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Developing the Framework for Integrating Autonomous Unmanned Aircraft Systems into Cloud Seeding Activities

DeFelice TP[1]* and Duncan Axisa[2]

[1]*Sykesville, Maryland, MD, USA*
[2]*Research Applications Laboratory, National Center for Atmospheric Research, Boulder, CO, USA*

Abstract

This paper introduces an engineering approach to develop autonomous unmanned aircraft systems technology for integration in future weather modification (cloud seeding) programs with the goal to improve operational efficiency and evaluation accuracy. It builds upon the process already established in a previous paper by Axisa and DeFelice who constructed a framework underlying the development of new technologies for use in cloud seeding activities, identifying their potential benefits and limitations and providing initial guidance.

Keywords: Unmanned Aircraft; Autonomous UAS; Cloud seeding Operations; UAS and Cloud Seeding

Introduction

This paper addresses an approach to develop new sensing technologies and their integration in unmanned aircraft systems (UAS) for use in real-time guidance of airborne cloud seeding activities to increase precipitation efficiency (i.e., precipitation enhancement) based on an engineering and scientific process-based framework described in Axisa and DeFelice [1]. The new sensor suite will optimally provide *'in-situ'*, real-time temporal and spatial sensitivities to overcome the predictability issues related to, or sparseness of, environmental parameters needed to identify conditions suitable for airborne cloud seeding and to test the implementation of the seeding.

Precipitation enhancement projects have been conducted primarily in regions where orographic clouds (those developed by the lifting of moist air as it flows over elevated topography) are common in the cold season, or where warmer-season cumuliform clouds are generated by vigorous convection, since the mid-1940s [2] based on the scientific principles of the precipitation process [3-4]. Simply stated, cloud seeding is conducted on cloud systems or portions of clouds that are naturally inefficient at converting their moisture into precipitation, hence, cloud seeding makes clouds more efficient precipitators. Operational cloud seeding projects have been conducted since the first tests of both dry ice [2] and silver iodide, AgI [5,6], as cloud seeding materials [7-10]. Cloud seeding for enhancing winter snowpack in western mountainous areas is considered highly successful since the mid-1980s [11]. The results of mixed phase convective cloud seeding have been inconclusive. The seeding of isolated individual clouds has led to definite, mostly positive changes in the precipitation amounts [7,12-14]. Woodley and Rosenfeld [14] developed and tested a method for the objective evaluation of short-term, nonrandomized operational convective cloud seeding projects on a floating-target-area basis. Their results indicated that rainfall was increased downwind of the seeding activity, primarily as the seeded clouds moved out of the target and into downwind areas. Downwind or extra-area effects are further discussed by DeFelice et al. [15]. Cloud seeding evaluations are used to gauge operational efficiency of the seeding operation, and when successful a benefit/cost ratio greater than 200/1 can be achieved [16].

Airborne cloud seeding with AgI is conducted from near or at cloud base with strong updrafts or at cloud top depending on conditions, whereas dry ice is typically used via aircraft just inside or above cloud top depending on conditions. This type of seeding often referred to as glaciogenic seeding, is applied in clouds that contain high concentrations of super-cooled liquid water and relatively warm temperatures. Glaciogenic seeding, whether seeding near cloud base or cloud top requires maximum updrafts at cloud base, or cloud tops growing vertically above the freezing altitude, and to occur early in the convective cloud's lifetime. Cloud seeding may also be conducted in clouds too warm for AgI and dry ice, known as warm cloud seeding or hygroscopic seeding. Mather et al. [17] have carried out successful hygroscopic seeding in South Africa; Silverman et al. [12] report statistical significance and substantial increases in radar-estimated rainfall (ranging from 30% to 60%) from the seeded clouds using hygroscopic seeding techniques; Rosenfeld et al. [18] report a broadening of the drop size distribution following the seeding of continental convective clouds with hygroscopic salt powder, indicating that the salt material was acting to accelerate the warm rain process. Hygroscopic seeding usually occurs just below cloud base, in clouds that are microphysically continental (i.e. contain high concentrations of small drops due to the absence of large hygroscopic aerosols), in the area of maximum updraft to ensure that the cloud ingested the seeding agent, and early in the convective cloud's lifetime.

