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Field determination of multipollutant, open area combustion source emission factors with a hexacopter unmanned aerial vehicle☆

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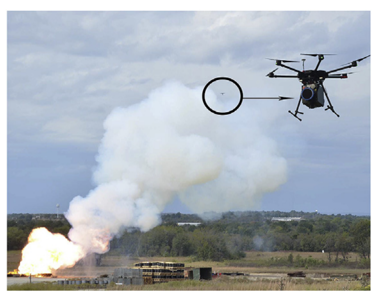
HIGHLIGHTS

- An unmanned hexacopter aircraft was coupled to an emission sampler.
- The system was flown into 84 combustion plumes.
- Gas and particles were sampled to determine emission factors.
- The system measured particulate matter, metals, volatile and semi-volatile organics.
- This system can safely and efficiently sample open area emission sources.

GRAPHICAL ABSTRACT



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ABSTRACT

An emission sensor/sampler system was coupled to a National Aeronautics and Space Administration (NASA) hexacopter unmanned aerial vehicle (UAV) to characterize gases and particles in the plumes emitted from open burning of military ordnance. The UAV/sampler was tested at two field sites with test and sampling flights spanning over 16 h of flight time. The battery-operated UAV was remotely maneuvered into the plumes at distances from the pilot of over 600 m and at altitudes of up to 122 m above ground level. While the flight duration could be affected by sampler payload (3.2–4.6 kg) and meteorological conditions, the 57 sampling flights, ranging from 4 to 12 min, were typically terminated when the plume concentrations of CO_2 were diluted to near ambient levels. Two sensor/sampler systems, termed "Kolibri," were variously configured to measure particulate matter, metals, chloride, perchlorate, volatile organic compounds, chlorinated dioxins/furans, and nitrogen-based organics for determination of emission factors. Gas sensors were selected based on their applicable concentration range, light weight, freedom from interferents, and response/recovery times. Samplers were designed, constructed, and operated based on U.S. Environmental Protection Agency (EPA) methods and quality control criteria. Results show agreement with published emission factors and good reproducibility (e.g., 26% relative standard deviation for $PM_{2.5}$). The UAV/Kolibri represents a significant advance in multipollutant emission characterization capabilities for open area sources, safely and effectively making measurements heretofore deemed too hazardous for personnel or beyond the reach of land-based samplers.

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1. Introduction

Characterizing emissions from open area sources such as fires poses unique challenges to fully quantifying the release of pollutants over a wide area. Short of sampling the whole emission plume, the carbon balance method (Nelson, 1982) is often used for combustion sources. The carbon balance method relies on sampling a subset of the emissions and relating that value back to the original fuel. The method employs co-sampling the target emissions along with carbon species such as CO_2 and CO and, with knowledge of the carbon content in the combustible fuel, allows calculation of an emission factor as mass of pollutant per mass of combusted fuel. These emission factors are used in dispersion models (for example Bjorklund et al., 1998) to predict exposure and environmental deposition as well as in emission inventories to set source priorities.

The challenges of sampling open area combustion sources include representative sampling of a wind-driven, mixing, and convective plume. Proximity to the source may present hazards to personnel and equipment alike. Sampling at a distance raises challenges of securing sufficient sample to exceed detection limits from a diluted plume. Solutions to quantifying these hard to sample sources often include aerial sampling of the plume. Airplanes equipped with gas samplers (Yokelson et al., 2013; Burling et al., 2011) have used the carbon balance method and plume transects (Lavoie et al., 2017) to determine emission factors. Tethered aerostats (helium-filled balloons) equipped with gas/particle samplers have been employed for oil fires at sea (Aurell and Gullett, 2010), prescribed forest fires (Aurell et al., 2015a), and open burning and open detonation of military ordnance (Aurell et al., 2011, 2015b). Both aerial sampling technologies have disadvantages. Airplanes can be expensive and can require long lead times to schedule. The speed of airplanes can limit the transect residence time in narrow plumes, limiting the sample size, resulting in non-detects. Many emission source types preclude the use of low-flying aircraft. Aerostats solve some of these issues but present other difficulties including the presence of obstacles to tethers, the need for a large ground-based crew, safety considerations, logistical issues such as the supply of helium cylinders, and limited freedom of movement.

