1. Executive Summary

This final report summarizes work performed for the National Science Foundation Phase I Small Business Innovation Research grant IIP-1214591 entitled “Next Generation Wireless Sensor System for Environmental Monitoring”. The Phase I project spanned eight months from 1 July 2012 through 28 February 2013.

The innovation at the core of the system is an ensemble of airborne probes that function as passive drifters with no active propulsion or flight. The novel probe design exploits miniaturization as well as integration of micro- and nanotechnology-based components to minimize complexity, cost, size, mass, terminal velocity (V_t), and power consumption. Microsensors including global positioning system chips onboard the probes are used to measure ambient air temperature, relative humidity, pressure, and velocity. Two other elements that comprise the system include deployment mechanisms and communication platforms to retrieve sensor data.

The Phase I project objectives were to determine the technical feasibility and commercial potential of the system. These objectives were met using a design-simulation cycle to study tradeoffs between system components and develop realistic cost estimates given the feasibility analyses. Results include a set of functional specifications to guide prototype development in subsequent projects.

The probe target mass is < 1 gram with size on the order of centimeters and aerodynamic characteristics based on bio-inspired shapes such as dandelion seeds to achieve V_t less than 0.5 m/s. Using available commercial-off-the-shelf (COTS) components, it is technically feasible to meet these mass and size specifications. Given a nonzero V_t, probes can make more measurements if released at high altitudes using aircraft or balloons. Communication will feature ultra-low power transmission (10 dB) directly from probes that can be detected by fixed or mobile receivers using a signal processing technique known as forward error correction. Key technical milestones that remain to develop and test a prototype system as part of a Phase II effort include probe form factor and antenna design, probe component integration and packaging, deployment packaging, and receiver station design. A system prototype is a critical milestone that must be met in order to commercialize the system.

System costs were estimated roughly based on COTS components and compared with existing in situ instrumentation. These comparisons demonstrate that an ensemble of low-cost probes can dramatically increase the amount and coverage of in situ observations by at least an order of magnitude for different applications without a commensurate increase in cost. It is not practical to obtain the same set of variables over such large areas with any current in situ or remote sensing platforms. Overall, results from the Phase I study support the conclusion that the system concept is technically feasible and cost-effective.

There are currently two viable pathways for system commercialization. For path 1, the system could be leased or sold to users interested in collecting and integrating raw data for specific applications. In path 2, revenue would be generated by selling data from the system or deriving value-added forecast information by integrating the data into forecast models to create products that significantly improve accuracy, uncertainty, or other factors important to clients. For either path, the fundamental value proposition is a greatly expanded suite of measurements at current cost levels that can provide substantial benefits to a broad range of applications sensitive to atmospheric conditions.

The annual revenue potential of path 1 ($24.1M) and path 2 ($45M) commercialization was estimated to be $69.1M based on sales to civilian government and commercial clients worldwide. However, the path 2 examples focused on a limited segment of energy markets and did not include other weather sensitive sectors of the U.S. and global economy. Therefore, this amount is a conservative estimate that would likely expand greatly when considering other weather applications as well as those related to environmental sampling for air pollution, global climate change, national security, and military operations. Additional work is needed before and during a Phase II project to validate these customer requirements and quantify specific market opportunities.

2. Introduction

The overarching vision of this project is to revolutionize, in situ, wireless atmospheric sensing by developing a system of probes that gather data as they drift passively through the air with no active propulsion or flight. The initial application is improving weather analysis and forecasting by greatly expanding the time and space density of temperature, pressure, wind velocity, and humidity measurements throughout as much of the relevant atmospheric volume as possible. Such data could also provide calibration and validation for space-based remote sensing of tropospheric winds using lidar and carbon dioxide or other trace gases. This capability could extend the commercial potential to applications involving air quality and greenhouse gases initiatives relating to global climate change. The system could have much broader impacts beyond traditional weather forecasting by measuring acoustic, magnetic, chemical, biological, nuclear, or other parameters of interest for surveillance, reconnaissance, and related applications.

The underlying framework for modern-day weather forecasting is numerical weather prediction (NWP). The accuracy of NWP is closely linked to the accuracy as well as the spatial resolution, temporal resolution, and coverage of atmospheric observations assimilated into the NWP models. Even the current and planned combination of in situ and remote sensing platforms leaves observational gaps that are insufficient to meet the requirements of NWP. Current government and commercial weather forecast providers generally have access to the same suite of publicly available (i.e. free) data and use similar NWP modeling systems/algorithms to generate products. Therefore, no single system typically outperforms others by large margins based on forecast accuracy when aggregated over weeks to months, although substantial variability in performance is common for specific cases, locations, and applications.

The key to improving short-range forecasts is to greatly expand coincident measurements of model-dependent variables. The system described here offers a unique approach to fill these data gaps. Improved forecast accuracy has significant social and economic value to many weather-sensitive sectors of the global economy including energy, transportation, agriculture, air quality, and recreation. In fact, a recent study by Lazo et al. (2011) estimated that weather variability impacts more than 3% of the United States (U.S) gross domestic product (~$485 billion in 2008).

This final project report on the next generation wireless sensor system for environmental monitoring summarizes the National Science Foundation (NSF) Phase I Small Business Innovation Research grant covering the period from 1 July 2012 through 28 February 2013. The two main objectives for the Phase I project were to (1) determine the technical feasibility of the system and (2) assess the commercial potential using realistic cost estimates and revenue models given results from the feasibility analyses. Table 2.1 provides a summary of tasks completed during the Phase I project and key milestones that remain for the Phase II effort.

Table 2.1. Phase I tasks completed (black text) and those remaining for a Phase II project (gray text).

Category	Task Summary	Status
Probe	Develop probe specifications (specs)	Completed
	Identify probe components to meet specs	Completed
	Develop probe power budget	Completed
	Optimize probe form factor and antenna design	Phase II
	Determine probe component integration and packaging	Phase II
	Examine probe contact issue	Phase II
Deployment	Identify viable deployment mechanisms	Completed
	Design, develop, test deployment packaging	Phase II
Communication	Examine feasibility of RFID communication strategy	Completed
	Identify new communication strategy	Completed
	Determine link budget for new communication strategy	Completed
	Design, build, and test fixed or mobile receiver stations	Phase II
Commercialization	Develop preliminary cost estimates for system components	Completed
	Provide preliminary market size for two business models	Completed
	Provide preliminary revenue potential for two business models	Completed
	Complete validation of customer and market potential	Phase II
	Complete detailed pro forma projections	Phase II
	Build system prototype and test in relevant environment	Phase II

The remainder of the report is organized into two main sections covering the project objectives. First, Section 3 provides a system description including probe design, deployment mechanisms, and interrogation strategies relating to technical feasibility. Section 4 follows with a discussion of commercial potential linking together costs, market potential, and plans for a Phase II project including investments required for commercializing the system.

