On the Utility of Airborne MEMS for Improving Meteorological Analysis and Forecasting

J. Manobianco and D. A. Short

ENSCO Inc., Aerospace Sciences and Engineering Division, 1980 N. Atlantic Ave., Suite 230
Cocoa Beach, FL, USA 32931, manobianco.john@ensco.com

ABSTRACT

Among the applications envisioned for Micro ElectroMechanical Systems (MEMS) sensors are weather observations from probes that are suspended in the atmosphere and carried by wind currents. This paper describes preliminary experiments with a state-of-the-science numerical weather prediction model and coupled Lagrangian particle model that are configured to simulate dispersion of and measurements collected by an ensemble of MEMS sensors for meteorological applications. Within the framework of observing system simulation experiments, model results are used to estimate the minimum sensor accuracy, separation distance, and sampling frequency required to improve meteorological analyses and forecasts. The simulation results will also help to refine the present and future design of sensor specifications including data storage and processing, networking, and communications capabilities.

Keywords: System and multi-level modeling, Micro ElectroMechanical Systems (MEMS), smart sensors, smart dust, environmental monitoring

1 INTRODUCTION

A continuing challenge in numerical weather prediction (NWP) is to provide high resolution forecast models with data of sufficient density and quality to determine more accurate and representative initial conditions. A recent comprehensive report from the National Research Council [1] has recommended the following as its second imperative for atmospheric research: "Develop new observation capabilities for resolving critical variables on time and space scales relevant to forecasts of significant atmospheric phenomena." Technological advances in computer speed and memory size over the past few decades have enabled significant reductions in horizontal grid spacings and advancements in model physics, resulting in improved weather forecasts. This trend of increasing complexity in weather models will persist if computer performance continues to double every two years following Moore's law.

Significant progress has been made in observing the atmosphere at finer spatial and temporal scales over many areas of the world using radars, satellites, aircraft, and other new and existing sensors. However, in-situ observations are not distributed evenly or densely around the globe and are sparse over oceans, high latitudes, and politically sensitive regions. In addition, satellites, radars, and other remote sensors do not provide a complete suite of measurements required to initialize models. Overcoming such limitations and providing both regional and global observing capabilities that are commensurate with advances in NWP models will require revolutionary technologies to gather and transmit real-time weather data. Micro ElectroMechanical Systems (MEMS) have the potential to enable that revolution and to improve the synergism between models and observations.

The goal of this study is to guide the present and future design of cost-effective MEMS probes for meteorological applications. To achieve this goal, a three-dimensional state-of-the-science NWP model known as the Advanced Regional Prediction System (ARPS [2], [3]) is configured and integrated in time to simulate observations collected by an ensemble of MEMS sensors.

Previous studies used NWP models to assess how adaptive observations can impact subsequent forecasts, especially if they are available in data-sparse regions where model errors can grow substantially due to large initial condition uncertainty [4]. However, the current research is unique in determining how simulated data collected from an array of MEMS-based sensors can improve weather analysis and forecasting.

2 WEATHER MEMS

The design and development of prototype, millimeter-scale probes using MEMS sensors is the focus of the "Smart Dust" project at the University of California Berkeley [5]. Kahn *et al.* envision numerous applications for Smart Dust and suggest that air currents could transport these probes to record meteorological observations for as long as they remain suspended in the atmosphere [5].

The nature of atmospheric flow patterns is sufficiently variable that weather MEMS could remain near their release point or be rapidly swept away by the wind. This atmospheric behavior strongly suggests that NWP models should play an important role in simulating the dispersion patterns for proof-of-concept studies and prototyping the sensors during the development and testing phase. In addition, simulated measurements of atmospheric temperature, pressure, humidity, and wind velocity from sensor networks can be used to evaluate the impact of these observations on meteorological analyses and forecasts for different weather regimes. Measurements from the sensor 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 sensor requirements relating to sampling frequency, data storage and processing, networking and navigation algorithms, and communications capability.

3 SIMULATION SYSTEM

The ARPS ([2], [3]) coupled with a Lagrangian particle model (LPM) is used to simulate dispersion of and observations collected by an ensemble of MEMS 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, [6]), a prediction model, and a post-processing package.