Background

The western hemisphere is in the midst of a significant drought [20], with millions in danger of starvation. Hence the need to develop the science and technology that improve the appropriate systems used to monitor and manage atmospheric water should remain at the forefront of current research. Better technology, appropriately designed and implemented to improve the efficiency of cloud seeding and independently verify such, will yield more water returned to the surface in the form of precipitation. More precipitation will help resolve the direct and indirect issues related to drought.

***Corresponding author:** DeFelice TP, Sykesville, Maryland, MD, USA, Tel: 920-917-7452; E-mail: clddoc1@gmail.com

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Cloud seeding technologies may be effectively applied [9,10,21,22)] to facilitate the water and energy cycles [15], which are key to dealing with many present and potential future scientific, environmental, public concerns, and socio-economic issues. This review paper builds upon the basic context and initial guidance for weather modification operators that might integrate UAS technology in future cloud seeding operations provided recently by Axisa and DeFelice [1]. Axisa and DeFelice [1] provide a first look at the integration of UAS for cloud seeding operations and research. They define cloud seeding operations and research with the greatest need for advanced technology and technique development into three functional components: (a) cloud seeding activity monitoring and simulation, (b) seeding agent delivery and dispersion, and (c) cloud seeding evaluation technology, techniques and protocols. Instrumented UAS technology was determined to be at the operational or near operational readiness level and therefore suitable for integration in cloud seeding operations. They identify the primary issues with UAS integration, noting such were most likely related to government policy, technology advancements, and operational considerations. They formulate a conceptual configuration for operations and for evaluation of the operational use of UAS for modern cloud seeding operations (Table 1). The use of UAS in operational cloud seeding operations also have benefits that go beyond overcoming some of the operational safety concerns, but they also provide:

1. A cost effective means to evaluate cloud seeding using near real-time cloud system relevant measurements for evaluating the operations.

2. A cost effective means to advance our understanding of the relevant science and engineering aspects, and

3. A framework for application to other science and engineering areas. For example, using UAS in tandem to gain the ability for cost effective, concurrent, real-time Eulerian and Lagrangian analyses of seeding processes throughout cloud life cycles on sub-cloud scales. The latter would benefit other disciplines including climate change, forecasting extreme and severe weather, flooding, drought and the impacts of such events on society, the economy and more.

Axisa and DeFelice [1] provide a more detailed list of benefits.

The configuration of a UAS for cloud seeding under either mode in Table 1 would be the ultimate goal. In practice, one would start with a much simpler version of the configuration in Table 1, guided by the modern-day cloud seeding operational capabilities [9,10,21,22].

Goal and Objectives

As we develop and assess an autonomous UAS platform for cloud seeding operations our first goal would be to (1) develop simple, calibrated and well-validated lightweight payloads that measure meteorological state parameters, wind, turbulence and aerosol-cloud microphysical properties in conditions that are conducive to seeding, and (2) develop algorithms that use *in-situ* real-time sensor data to guide the platform towards suitable targets to implement the seeding.

In its simplest form, the UAS could be guided by weather radar or satellite data products to navigate to regions of suitable convection. The UAS payload would consist of lightweight sensors designed to provide 'real-time' *in situ*-based measurements that support operational flight guidance of the UAS. The flight guidance system would navigate the UAS autonomously to areas of suitable temperature, relative humidity, updraft velocity, aerosol size distribution and droplet size distribution to implement optimal seeding. Optimal seeding means that seeding starts and proceeds at a rate that will yield maximum conversion of cloud water to precipitation that falls in the intended location on the ground, or target area. The latter ability to have the precipitation fall in an intended area on the ground is known as targeting. The data collected from the payload sensors, and seeding apparatus, during an entire flight would be collected and downloaded for use by others to improve and validate model parameterizations especially when applied to simulating seeding agent dispersion

Large datasets collected during airborne cloud seeding experiments already exist [e.g. 17, 23-36] and provide valuable sources of data to develop and constrain the algorithms that guide the UAS. These data can be mined, analyzed and features extracted to locate representative time-series of key sensors from research aircraft flying at or below cloud base (e.g. sensors that measure updraft velocity, aerosol size distribution and droplet size distribution). Similar analysis would also be conducted on weather radar and satellite data in regions that are known to be suitable for seeding in order to establish representative radar [37] and satellite signatures [38] for the corresponding periods and locations.