3. System Technical Feasibility

The system (Fig. 3.1) combines three main elements including: (1) an ensemble of disposable, airborne probes, (2) mechanisms to deploy probes and (3) receiver platforms to gather data from the probes. Details about each component such as functional specifications, technical feasibility, and design tradeoffs between components are provided in the subsections below.

3.1 Probe Design. The novel probe design exploits component miniaturization as well as integration to minimize complexity, cost, size, mass, terminal velocity (V_t), and power consumption yet still provide measurement accuracy equivalent to or better than currently accepted observing technology. This innovation is based on the trend for ubiquitous sensing (O'Grady et al. 2007) and "smart dust" (Kahn et al. 2000; New York Times 2010a) – extremely large numbers of disposable, low cost electronic devices that measure various parameters and communicate that data to support research and operations for many applications. The original vision for smart dust was to build self-contained, millimeter-scale computing, sensing, and communication platforms to enable integrated, massively distributed, ad hoc networks (Warneke et al. 2001).

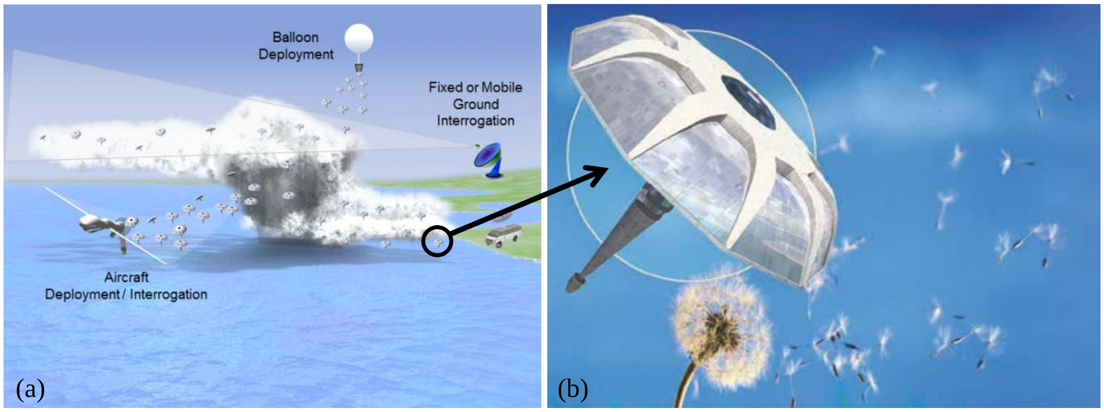

Figure 3.1. System concept showing main components in panel (a) and expanded probe view in panel (b).

The baseline functional specifications for probes are provided in Table 3.1. The probes will integrate micro and nanotechnology-based components to achieve the size and mass targets. With mass < 1 gm and an aerodynamic shape based on bio-inspired designs (e.g. dandelion seeds as illustrated in Fig. 3.1b), probes could remain airborne and make measurements for hours or longer depending on atmospheric conditions (mainly updrafts/downdrafts) and release altitude. For example, with minimal vertical air motion, probes released at an altitude of 3 km above ground would remain airborne almost 3.5 hours given a V_t of 0.25 m/s.

In addition to minimizing V_t, a 1-gm target mass also greatly reduces hazards to people or property (structures, airframes, aircraft engines) as probes settle through atmosphere. The contact hazard for ground-based objects and/or people should be minimal given the target mass and V_t. Probes will be larger than ~¾" hailstones (i.e. 2.0-cm diameter or 1.0-cm radius) but less massive by almost a factor of four. However, the probe target V_t will be smaller than even raindrops so the collision hazard should be negligible. This hazard also depends on the number of probes deployed, deployment location/frequency, and distance they drift before reaching the ground. These factors can be quantified to estimate the probability that probes will strike anything before settling on land or water.

Table 3.1. Probe functional specifications.
Size: (< 10 cm); *Mass*: ≤ 1 gm; *Terminal velocity*: ≤ 0.5 meter per second (m/s) in calm wind
Measurement type: air temperature (T), pressure (P), relative humidity (RH), velocity (V), position (x, y, z)
Measurement accuracy: T (0.25 C); P (0.001 atm); RH (2%); V (1 m/s), position (25 m)
Measurement frequency: ≤ 5 minutes
Dynamic range: temperature (-70 to 40 C); humidity (0 to 100%); pressure (0.1 to 1.0 atm); velocity (< 150 m/s)
Communication: transmit low power (order 10 dB) signals
Form factor: suitable for automatic deployment from aircraft or balloons
Deployment: No manual preparation for power on, calibration, etc.
Operation: all hours of day and night for up to 24 continuous hours

Under certain conditions, winds may accelerate probes to higher speeds (e.g. thunderstorm updrafts) or drifting probes may encounter aircraft traveling at higher speeds. In these instances, the collision hazard may be more significant given that impact energy is proportional to the square of velocity. Previous studies examined this issue based on bird strikes and jet engine ingestion (Manobianco 2005). The probe mass will be substantially lower compared with birds (hundreds of grams to a kilogram or more) that typically pose a strike threat to airframes, windshields, and engines. However, 98% of all bird strikes occur below one kilometer above ground at lower flight speed. The contact issues will be explored in the Phase II project but more rigorous evaluation of aviation hazards will require engine ingest and other tests as further refinements are made to the probe.

Another potential concern for a fully operational system is the environmental impact caused by the probes settling out of the atmosphere. For the foreseeable future, this issue can be mitigated by designing "biologically inert" probes and minimizing the number of components that could have any negative environmental impacts. Ultimately, probe components would be biodegradable but significant advances in materials science and organic electronics will be needed to achieve these design goals. The probes will not contain materials or components including power sources that pose any significant mechanical, electrical, or environmental hazards.

3.2 Probe Components. The probes will require sensors, central processing unit, radio frequency (RF) transmitter, antennas, power source, interface electronics, and packaging. The technical feasibility of achieving the mass and size specifications was determined by considering commercial-off-the-shelf (COTS) components where practical or emerging trends in research efforts for enabling technologies. Table 3.2 lists suitable COTS components with various attributes including size and mass parameters. These components were also used to estimate the probe power budget discussed later in this section.

Microsensors will be used to measure ambient air temperature (T), relative humidity (RH), pressure (P), and velocity (V). The proliferation of cell phones, digital cameras, navigation units, and other devices has driven the size and power requirements of micro global positioning system (GPS) chips to the point where they can be leveraged to provide onboard probe velocity and position measurements. The accuracy and dynamic range of the microsensors (Table 3.2) meet or exceed the probe functional specifications (Table 3.1). Separate antennas will be needed for the RF transmitter and micro GPS because these components operate at different frequencies (900 MHz versus 1.5 GHz, respectively). The U-Blox micro GPS module requires an external antenna and several additional components. Possible candidates for the antenna include dipoles, folded dipoles, spirals, and planar elliptical patch. Atchison (2008) discussed using a printed antenna in a linear dipole or looped dipole configuration for centimeter-scale spacecraft. The optimal antenna configuration will be a custom design based on the probe form factor and overall component geometry to be explored in the Phase II project.