3.1 Advanced Regional Prediction System

The numerical forecast component of the ARPS is a three-dimensional, nonhydrostatic model appropriate for use on scales ranging from a few meters to hundreds of kilometers. The ARPS model is based on the compressible Navier-Stokes equations describing atmospheric flow using curvilinear, terrain-following coordinates. The model also contains comprehensive parameterizations to represent atmospheric turbulence, radiation, clouds, precipitation, surface heat, moisture and momentum fluxes, and land-surface energy budgets.

3.2 ARPS Data Analysis System

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 [7] 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.

3.3 MEMS Dispersion

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

$$X(t + \Delta t) = x(t) + [\ u(t) + u'(t)\ ]\ \Delta t \qquad (1)$$

$$Y(t + \Delta t) = y(t) + [\ v(t) + v'(t)\ ]\ \Delta t \qquad (2)$$

$$Z(t + \Delta t) = z(t) + [\ w(t) + w'(t) + w_d\ ]\ \Delta t \qquad (3)$$

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 [8] that is very similar to the SGS scheme of Deardorff [9] used in the ARPS model. The w_d term in equation (3) is the vertical slip velocity for gravitational settling. The sensors are assumed to be passive tracers moving independent of one another and transported by the wind.

A large number ($>10^6$) of simulated sensors 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 sensor locations. The sensors are assumed to have an infinite lifetime until the wind carries them beyond the boundaries of the model domain. The sensors 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.

To simulate measurements obtained from MEMS probes, the tri-linear interpolation algorithm is used to extract values of temperature, humidity, pressure, cloud water, and other model variables at sensor locations throughout the model integration. Assuming the sensors 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 of MEMS-based sensors.

4 SIMULATION EXPERIMENTS

Forecast models can be used to simulate dispersion of and observations collected by MEMS sensors for a variety of deployment scenarios and weather patterns in a cost effective and controlled environment. Candidate deployment patterns include sequential release from: (1) a network of stations at or above the surface of the earth, (2) unmanned aerial vehicles for selected remote deployments, and (3) routine transportation systems such as airlines and ocean going vessels to obtain global coverage.

4.1 Simulated Dispersion

Preliminary experiments are designed to test the LPM and simulate a deployment of sensors from 20 surface observation sites across Florida beginning at 1500 UTC 28 February 1999. This date is selected because the ARPS and ADAS were already configured to assimilate conventional weather observations as part of an ongoing study to evaluate the utility of local data integration systems in east central Florida [10]. The ARPS horizontal grid resolution used for the simulation is 10 km covering a 500 km x 500 km area shown in Figure 1. The model grid contains 30 vertical layers of varying thickness from 20 m near the surface of the earth to about 1.8 km at the top of the domain (~16.5 km), and the model time step is 10 s [Δt in equations (1) – (3)].

The hypothetical sensors are released at an altitude of 500 m every minute during a 6-hour integration of the model from 1500 UTC through 2100 UTC 28 February 1999. The w_d term in equation (3) is set to zero for the preliminary experiments so the sensors are assumed to be neutrally buoyant (i.e. no gravitational settling). At the end of the 6-hour integration, 7200 sensors have been released into the model domain (1 per minute x 360 minutes x 20 stations). However, the total number of active sensors at any given time varies depending on how rapidly the wind carries the sensors out of the tracking domain.

Figure 1 shows a simulated dispersion pattern at 2100 UTC 28 February after 6 hours of model integration. It is clear that the sensors are being swept northeastward and are becoming more widely separated as they move farther from their respective release points. Sensor altitudes average about 506 m, but are widely dispersed ranging from 15.6 – 2194 m with a standard deviation of about 266 m. There are a total of 5581 active sensors within the model domain at 2100 UTC 28 February which indicates that more than 20% of the 7200 simulated sensors have impacted the surface or moved into the boundary zones.

A statistical analysis of the nearest-neighbor distances is performed for 60 sensors deployed from all 20 sites during the first hour of the model integration. The minimum separation distance for these sensors as they propagate in the low-level atmospheric flow is plotted as a function of time in Figure 2. After one hour, the mode separation distance of ~900 m is consistent with a wind speed of 15 m s^{-1} and a deployment interval of 60 s. The frequency distributions illustrate that both the average nearest-neighbor distance and its spread increases with time as implied by the dispersion pattern shown in Figure 1.