The confluence of developments in global positioning system (GPS) technology, battery power density, miniaturization of circuitry, small gas sensors, carbon fiber materials, 3D printers to create custom structures, and unmanned aerial system (UAV) technology have erased many of the barriers to aerial emission sampling. Recent advances have demonstrated the use of UAV for atmospheric (Peng et al., 2015), laboratory-generated (Alvarado et al., 2017), and surf zone (Brady et al., 2016) particulate matter (PM) distributions. Volcano measurements of sulfur gas species have been measured by sensor-equipped UAVs (McGonigle et al., 2008; Shinohara, 2013). Multisensor-equipped UAVs have been tested on a stationary diesel engine (Villa et al., 2016) and on a roadway tunnel (Chang et al., 2016).

Applications to field sources involving multiple pollutant types, particularly trace air toxics, and determination of source emission factors, are not yet demonstrated. Preliminary laboratory and field results of a UAV-based emission sampler measuring open area combustion emissions showed emission factors consistent with those from an aerostat-lofted system (Zhou et al., 2016). This current paper extends this work, describing field applications of a more comprehensive UAV-based sensor/sampling system (termed the “Kolibri”) for characterizing gas and particle emissions from open area sources. Sensors/samplers included CO, CO_2, and particulate matter ($PM_{2.5}$), and novel measurement of metals, chloride, perchlorate, volatile organic compounds, chlorinated dioxins/furans, and nitrogen-based organics. The system performance is demonstrated at three military open burn campaigns at the Radford (Virginia) and McAlester (Oklahoma) Army Ammunition Plants (RFAAP and MCAAP, respectively) where hazardous, obsolete, and off-specification ordnance is demilitarized. These open area sources are particularly challenging, as the events are short in duration, typically less than 5 s, and the rapid heat release gives rise to a fast-moving, convectively-driven plume. The potential hazards to personnel and equipment require careful consideration. These challenges have been successfully addressed with the use of a highly mobile UAV coupled to an instrumented system with fast-response/recovery sensors and high throughput samplers. The performance of the UAV is characterized by its ability to maneuver into the plume, maintain position, and follow the wind-driven plume. The functioning of the Kolibri system is described in terms of concentration determinations and emission factor reproducibility.

2. Method

The Department of Defense enlisted NASA to fly their UAV into the plumes from open burning of obsolete and hazardous military ordnance while carrying a lightweight battery operated system of gas and particle samplers/sensors (termed the “Kolibri”) developed and operated by the U.S. Environmental Protection Agency (EPA) and the University of Dayton Research Institute (UDRI). The systems were used at two test sites in Virginia and Oklahoma, USA.

2.1. Test sites and materials

Both tests sites were U.S. Army ammunition facilities. The Radford Army Ammunition Plant (RFAAP) is located in the rolling hills of southwest Virginia, approximately 5 km northeast of the city of Radford, Virginia (37° 11′ 35.93″ N; 80° 31′ 16.35″ W). RFAAP lies along the New River in the relatively narrow northeastern corner of the valley. The RFAAP site consists of eight pairs of burn pans in a 420 m row. Trees and a river parallel the burn pan row, separated by approximately 15 m. On the other side of the pan row, a tree-covered ridge forms the other side boundary, approximately 65 m from the pans. The pans were loaded with off-specification rocket motor propellants and manufacturing process waste (“skid” waste).

The second sampling site is located at the McAlester Army Ammunition Plant (MCAAP). MCAAP is in central Oklahoma, approximately 220 km south of Tulsa (34° 48′ 50″ N; 95° 54′ 28″ W). The site's terrain is fairly level, surrounded by fields, and centrally located between pine forests, with the shortest distance from the pan site to the tree line being 142 m. MCAAP conducts open burning of projectile propellants that are excess, obsolete, or unserviceable.

RFAAP's rocket motor propellants consist primarily of nitrocellulose and nitroglycerin (NG); sampling targeted residual nitrocellulose and other nitroaromatics to evaluate the presence of unburned propellant and its combustion byproducts. The rocket motor propellants were bagged and placed into a 5 m × 2 m pan after which they were remotely ignited using an electric arming and ignition coil. Typically, a total of about 1300 kg of propellant was placed in the three pans which were ignited over the course of an hour. The skid waste contained a variety of waste materials from propellant manufacture totaling between 227 and 736 kg. To assist the skid waste combustion, wood pallets, corrugated cardboard sheets, and diesel fuel were added to each pan. The skid waste pans were similarly ignited remotely but in three single-pan burns per day. Eight days of testing at RFAAP in a two-week period saw 25 UAV/Kolibri plume sampling flights. The total flight time including UAV test flights was 7 h 30 min.