Data collected in previous campaigns can be aggregated following the data assimilation process and passed through a UAS simulator for evaluation. The simulator can implement software in the loop (SIL) technology that has the ability to simulate the UAS flight characteristics, with navigation driven by sensor data collected from previous campaigns. Radar and satellite algorithms can be implemented to now-cast convection that may be suitable for targeting the seeding. The simulations can be compared to actual flight paths flown on previous cloud seeding missions to understand differences in behaviors between manned operations and that performed by the UAS in the simulation. This analysis can serve as guidance for improving the simulation software.

Function	Capability
Sensing	Atmospheric profiles surface to flight-level: air temperature, dewpoint temperature, wind field, turbulence, static pressure, spectral irradiance, supercooled liquid water content (SLW) Atmospheric constituents (aerosols, cloud, precipitation, trace gases, total water content) Surface characteristics (temperature, moisture content, spectral reflectance, soil moisture, soil temperature profiles). Ancillary, auxiliary (e.g. GPS, platform velocity, acceleration, attitude, pitch, roll, video) [e.g. AgI, dry ice (DI), hygroscopic agent dispenser].
Sensor Coverage	Omni-slight skew toward forward hemisphere; [Sub-UAS point^ (AgI; DI)].
Data Processing	Able to process hundreds of Terabytes of data per second; functional tools, decision support; calibration/validation; archive; [Seed start and stop, GPS locations, amount AgI/DI dispensed].
Software	Algorithms to yield required information: Capability Maturity Model Integration, level III (CMMI III). Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR); data logging; data processing; [Algorithms to yield required information (e.g. seeding decision), control operations (e.g. ignite squib-burn AgI solution/flare or other, flight path, sensing); data logging; data processing].
^Sub-UAS Point is defined as the "point of intersection with the earth's surface-geoid of a plumb line from the UAS to the center of the Earth" (i.e., intersects surface at a 90 degree angle).	

Table 1: Conceptual functional configuration of a system to identify and monitor cloud seeding opportunities and [Additional configuration included to conduct cloud seeding operations]. Adapted from Axisa and DeFelice [1]).

Once the simulations have been refined then at least two field campaigns involving the lightweight UAS can be conducted. The first campaign would evaluate the sensors for performance within their operational limits. The second campaign would test the sensor and algorithm equipped UAS as a unit for the first time during an intensive observation period (IOP). The location of the IOP would be in an area where cloud seeding has a high potential of success, and may even be piggy-backed on an existing operational program. The IOP will help establish the viability of UAS as a weather modification research platform with possible cloud seeding applications. Specifically, it would achieve a range of technological objectives, including:

1. Assimilate data from previous rainfall enhancement field campaigns to define the key sensor parameters required for optimizing and evaluating cloud seeding operations and determining a suitable sensor payload for these parameters.

2. Develop software in the loop (SIL) based simulator that tests the performance of cloud targeting algorithms.

3. Evaluate the use of UAS in seeding of convective clouds with real time guidance from radar, satellite and an *in-situ* measurement based systems.

An approach to develop and assess an autonomous UAS platform that utilizes *in-situ* real time data to sense, target and implement seeding might proceed generally as provided in the following sections for each technical objective.

