

# A Novel Approach to Atmospheric Measurements Using Gliding UASs

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**Abstract.** Atmospheric aerosols and ozone (O<sub>3</sub>) have lifetimes of days to weeks and continuously evolve chemically and physically. Frequent and globally spaced vertical profiles of O<sub>3</sub>, aerosol optical density, particle size distribution, hygroscopic growth, and light absorption coefficients are highly desired in order to understand their controlling processes and subsequent effects on air quality and climate. High costs and logistical restrictions prohibit frequent profiling on a global scale using current technologies. We propose a new approach using state-of-the-art technologies including 3D printing and an unpowered small Unmanned Aircraft System to make the desired measurements at a fraction of the cost of current conventional methods.

## 1 Introduction

Atmospheric aerosols play an important role in Earth's climate and are the single largest source of uncertainty in climate model predictions of future climate [1]. Aerosols scatter sunlight, thus directly exerting a negative radiative forcing on climate [2]. A fraction of aerosol particulate mass absorbs sunlight, producing a positive direct radiative forcing [3]. Aerosols also interact with clouds producing either negative or positive forcing depending on the aerosol and cloud properties as well as the atmospheric state.

Aerosols are measured globally using satellites and networks of sun photometers. However, several key properties are not measured regularly due to physical limitations. The most common observations are of column properties such as the aerosol optical depth, giving no vertical profile information. Vertical profiles are key for understanding aerosol sources and cloud interaction; aerosols cannot interact with clouds if they are in a completely different layer of the atmosphere. Vertical information from LiDAR

installations is not sufficiently complete, generally returning only limited information on particle properties such as their size.

Size distributions give key information about how aerosols evolve in time and determine how particle mass impacts climate and air quality. Hygroscopic aerosol particle sizes are affected by ambient relative humidity (RH). These particles grow when ambient RH increases, leading to increased light-scattering. This aerosol hygroscopic effect (AHE) can lead to large changes of the aerosol radiative forcing and visibility following RH changes. Despite its importance, the AHE has not been well characterized observationally due to the continuous evolution of aerosol hygroscopicity throughout aerosol lifetime and the lack of systematic global measurements.

Another parameter that is difficult to determine remotely is the light absorption by particles, which can change the sign of the aerosol climate forcing. Most of the remote observations of aerosol light absorption are from the Aerosol Robotic Network (AERONET), but the uncertainty of these observations is quite high unless the overall aerosol optical depth (AOD) is higher than 0.4 at 440 nm [4, 5]. Since the AOD is above 0.4 only about 10 % of the time, AERONET alone is insufficient for studying light absorption by aerosol.

Ozone ( $O_3$ ) is a reactive greenhouse gas that can be rapidly produced under poor air quality conditions and warm temperatures in the troposphere. High concentrations of  $O_3$  harm human populations and vegetation. Surface  $O_3$  concentrations are partially controlled by transport [6]. Vertical profiles of  $O_3$  are thus key to accurate forecast of air quality. Currently routine high-resolution  $O_3$  profile measurements are only made in few locations around the globe on a monthly basis. Satellite observations are inadequate for tracking tropospheric  $O_3$  transport due to their low temporal and vertical resolutions.

Both  $O_3$  and aerosol particles in the troposphere have lifetimes of days to weeks in the atmosphere. Understanding their evolution requires extensive observations because ozone and aerosols spread far from their sources yet never become well-mixed enough for a few observations to characterize a global distribution of pollutants. Aerosols continuously change both chemically and physically during their lifetimes. Frequent and globally distributed vertical profiles rather than ground-based measurements alone are highly desired in order to understand the processes that control  $O_3$  and aerosols and their subsequent effects on air quality and climate, and to map aerosol light absorption and its evolution. Conventional profiling using aircraft provides excellent data, but is cost prohibitive on a global scale. Three requirements necessary for a successful global monitoring program are: Low equipment cost, low operation cost, and reliable measurements with well characterized uncertainties.

