particles in pollution and clouds while reflected solar radiation was simultaneously measured. The science mission was a great success[16] logging over 120 flight hours that included 55 takeoffs and 18 science missions and collected data on pollution and dust transported from S. Asia, Arabian and SW Asian deserts and their impacts on global dimming at the sea surface, the energy absorbed in the atmosphere and cloud properties. The specific suite of sensors[17-20] that was selected for this mission were identified and configured by the SIO near San Diego CA. Some were commercially available sensors and some were developed and configured by SIO specifically for the Manta. The Maldives Autonomous UAV Campaign (MAC) was unique in that it required the movement of three UAVs at different altitudes to be synchronised with respect to flying over the same ground position. The target footprint was typically within 60ft width and within a 100ft distance in the direction of travel. The aircraft at the different altitudes contained different combinations of sensors depending on the scientific requirement. A complete list of sensors is shown in Table 1.

The MAC campaign was the culmination of over 12 months of discussions, designs and testing and involved a combined approach to reduce weight and pair suitable sensors for each of the three aircraft. For instance, the cloud condensation nuclei counter (CCN) was a fundamental sensor for providing the link between cloud microphysics and the physical and chemical properties of the aerosol. The commercial instrument weighed 10kg (5kg for the chamber and 5kg for the electronics) and was redesigned into a compact, automated instrument that weighed less than 2kg and autonomously measure cloud condensation nuclei counter (CCN) concentrations at 1Hz at a single supersaturation between 0·13% and 2%. This evaluation was given to all the sensors under consideration.

There were a number of reasons why the Manta UAV was selected for these experiments. It has a large payload volume (0·45ft^3, (0·013m^3)) that is readily accessible and can accommodate a number of sensors. It is also a 'pusher' meaning that the sensors can sample 'clean' air uncontaminated with exhaust gases. Figure 12, shows the type of consideration that was given to the sensor mounting, cabling and physical placement within the available payload volume and on the airframe.

Selection of specific sensors for each of the three platforms was also considered with respect to the data, altitude and mission durations for each of the vehicles. A summary of these instrumented UAVs is shown in Table 2. The above cloud UAV flew at between 10,000 and 12,000ft, the in-cloud UAV approximately 3,500ft and was directed manually to the specific region of cloud by the on-board video camera, and the below-cloud UAV at between 1,000 and 2,000ft.

Table 1
Payload description and specifications for aerosol, cloud and radiation experiments for MAC

Instrument	Weight (kg)	Power (W)
1. Condensation particle counter	0·87	2·3
2. Optical particle counter	0·27	5·4
3. Pyranometer	0·17	<0·2
4. Temp & relative humidity	0·05	<0·1
5. Data acquisition system	0·15	<0·2
6. Aerosol inlet	0·21	NA
7. Digital video camera	0·1	0·5
8. Cloud cond. nucleus counter	<2·0	25·0
9. Grating spectrometer	0·3	<1·0
10. Aethalometer	0·85	~5·0
11. Cloud droplet probe	1·42	14·0
12. Narrowband radiometer	0·29	<0·2

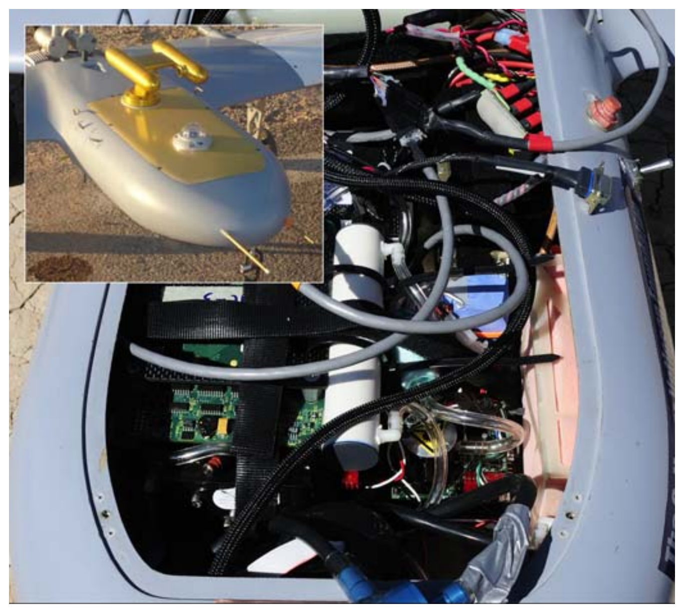

Figure 12. The Manta payload volume showing sensor instrument installation. Insert shows the cloud droplet probe and pyranometer mounted on top.

