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GLOBAL ENVIRONMENTAL MEMS SENSORS (GEMS): A REVOLUTIONARY OBSERVING SYSTEM FOR THE 21ST CENTURY

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1. INTRODUCTION

Technological advancements in MicroElectro-Mechanical Systems (MEMS) have inspired the concept for a new observing system called Global Environmental MEMS Sensors (GEMS). GEMS features in situ, micron-scale airborne probes that can measure atmospheric variables over all regions of the Earth with unprecedented spatial and temporal resolution. Meteorological observations from a GEMS network have the potential to provide a quantum leap in our understanding of the Earth's atmosphere and improve weather forecast accuracy well beyond current capability. In addition to gathering meteorological data, probes could be used for environmental monitoring of particulate emissions, organic and inorganic pollutants, ozone, carbon dioxide, and chemical, biological, or nuclear contaminants. Once the probes settle out of the atmosphere, they could continue making measurements over land or water.

Assessment of the optimum probe design and deployment requires an interdisciplinary collaboration to examine complex trade-off issues such as the number of probes required in the network, development and manufacturing costs, and the impact of probe observations on forecast accuracy. This paper provides background, expected significance, concept description, and previous work done, and summarizes the meteorological and MEMS disciplines necessary for system design and development.

2. BACKGROUND

Significant progress has been made in observing the atmosphere at finer spatial and temporal scales over many areas of the world; however, in situ observations are not distributed evenly around the globe, and are sparse over oceans, high latitudes, and politically sensitive regions. Space-based observing technology such as low Earth orbiting (LEO) satellites currently provide high spatial resolution, but suffer from inadequate temporal resolution, insufficient vertical resolution, and uncertain or unknown calibration and accuracy between years (Unninayar and Schiffer 1997). The most sophisticated current-generation sensors (e.g. ground or space-based lidars and infrared instruments) do not provide all-weather capability since they cannot penetrate optically thick clouds.

Numerical weather prediction (NWP) models have become increasingly important to generate forecast guidance for operational meteorologists since their introduction over four decades ago (Shuman 1989). Satellites, radars, and other remote sensors do not currently provide a complete data set required to initialize NWP models since they measure radiance or reflectivity instead of direct measurements of model dependent variables such as temperature, moisture, and wind velocity. Because of these limitations, operational centers are required to develop and use complex and computationally expensive data assimilation methods to transform measurements from remote sensors into dependent variables for initializing models. Although satellite data comprise more than 80% of observations ingested by operational NWP models at the National Centers for Environmental Prediction, the models use less than one-fifth of available data from LEO satellites (Uccellini et al. 2001).

Technological advances in computer speed and memory size over the past few decades have enabled significant reductions in horizontal and vertical grid spacings, advancements in model physics, and development of more sophisticated procedures to initialize NWP models. This trend of increasing complexity in weather models has resulted in improved weather forecasts; however,

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chaotic systems like the Earth's atmosphere have a limit of predictability even with perfect models due to differences between the true and observed state of the atmosphere (Lorenz 1969). If future computer performance continues to double every 18 months following Moore's law (Moore 1965), model complexity and grid resolution will increase to a point where in situ observations will be inadequate to determine accurate and representative initial conditions. Without high-resolution observational data to constrain the initial conditions, progress toward attaining the theoretical upper limit of predictability with NWP models will likely be halted prematurely.

Overcoming limitations with current meteorological sensor technology and providing observation capabilities that are commensurate with advances in NWP models will require revolutionary technologies to gather and transmit real-time weather data. MEMS that combine electrical functions with sensors and other mechanical devices embedded in semiconductor chips have the potential to enable that revolution.

2.1 Concept Description

The objective of the GEMS project is to design an integrated system of MEMS probes that can provide ultra-high spatial and temporal resolution measurements of atmospheric pressure, temperature, humidity and wind velocity (based on changes in probe position) as they are carried by atmospheric currents (Fig. 1). The probes will have to make measurements over a broad range of atmospheric conditions. Aerodynamic design is relatively unimportant for probe sizes below one cubic millimeter. Depending on the specific application, it may be desirable to design and deploy probes larger than one cubic millimeter where aerodynamic design could reduce the ballistic coefficient [weight/(drag coefficient x area)] and terminal velocity. There are many examples of such design in the natural world, including simple dandelion spokes and threads of balloon spiders, as well as sophisticated evolved forms like the auto-rotating samaras (Walker 1981). Future advancements in materials science and nanotechnology could help pave the way for the design and development of morphing probes.