Table 3.2. Probe components with attributes listed or not applicable (N/A). Estimated mass is denoted as "est".

Component	Manufacturer/Model	Size (mm)	Mass (mg)	Accuracy	Dynamic Range
T/RH sensor	Sensirion STH25	3.0×3.0×1.1	25	±0.2 ^{o}C; 1.8%	-40 to 125 ^{o}C; 0 to 100%
Pressure sensor	Bosch BMP180	3.6×3.8×0.93	26	0.001 atm	0.3 to 1.0 atm
Micro GPS	U-Blox MAX-6G	10.1×9.7×2.5	200 (est)	0.1 m/s; 2.5 m	500 m/s, 50 km
GPS Antenna	Pulse W3011	4.0×4.3×6.3	33	N/A	N/A
Zinc Air Battery	Panasonic PR5H	5.8 (dia) x 2.2	200	N/A	N/A
Microprocessor/RF	TI* MSP430 + radio	4.0×4.0×1.0	169	N/A	N/A
RF Antenna	Custom	20.0×1.0×0.8	20 (est)	N/A	N/A
Interface electronics	Custom	1.0 to 5.0	25 (est)	N/A	N/A
Packaging	Custom	20.0 to 30.0	75 (est)	N/A	N/A

*TI = Texas Instruments

Interface electronics such as resistors, switches, wire bonds, etc. and packaging will be required to connect the main components. The packaging will need to isolate certain components from the effects of turbulence, liquid and frozen water as well as direct solar radiation. The total mass of all components in Table 3.2 is 973 mg (0.973 gm), which is marginally less than the target mass of 1 gm (Table 3.1) but includes two zinc air batteries (200 mg x 2) connected in series to achieve the required voltage for most components. The packaging may include standard printed circuit boards that could clearly increase probe mass beyond the 1-gm target using the current suite of components. The power source is by far the largest percentage of total probe mass at 41% and could be reduced using ultra-low power custom components (Seok et al. 2008).

Alternative strategies for component integration include modular die-stacked structures (Seok et al. 2008), flexible substrates and components (Kim et al. 2011), and monolithic "systems on a chip" (Cook et al. 2006; Atchison 2008). Previous work with electrospun nanofibers demonstrated that it is possible to fabricate bio-inspired designs (e.g. dandelion seeds) with mass less than 200 mg and V_t on the order of 0.5 m/s (Zussman et al. 2002). Additional work in the Phase II project will be required to optimize the probe form factor and aerodynamic design as well as explore various materials for component integration and packaging. These efforts can proceed in parallel with development and testing of probe prototypes to demonstrate overall system functionality. The initial probe prototypes will not likely meet the mass, size, and V_t specifications until the optimization efforts are completed.

The microprocessor unit (MPU) will store a set of instructions, make measurements, store/process sensor data as well as control the active versus sleep cycles for the micro GPS and communication functions. The Texas Instruments MSP430 with a built-in RF transmitter is an ultra-low power device drawing 160 μA/MHz with software-adjustable clock speeds up to 20 MHz. The RF transmitter requires roughly 33 mA to generate a 10-dB (10-mW) signal at 900 MHz. Details of the communication function link budget are described in Section 3.4. The MSP430 also has a number of low-power modes that can be controlled with a real-time internal clock to limit power consumption as part of an overall probe sleep cycle. The other MSP430 attributes include 32 kilobytes (kB) of programmable flash memory, 4 kB of random access memory (RAM), high performance 12-bit analog-to-digital converter, six external inputs, and internal temperature plus battery sensors.

The MSP430 is more than adequate to control all probe functions. For example, sensor data comprised of ten different parameters (T, RH, P, three components of V, altitude, latitude, longitude, and time) would typically be logged in memory at some pre-determined frequency then combined in a packet for transmission. The raw packet length is estimated to be about 125 bits given the accuracy and resolution needed to meet measurement specifications (Manobianco 2005). Additional layers and error control bits will be used as part of the communication paradigm as discussed in Section 3.4. The overall packet length of about 64 kbits along with the MPU instruction set (i.e. control software) can be stored in flash memory.

A key challenge in miniaturization is energy density and power consumption. Energy density scales with volume and suitable power sources such as small batteries do not often provide high enough peak power output or energy capacity. The key design tradeoff is to minimize component power requirements and effectively manage available power using ultra low-power or sleep modes. In order to explore power source options, a power budget (Table 3.3) was computed by making initial assumptions about event frequency (e.g. communication, data acquisition) and using component specifications from Table 3.3.

The measurement frequency listed in Table 3.3 corresponds to acquiring T, RH, and P sensor data every 30 s (0.5 min) with velocity and position data every 120 s (2 min). The MSP430 radio would then transmit the ten-parameter packet every 120 s (2 min). The microprocessor is assumed to operate in an active mode 5% of the time and be in a much lower power state (i.e. sleep mode) for the remaining 95% of operational cycle. For a 6-h period, that time split corresponds to 1080 s (18 min) versus 20,520 s (342 min). If the MSP430 is operated at 8 MHz drawing 160μA/MHz at 3 V, the total power consumed over 6 h is 8 MHz x 160 μA/MHz x 0.000001 A/μA x 3 V x 0.05 x 21600 s or 4.1 J. The same calculation was performed for the low power or standby mode that uses 2 μA at 3 V. All assumptions used to derive the power budget can be adjusted depending on the available power source(s) and component specifications.

The total energy required to operate a probe for 6 hours given these assumptions is roughly 48.5 J. The Panasonic PR5H is rated at 35 mAh for 1.4 V so two of these batteries connected in series produces 35 mAh at 2.8 V or about 352.8 J (0.035 A x 2.8 V * 3600 s/h). This energy is sufficient to operate the probe for more than 36 h with a significant margin of ~60 J. Given this surplus energy, GPS measurement and transmission frequency could be increased to match the T, RH, and P sensors at 0.033 Hz (i.e. every 30 s). This mode of operation would require 139.7 J so the probe could still operate for 12 h with a margin of ~70 J.

The last column in Table 3.3 shows that the micro GPS uses more than two thirds of the total energy (67.6%) and more than double the radio. The tradeoffs relative to the energy budget suggest that decreasing the GPS and radio energy requirements could extend the probe operating time given the same energy density or require a lower capacity and potentially less massive power source.

Table 3.3. Probe energy requirements computed from component data sheet specifications.

