In Situ Atmospheric Profiling Using Mobile Ad hoc Sensor Networks

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ABSTRACT

ENSCO, Inc. is developing an innovative atmospheric observing system known as Global Environmental Micro Sensors (GEMS). The GEMS concept features in situ airborne buoyant probes that can take measurements over all regions of the Earth. The probes will communicate with other probes and remote ground and/or space-based receiving platforms using radio frequency transmissions to form a wireless network of passive Lagrangian drifters. For a successful GEMS system, the most important network function is to relay timely data to one or more receiving stations. In this paper, we describe both the GEMS system and probe design as well as discuss the trade-offs associated with optimizing a three-dimensional, mobile, airborne network comprised of low-cost, low-power probes. We also analyze and present measured data to determine the performance of a representative GEMS prototype system under actual environmental conditions and various aspects of mobility.

Keywords: airborne, buoyant, ad hoc, mobile, microsensor.

1 INTRODUCTION

The GEMS concept features an integrated system of buoyant, airborne probes that will make in situ measurements of wind velocity, pressure, temperature, and humidity as they are carried by atmospheric currents. Each probe will be a constant-altitude (super pressure) vessel containing a payload inside a polymer composite shell and filled with a lighter-than-air gas such as helium to make the probe buoyant. Initial prototypes assembled for the functional demonstration using commercial-off-the-shelf (COTS) components will be roughly spherical or possibly disk shaped with a total mass of 70 gm and diameter of 50 cm. Operational probes developed as part of future efforts would achieve further reductions in mass and diameter (order 5 gm and 15 cm, respectively) by leveraging expected advances in micro and nanotechnologies that will allow miniaturization of the sensors and electronics. The shell size and the payload mass will determine the altitude where the probes would be neutrally buoyant. By varying the size, mass, and deployment scenarios, the GEMS system will provide four-dimensional observing capabilities spanning a broad range of time and space scales. A proposed concept of operations is illustrated in Figure 1.

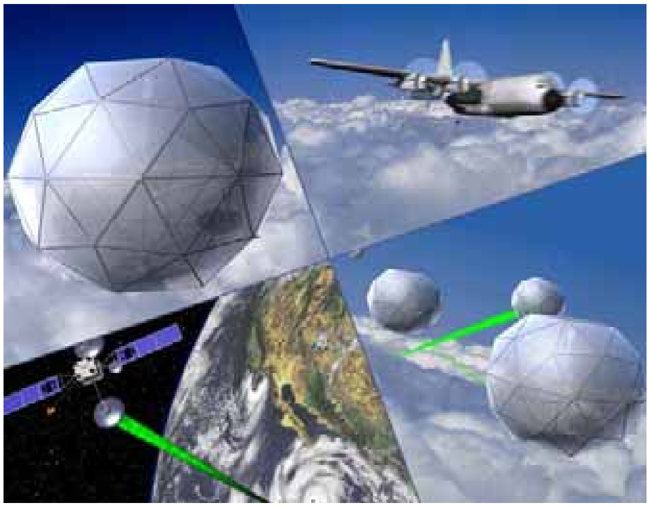

Figure 1. Conceptualization of GEMS illustrating possible probe design, deployment, dispersion, and communication / networking.

Each probe will be self-contained with a power source to provide sensing, data processing, geolocation, and communication functions. The probes will communicate with other probes and remote ground and/or space-based receiving platforms using radio frequency transmissions to form a wireless network of passive Lagrangian drifters – in effect, the “distributed instrument” is the system of probes. In addition to wind and other meteorological parameters, the probes could provide in situ sampling of ozone, carbon dioxide, and other chemical constituents and trace gases in the lowest levels of the atmosphere.

As envisioned, GEMS could provide observing capabilities spanning temporal and spatial scales from the detailed life cycle of individual clouds through planetary-scale weather. Such measurements would greatly expand our understanding of the Earth system, leading to dramatic improvements in basic science, including a more thorough understanding of physical processes in the atmosphere (e.g. cloud physics) and thereby improved representation of such processes in weather and climate models [1]. By providing capabilities to improve model physics and increasing the number of in situ observations that are most easily assimilated as dependent variables in numerical weather prediction models, GEMS data have the potential to improve operational analyses and forecasts, especially for high impact weather events, well beyond current capability.