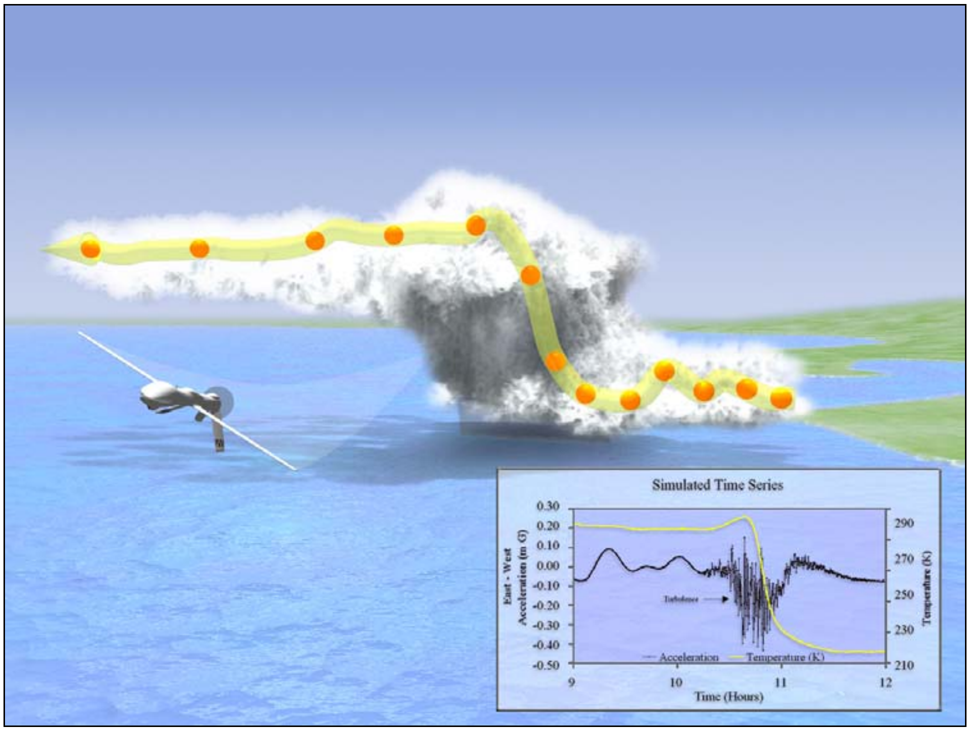

Figure 1. Conceptualization of probe deployment around a thunderstorm. The yellow tube denotes a single probe trajectory with the spheres showing instantaneous locations as the probe is carried by the airflow through the thunderstorm updraft and into the anvil.

Each probe will be self-contained with a power source to provide sensing, navigation, and communication functions. The probes will communicate with each other and remote receiving platforms to form a mobile, in situ network. Since each probe will include sensors to measure all weather variables, there is significant redundancy if several probes in the network fail. The probes will have to be robust enough to ensure that the electronics are isolated from the effects of liquid and frozen water, dust, chemical pollutants, radiation, and static electricity. In order to regulate power consumption, active power management may be necessary using adaptive measurement strategies whereby the temporal (and therefore spatial) frequency of sensing and communicating is linked with vertical and horizontal changes in atmospheric parameters.

While GEMS will likely complement the current and even next generation suite of in situ sensors and ground/space-based remote sensing platforms, the concept is revolutionary because it:

- Provides a 100-fold increase in the horizontal resolution of in situ, tropospheric and lower stratospheric observations that are most easily assimilated by NWP models,
- Uses the natural dispersive characteristics of the atmosphere to transport probes into regions where it is not practical or possible to obtain data and where very few or no in situ observations currently exist,
- Features devices that (a) are disposable, (b) are envisioned to be mass produced at very low per unit cost, (c) do not require recovery to collect data, and (d) are small enough to pose virtually no threat upon contact with persons or property during flight.

2.2 Expected Significance

The Department of Commerce estimates that $2.5 trillion dollars of the U.S. economy has weather and climate sensitivity (NRC 1998). For example, the best hurricane track forecasts still have errors of more than 200 nautical miles at 72 hours; thus, over-warning of affected areas is required to account for such uncertainty (Franklin et al. 2001). Since it costs more than half of a million dollars to evacuate one linear mile of coastline (OFCM 1997), a 10% reduction in forecast track errors would result in a potential savings of at least $10 million for each storm affecting populated areas. In addition, severe weather is estimated to cause billions of dollars in damages annually throughout the U.S. (Pielke et al. 1997); so there are enormous economic incentives to improve the forecasts of high impact weather events. Ultra-high spatial and temporal resolution measurements could lead 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 NWP models. A long-term observational database from GEMS could prove valuable to monitor climate changes.