3.4 Greenland expedition August 2007

Greenland has long been identified as having an important influence on global climate and as being one of the thermometers for climate change. It has recently been suggested that the ice cap at Swiss Camp is moving towards the sea at an astounding rate of 20 inches/day[21].

Table 2
Summary of the instruments flown on each of the three Manta UAVs with total weights and power

UAV	Payload(kg) (W)	Instrumentation
Above-cloud	2.7 14	Aethalometer Optical particle counter Up and down pyranometers Condensation particle counter
In-cloud	3.7 27	Cloud droplet probe Condensation particle counter Digital video camera Optical particle counter
Below-cloud	4.0 40	Aethalometer Optical particle counter Up and down pyranometers Condensation particle counter Cloud cond. nuclei counter

Other measurements have suggested that the melting of the Greenland Ice Sheet alone could raise sea level by 21ft. The large amount of freshwater changes density currents regulating the Gulf Stream, disrupting the movement of the North Atlantic waters that regulate weather in Europe. With climate change, increased surface snow and ice melt provides additional melt water to lubricate the bottom of the ice sheet and increases the ice flow velocity toward the coast according to Konrad Steffen[21] who has been studying the ice cap for over thirty years. Measuring the melt pools such as the one shown in Fig. 13, and being able to better calculate the volume of melt water on the ice sheet would significantly aid the ability to model the potential impacts of the melting ice sheet.

Figure 13. A typical ice melt pool found on the Greenland Ice Cap, that was analysed by HSI.

Three primary sensors were evaluated in Greenland – high resolution imagery, HSI and SAR. Initial indications were that hyperspectral imagery could be used to calculate the depth of water within the melt pools and researchers at NOAA and CIRES proposed using the hyperspectral imager on a UAV to collect preliminary data over the ice sheet during August 2007.

High resolution imagery and SARs were selected as additional sensor payloads that could provide important information about the local environment and about the sea ice, which was another important indicator for climate change.

3.4.1 High resolution imagery

A commercial high resolution camera with a resolution of approximately 4Mpixel was mounted into the Silver Fox payload and triggered through the autopilot. Selected pictures (1,660 by 4,260 resolution) were taken and stored on a memory card associated with the camera. These pictures were post-processed following the mission and the associated autopilot telemetry used to georectify the images. The images were also built into high resolution mosaic maps as shown in Fig. 14, using commercially available software products showing a flight transition from the coast (left) up to the ice cap (right),

3.4.2 Hyperspectral imagery

One objective of the Greenland mission was to gather preliminary hyperspectral data to assist in the development of algorithms that would use the imager to remotely measure the depth of supraglacial melt pools. The depth of the melt pools is important in quantifying the melt occurring the Greenland Ice Sheet in order to advance the models that are used for predicting the melting of the massive ice sheet as well as the global implications of the observed acceleration in melting.

The miniaturised hyperspectral imager (HSI) collected 52 channels in the 400-800nm range with data rates at 12bits and 135fps. Though initial plans were to fly the HSI in the Manta UAS, a technical issue and closing window of opportunity forced the supraglacial melt pools to be remotely measured using from a manned aircraft. The flight on 24 August 2007 collected data at 500-1,000ft AGL and at 80-85kt. Data was logged inside the HSI system and post-processed. Preliminary analysis of data from one of the melt pools is shown in Fig. 15.

This data indicates a good potential for the remote sensor to measure water depth and therefore melt-pool volume. Further analyses is being conducted by scientists at the University of Colorado and processing of the several sets of hyperspectral data is as yet incomplete. Fig. 15 shows a hyperspectral scan from the edge of the ice sheet out into one of the melt pools where the increase in water depth can be seen from a deepening on the blue colour (from top to bottom). The insert shows a graph of the spectral response for three individual colours (red, green and blue) for the vertical profile show in the image as a white vertical line. The graph shows that there is an change in the absorption coefficients between green and blue light with water depth, from which the actual depth will be determined.

Figure 14. High resolution mosaic image from Greenland using the Silver Fox UAV, built up from a series of high resolution frames.