Approach for developing the sensor payload

The first step in this development process is to determine which physical quantities best describe clouds that are amenable to seeding. Once these operational and research-like quantities have been established, their threshold values for seeding need to be determined by analyzing large datasets collected during airborne cloud seeding experiments. This would require developing the capability to directly measure those values inside and around clouds. The sensor payload would be designed with the capability to measure properties (i.e., temperature, relative humidity, wind, updraft velocity, aerosol size distribution and droplet size distribution) within threshold values of operational quantities to determine when to seed, and research quantities for subsequent operations verification or evaluation. For example, determining thresholds based on analysis of measured drop size distribution and their relationship to the production of rain. A broad drop size distribution with a tail of large drops might not be suitable for hygroscopic seeding especially if large hygroscopic aerosol particles are present below cloud base. This would necessitate the design of a system consisting of two UAS, one flying below cloud base (at the cloud formation level) while another flying in the vicinity of the optimal seeding location inside the candidate cloud (at a flight level above the cloud base). Each of the UAS would have a similar sensor payload, each transmitting data to the ground control station. These data would need to be simultaneously processed to determine aerosol and drop size distribution parameters for concurrent periods, and then compared against the thresholds to determine cloud seedability.

The two UAS, UAS1 (high cloud base/spotter) and UAS2 (cloud formation level/seeder), would each have on-board data processing systems, and each be controlled by a ground control station that controls the actions of each UAS. UAS1 and UAS2 should be equipped with a lightweight payload that measures basic thermodynamic properties (i.e., pressure, temperature and relative humidity), wind velocity, aerosol size distribution, and drop size distribution. UAS2 would also be equipped with seeding apparatus (i.e., dry ice dispenser, acetone generator, hygroscopic flares and/or glaciogenic flares).

An instrument that measures 3D wind velocity could be the Rain Dynamics multi-angle inertial probe (MIP), and one that measures drop size distributions could be the Droplet Measurement Technologies (DMT) backscatter cloud probe (BCP), [41], and one that measures aerosol size distribution could be the Hendix Scientific printed optical particle spectrometer (POPS),[42]. (These instruments are merely listed as examples and other instruments that perform a similar function might be suitable.) We have considered the concept of UAS1 sampling cloud drop-derived aerosol residuals through a counter-flow virtual impactor, and to have these residual particles collected on scanning electron microscope (SEM) stubs, for example, for analysis of their chemical composition. The aerosol chemistry, especially the residual aerosols that form the drops, are important in understanding the aerosol-cloud interactions inherent to the cloud and its formation [e.g. 40] as well as in evaluating the impact of the seeding within the cloud [e.g., 18,19]. This sampling technique could be very important in determining whether a seeding response is present in the cloud being modified and would also be useful in evaluating the seeding operation and assessing any environmental impacts during post operational assessments. However, this technique is dismissed as immediately feasible due to technological limitations of obtaining the simplest chemical composition of a single aerosol residual, given the stopping distance of a drizzle drop may be too large for a UAS inlet (and inlet counter-flow rate), for example.

The data processing system onboard the UAS would feed information to a more powerful computational platform at the ground station. Our autonomous control module will interface with a back trajectory module that uses wind measurements from the two MIPs. Both UAS1 and UAS2 processing systems will calculate back trajectories but the final position of UAS2 will be adjusted to be relative and downstream of UAS1. By positioning the aircraft in this formation, the position of UAS2 would be ideal for cloud seeding in the case when UAS1 is sampling seedable clouds. Hence, UAS1, which needs to spot the conditions for seeding, would use the environmental information and the trajectory results to arrive at the location where conditions are conducive for seeding, and similarly but also taking into account location of UAS1, UAS2 would use that information to implement the seeding.

The existing datasets collected from research aircraft on past campaigns would be processed so that their output will be similar to that produced by the UAS payload (i.e. temperature sensor, relative humidity sensor, MIP, BCP and POPS). These data would then be analyzed to develop and constrain the algorithms that guide the UAS, to finalize and test sensor payload algorithms; to perform the data analyses; and to develop the radar and satellite algorithms. The results of these activities would be used in the next phases of development, including aerodynamically optimizing the sensor payload weight and location on each platform. In cloud seeding operations, small UAS might be capable of carrying some seeding material in the form of ejectable or burn-in-place flares. However the seeding material to be carried will depend on the payload capability and the type of seeding to be performed. In this paper, we will assume that UAS1 and UAS2 stay in the warm parts of the cloud system, so unlike for the glaciogenic seeding application, there would not be a need for de-icing. At the end of the simulations our sensor and seeding payloads will be aerodynamically optimized on UAS1 and UAS2 and ready for the next phases of development. Small UAS, despite their payload limitations, have operated successfully in the vicinity of thunderstorms as part of an observational campaign [43].