Weather-sensitive customers worldwide including those in areas of ground transportation, agriculture, aviation, utilities, insurance, air quality monitoring, operational/research meteorology, and other earth sciences could benefit from improved observations and forecasts enabled by GEMS. With a modular sensor suite, probes could be used to measure acoustic, chemical, biological, nuclear, or other parameters of interest to defense agencies for intelligence gathering, battlefield situational awareness, and urban warfare monitoring. The probes could monitor oceans, rivers, and other surface water bodies as well as take measurements on land once they complete the airborne portion of their mission.

2.3 Previous Work Done

The design and development of prototype, millimeter-scale probes using MEMS sensors has been the focus of the “Smart Dust” project at UC Berkeley since 1998 (Kahn et al. 2000). Kahn et al. (2000) envision numerous applications for smart dust and suggest that air currents could transport the probes to record meteorological observations for as long as they remain suspended in the atmosphere. Engineers at the Center for Wireless Integrated Microsystems (University of Michigan) have developed an integrated gas chromatography system operating at 1 milliwatt in 1 cubic centimeter, capable of detecting over 40 specific gases (Adrian 2001).

The probe size is critical because the devices must ultimately be small enough to remain suspended in the atmosphere for periods of time on the order of hours to days. At the current millimeter size, a probe deployed at 20 km altitude would reach the ground in less than 0.5 hours in the absence vertical air motion. Under identical conditions, a 100 μm sized probe would take nearly 70 hours to fall from the same altitude. Studies of natural aerosols such as African dust and volcanic ash indicate that micron-size particles remain suspended in the atmosphere for days to weeks (Sarna-Wojcicki et al. 1981; Prospero 1999).

The ultimate GEMS design will likely require a paradigm shift in the areas of microelectronics and miniaturization to address the technical challenges with power, communication, navigation, and networking. For example, organic cells feature complex “machines” and systems that may guide the design and functionality of micro and nanoscale devices and components (Soong et al. 2000). Material science will play a key role to limit probe mass and potentially make them biodegradable thereby minimizing environmental impacts when the probes settle out of the atmosphere.

3. MEMS

In order to substantiate the GEMS concept, it is necessary to define the major feasibility issues for miniaturizing the volume of current prototypes and provide baseline parameters and realistic projections for the following characteristics.

Overall Design: The probes should be sufficiently small and light to remain aloft as long as possible. Materials will be an important consideration in minimizing the mass of the probes. With linear dimensions of a few millimeters, current prototype devices possess the power, sensing, computing and communication capabilities that would be desirable for a much smaller probe. To miniaturize the probes’s linear dimension by one order of magnitude requires that the probe volume be reduced by three orders of magnitude assuming all critical attributes such as energy density, data storage and computational power can be scaled accordingly. These issues and others including component geometry, aerodynamic design, and buoyancy solutions are being examined as part of the overall design.

Sensors: Present commercial-off-the-shelf MEMS sensors are being examined to determine if their accuracy and dynamic range is sufficient to meet requirements for measurements of temperature, pressure, and moisture. Projections of future advances in sensor technology are being explored to determine if there are limits to the size of sensors for making such measurements at the required accuracy. Other issues being considered are calibration, noise suppression, self-test and activation procedures along with the amount of data that can be stored and processed on-board probes given the expected advances in microprocessor technology and available power.

Power: Several candidate power sources are under consideration including batteries, micro fuel cells (Lee et al. 2000), vibration/solar energy (Pister 2001), and biochemical analogs such as MEMS cilia (Saffo 1997). It will be important to identify power requirements (Pister 2001), output from each source, and trade-offs in probe functions to communicate, sense, and compute for specified values of power, size, sensor lifetime, accuracy and communication range. In order to regulate consumption, active power management may be necessary using adaptive measurement strategies whereby the temporal (and therefore spatial) frequency of sensing and communicating is linked with vertical and horizontal changes in atmospheric parameters. For example, it would be advantageous to have higher (lower) temporal resolution measurements in weather scenarios characterized by stronger (weaker) gradients in velocity, temperature, moisture, etc.

Communication and Networking: A critical challenge is to define viable communication and networking solutions given available power and probe separation. It is important to examine communication protocols, networking strategies, data structures, and determine how many bits of data must be exchanged per unit time and at what power cost given requirements of accuracy and sampling rate. Potential methods to retrieve data from probes include active transmission via radio frequency (RF) or free space optical transmission (Kahn et al. 2000) as well as passive RF techniques (e.g. backscatter modulation; Kossel et al. 2000). These (and other) communication technologies are being examined to determine reliability, achievable range, bandwidth, and latency. The probe separation distance as well as power constraints and communication range will determine if each probe can transmit to a remote receiving station (aircraft, LEO satellite, etc.) or if mobile networking via multihop routing (Delin and Jackson 2000; Kahn et al. 2000) is viable.