Component	(a) Measurement Frequency (Hz)	(b) Standby Energy (J)	(c) Energy Per Measurement (J)	(d)* Total Energy For 6-h Operation (J)	Total Energy For 6-h Operation (%)
T/RH sensor	(1/30)	3.3×10^{-5}	2.7×10^{-5}	4.3×10^{-2}	0.1
Pressure sensor	(1/30)	6.0×10^{-6}	6.5×10^{-6}	9.0×10^{-3}	< 0.1
Micro GPS	(1/120)	2.5×10^{-3}	1.1×10^{-1}	20.1 (+ 12.7)@	67.6
Radio	(1/120)	5.2×10^{-4}	6.3×10^{-2}	11.4	23.5
Microprocessor	----	0.1#	4.1#	4.2	8.7
Total	----	----	----	48.5	100

*Except for the microprocessor, total energy computed as (col b + col c) x (21600 s) x (col a)

#Energy for microprocessor estimated based on active (5%) versus sleep (95%) mode

@Must include warm start every hour to update ephemeris data (0.047 A x 1.8 V x 30 s x 5 updates = 12.7 J)

3.3 Deployment Mechanisms. In order to observe as much of the relevant atmospheric volume as possible, probes should be deployed at high altitudes using either balloons or aircraft. The deployment strategy depends on a number of factors such as the phenomena of interest, areas to be covered, and probe V_t. The advantage of aircraft deployment is that probes can be targeted to very specific locations and altitudes. However, this option may not always be cost-effective or practical especially if flights are not already being leveraged for operational or research missions. Both manned and unmanned aircraft missions may also be limited in coverage because of routing, flight patterns, and flight path restrictions.

Standard weather balloons are released twice daily by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) at 92 sites around the U.S. The balloons typically carry instrumentation payloads known as rawinsondes that weigh almost 300 gm, collect P, T, RH, and V measurements during ascent, and relay data to ground stations. Rawinsonde stations are separated by hundreds of kilometers but could be supplemented with additional manual or automated balloon launches (YES 2011) as well as unmanned aircraft systems (UAS; Lin and Lee 2008; Elston et al. 2011). Given the proposed probe mass and size, even small UAS could carry a substantial number of probes for research and operational missions (Elston et al. 2011).

NOAA flies operational and research aircraft reconnaissance missions into Atlantic hurricanes and winter storms over the eastern Pacific Ocean. Recent NOAA efforts have also focused on using UAS such as the Global Hawk for hurricane reconnaissance (http://news.nationalgeographic.com /news/2012/09/pictures/120921-hurricane-drones-nasa-usgs-environment-science/). Both manned and unmanned aircraft are equipped with hardware to release small, cylindrical instrument packages known as dropsondes. Small parachutes stabilize the dropsonde and limit V_t to ~12 m/s as they descend toward the surface. Dropsondes measure the same parameters but are larger (40 x 7 cm) and heavier (150 gm) than the probes. The dropsonde deployment tubes are large enough to accommodate tens to a hundred or more probes (depending on form factor) that would most likely be encapsulated in a dropsonde cylinder or other rigid packaging to withstand ejection from the aircraft. Given the size and payload capacity of UAS, it may be more effective to design and build an aerodynamic pod on the aircraft exterior to facilitate deployment.

The Weather Research and Forecast (WRF) model (Skamarock et al. 2008) was used to simulate three high-impact weather events summarized in Table 3.4.These events included Hurricane Katrina (2005), a tornadic supercell thunderstorm over Nebraska (2008), and an extratropical cyclone known as the Superstorm (Uccellini et al. 1995) that generated record-breaking snowfall over the eastern U.S. in March 1993. These cases featured diverse weather phenomena on a very broad range of space and time scales that were used to estimate probe drift and determine tradeoffs between deployment, power budgets, and communication strategies. For the supercell thunderstorm case, the WRF model was run in a nested grid configuration starting with an outer grid spacing of 6 km that decreased to 0.4 km (400 m) over a smaller domain in the immediate area around the feature of interest (Table 3.4). This approach was computationally demanding but necessary to simulate realistic flow fields associated with thunderstorm genesis and evolution (Schenkman et al. 2012).

Table 3.4. Summary of cases and simulation attributes used to study probe deployment and dispersion.

Case	Date	Grid Spacing (km)	Grid Dimensions* (NX x NY x NZ)	Simulation Length (hours)	Deployment Mechanism
Hurricane Katrina	27-29 August 2005	3	578 x 541 x 40	60	Recon aircraft
Supercell thunderstorm	23-24 May 2008	6, 2, 0.4	249 x 190 x 60#	12, 12, 3	UAS
Superstorm	1-31 March 1993	15	416 x 275 x 45	744	Balloon

*Number of points in the east-west, north-south, and vertical directions
#Dimension of 6-km grid

A Lagrangian Particle Model (LPM) was used to simulate the deployment and dispersion of an ensemble of probes (Manobianco 2005). The LPM was patterned after the HYbrid Particle And Concentration Transport model (HYPACT; Uliasz 1996) which is one of several approaches to simulate the physical properties of a fluid dynamical system. The LPM tracked the location of each probe based on simulated three-dimensional (3D) wind components from WRF and various parameterizations to account for probe V_t. In addition, the LPM accounted for the effects of precipitation which altered probe trajectories by increasing their mass and imparting downward momentum through collisions with liquid or frozen particles.

The force balance model that estimates V_t in the LPM was modified for a probe form factor similar to the shape in Figure 3.1 with a diameter of 8 cm, mass of 100 mg, and drag coefficient of 2.5. These values were selected by trial and error to achieve a target V_t around 0.5 m/s but could be further optimized given other constraints such as packaging, available materials, and component geometry. This optimization was not performed as part of the Phase I simulations.

The deployment mechanism for each case is summarized in Table 3.4. Probe deployment for Hurricane Katrina was simulated as part of routine reconnaissance flights using a typical "ALPHA" pattern (including eye wall penetration (http://www.ofcm.gov/nhop/12/pdf/05-chap5.pdf). The probes were released during 3 separate flights at 6-h intervals from 36 through 48 h of the simulation (1200 UTC 28 August through 0000 UTC 29 August 2005) as the hurricane tracked towards New Orleans, LA. During each simulated reconnaissance mission, 50 probes were deployed every 2 minutes from the dropsonde dispenser at an altitude of 6 km for a total of 3250 probes per flight.

Probe deployment for the thunderstorm case was simulated as part of low-level UAS flights along a 10-km line southeast of the developing storm following patterns that have been used in actual field experiments (Elston et al. 2011). A cluster of 50 probes was released at 500 m, 1000 m, 1500 m, and 2000 m above ground level every minute for about 9 minutes during 4 separate flights. For the extratropical cyclone case, deployment was simulated from weather balloons at more than 100 stations across North America. This strategy assumed that balloons carried “pods” of 20 probes to 9000 m above ground level as part of routine launches every 12 h then released them all at that altitude.