The increase in nearest-neighbor distances (Figure 2) and the dispersion pattern (Figure 1) illustrate the challenges to design communications and networking strategies for MEMS so they can provide useful data to improve weather analyses and forecasts. Simulation studies such as those described in this paper can provide guidance for the design and testing of prototype networking solutions [5].

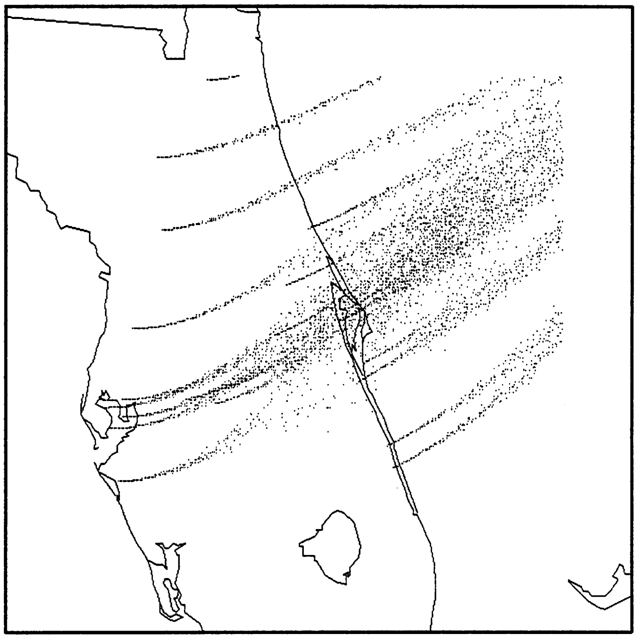

Figure 1: The ARPS model domain used for the simulated MEMS sensor deployments. The dots represent the location of 5581 sensors at 2100 UTC 28 February 1999.

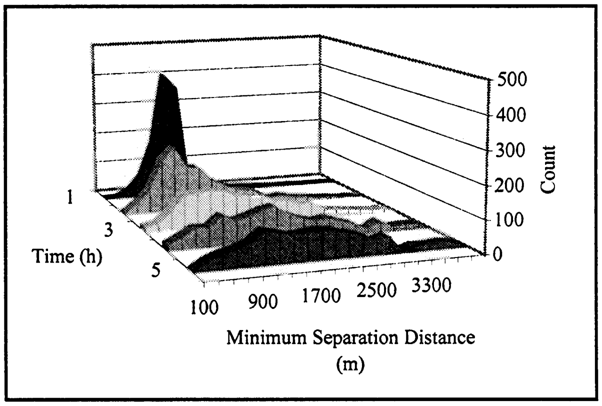

Figure 2: Frequency distribution of minimum separation distance (m) as a function of time (h) for a simulated ensemble of sensors.

4.2 Simulated Observations

Observing system simulation experiments (OSSEs) are used to assess the potential impact of MEMS-based measurements on weather analyses and forecasts [11]. The ARPS model will be initialized at t_0 by ADAS using all available conventional data and run for 12 hours to provide a complete simulated weather history referred to as the reference run. Simulated observations from the dispersed MEMS sensors (as in Figure 1) will then be extracted and used by ADAS to initialize a new forecast at t_0+6 hours. The new forecast will be run for 6 hours and compared to the reference run to evaluate the impact of the MEMS sensor data on forecast accuracy. The accuracy of the MEMS-based forecast will also be compared to a second forecast initialized at the t_0+6 hours using simulated conventional observations. A third forecast will be initialized by ADAS using a combination of simulated MEMS sensor and conventional data and run for 6 hours. The design and execution of a series of OSSEs is envisioned to provide feedback and guidance for the specifications of weather MEMS sensors for a variety of weather patterns and flow regimes.