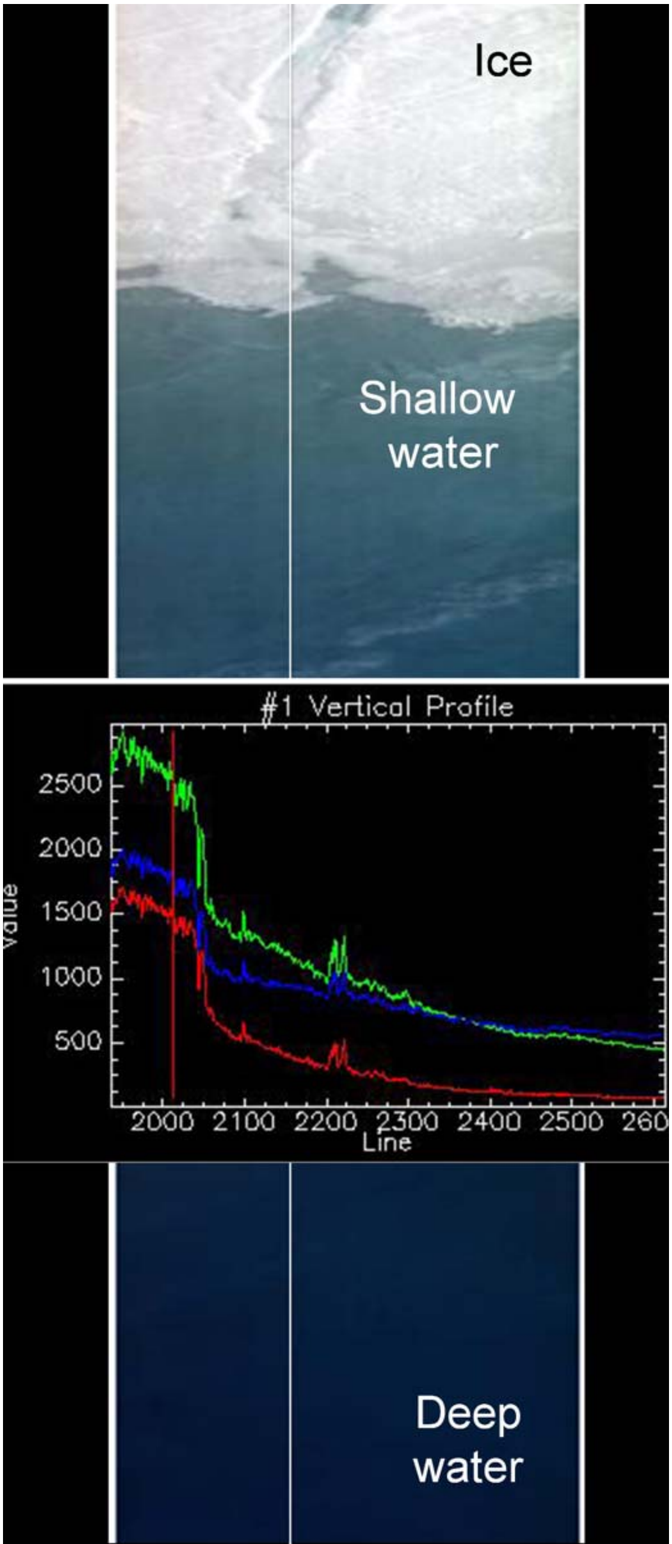

Figure 15. Data from the miniature hyperspectral imager showing the transition from the ice shelf (top) into one of the melt pools (deeper at the bottom). The spectral response for the vertical profile shows differential absorption between the green and blue light with water depth.

3.4.3 Synthetic aperture radar (SAR)

Synthetic aperture radar is often used to complement optical imaging capabilities as SAR can acquire imagery in inclement weather (through cloud cover) and at night. Working jointly with Dr James Maslanik at the University of Colorado, who was instrumental in the development of the MicroSAR, the system was mounted onto an 'electric' Silver Fox as shown in Fig. 16 during the Greenland mission in August 2007.

Figure 16. The MicroSAR mounted on to the electric Silver Fox UAV prior to launch in Greenland.