Navigation: Since atmospheric wind velocity will be determined based on changes in probe position, it is critical to assess whether miniaturization of accelerometer, gyroscope, and GPS technology (Allen et al. 1998) will provide viable opportunities for navigation. If navigation sensors record all components of motion, on-board processing will likely be required to determine velocity from signals containing rotation/spin, translation, and drift due to gravitational settling. Furthermore, it is important to consider if on-board signal processing is possible given projected microprocessor computational capability and power required for other functions including data storage, sensing, and communication.

4. METHODOLOGY

Pursuit of the GEMS concept is necessarily interdisciplinary, guided by realistic projections of progress in the miniaturization of probe components. Interdisciplinary collaboration is the key element of a design-simulation-test cycle quantifying trade-offs between weather forecast impacts and sensor characteristics. For example, probe lifetime may vary significantly depending on how long they remain airborne as well as other factors such as sampling rate, communication frequency, and on-board data storage and processing. These characteristics will affect the quantity and latency of data available for assimilation into NWP models as well as the subsequent forecasts initialized using such data.

The large number of possible trade-offs based on design characteristics such as sensor accuracy and sampling frequency, data assimilation methodologies, weather scenarios, and other factors constitute a multi-dimensional parameter space. System modeling is used as a cost-effective and controlled way to explore the trade-offs.

4.1 Simulation System

The nature of atmospheric flow patterns is sufficiently variable that probes could remain near their release point or be rapidly swept away by the wind. NWP models are capable of resolving this variability and are therefore ideal tools to simulate probe dispersion and deployment. In addition, simulated measurements of atmospheric temperature, pressure, humidity, and wind velocity can be used to evaluate the impact of these observations on meteorological analyses and forecasts for different weather regimes. Measurements from the probe network must be of sufficient accuracy and spatial coverage to improve the diagnosis and forecasting of weather patterns, above and beyond the skill obtainable with conventional weather observations. Simulation experiments can also provide guidance for probe requirements relating to sampling frequency, data storage and processing, networking and navigation algorithms, and communications capability.

The Advanced Regional Prediction System (ARPS; Xue et al. 2000; Xue et al. 2001) coupled with a Lagrangian particle model (LPM) is used to simulate dispersion of and observations collected by an ensemble of probes. The ARPS is a complete, fully automated, stand-alone system designed to forecast explicitly storm- and regional-scale weather phenomena. It includes a data ingest, quality control, and objective analysis package known as ADAS (ARPS Data Analysis System; Brewster 1996), a prediction model, and a post-processing package.

The ADAS generates initial conditions for the ARPS model by combining weather observations with a background grid, typically provided by a larger-scale atmospheric model. ADAS utilizes the Bratseth objective analysis procedure (Bratseth 1986) consisting of an iterative successive corrections method (SCM) that converges to the statistical or optimum interpolation (OI). The Bratseth scheme is superior to traditional SCM methods because it accounts for variations in data density and observational errors, similar to OI. This capability is critical to determine how the accuracy and distribution of simulated MEMS-based observations affect meteorological analyses and forecasts.

4.2 Probe Dispersion

The dispersion of probes is simulated using a LPM embedded within the ARPS. The LPM tracks the location of each probe based on three-dimensional wind components and updates probe position (x, y, z) from the following:

$$x(t + \Delta t) = x(t) + [\, u(t) + u'(t) \,] \Delta t \tag{1}$$

$$y(t + \Delta t) = y(t) + [\, v(t) + v'(t) \,] \Delta t \tag{2}$$

$$z(t + \Delta t) = z(t) + [\, w(t) + w'(t) + w_d \,] \Delta t \tag{3}$$

where Δt is the model time step, u, v, and w are the resolvable-scale west-east, north-south, and vertical components of wind velocity, respectively, obtained directly from the ARPS model, and u', v', and w' are the turbulent velocity fluctuations estimated from a subgrid scale (SGS) turbulence parameterization (Mellor and Yamada 1982) that is very similar to the

SGS scheme of Deardorff (1980) used in the ARPS model. The w_d term in equation (3) is the vertical slip velocity for gravitational settling. The probes are assumed to be passive tracers moving independent of one another and transported by the wind.

