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European networks observing the atmospheric boundary layer: Overview, access and impacts

Chapter: Un-crewed Aircraft Systems (UAS) profiling

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Authors	Document preparation conducted by A. Hirsikko Authors: Anne Hirsikko, Debbie O'Sullivan, Olivier Traulle, Damyan Barantiev, Gregoire Cayes

COST Association AISBL | Avenue Louise 149 | 1050 Brussels, Belgium
T +32 (0)2 533 3800 | F +32 (0)2 533 3890 | office@cost.eu | www.cost.eu

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Introduction

This report provides a short overview of operating UAS, including introduction to sensor, products, manufacturers, instrument types, instrument setup and required regular maintance on site, calibration, measurement configuration, data formats, QA/QC methods and retrieval methods.

Part 1 General overview

Introduction and products

Un-crewed Aircraft Systems (UAS) include both unmanned fixed wing planes and multi-rotor copters. Measurements are made with on-board in-situ sensors. The observations can include meteorological variables, gas, aerosol particle & cloud properties, and state of surface depending on use case. Meteorological services are typically interested in meteorological variables in the vertical profile of atmosphere. The accuracy of wind, temperature, and humidity measurements obtained with UAS is now comparable to that of calibrated tower and radiosonde measurements[1],[2]. There is also interest in UAS for profiling as they can be automated, and operated more frequently than radiosoundings, and which has the potential for more data at a reduced cost. In addition, UAS are attractive from an environmental perspective, as they are re-usable and have the potential to reduce the number of disposable radiosondes used.

Known challenges with the measurement technique include weather resilience [3], safety and regulations, flying duration, maximum altitude and range, and the continued need for a remote pilot. Benefits of UAS include: additional profile data available to weather forecasters to supplement radiosounding information; greater temporal and spatial sampling in data sparse regions, automation, reusable and adaptable systems[4], reduced costs[5], and the ability to provide observations in hazardous environments (for example volcanic plumes) [6].

Manufacturers/Instrument types

There are now hundreds of manufacturers of small UAS for recreation and industry, too many to list here (for example see: The Top 100 Drone Companies to Watch in 2021, UAV Coach [7]). In contrast there are not many manufacturers who make or fit meteorological instruments to UAS. Then few that we are currently aware of that do are: Blackswift and Flyht in the USA, Meteomatics and Rumble Tools in Europe (Table 1). However, there are a number of small lightweight general purpose and radiosonde instruments which are being tested on UAS. These are summarised in Table 2, below.

Table 1: Overview of manufacturers of UAS for meteorological applications (information collected from manufacturers' web pages).

Product	Technical info		Flying info		Measurements/ sensors		Comments
Mete-odrone SSE (Mete-omatics)	Number of engines	6	Max. climb rate [ms^{-1}]	10	Temperature	yes	Available formats: WMO TEMP (FM35), WMO TEMP MOBILE (FM38), PILOT (FM32), WMO PI-LOT MOBILE (FM34), WMO BUFR, CSV
	Payload Weight [kg]		Max. wind en-dured [ms^{-1}]	27	Wind speed/comp.	Yes	
	Takeoff Weight[kg]	1.1	Max. flight alt. [m]	1000	Wind direction	yes	
	Dimensions [cm]	40 x 40	Flight duration [min]	12	Humidity/Dew point	yes	
	Waterproof	no	Sample rate [ms]	250	Air pressure	yes	
	Propeller Heating	no	Flight plans	yes	$PM_{2.5}$, PM_{10}	no	