The GEMS system would be ideal for targeted or adaptive observational campaigns as part of research (e.g. field experiments) and operational (e.g. hurricane reconnaissance) missions especially in data-sparse regions where it is only cost effective and practical to obtain high-resolution spatial and temporal resolution in situ measurements over limited domains. In fact, Gelaro et al. [2] suggest that advanced space-based wind measurements in combination with high quality in situ data, especially over regions covered with clouds, will be required to maximize the utility from targeted observations.

2 SYSTEM DESCRIPTION

The proposed GEMS system would be comprised of a network of airborne probes that report their positions and velocities from onboard micro global positioning system (GPS) hardware [3] so that exact wind velocities can be measured. Due to the adaptability of the system, the in situ probes could also sample carbon dioxide, ozone, or other trace gases through the addition of a gas sensor. The measurement of trace gases is highly dependent upon the sensitivity of the sensor. Due to the recent maturity of MicroElectroMechanical System (MEMS) sensors, ozone levels commonly found in the lower troposphere are detectable [4], but the sensitivity of MEMS sensors to gases such as CO, CO_2, hydrocarbons, NO_x and volatile organics is still limited for atmospheric applications.

The probes would communicate via a network hierarchy built around either ad hoc or mesh networking [5], [6]. The ad hoc network would enable the GEMS system to be both self-configuring and self-healing. These properties would allow for a stable and reliable communication system. For situations in which a mobile ad hoc network might not work effectively, direct satellite exfiltration, or a combination of satellite / ad hoc exfiltration could be used.

Buoyancy will be used to compensate for the weight of the electronics payload and keep the probes airborne for extended periods of time. The electronics, minus the sensors, will be encapsulated by a helium-filled polymer composite shell. The deployment of probes can occur in several ways depending on the application and desired spatial resolution and coverage patterns. For regional areas such as the continental U.S., the probes can be released like weather balloons. However, for more targeted applications including field experiments or operational reconnaissance missions, the probes could be deployed from aircraft or the surface.

For initial prototypes, the electronics payload will consist of COTS hardware, including a low-power radio, microcontroller, temperature, humidity, pressure and light sensors, miniaturized GPS unit [7], and power conditioning components. Due to the nature and weight of current battery technologies, power will be provided by thin-film solar cells working in tandem with electrolytic double layer (super) capacitors [8]. The solar cells and capacitors would allow the probes to function both in daytime and nighttime conditions. The GPS and radio would be the primary consumers of electrical power, so adaptive power management routines will be developed to minimize power usage.

The communication range of the probes will limit the maximum probe separation distance since an ad-hoc network will only work if the probes can communicate with one another. Transmission power can be modulated to conserve power by relaying messages using the minimum energy required. The network will require one or more points where data can be easily extracted or exfiltrated and eventually combined for data analysis. For measurements over populated land areas, existing ground assets such as cellular towers and modified weather stations could be used for data exfiltration. In contrast, a satellite uplink would likely be necessary for oceanic regions and non-populated land areas. The overall GEMS system will be heterogeneous, comprised of short- and long-haul communication probes, thus allowing scalability from local and regional to global scales.

3 NETWORKING / DATA EXTRACTION

Atmospheric data acquired from the airborne probes must be extracted and processed at a central facility. Since the probes are passive drifters, exfiltration becomes very complex as the size of the network grows. Extensive simulations have been performed to study the network scaling behavior.