Simulations with the WRF and LPM models were used to estimate how long probes remained airborne given estimated V_t and updrafts or downdrafts in the three different cases. A histogram of the airborne time for the hurricane case reveals that most probes drift 4 to 10 h before reaching the surface although a substantial number were still embedded in the circulation well after 12 h (Fig. 3.2a). A detailed analysis (not shown) indicates that probes with the longest airborne residence time were typically those carried to levels well above release altitude in convective updrafts.

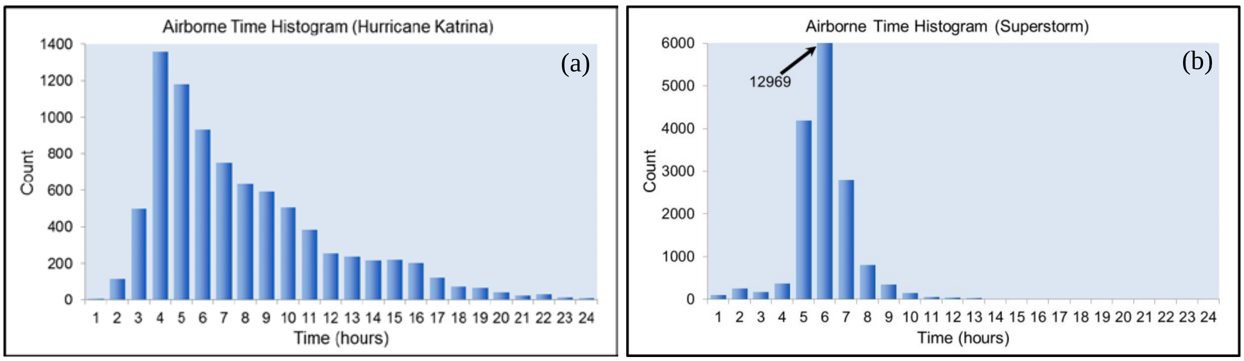

Figure 3.2. Histogram showing number of probes (count) that remain airborne for a given time (hours). Panel (a) is for the Hurricane Katrina case and panel (b) is for the Superstorm case. Note the bar at hour 6 in panel (b) extends to 12969 and was truncated to expand the distribution at lower counts.

The corresponding histogram for the extratropical cyclone case covering a 3-day period from 1200 UTC 12 March to 1200 UTC 15 March 1993 is shown in Figure 3.2b. The distribution reveals most probes remained airborne in this simulation for 5 to 7 hours which is consistent with a higher release altitude (9000 m) compared with the hurricane case (6000 m). There is also no appreciable “tail” in the histogram beyond 8 to 10 h because extratropical cyclones do not typically contain wide-spread convective updrafts that force probes to levels above their release altitude. The airborne time histogram for the thunderstorm case is not as relevant (and therefore not shown) because probes were released at or below 2000 m and reached the surface in less than 2 hours except when lofted to the upper atmosphere by strong convective updrafts.

The airborne time statistics are important relative to the power budget presented earlier because the power source was estimated to last between 12 to 36 h depending primarily on GPS measurement and communication frequency. For the broad range of conditions simulated in these three cases, the proposed power source is adequate to keep probes functioning for the time they remained airborne given the functional specifications. However, this situation would change if specific applications require probes to operate for longer periods of time, make higher frequency GPS measurements, or transmit data packets more often.

3.4 Interrogation Platforms. Communication with each probe was originally proposed using far-field, radar responsive Radio Frequency IDentification (RFID) technology already developed for military applications involving tagging, tracking, and location (Swedberg 2007). With radar responsive RFID tags onboard probes, interrogators would be airborne or ground-based radars. The communication protocol would be two-way (i.e. semi-active RFID tag) so that incoming radar energy would be modulated by the probe and retransmitted at much lower power. The probe signals would then be received and decoded using the same (monostatic) or different (multistatic) radar system. Amplitude, frequency, or phase shift keying modulation schemes would be used to maintain the integrity of the individual probe data packets. Depending on transmit power of the interrogators as well as probe attributes such as antenna size, it is possible to receive data from each device at ranges of at least 10 kilometers.

A significant portion of the Phase I effort was devoted to examining the technical feasibility of this approach. The tradeoff study examined different interrogation frequencies considering atmospheric propagation loss, antenna gain, RF link budgets, signal-to-noise ratios, and detection range. The concept of operations (CONOPs) focused on leveraging existing airborne or ground-based radars since deploying fixed or mobile systems solely to communicate with probes was deemed not economically feasible for most applications. For hurricane reconnaissance over water, the radar systems would likely be those onboard the NOAA research (Gulfstream IV, WP-3D; NOAA 2013) or operational aircraft (WC-130J; USAF 2013) in the C or X bands (4 to 8 GHz). For land-based applications such as the Superstorm covering large geographic areas, the NWS Weather Surveillance Radar-1988 Doppler (WSR-88D) units would be a logical choice. These systems are deployed throughout the U.S. and operate at a frequency of 2.8 GHz (S-Band) with 750 kW of transmitted power. Mobile, ground-based X-band radars such as the Doppler-on-Wheels (Wurman 1997) with peak power output of 45 kW could be used over smaller space and time scales for the thunderstorm application discussed previously.

Results indicated that it would be technically feasible to interrogate probes using far field RFID tags. However, two significant limitations emerged when examining various tradeoffs between functional requirements, detection range, and CONOPs including the location and number of interrogators needed to operate a viable system. These issues are summarized below, without presenting the detailed analysis that was done for Phase I study, in order to focus on an alternate method.

1) Existing weather radar assets generally operate in the lower GHz bands but not at one unique frequency so different RFID tags operating at the appropriate band would be needed depending on the application. This functional requirement makes it more challenging to standardize probe hardware design. An additional requirement is that existing radar systems must be modified to receive probe signals and process data packets. While the antenna and other portions of the radar signal processing (including transmitter waveforms) would remain intact, a new receiver unit would be designed to process probe signals. Here again, customization for different radar systems would likely increase cost and complexity of the overall system although these tradeoffs were not explored during the Phase I project.

2) The RF link budget showed that maximum detection range under ideal conditions (i.e. minimal attenuation from precipitation) using WSR-88Ds with high gain antennas is < 25 km. The range is further limited using mobile ground or airborne radars that typically transmit less power than WSR-88Ds and have lower-gain antennas. For the hurricane application, the probe distribution is spread out over linear dimensions of more than 250 km (not shown). Even aircraft flying at high altitudes with onboard lower fuselage-mounted radar would retrieve data from less than 10% of the probes at any given time. A single, mobile radar asset would not be able to receive and process data packets every few minutes because most probes would be out of range.