In preparation for the Greenland project, the Micro-SAR stack containing the RF boards and data acquisition module (PC104 A/D and single board computer with two FlashDisks) was separated into two stacks to fit inside of the Electric Silver Fox fuselage. Mounts were constructed to hold the two RF flat panel antennas at a 60°degree angle on the side of the fuselage as shown in Fig. 16. During these flights an additional digital camera was also flown, positioned under the wing between the two antennas.

A mission was conducted in the river valley to the northwest of Kangerlassuaq International Airport. The mission consisted of three passes in the same valley and the flight plan of each pass was altered slightly to fully cover the main features of the valley. The launch and recovery site was on a sandy riverbank with the direction of the flight heading approximately southeast towards the airport. The river bottom consisted of a flowing river and glacial till with vegetated hillsides on either side creating the river valley. The temperature was approximately 50°F, with wind <5kt and overcast skies.

Data was recorded throughout the duration of the flight on the FlashDisk card and backed-up by downloading to a laptop computer upon landing. The data was evaluated by scientists at the University of Colorado who plan to use the MicroSAR in the future for sea ice monitoring and research in the Arctic.

4.0 CONCLUDING REMARKS

Over the past few years we have seen a significant rise in both the miniaturisation and capability of small sensors. This has been driven to some extent by the personal electronics industry which is moving to make small hand held devices such as high definition cameras and data storage devices, ever more powerful, and the desire to link 'gadgets' together for 'designer' devices that perform several tasks, but is also getting traction from the small UAV market which are projected to grow substantially over the next few years. With more capable sensors being developed for the UAV market and far greater data collection rates being projected there will be a need for an on-board processing capability, able to interact with the autopilot and sensors, and capable of performing predetermined tasks based on the requirements that are desired. In an effort to conserve weight and space while maintaining an aerodynamic exterior more thought will be given to sensor integration into the airframe. Radiating and receiving surfaces will become conformal where possible and the overall weight, power and space budget will be better managed.

When a mature UAV is integrated with a mature sensor system, the problems that are encountered assuming suitable size, weight and environmental compatibility are generally small and can be readily overcome following a structured integration and test flight procedure to provide a combined platform capable of collecting data in a reliable manner. When the sensor is still 'in flux', which could refer to continued development of its capabilities or reconfiguring to fit within the weight and size restriction, the integration and operation can be far more challenging and significantly increase the risk for reliable data collection. This situation is similar if the UAV is still under development or if large modifications are being adopted in order to carry the sensor. Typically this integration stage is not considered early enough or at worst, is overlooked till the data is actually required.

Present configurations discussed in this paper have covered the integration and operation of spectral, radio frequency, and aerosol sensors which have been evaluated during various UAV exercises/missions.

For spectral imagery there are a number of commercially available programs that can be used to process and manipulate the data. One of the most sophisticated spectral sensors available today in a small format is the hyperspectral sensor which relies heavily on both data capture and data interpretation for which many algorithms presently exist. Multispectral imaging, where three or four spectral bands are compared, also provides significantly better discrimination than is available from simple EO or IR imagery.

Radio frequency sensors such as the EMG have finally been integrated into small UAV platforms and successfully used to determine the position of IED detonation wires and underground tunnels. Although still in development, the signal processing capability has progressed quickly and it is likely that this area will become a significant player for natural resource exploration and in future electronic warfare applications.

Aerosol sensors have been miniaturised significantly and several particle size analysers, and associated pollution measuring sensors which might include the capture of chemical and biological agents, are presently available. Thorough planning and flight testing of these sensors prior to their fielded use goes a long way in reducing technical problems and ensuring scientifically valuable data can be collected.

Above all, it is important to provide a successful flight for the data collection no matter how small or simple that data appears to be. This is still significantly more valuable than a failed flight. There are several other, more capable sensors that will be available in the coming years that will operate from these small tactical size UAV platforms. It is expected that they will be not only adopted for military application but will find a wide range of commercial uses.