## 2 An Innovative Approach

We have devised a new approach that satisfies all three requirements for a successful global observational network (Fig. 1) using instrument packages deployed with a new platform. The platform will consist of a small balloon and a small gliding unmanned aircraft system (gUAS). The gUAS will be released from the balloon at about 5 km altitude, returning a light instrument package to the launch location, and thus allowing

for consistent recovery of the payload. Atmospheric profiling can be performed either during ascent or descent (or both) depending on measurement requirements. The new approach, once validated, will be used to form an observation network (Global Ozone and Aerosol profiles and Aerosol Hygroscopic Effect and Absorption optical Depth (GOA<sup>2</sup>HEAD) network) around the globe.

## 2.1 New Platform and Instruments

Balloon flights are exempted from U. S. Federal Aviation Administration (FAA) regulations if their payloads are less than 6 lbs. Small weather balloons are fairly inexpensive (\$350 per launch) and are essentially the entire disposable operational cost of the GOA<sup>2</sup>HEAD project since the gUAS and instrument packages are recoverable and reusable. Considering the 6-lbs. FAA limit, the gUAS must be as light as possible. Auto-piloted gliders and small UASs have been evaluated as gUASs. One of the small UASs, 3DRAero by 3DRobotics with a Pixhawk autopilot (<https://store.3drobotics.com/products/3DR-Aero>), which weighs about 2 lbs. without a motor, propellers, and battery, is currently under consideration for this application in the Global Monitoring Division (GMD) of the NOAA ESRL. Another gUAS, a SkyWisp (Southwest Research Institute, San Antonio, Texas, USA) glider, is also under evaluation. However, parafoils might eventually be more desirable due to their small weight.



**Fig. 1.** A conceptual sketch. A small weather balloon carries the payload to a desired altitude. Once released from the balloon, the gliding UAS (gUAS) brings the payload back to the launch point. The payload takes data during both ascent and descent.

Sondes that measure relative humidity (RH), pressure (p), and temperature (T) (e.g. iMet-1-RS, InterMet, Grand Rapids, MI, USA) are relatively inexpensive ( $\sim$  \$230). Electrochemical Concentration Cell ozone sensors (ECC ozonesonde, Droplet Measurement Technologies, Boulder, CO, USA) are available for  $\sim$  \$800 per unit. However, there are no commercially available aerosol and radiation sondes for small balloons. A few key instruments have been or are being developed in NOAA laboratories that are ideal

for balloon applications. The Printed Optical Particle Spectrometer (POPS, 1.8 lbs.) sizes individual aerosol particles between 140 and 3000 nm diameter at ambient RH. This size range is adequate for AOD derivations. The POPS measurements compare well with proven instruments. Dry aerosol particle sizes can be measured with a dryer attachment. The miniature Scanning Aerosol Sun Photometer (miniSASP, 0.7 lbs.) is a 4-wavelength, sun-tracking, azimuth-scanning sunphotometer with a detection limit of 0.02 AOD. Both instruments have been developed at the National Oceanographic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL) in the Chemical Sciences Division using advanced manufacturing techniques such as 3D printing to reduce cost. The NOAA ESRL GMD has developed a filter-based aerosol absorption instrument, the Continuous Light Absorption Photometer (CLAP), which was designed for ground operations, but can easily be miniaturized for this balloon application. The costs for the three instruments and the 3DAero are in the \$2 K-\$5 K range, quite inexpensive for science-quality instruments, and should satisfy the requirement of low equipment cost mentioned previously. These instruments are not limited to the nighttime operations, thus can be used to track the diurnal changes in aerosol size growth and optical modifications.