Following work by Atchison et al. (2010) on microscale atmospheric re-entry sensors, an alternate method for probe communication addresses the shortfalls and provides a potentially much more robust communication strategy. The probe radio would transmit data packets at a constant power level of 10 mW (10 dB) using an onboard radio (Table 3.2) in the MHz range at pre-determined intervals. The critical step is to pad the data packets with extra bits before transmission using a signal processing technique called forward error correction (FEC). When combined with code division multiple access, hundreds of probes could transmit on the same frequency without interference.

The FEC communication protocol has been used for years by GPS satellites and cellular telephone networks. It provides gain similar to antennas or amplifiers that increase signal strength, effectively lowering the noise floor so that weaker signals can be detected at greater ranges and decoded with fewer errors. However, the scheme increases the packet size by adding a sequence of bits known as pseudo-random noise or chips so the effective transmission rate after accounting for the additional bits is much lower. This limitation is not deemed significant for the current application because FEC could overcome range issues with the radar responsive RFID paradigm while simplifying the overall communication and interrogation requirements.

A sample link budget for probes using FEC is shown in Table 3.5. The transmission frequency was assumed to be 900 MHz (per MSP-430 specifications) with 512 bits per chip but no atmospheric attenuation or receiver antenna polarization loss used by Atchison et al. (2010). The free space loss over a path length of 250 km was computed using the standard Friis transmission equation and system noise power as kTB where k is the Boltzmann constant, T is temperature, and B is receiver bandwidth. The critical metric to evaluate the link budget is the energy per bit to noise ratio (E_0/N_0). This quantity is effectively a normalized signal-to-noise ratio that accounts for the additional gain using FEC. The E_0/N_0 was estimated to be 12 dB over a range of 250 km, leaving a 2 dB margin at the receiver if the minimum E_0/N_0 is 10 dB. The link budget can be computed at different ranges and include other losses or gains in the system or environment.

Table 3.5. Sample probe link budget using forward error correction.					
Parameter	**Value**	**Units**	**Parameter**	**Value**	**Units**
Transmitter (Probe)			**Signal Encoding**		
Power	-20	dB	Chip Rate	64	kbps
Antenna gain	0	dB	Chips/Bit	512	
Frequency	900	MHz	Effective Data Rate	125	bps
Path length	250	km	Signal Processing Gain	27	dB
Free-space loss	-146	dB			
Receiver (Fixed or Mobile)			**Link Quality**		
Antenna gain	5	dB	Received Power	-154	dB
Temperature	300	K	E_b/N_0	12	dB
Noise factor	5	dB	Minimum E_b/N_0	10	dB
Bandwidth	50	kHz	Margin	2	dB
System Noise (N_0)	-139	dB			

The communication protocol using FEC increases probe detection range by at least a factor of ten compared with the radar responsive RFID tags. The primary limitation then becomes RF unobstructed line-of-sight which depends on altitude of the transmitter and receiver as well as obstructions such as trees, buildings, and hills. For an aircraft flying at 10 km over open water, the line-of-sight horizon is greater than 400 km. However, a fixed or mobile ground-based receiver would likely have more limited range as most locations do not have clear line-of-sight to the horizon at zero elevation angles. The extended range capability of the alternate communication strategy would be most advantageous for airborne receivers such as those carried onboard hurricane reconnaissance aircraft.

4. Commercialization Potential

There are currently two pathways envisioned for system commercialization. These pathways are positioned at different levels of the value chain in terms of products and services. For path 1, the system would be licensed or sold to users interested in collecting and integrating raw data for specific applications. In this scenario, clients would lease or own and operate the system with reoccurring revenue generated from the purchase of disposable probes. Other system components such as the receiver hardware and software could be leased or sold then operated and maintained by service agreements or internally as part of customer inventory. It would be most cost effective for customers to leverage and/or modify existing infrastructure for deployment and communication hardware.

In path 2, revenue would be generated by selling data from the system or deriving value-added forecast information by integrating data into diagnostic or forecast models to create products that significantly improve accuracy, uncertainty, or other attributes of meteorological information that are important to clients. This pathway for commercialization involves extracting and selling the application-relevant value from the sensor data rather than selling and/or leasing system hardware (including probes). For either path, the fundamental value proposition (VP) is a greatly expanded suite of measurements that can provide substantial benefits to a broad range of applications sensitive to atmospheric conditions.

4.1 Market Potential. The technical and market analysis for the Phase I project focused on improving weather forecasts for high impact events such as hurricanes, severe thunderstorms, and winter storms but could easily be extended to other applications. The market opportunity for selling or licensing the system follows the business model of most instrumentation companies (e.g. Vaisala; www.vaisala.com). In the U.S., the primary customers would be civilian (NOAA NWS) and military weather agencies. Although there are a number of weather sensitive sectors (transportation, agriculture, energy), many of the industry and government agencies (e.g. Federal Aviation Administration) rely on and/or collaborate with the NWS to provide both data and products. Most major countries around the world also have government-sponsored agencies that provide similar products and services as the NWS so the market has global potential.

4.2 System Cost. In this subsection, system costs are estimated and compared with current in situ weather instrumentation such as dropsondes and rawinsondes because they are similar in terms of functionality, deployment, and current applications. The dropsonde price is on the order of $750 per unit not including deployment costs or communication hardware typically installed onboard aircraft (Dr. Frank Marks, NOAA Hurricane Research Division, personal communication). An estimated probe sales price around $75 is consistent with low-volume COTS component costs (not shown) and would include other business expenses for production, sales, and marketing.

The key price driver is currently the micro GPS (U-Blox) and T/RH sensors (Sensirion) which currently sell for at least tens of dollars apiece. The target price point would be roughly two orders of magnitude less than dropsondes so 100 probes with packaging would cost about the same as a single dropsonde. This figure is achievable by leveraging continued electronics miniaturization and integration in the next three years as well as higher volume fabrication but not in the first several product cycles. For the remainder of the system cost analysis, probes are assumed to be sold at $6.50 per unit. A rough estimate for aircraft packaging cost would be on the order of $100 that may require a parachute to decrease the fall speed of the container after probes have been released

Dropsonde deployment costs are nearly twice the dropsonde per unit price at about $1333 per launch (Aberson et al. 2006; Frank Marks, personal communication). This estimate is based on $5000 per hour to operate the Gulfstream IV or WP-3D from a home base for a nominal 8-h mission and deploy 30 dropsondes. However, this cost would decrease with more dropsonde launches assuming a fixed cost for aircraft operations. On the other hand, aircraft operational costs increase if flights originate from remote locations due to additional fuel and crew support. This analysis represents an upper bound on deployment costs because it does not account for other data including radar, radiometer, and aircraft observations that are also collected during the flights. Unless missions are designed to collect only dropsonde data, more representative deployment costs are some small fraction of fixed aircraft operating expenses normalized by the number of launches.