Mobile ad hoc networks are an option for extracting data over regions where a base station can be placed to downlink and forward packets to the final destination. Assuming a simulated mean probe separation on the order of 10 km, a message hops from one node to another towards a destination where the information is collected. Tens or hundreds of such hops occur to route the information to the final destination. Each node acts as both a sensor probe and network relay. After receiving a message for routing, the probe appends its own measurement and forwards the new packet. Position-based forwarding strategies can be implemented to dynamically generate energy efficient routes based on

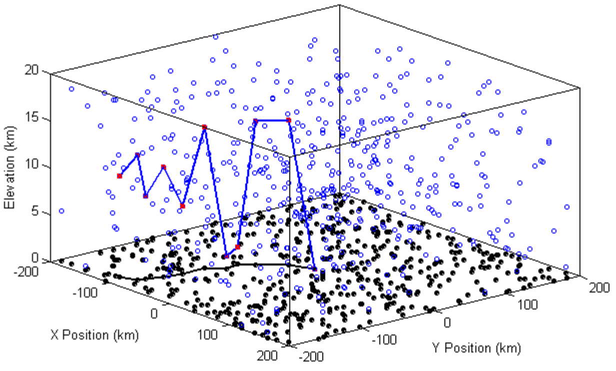

Figure 2. Example routing for simulated mobile network.

location information available to each probe via eavesdropping of nearby packet transmissions. Based on an all-for-some location service to identify the final destination point, each probe decides on a locally optimum choice to forward its data. Figure 2 shows a simulation of three-dimensional routing which is implemented to move data from one node to the final destination. A complicated branch structure results from the combined hops through the network. The nodes closest to the home destination become saturated with message traffic from distant nodes which must be passed through to the final destination. This issue becomes especially challenging as the size of the network grows.

4 DATA AND RESULTS

The goal for the experiments described here was to provide a proof-of-concept for the GEMS system. Initially a few devices were tested to determine if a limited vertical profile of the atmosphere could be reliably sampled. The experiment also allowed us to determine the feasibility of deploying larger numbers of probes in a controlled environment and develop techniques for deployment and reacquisition of the probes.

4.1 Experimental Design

Initial testing was performed using Crossbow MicaZ motes, Crossbow MTS310 sensor boards, and MTS420 weather boards with on-board GPS [7]. The motes and sensor boards were encased in Styrofoam to protect them from possible impact with stationary objects. The Styrofoam casings were passively aspirated by perforating them with holes to allow air to flow around the sensors. Initially the motes were packaged without any aspiration which resulted in temperature measurements that varied substantially from the reference temperature recorded by an Oregon Scientific WMR968 outdoor weather station (not shown).

Three MicaZ motes (ID 2, 4, 7 - highest to lowest in altitude) with MTS310 sensor boards installed were attached to a nylon filament which was then tethered to helium-filled latex balloons to provide lift. The motes were separated on the tether by approximately 15 meters. The separation allowed for a minimal vertical profile of the atmosphere. A fourth mote (ID 5 with MTS420 weather board) was attached to the tether near mote 4 to provide additional meteorological data such as pressure and humidity. The tether assembly was attached to a heavy duty reel to facilitate deployment and retrieval of the mote/balloon assembly.

The MicaZ motes were programmed with the appropriate device drivers developed by Crossbow. Unfortunately, it was not possible to combine both the MTS310 and MTS420 motes into one ad hoc network using the current software so the MTS310 motes were programmed to operate as a mesh and the MTS420 mote was operated in broadcast mode. This configuration limited the transmission range of the MTS420 mote to approximately 46 m.

4.2 Data

A control experiment was conducted indoors in a regulated environment to determine the effect of the packaging on the motes. The actual temperature was recorded by an Oregon Scientific BTHR968 indoor wireless sensor. The average difference measured was 2°C for the MTS310 sensor boards and 9°C for the MTS420 board after an hour of continuous operation.

The outdoor experiment was conducted from the top of a two-story building approximately 9 m above ground level. The Oregon Scientific WMR968 weather station located on top of the building was used to provide ground truth for the measurements. The weather conditions at the time of release were an average wind of 3.9 m s^{-1} with periodic gusts up to 5.9 m s^{-1} and prevailing wind direction of 326^{o}. The outdoor temperature was 26.1°C with 43% relative humidity (RH) and a barometric pressure of 1008 millibar (mb). Data were acquired for approximately 45 minutes before the balloon assembly failed. A sample of the measured data is presented below in Table 1 and Figure 3.

Table 1. Mote 5 with a MTS420 weather board. Readings acquired over a 45-minute interval.