	Rescue system	no	Radio Frequency	?	SO_2,CH_4,H_2S,CO_2, O_3	no	
	Manual control	?	Telemetry Frequency	?	Radioactivity	no	
	Autonomous control	yes	-		MultiSp. camera	no	
	Ground station	yes	-		Infrared camera	no	
Meteodrone MM-670 ML (Meteomatics)	Number of engines	6	Max. climb rate [ms^{-1}]	10	Temperature	yes	Available formats: WMO TEMP (FM35), WMO TEMP MOBILE (FM38), PILOT (FM32), WMO PILOT MOBILE (FM34), WMO BUFR, CSV
	Payload Weight [kg]		Max. wind endured [ms^{-1}]	25	Wind speed/comp.	yes	
	Takeoff Weight[kg]	5.0	Max. flight alt. [m]	6000	Wind direction	yes	
	Dimensions [cm]	70 x 70	Flight duration [min]	30	Humidity/Dew point	yes	
	Waterproof	yes	Sample rate [ms]	250	Air pressure	yes	
	Propeller Heating	yes	Flight plans	yes	$PM_{2.5}$, PM_{10}	yes	
	Rescue system	yes	Radio Frequency	?	SO_2,CH_4,H_2S,CO_2, O_3	yes	
	Manual control	?	Telemetry Frequency	?	Radioactivity	yes	
	Autonomous control	yes	-		Multispectral cam.	no	
	Ground station	yes	-		Infrared camera	no	
Black Swift E2 (Black Swift Technologies)	Number of engines	4	Max. climb rate [ms^{-1}]	?	Temperature	?	Software: SwiftCore Flight Management System (FMS)
	Payload Weight [kg]	1.99	Max. wind endured [ms^{-1}]	15	Wind speed/comp.	?	
	Takeoff Weight	8.78	Max. flight alt. [m]	?	Wind direction	?	
	Dimensions [in]	40 x 30	Flight duration [min]	20	Humidity/Dew point	?	
	Waterproof	?	Sample rate [ms]	?	Air pressure	?	
	Propeller Heating	no	Flight plans	yes	$PM_{2.5}$, PM_{10}	?	
	Rescue system	?	Radio Frequency	?	SO_2,CH_4,H_2S,CO_2, O_3	?	
	Manual control	?	Telemetry Frequency[bps]	9500	Radioactivity	?	
	Autonomous control	?	-		Multispectral cam.	?	

	Ground station	*yes*	*-*		*Infrared camera*	*?*	
E1250 + Atmospheric Characterization Payload (WP-V2 ACP) (The AEgis Technologies Group)	*Number of engines*	*4*	*Max. climb rate [ms^{-1}]*	*?*	*Temperature*	*yes*	
	Payload Weight [kg]	*2.2*	*Max. wind endured [ms^{-1}]*	*17*	*Wind speed/comp.*	*yes*	
	Takeoff Weight	*?*	*Max. flight alt. [m]*	*2700*	*Wind direction*	*yes*	
	Dimensions [in]	*26x8.5*	*Flight duration [min]*	*30*	*Humidity/Dew point*	*yes*	
	Waterproof	*?*	*Sample rate [ms]*	*?*	*Air pressure*	*yes*	
	Propeller Heating	*?*	*Flight plans*	*?*	*$PM_{2.5}$, PM_{10}*	*no*	
	Rescue system	*?*	*Radio Frequency [GHz]*	*2.4*	*SO_2,CH_4,H_2S,CO_2, O_3*	*no*	
	Manual control	*?*	*TelemetryFrequency[MHz]*	*915*	*Radioactivity*	*no*	
	Autonomous control	*?*	*-*		*Multispectral cam.*		
	Ground station	*?*	*-*		*Infrared camera*		

Table 2: Overview of instrument types currently in use on UAS for meteorology, including resolution, range, available products, uncertainties/limitations.