**Table 1.** Measured and derived quantities from the two proposed instrument packages

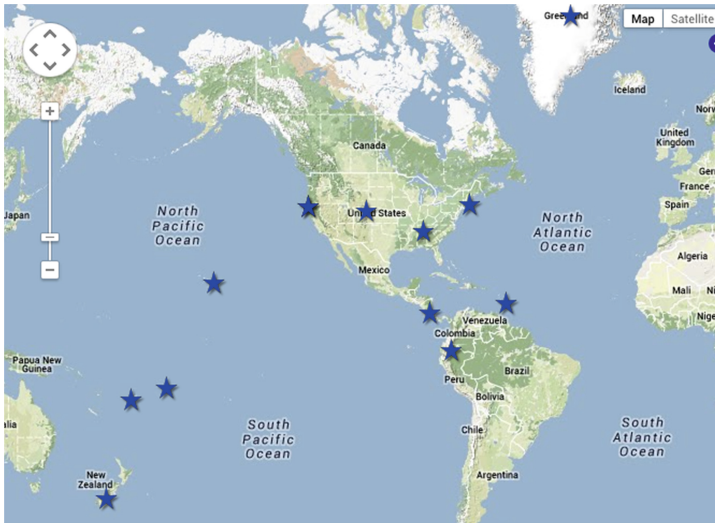
	Package 1	Package 2
Measured	Aerosol optical depth profile miniSASP	Aerosol absorption coefficient profile (mini-CLAP)
	Dry aerosol number and size distribution profiles (POPS with a dryer)	Ambient RH aerosol number and size distribution profiles (POPS)
	p, T, RH profile (iMet-1-RS)	p, T, RH profile (iMet-1-RS)
	Ozone profile (ECC ozonesonde)	
Derived	RH effect on aerosol size distributions (both packages launched together)	
	Dry AOD	Aerosol absorption optical density (AAOD)
	RH effect on AOD	

## 2.2 Instrument Packages in Development

Instrument packages must be deployed separately to provide the entire desired measurements due to the 6-lb FAA limit. Two instrument packages are currently under development. The first one consists of an ECC ozonesonde, a POPS with a dryer, a miniSASP, and an iMet-1-RS (for p, T, RH). The second consists of a POPS, an absorption spectrometer (miniaturized Continuous Light Absorption Photometer, or mini-CLAP), and an iMet-1-RS. The POPS computer can serve as a central data system for both instrument packages. Measured and derived quantities from the two instrument packages are listed in Table 1.

**Table 2.** Comparison between GOA<sup>2</sup>HEAD and commercial/mature instruments

GOA <sup>2</sup> HEAD		Commercial/Mature	
Instr.	Performance	Instr.	Performance
ECC O <sub>3</sub>	Equivalent	ECC O <sub>3</sub>	Equivalent
POPS	140–3000 nm diam.	DMT PCASP	100-3000 nm diam.
miniSASP	4 wavelengths, 0.02 % precision	CIMEL	8-9 wavelengths < 0.1 % precision
Mini-CLAP	Equivalent	CLAP	Equivalent
iMet-1-RS	Equivalent	iMet-1-RS	Equivalent



**Fig. 2.** NOAA O<sub>3</sub> sonde stations (Source: <http://www.esrl.noaa.gov/gmd/ozwv/network.php>)

### 3 Implementation

We envision a 3-step implementation program. The first step is validating the instruments with other proven in situ instruments in the laboratory and at the NOAA Table Mountain Test Facility (TMTF) via comparison with remote sensing instruments. This initial part of the program will include test launches of the instrument packages at NOAA TMTF, as well as the development of operational and data reduction procedures.

Once the instrument packages are validated and procedures are perfected, the second step of our program would be to deploy at all NOAA ozonesonde stations (Fig. 2). Since these stations use the same type of balloon for ozonesondes, it will be straightforward to launch our packages at these sites. Science quality data are expected from flights at these sites.

The last step would be the full scientific deployment around the world. It is our intention to include as many research institutes as possible. This step is likely several years away, and many details have to be worked out before implementation. Two critical issues are data quality control (including instrument calibration and intercomparison) and data sharing. Careful attention to collaboration with scientific agencies from multiple nations will be necessary to ensure global deployments and maximize scientific return. There are a number of global networks of atmospheric observations stations such as the World Meteorological Organization's Global Atmosphere Watch (GAW) and the GCOS Reference Upper Air Network (GRUAN). These stations could be natural hosts for the GOA<sup>2</sup>HEAD operations (Table 2).

## 4 Conclusions

A novel approach for affordable tropospheric O<sub>3</sub> and aerosol profiling has been presented. The approach is based on the use of small weather balloons, a small gliding UAS, and relatively inexpensive state-of-art instrument packages with scientific quality. Measurements currently feasible include profiles of O<sub>3</sub>, RH, p, T, aerosol particle size distribution, AOD, and aerosol absorption coefficient.

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