Relative Humidity (%)	Pressure (mb)	Temperature (°C)
18.0	1002.3	43.47
17.9	1002.0	43.64
17.7	1008.5	44.11
17.8	1001.0	43.98
15.4	1000.1	46.00

4.3 Results

The data indicate that the mote packages are still not aspirated well enough. The temperature recorded by the motes was significantly higher than both the indoor and outdoor temperature. These differences can be attributed to the Styrofoam packaging trapping the heat generated by the mote and to solar heating for the outdoor experiment. Another interesting discrepancy was the difference in RH levels. During indoor testing, the RH was verified against the BTHR968 sensor with very good agreement (not shown). However, the outdoor RH measurements were considerably lower than the reference values obtained from the WMR968 weather station probably due to inadequate aspiration. Essentially, the mote was measuring the warmer (and considerably drier) air inside the Styrofoam package. The Crossbow MTS420 boards do not have built in power management for the GPS unit which is the main generator of heat around the circuit board.

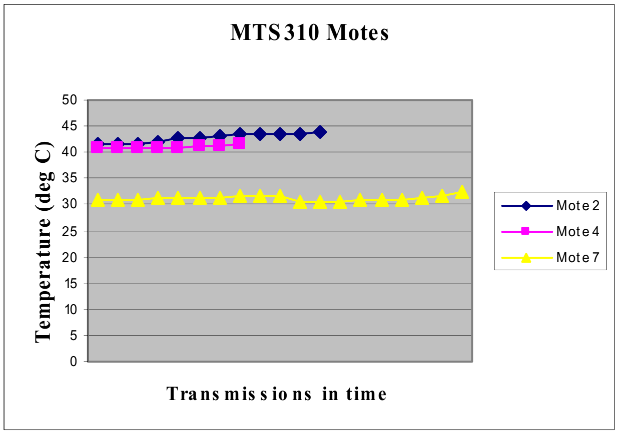

Figure 3. Temperature data acquired from motes equipped with MTS310 sensor boards. The temperatures trend upwards in time indicating that the motes are experiencing some heating.

The pressure measured by the MTS420 sensor board correlated well with the WMR968 reference pressure. The measured pressure also gives a good indication of the altitude of mote 2 at the time of the measurement. One millibar of pressure change roughly equates to ten meters of altitude change. The range of altitudes can be determined by noting the change in pressure from the ground truth. The measured pressure differed by at most 8 mb from the WMR968 which was located approximately 10 meters off the ground. Therefore, the maximum altitude reached by mote 5 was estimated at 80 meters above the WMR968 sensor.

The transmission range of the motes is very problematic for the current application. The MicaZ motes were originally designed to operate indoors and therefore have a limited range. The balloon / mote assembly often drifted out of transmission range limiting the number of measurements made during the preliminary experiment. We are currently looking into higher power motes such as the Crossbow Mica3 for further experimentation.

4.4 Future Work

Prototype development will continue with the design and implementation of the solar panel / super capacitor adaptive power system. Once the power system has been implemented, testing will continue with the GEMS probe including a variety of environmental and mobility conditions. Since sensor aspiration is also a critical issue, a new scheme will be developed that optimizes sensor performance to increase accuracy and repeatability of the measurements. New drivers will also be developed to incorporate both the MTS310 and MTS420 equipped MicaZ motes to function in one ad hoc network. The mobile ad hoc network will also be tested more thoroughly by flying the probes independently and monitoring the network performance. Eventually, our goal is to fly a larger number of probes in a non-tethered arrangement to fully test the GEMS system.

The longer term goal for the system is to create ultra lightweight probes that take advantage of advances in micro / nanotechnology for the sensors, electronics and materials. These probes are envisioned to be very low cost, unobtrusive, and bioinert (or possible biodegradable) thereby minimizing environmental impacts especially when deployed in large numbers around the world.

5 CONCLUSIONS

In this work we have described a revolutionary system for in-situ sampling of the atmosphere. The GEMS system once developed could have a significant impact on our understanding of atmospheric processes. Although, the system has been simulated extensively, much work is still needed to develop a functional prototype. Issues such as aspiration, ad hoc networking, and power generation still need to be resolved. We are working to produce a small-scale prototype system that can be tested under actual environmental conditions to demonstrate the effectiveness of the GEMS concept.

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