Manufacturer/Instrument	Parameter	Resolution	Response time/ sampling rate	Uncertainty/ accuracy	Measurement range
FP07 fast tip thermistor [8]	temperature	See data Sheet [8]	0.1 s	See data Sheet [8]	See data Sheet [8]
Vaisala HMP 110 [9]	temperature humidity		1 – 4 s 1 – 4 s	1-0.4 °C 1.1 – 1.8 % RH	-40 – +80 °C 0 – 100 % RH
HYT-271 [10]	Temperature humidity	0.015 °C 0.03 % RH	< 5 s < 4 s	± 0.1 K ± 0.2 % RH	-40 – +125 °C 0 – 100 % RH
BMP 280 [11]	Temperature Pressure	1.01 °C 0.0016 hPa	< 1 s 157 – 182 Hz	± 0.5 – 1.0 °C ± 1.1 – 1.7 hPa	-40 – +85 °C 300 – 1100hPa
BMF055 9-axis sensor [12]	Pitch, roll and direction	See data Sheet [12]	See data Sheet [12]	See data Sheet [12]	See data Sheet [12]
Vaisala radiosonde RS41-SG [13]	Temperature humidity	0.01 °C 0.1 %RH	0.5 s 0.3 – 10 s	0.2 – 0.4 °C 2 – 4 % RH	-95 – +60 °C 0 – 100 % RH

Part 2 Practical considerations

Instrument setup

UAS allows custom flight patterns in 3D, which could be used for a number of applications including nowcasting, more traditional numerical weather prediction, air quality and hazard monitoring among others. This document only considers vertical profiling of atmospheric state variables (i.e. temperature, humidity, pressure, wind) since they would be feasible for data assimilation and be likely the most beneficial for forecasters using observations in near real-time.

Operation of UAS is strictly regulated for safety reasons. Information on EU level regulation can be found at https://www.easa.europa.eu/domains/civil-drones-rpas. For national guidance please contact the national contact points.

Requirements for sensors in operational use likely differ from requirements in research use. When measuring operationally with UAS, sensors should ideally be able to remain in calibration for as long as possible. The sensor response time depends upon the ascend/descend rate of UAS and should be fast enough to be able to follow changes in the phenomena of interest. Sensors can be mounted on different locations around the UAS (Table 3).

Table 3. Pros and cons for sensor location.

Location	Pros.	Cons.
On top of multi-rotor copter	Some wind sensors	
Under multi-rotor copter	Good aspiration when descending	Heating from UAS when ascending
Under one of the rotors	Good aspiration while ascending & de-scending	
Fixed wing	Measurements of any kind well known (from airplane techniques)	Not unmanned due to takeoff and land-ing

For wind there are methods of estimation to base a function that can correlate multicopter behavior and wind considering that the main force that affects the UAV on a windy flight is the drag force. For more information please see references e.g. [14,15,16,17]. Similar methods exist for fixed wing systems[18]. For example the Paparazzi system (https://wiki.paparazziuav.org/wiki/Main_Page) estimates the wind considering the actions of the autopilot on throttle and servos to make the plane following a circle.

Required regular maintenance on site

Technical maturity of UAS currently allows preprogrammed autonomous missions without manual control during the measurement operation. However, a pilot or the system must be able to take over the control of UAS if required. Additionally, battery exchange and recharge, sensor replacement, and monitoring shape of UAS require presence of a human 'pilot'.

Manufacturers are developing remote control systems and automated charging stations for UAS. It is imaginable that remote monitoring of a completely autonomous operation (i.e. takeoff, flight mission, landing and battery recharging) can become possible in some countries in future, which would increase the level of autonomy of this measurement type.

Calibration

The need for sensor calibration depends on the quality of sensor and its ability to maintain calibration. For operational UAS site calibrated reference observations would be recommended. The reference observation could include standard weather station or operational radiosounding profiles, if available.

There may also be value from third party and opportunistic observations which are less well calibrated. Data acquired in this way would have larger uncertainties, but could still be useful, especially if the accuracy and uncertainty characteristics can be understood.

Frequency of calibration depends on the quality of sensor. Good reference practices include onsite reference measurements. Standard automatic weather station serves as a good reference. If measurements are made at the vicinity an operational sounding station one parallel profile per day would be ideal reference. Good practices include near-real time monitoring of sensor drift against reference observation. Data from the same sensors and those measuring the same parameters located at different locations on the UAS could be compared and used for data quality purposes and their appropriate location localization. It is good to monitor the various sensors' responses as they are important to determine the required sampling time.