Table 1 gives first guess estimates of the dynamic range and accuracy of simulated sensor variables, along with data storage requirements. At 20 bytes per observation per sensor and an observing interval of 15 minutes that is sufficient for regional analysis and forecasting, a total of 160 bits of information from each sensor would be obtained every 900 seconds. Remote transmission of the data would be well within the bit-rate capability of prototype systems [5]. The OSSEs provide a framework to conduct trade-off studies between MEMS functions such as sense, compute, and transmit as outlined by Kahn *et al.* [5] and weather forecast accuracy.

Table 1: Variable specifications for each sensor

	Dynamic Range	#bytes	Accuracy
Temperature	-80 to +40°C	1	+/- 1°C
Pressure	50 to 1050 mb	2	+/- 1 mb
Humidity	10 to 100 %	1	+/- 5%
Latitude	-90 to +90°	3	+/- 0.001°
Longitude	0 to 360°	3	+/- 0.001°
Altitude	-1 to +20 km	2	+/- 100 m
Time	$t_0 + 10^7$ s	4	+/- 10 s
Sensor ID	1 to 10^6	4	N/A

5 SUMMARY AND FUTURE WORK

This paper describes preliminary experiments with the ARPS and an embedded LPM that are designed to simulate dispersion of and measurements collected by an ensemble of hypothetical MEMS sensors for meteorological applications. The simulation results are used to assess sensor dispersion as a function of time. Within the framework of an OSSE, simulated observations from a network of MEMS sensors will be used to estimate the minimum accuracy, separation distance, and sampling frequency required to improve meteorological analyses and forecasts for different weather patterns and deployment scenarios. The model results will also help to refine the present and future design of sensor specifications including data storage and processing, networking, and communications capabilities.

The remaining tasks to perform for the project are as follows.

a) Expand the horizontal extent of the ARPS domain so that dispersion can be simulated for longer periods of time before sensors reach the lateral boundaries.
b) Develop and test other deployment scenarios.
c) Extract simulated MEMS and conventional observations from the model runs.
d) Run OSSEs and analyze results.

Progress on these efforts will be reported at the conference.

REFERENCES

[1] National Research Council, Board on Atmospheric Sciences and Climate, Commission on Geosciences, Environment, and Resources. *The Atmospheric Sciences: Entering the Twenty-First Century*. National Academy Press, Washington D. C., 364 pp., 1998.

[2] M. Xue, K. K. Droegemeier, and V. Wong, "The Advanced Regional Prediction System (ARPS) – A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part I: Model dynamics and verification," In press for *Meteor. Atmos. Physics*, 2000.

[3] M. Xue, K. K. Droegemeier, V. Wong, A. Shapiro, K. Brewster, F. Carr, D. Weber, Y. Liu, and D.-H. Wang, "The Advanced Regional Prediction System (ARPS) – A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part II: Model physics and applications," In press for *Meteor. Atmos. Physics*, 2000.

[4] T. Bergot, H. Gwenaelle, A. Joly, and S. Malardel, "Adaptive observations: A feasibility study," *Mon. Wea. Rev.* 127, 743-765, 1999.

[5] J. M. Kahn, R. H. Katz, and K. S. J. Pister, "Emerging Challenges: Mobile Networking for Smart Dust," *J. of Commun. and Networks*, 2, 188-196, 2000.

[6] K. Brewster, "Application of a Bratseth analysis scheme including Doppler radar data," *Preprints, 15th Conf. on Weather Analysis and Forecasting*, Norfolk, VA, 92-95, 1996.

[7] A. Bratseth, "Statistical interpolation by means of successive corrections," *Tellus*, 38A, 439-447, 1986.

[8] G. L. Mellor and T. Yamada, "Development of a turbulence closure model for geophysical fluid problems," *Rev. Geophys. Space Phys.*, 20, 851-875, 1982.

[9] J. W. Deardorff, "Stratocumulus-capped mixed layers derived from a three-dimensional model," *Bound.-Layer Meteor.*, 7, 199-226, 1980.

[10] J. L. Case and J. Manobianco, "Local data integration over East-Central Florida using the ARPS data analysis system," Submitted to *Wea. Forecasting*, 2001.

[11] R. Atlas, "Atmospheric observations and experiments to assess their usefulness in data assimilation," *J. Royal Meteor. Soc. Japan*, 75, 111-130, 1997.