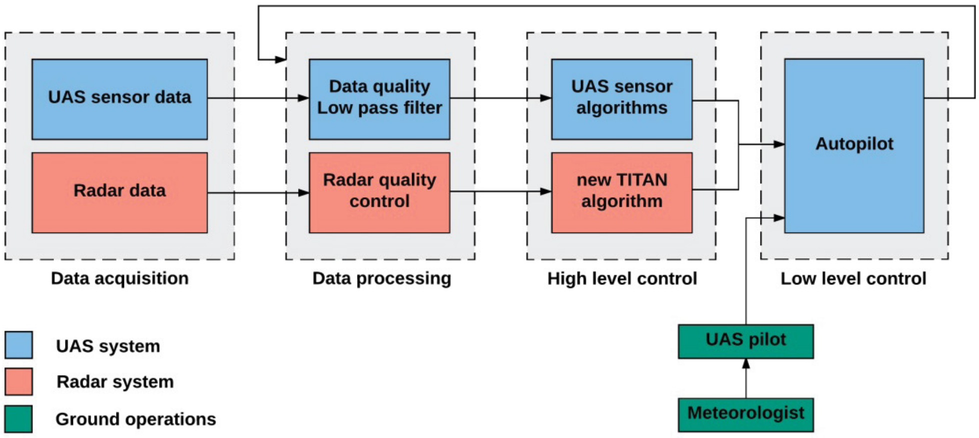

Figure 1: Autonomous UAS control routine for cloud seeding operations. Sensor and radar data equipped with cloud seeding algorithms provide seeding actions to the UAS. A UAS pilot and meteorologist have the option to modify or interrupt the actions taken by the UAS.

Approach for developing an algorithm that uses sensor data to guide the platform towards suitable targets to implement the seeding

In this section the approach shifts toward transferring the verified algorithm to the on-board data system computer and interfacing it with the actual sensors using standard software development lifecycle principles. The development proceeds on the hypothesis that weather radar software such as TITAN (Thunderstorm Identification, Tracking, Analysis, and Now-casting, [37]) can be modified to not only now-cast the location of convection, with real-time radar echo data input about the cloud environment, but also with sensor data input from the UAS. The combination of radar and sensor data would improve the ability to forecast optimal seeding conditions.

Once operational the new TITAN algorithm would provide the UAS with the coordinates of the ideal region to sample and the UAS, equipped with the sensor payload, would proceed with *in-situ* sampling as they navigate to those new locations. TITAN continuously updates optimal seeding coordinates throughout the flight, but once the UAS reach the ideal location, seeding begins and ends once the sensors indicate favorable and then unfavorable seeding conditions, respectively. The seeding cycle continues until the UAS must return for fueling or there is an unsafe situation. The algorithm controlling the seeding simply ingests the location coordinates and time stamps from TITAN and the time stamps from the sensors, along with the environmental (e.g., 3D winds, temperature, relative humidity, pressure), aerosol and drop microphysical properties (e.g., drop concentration, drop size distribution, effective drop size) from the sensor payload. The data are quality controlled using a simple test (e.g. range test), and processed in real time (e.g. passed through low pass filter) to provide updraft velocity, droplet size and corresponding droplet concentration, and total aerosol concentrations in the fine, accumulation and coarse mode of the size distribution. These values are then passed through a series of if/then statements which essentially encompass the threshold criteria to indicate seedability. If the thresholds are met, then seeding occurs via UAS2, and UAS1 continues to make measurements in formation. The thresholds are not exclusively used for seeding, but also for establishing natural variability and addressing Lagrangian analyses, among others. They may in some circumstances be relatable to control cases in the event seeding occurred in a nearby cloud. The latter will be approached following the proven design of a software module that simulates software in the loop (SIL) technology, based on the autonomous control schematic shown in Figure 1.