Measurement configuration

As UAS is not yet part of any network, requirements for measurement configuration (i.e. vertical legs) come from end users such as meteorological services. Based on feedback from weather forecasters vertical profile observations comparable to radiosounding would best fulfil their needs.

Data formats

There are currently no standard data formats for UAS meteorological measurements. National Meteorological and Hydrological Services (NHMS) and researchers in the USA have started agreeing to use CF compliant NetCDF files to enable the sharing of UAS data[19]. For data assimilation, currently the data needs to be in either radiosonde or AMDAR BUFR format to enable assimilation trials on the data. There are tools available (such as EC-Code) to convert NetCDF and other common data formats into the required BUFR format for DA. Table 4 below gives a suggested list for the variables ideally required from UAS data for meteorological purposes.

Table 4. Suggested template for file content.

Variable	dimensions
latitude	time
longitude	time
time	time
height	height
temperature	time
pressure	time
Humidity (mixing ratio)	time
Wind speed	time
Wind direction	time
Vertical speed	time
EAS speed	time

In Table 5, an indication of the minimum requirements needed from UAS meteorological data is given. There is not yet much information available on what these values should ideally be, so we are using the WMO OSCAR requirements as a starting point. For comparison the current capabilities of the Vaisala RS41 radiosonde are shown in the Table 2.

Table 5. Minimum (threshold) and goal requirements for basic meteorological parameters for nowcasting/ high resolution NWP (whichever is more stringent) and Global NWP in the planetary boundary layer, from the WMO OSCAR database of observation requirements (https://www.wmo-sat.info/oscar/requirements).

variable	Global NWP/ Now-casting/ High res	uncer-tainty		Hori-zontal res (km)		Ver-tical res (km)		Ob-serving cycle		timeli-ness	
		min	goal	min	goal	min	goal	min	goal	min	goal
Pressure	Global NWP	1 hPa	0.5 hPa	500	15	0	0	12 h	60 min	6 h	2 h
	High res	1 hPa	0.5 hPa	40	2	0	0	60 min	30 min	2h	15 min
Tempera-ture	Global NWP	3 K	0.5 K	500	15	3	0.3	24 h	60 min	6 h	6 min
	High res	3 K	0.5 K	10	0.5	1	0.1	60 min	5 min	60 min	5 min
Relative humidity	Global NWP	5%	5 %	Not specified	25	Not speci-fied	2	Not speci-fied	Not speci-fied	Not speci-fied	Not speci-fied
Specific hu-midity	Global NWP	10 %	2 %	250	15	3	0.3	12 h	6 h	6 h	6 min
	High res	10 %	2 %	20	0.5	1	0,1	60 min	15 min	2 h	5 min
Wind (hori-zontal)	Global NWP	5 $m.s^{-1}$	1 $m.s^{-1}$	500	15	3	0.5	12 h	60 min	6 h	6 min
	High res	5 $m.s^{-1}$	1 $m.s^{-1}$	20	0.5	0.4	0.1	3 h	5 min	60 min	5 min
Wind (ver-tical)	Global NWP	5 $cm.s^{-1}$	1 $cm.s^{-1}$	500	15	3	0.5	12 h	60 min	6 h	6 min
	nowcasting	5 $cm.s^{-1}$	1 $cm.s^{-1}$	10	0.5	0.5	0.1	3 h	5 min	30 min	5 min

QA/QC methods

To be specified. A demonstration campaign by WMO would provide further information during coming years.

Retrieval methods

Currently national research projects and tests are demonstrating the potential of UAS towards operational deployment. The UAS are not part of any network in this development state. Harmonized retrieval tools do not exist yet.

Part 3 References

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