Probe deployment cost could vary by a large margin depending on whether aircraft assets are already dispatched making other measurements during the flights. In that case, the incremental probe deployed cost would be very small. On the other hand, deployment costs could approach those for dropsondes especially if aircraft missions are focused mainly on probe deployment. Assuming 100 probes fit in a single dropsonde cylinder, the deployment cost from manned aircraft, based on dropsonde estimates, would be $1333 / 100 or ~$13 per probe. More detailed cost analyses for aircraft deployment were not considered in the Phase I project.

For other applications, weather balloons launched with rawindsondes over land could carry probes to pre-defined altitudes and release them automatically. Operational rawinsonde deployment costs are estimated to be about $150 per launch assuming manual, twice-daily releases 365 days per year (Douglas 2010). This cost is considerably less than dropsondes but still roughly the price of a rawinsonde unit that costs ~$150 in large volume. In cases where it is not practical or possible to leverage existing infrastructure, automated balloon launchers could be used but they generally do not decrease launch cost given they are low volume, custom products (price range $250K-$500K depending on capacity, size, and other factors). Automated systems remove the labor expense associated with manual launch but still require maintenance and resupply of expendables such as balloons and lift gas. In addition, procuring even a small number of automated launchers only for probe deployment would require significant capital expense. This approach may be feasible depending on the application.

A "pod" of probes would be attached to balloons as a secondary payload. The pod would consist of additional hardware to store probes and minimal electronics to release them at predefined altitudes. For the Superstorm simulation, the pod was assumed to carry 20 probes, which would add an estimated 40 gm to the balloon payload (20 probes x 1 gram per probe + 20-gm pod mass). Neither the design nor detailed cost for such a mechanism was explored in the Phase I project. A rough estimate would be about $20 for a simple mechanism but more costly to have flexibility for releasing a subset of probes at different altitudes. At a price point of $6.50 per probe, the complete package (probes + pod) would cost ~$150 (20 probes x $6.50 per probe + $20).

The balloon deployment costs could vary considerably depending on whether it is possible to leverage existing infrastructure. For example, a secondary payload would require slightly more lift gas and minimal labor to attach the pod to the balloon. In this case, the incremental deployment cost would likely be a small percentage of $150 (roughly 10% or $15). On the other hand, pods deployed from automated systems not used for other applications could cost as much as $150 or more per launch depending on launch frequency.

Regardless of deployment strategy, the system still requires fixed or mobile stations to receive probe data similar to rawindsondes and dropsondes. An approximate receiver sales price was estimated based on COTS hardware components and limited custom software development. The minimal components would include a software-defined radio receiver (e.g. http://www.amazon.com /Receiver-RTL2832U-Compatible-Packages-Guaranteed/dp/B009U7WZCA), low-noise amplifier, and antenna as well as assorted cables, connectors, and mounting hardware. Depending on the application and environment (e.g. inside an aircraft versus outside on a tower), the receiver hardware would cost on the order of $1500 not including a LINUX-based laptop or equivalent system ~($1500) to handle data processing. This component would be required if data processing is handled at each receiving site rather than at a centralized location.

The receiver software would decode probe signals and collect data from multiple probes. Software costs could vary depending on whether systems or data are sold because the latter would likely involve reoccurring services. The software would add 30-35% to the receiver cost so a reasonable per unit sales price including typical business expenses would be $2000. This price does not account for mounting hardware, installation, leases fees for tower space, or utility charges (power and internet connection). Similar estimates on the order of $6000 have been quoted for low-cost rawinsonde ground receiving stations, which is an order of magnitude less than the price of such systems a decade ago (Douglas 2010).

Table 4.1 summarizes costs using manned aircraft or balloons at existing rawinsonde sites as deployment mechanisms. For either case, the total cost per probe deployed is much lower when normalized by the number released per deployment cycle (Table 4.1, last column). Note that deployment costs are not included in Table 4.1 given their wide range and dependence on deployment strategy, mission parameters, and other factors as mentioned previously.

An ensemble of probes could make substantially more measurements than dropsondes or rawinsondes over a larger volume of the atmosphere even after accounting for differences in V_t as well as measurement and transmission frequency. For example, approximately 90 dropsondes would be released during the three standard reconnaissance flights (30 per flight) simulated for the hurricane case discussed in Section 3.3. Assuming no instrument failures or communication issues, these deployments at 6-km attitude would result in ~10^5 observations of P, T, RH, and V given a V_t of 12 m/s and measurement frequency of 2 Hz. The simulated probe deployment strategy for this case summarized in Section 3.3 would yield an order of magnitude more observations (~10^6) assuming that most probes remain airborne for 3-4 hours consistent with the results shown in Figure 3.2a. A similar analysis for the extratropical cyclone case suggests that the probes could provide roughly two orders of magnitude more measurements (10^7 versus 10^5) than rawindsondes over a month-long period. This comparison illustrates that an ensemble of low-cost probes can dramatically increase the amount and coverage of in situ observations by at least an order of magnitude for different applications without a commensurate increase in cost. It is not practical to obtain the same set of variables over such large areas with any current in situ or remote sensing platforms.

The receiver costs are not summarized in Table 4.1 because there is potentially a large variation in the number of units needed to provide adequate coverage given range limitations. For applications such as hurricane reconnaissance over water, a single receiver unit mounted in the aircraft may be sufficient depending on flight path, mission duration, and number of probes deployed. For land-based applications, a substantially larger number of fixed or mobile ground-based units would be required to achieve the same coverage as aircraft. For example, about 10 units (approximate cost $20,000) would be needed to receive data from the same probe "footprint" of ~50,000 square km (not shown) for the hurricane case assuming a 50-km range with some overlap for ground based receivers. In mountainous areas of the western U.S. or locations with more restricted line-of-sight due to vegetation or buildings, additional units would be needed unless they could be elevated well above the ground.

Table 4.1. Estimated probe costs (U.S. dollars) for two deployment scenarios.

Deployment Method	Per Unit Probe Cost	Probe Cost Per Launch*	Probe External Packaging Cost	Probe Total Cost@	Comparative Instrument Total Cost@	Total Cost Per Probe Deployed
Manned aircraft	6.50	650	100	750	750	7.50
Existing balloon site	6.50	150	20	150	150	7.50

*Assumes 100 probes released by aircraft and 20 probes released by balloon

@Devices + packaging (probes only)

4.3 Revenue Estimates. The market size for path 1 can be estimated based on statistics for the total number of dropsondes sold worldwide each year by Vaisala. The number of probes released from aircraft is envisioned to be at least two orders of magnitude larger than what is practical with dropsondes considering the differences in size, mass, and V_t. A 2009 press release indicated that Vaisala signed a 5-year, $9.2M contract with NOAA to deliver next generation dropsondes used for hurricane reconnaissance, research, and storm track forecasting by the U.S. National Hurricane Center (Vaisala 2009). Assuming that revenue for this contract is roughly uniform each year ($1.84M) and limited just to the device, these numbers imply an annual sales volume of ~2800 units.