We realize the scientific complexity of this task and more importantly the difficulty in operationally getting such a routine to work consistently and accurately and our approach adds the critical first step of starting with trial and error flights in a simulated environment. The simulations will include placing a cloud in the "new TITAN" with a set of assimilated observable parameters, then running the simulation to see if the UAS finds that target cloud. If it finds the area of maximum threshold condition, then it starts seeding there, until it then finds the position of the minimum threshold condition where it stops seeding. This is repeated for different clouds and environmental conditions until the "new TITAN" updates with new seeding coordinates. The simulator implementing SIL technology simulates the UAS flight characteristics, with navigation driven by sensor data collected from the previous campaigns. The SIL simulation and algorithm performance of the targeting will be evaluated by running an ensemble of simulation scenarios. Our approach using the simulations would follow the guidance of Axisa and DeFelice [1] and once the updates to the "new TITAN" software result in near perfectly accurate simulation results in selecting seedable areas and their locations, we would take UAS1 and UAS2 into the field for experimentation.

Approach for field testing the algorithms that use sensor data to guide the platform towards suitable targets to implement the seeding

Once the guidance algorithm is interfaced with the sensors and working adequately, our approach shifts toward using a UAS with the lightweight payload to locate regions of seedability, and a UAS to monitor the results following a scheme first mentioned in Axisa and DeFelice [1]. The approach would include deployment during at least two field campaigns, in an area conducive for effective cloud seeding, and preferably with active seeding programs underway, with a sole objective of testing how well the updated TITAN software performs. The system would not and should not yet be intended to be operational in any way, but meant to simply work out any challenges implementing the system.

UAS1 and UAS2, as previously defined, would be programmed to fly in a manner that exploits the advantages of flying in formation. For example, UAS1 would profile the planetary boundary layer to determine the thermodynamic and aerosol microphysical properties. It would then climb to the 5°C isotherm while UAS2 would profile downwind of UAS1 and up to the cloud formation level. Both UAS would fly in formation while approaching the cloud and profile up and down (in a saw tooth type pattern) through the top of the boundary layer while keeping a safe minimum separation. Once near the cloud each UAS would assume their position and commence their seeding mission profile where UAS1 penetrates the cloud and UAS2 samples the cloud updraft and the cloud formation level. Once seeding stops more sampling could resume which may involve a series of cloud penetrations and sampling of aerosols below cloud base (while maintaining separation).

Besides the technological challenges that must be overcome or adequately worked around, the societal and regulatory issues remain and must be respected. Axisa and DeFelice [1] highlight the latter, but the most immediate issue in this research and development case lies with aviation regulatory limitations [39]. In the United States, the Federal Aviation Administration (FAA) is the regulatory entity for air safety from the ground up, whether manned or unmanned, and irrespective of the altitude at which the aircraft is operating. While Axisa and DeFelice [1] provide details, suffice it to say that in the United States [39] the regulatory agency does not provide for UAS to be used for weather modification operations, and certainly not without a certificate of waiver or authorization (COA). The COA would at least allow an operator to use a defined block of airspace and includes special provisions unique to the proposed operation, such as, requiring flight under Visual Flight Rules (VFR) only, and/or only during daylight hours. An example of UAS operations with a COA in a cloud environment is the Verification of the Origins of Rotation in Tornadoes Experiment, or Vortex2, field campaign where a lightweight UAS measured meteorological state parameters and wind along gust fronts associated with super-cell thunderstorms [43].

Concluding Remarks

We have developed a concept for autonomous cloud seeding using UAS. We introduced an engineering approach to develop autonomous unmanned aircraft systems technology for integration in future weather modification (cloud seeding) programs with the goal to improve operational efficiency and evaluation accuracy. The broader impacts and benefits lie within evolving improved technology and automation of cloud seeding operations while lowering the operational footprint in order that we can optimize the effectiveness and efficiency of cloud seeding programs. The proposed technology could have an impact on the future of rainfall enhancement operations in arid and semi-arid regions of the world especially in those countries with limited infrastructure. The sensor package and algorithms can also be used on manned project aircraft to guide the seeding. The data collected from each seeding mission can be used in real-time to improve model parameterizations, and improve processing throughput while maximizing quality by acting as input into coupled models. The latter will also facilitate the development, improvement and/or validation of weather modification-relevant operational and evaluation models, and decision support tools.

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