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REFERENCES

1. GAIL, W.B. Remote sensing in the coming decade: the vision and the reality, *J of Applied Remote Sensing*, 19 January 2007, **1,** 012505.
2. SZEKIELDA, K.H., MARMORINO, G.O, MANESS, S.J, DONATO, T, BOWLES, J.H, MILLER, W.D and RHEA, W.J. Airborne hyperspectral imaging of cyanobacteria accumulations in the Potomac River, *J of Applied Remote Sensing*, 26 October 2007, **1**, 013544.
3. SUGUMARAN, R., GREEN, N. and CLAYTON, M. Monitoring intra-annual water quality variations using airborne hyperspectral remote sensing data in Iowa lakes, *J of Applied Remote Sensing*, 7 September 2007, **1**, 013533.
4. YANG, C., and EVERITT, J.H. Evaluating airborne hyperspectral imagery for mapping waterhyacinth infestations, *J of Applied Remote Sensing*, 15 November 2007, **1**, 013546.
5. CHENG, Y-B, TOM, E. and USTIN, S.L. Mapping an invasive species, kudzu (Pueraria montana), using hyperspectral imagery in western Georgia, *J of Applied Remote Sensing*, 23 May 2007, **1**, 013514.
6. BLANCO, A. (US Environmental Protection Agency) Private Communications, May 2006.
7. SKIDMORE, E.L, DICKERSON, J.D. and SHIMMELPFENNIG, H. Evaluating surface-soil water content by measuring reflectance, 1975, Soil Sci Soc Am Proc, **39**, pp 238-242.
8. TUCKER, C.J. Remote sensing of leaf water content in the near infrared, 1980, *Rem Sens Environ* **10**, pp 23-32.
9. LOBELL, D.H. and ASNER, G.P. Moisture effects on soil reflectance, 2002, *Soil Sci Soc Am*, **66**, pp 722-727.
10. FLETCHER, R.S. and BARTELS, D.W. Mid-infrared digital electronic camera system for assessing natural resources, *J of Applied Remote Sensing*, 15 October 2007, **1**, 013542.
11. NASRABADI, N., TATES, M., and KWON, H. Change detection methods for identification of mines in synthetic aperture radar imagery, *J of Applied Remote Sensing*, 7 August 2007, **1**, 013525.
12. DONALDSON, P. Good with Colours, *Unmanned Vehicles,* October 2007, pp 15 – 19.
13. Eye in the sky uses radio gradiometer to detect IEDs, underground tunnels http://www.dcmilitary.com/stories/013108/tester_27998.shtml
14. PATTERSON, M.C.L. and BRESCIA, A. Requirements driven UAV development, 22nd Bristol UAV Systems Conf Proc, April 2007.
15. RAMANATHAN, V. Global dimming and its masking effect on global warming, Paper A23D-01, Pres American Geophysical Union Fall Meeting, San Francisco, CA, USA, 11–15 December 2006.
16. RAMANATHAN, V., RAMANA, M., ROBERTS, G., KIM, D., CORRIGAN, C., CHUNG, C. and WINKER, D. Warming trends in Asia amplified by brown cloud solar absorption, *Nature,* 2 August 2007, **448**, pp 575 - 578.
17. ROBERTS, G., RAMANATHAN, V., CORRIGAN, C., RAMANA, M., and NGUYEN, N. Simultaneous observations of aerosols, clouds, and radiometric fluxes using light weight autonomous UAVs, Paper A33B-1007, Pres. American Geophysical Union Fall Meeting, San Francisco, CA, USA, 11–15 December 2006.
18. RAMANATHAN, V., ROBERTS, G., RAMANA, M., CORRIGAN, C. and NGUYEN, N. Simultaneous measurements of direct, semi-direct and indirect aerosol forcing with stacked autonomous UAVs: a new observing platform paper A21G-08, Pres. American Geophysical Union Fall Meeting, San Francisco, CA, USA, 11 – 15 December 2006.
19. CORRIGAN, C., RAMANATHAN, V., RAMANA, M., KIM, D. and ROBERTS, G. Chasing black carbon using autonomous unmanned aerial vehicles, Paper A43A-0106, Pres. American Geophysical Union Fall Meeting, San Francisco, CA, USA, 11–15 December 2006.
20. RAMANA, M., RAMANATHAN, V., CORRIGAN, C., KIM, D., ROBERTS, G. and NGUYEN, N. Direct measurements of albedo and solar absorption over the Northern Indian Ocean with a new observing system of stacked multiple UAVs. Paper A13B-0921, Pres American Geophysical Union Fall Meeting, San Francisco, CA, USA, 11 – 15 December 2006.
21. http://www.popsci.com/popsci/science/6661e3568cc83110 vgnvcm1000004eecbccdrcrd.html
22. http://www.cs.ubc.ca/~mbrown/autostitch/autostitch.html