4.3 Deployment

A large number ($>10^6$) of simulated probes can be deployed any time during the model integration at any latitude, longitude, and altitude within the three-dimensional model domain. The LPM provides accurate position information because the velocity variables in equations (1) – (3) are updated every model time step by tri-linear interpolation to the actual probe locations. The probes are assumed to have an infinite lifetime until the wind carries them beyond the boundaries of the model domain. The probes are not tracked within six grid zones of the lateral boundaries where enhanced numerical diffusion is used in the transition to external model boundary conditions.

Candidate deployment patterns to be explored include release from: (a) a network of stations at or above the surface of the earth, (b) unmanned aerial vehicles (Holland et al. 2001) for selected remote deployments, (c) conventional aircraft and ocean going vessels, and (d) high altitude balloons (Girz et al. 2002; Pankine et al. 2002). In fact, simulated or virtual weather scenarios make it possible to test these and many other deployment strategies and evaluate how deployment patterns affect probe dispersion, separation distance, and transport lifetime.

Probe deployment is envisioned for numerous scenarios where high spatial and temporal resolution data are required to assess the potential for and development of tornadoes, severe thunderstorms, and hurricanes, or to support military operations in data-limited or data denied-regions. The grand vision is to design a deployment strategy that could sustain global coverage. To achieve the grand vision would require $\sim 10^{10}$ airborne probes at any given time assuming a uniform horizontal and vertical probe spacing of 1 km from the surface up to about 20 km. A rough estimate of the data rate produced by such a network would be $\sim 10^{12}$ observations per day if temperature, pressure, humidity, and wind velocity are retrieved once per hour. It will be important to determine whether it is even practical, cost effective, and necessary to design a deployment strategy to achieve and sustain 1-km global coverage.

Uccellini et al. (2001) anticipate a 5-order of magnitude increase from the current $\sim 10^6$ to 10^{11} upper-air observations per day within 10 years primarily due to planned operational satellite instruments. Although data rates from a global GEMS network are comparable with future observing systems in the next decade, there are still substantial challenges for data communication and management which will require optimization of observing systems and new paradigms for data mining, sampling, selection, and assimilation.

4.4 Simulated Observations

To simulate measurements obtained from probes or conventional instrumentation, the tri-linear interpolation algorithm is used to extract values of temperature, humidity, pressure, cloud water, and other model variables at locations throughout the model integration. Assuming the probes are passive tracers, temporal changes in their absolute or relative position are used to estimate wind velocities. Finally, a random component that represents measurement error is added to the simulated observations in order to address questions regarding instrument accuracy.

4.5 OSSEs

OSSEs are used to assess the impact of probe measurements on weather analyses and forecasts following Atlas (1997) and Lord (1997):

- Initialize the ARPS model at time t_0 with ADAS and integrate the model forward in time to provide a complete simulated weather history known as the reference run.
- Extract simulated conventional and probe observations from the reference run at $t_0 + \Delta t$ and add appropriate random components to simulate observational error.
- Initialize the ARPS model using simulated conventional and probe observations at $t_0 + \Delta t$ with a different background field (and boundary conditions) than the reference run and integrate the model forward in time for each experiment.
- Assess the impact of data from GEMS on forecast skill by comparing the conventional and GEMS-based forecasts with the reference run using quantitative measures such as root mean square error, bias, etc.

The results from OSSEs are generally considered more robust if (a) different models are used for the reference run and subsequent assimilation and forecasts and (b) benchmark experiments are performed with the system using real observations to assess the actual impact of current operational systems and compare these results with the OSSEs. While these characteristics of an OSSE design are desirable, they are not essential to obtain meaningful OSSE results as demonstrated recently by Kuo et al. (1997).

5. RESULTS

The analysis of OSSE results for a severe thunderstorm/tornado-producing event over east-central Florida on 15 June 2001 was not completed in time to include in this paper. The results will be summarized at the conference including both qualitative and quantitative measures of the impact of probe data on 12-h forecasts within a regional domain covering the Florida peninsula and adjacent waters in the eastern (western) Gulf of Mexico (Atlantic Ocean).

6. FUTURE DIRECTION

In future efforts, the multi-dimensional parameter space can be explored more completely as part of a detailed cost-benefit analysis. If appropriate and practical, experimentation can be used to study key technology issues such as navigation, networking, and communication. Once an acceptable virtual probe design is achieved, prototypes can be built in a logical sequence including static and dynamic tests in cloud chambers and wind tunnels, and limited deployment from manned aircraft and/or unmanned aerial vehicles as part of field experiments.

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