Ikonen et al. (2010) report that several thousand Vaisala dropsondes (~3000) are deployed each year from eight countries for meteorological research and operational hurricane reconnaissance, which is consistent with the estimates based on the Vaisala press release. Although Vaisala is not the only dropsonde provider, they are one of the largest and well-known instrumentation companies in the world so their market share likely represents an upper bound. If the annual sales volume of the probes is 100 times the Vaisala dropsonde market, revenue from selling just probes for global meteorological research and hurricane reconnaissance could be on the order of $2.25M (see Table 4.2). This estimate does not include communication hardware revenue but still may be an upper bound, at least for this market segment, because Vaisala has both mature technology and market channels.

Beyond hurricane reconnaissance, NOAA (and operational weather agencies in other countries) could deploy probes using targeted or adaptive observing strategies (Buizza et al. 2007). This method focuses on making additional measurements at specific times, locations, and altitudes that are most likely to improve forecasts of specified parameters (e.g. temperature). These locations or sensitivity zones often change as a function of season, weather feature, and geographic location but can be estimated using specialized versions of NWP models. Once the zones are identified, probes could be deployed from balloons or aircraft depending on location and extent of areas to be covered.

NOAA deploys about 75,000 rawinsondes per year which is roughly 13% of the total number released worldwide. If 25% of these balloon launches are used for targeted observing and each balloon carries a pod containing 20 probes, the revenue generated from such applications could be on the order of $22M not including revenue from communication hardware (Table 4.2).

Targeted observing is potentially more cost-effective than making routine measurements everywhere or deploying instrumentation at fixed locations that may not always be in sensitive regions. However, the cost to make these additional measurements must be weighed against the benefit of improved forecasts. A recent study demonstrated generally neutral forecast impacts for 2011 winter storms sampled using dropsondes deployed from nearly 100 aircraft flights as part of NOAA's Winter Storm Reconnaissance (WSR) program (Hamill et al. 2013). In this paper, the authors speculated that the limited impact was due to under sampling the target zone, which could potentially be overcome by aircraft deploying probes in addition to dropsondes.

In the area of severe storm research and forecasting, there is a need for new systems to measure parameters that cannot be readily obtained with current or even planned observing technology. For example, NOAA's Warn-on-Forecast (WoF) initiative is designed to extend the tornado warning lead-time beyond the plateau reached using Doppler weather radars (Stensrud et al. 2009). A scientific challenge for WoF is to measure low-level boundary layer fields at space and time scales that are not currently feasible with weather radars or GPS water vapor retrievals (Guo et al. 2011). Probes would be ideal to provide such targeted observations as simulated with the deployment scenario for the thunderstorm case discussed previously. For severe storm forecasting, a CONOP analogous to the WSR program may be suitable with sensitive regions identified ahead of time then sampled by probes deployed from UAS potentially in multiple locations.

Detailed cost-benefit analyses including forecast accuracy impacts due to different deployment and mission scenarios for targeted observing of winter storms, hurricanes, severe thunderstorms, or other high impact weather events were outside the scope of the Phase I study. Depending on the cost and practicality for these applications, end users could lease (or purchase) systems and collect data or purchase data from one or more groups operating the system for them. As an example, NOAA is the only agency who flies Atlantic hurricane reconnaissance missions. Therefore, it would be more cost-effective for NOAA aircraft to deploy probes and receive data since these assets have a fixed operating cost and are already making other measurements during the flight.

A thorough analysis of the customer value chain is required to estimate market opportunity and size for selling probe data and/or improved forecasts derived from the data. In 2010, an article appearing in the New York Times claimed "the innovator who manages to aggregate key data about weather patterns…to predict weather and how it affects our grid, stands to make a massive amount of money…[and] potentially upend…the multi-trillion-dollar energy markets" (New York Times 2010b). Studies funded by the National Renewable Energy Laboratory (NREL) suggest potential annual savings in U.S. renewable energy integration costs as large as $1 to $2 billion with improved wind power forecasts (Marquis et al. 2011). Follow-on work at NREL showed that the initial 10-20% improvements provide the greatest relative benefits with diminishing returns as forecast errors approach zero (i.e. perfect forecasts; Lew et al. 2011). With 24% wind energy penetration in the Western Electricity Coordinating Council region covering 14 western U.S. states, Lew et al. (2011) estimated that 20% improvement in wind generation forecasts would reduce costs by about $195M per year. The same improvement translated to the entire U.S. power system would reduce operating costs by about $975M per year (Lew et al. 2011).

These references are generic but imply that improved short-range weather forecasts of wind and temperature for energy management, specifically energy traders, grid operators, and power producers focused on the day-ahead spot markets have significant economic value. A more specific example was recently reported by power producer Xcel Energy (PR Newswire 2011). The utility saved nearly $6M in 2009 using a new forecasting system that integrates detailed observations of atmospheric conditions into a suite of computer models. This analysis revealed that decreasing mean absolute error of Xcel power forecasts by one percentage point results in an annual savings of $1.8M over three regions (Ahlstrom et al. 2011) in direct proportion to the percent power generated from wind also known as penetration level. Xcel is currently reporting an overall wind penetration level of 12% (Xcel 2013).

The challenge is to quantify forecast improvements that can be derived using probe data without having a prototype system for actual testing. Previous studies demonstrated that integrating simulated probe data into NWP models led to more accurate upper-level wind and surface temperature forecasts for aviation and energy applications (Manobianco 2005; Manobianco et al. 2008). Results from Manobianco (2005; Fig. 4.25i) suggested that the accuracy of low-level wind forecast errors one day in advance can be improved by ~6% using data from a system of probes similar to the one described here. Wind power is proportional to the cube of wind speed in the most rapidly changing part of the power curve (wind speeds between 5-12 m/s) for pitch controlled wind turbines. Therefore, power forecasts would be about 20% more accurate on average given wind forecast improvements in that speed range.

Using the Xcel example, a 20% improvement in power forecasts translates to an annual savings of $36M which is consistent with the relationship between cost savings and percent improvement for different penetration levels (Lew et al. 2011). There are currently 66 U.S. utilities that bought or owned wind power plants at the end of 2012 (ELP 2013). If the top 5 U.S. utilities with the largest penetration levels (including Xcel) invest 5% of their annual savings to improve power forecasts, the revenue potential is on the order of $9M per year. Expanding this analysis to global markets where the U.S. had just over 20% of the nameplate wind power capacity at the end of 2012 (GWEC 2013), the revenue potential could increase to $45M (see Table 4.2) considering other utilities in Europe (Germany, Spain, Italy, U.K., France, Portugal), North and South American (Canada, Brazil), and Asia (India, China).

The preliminary estimates summarized in Table 4.2 suggest an annual revenue potential of $69.25M for path 1 and path 2 commercialization. The path 2 scenario using Xcel focused on wind power production but similar impacts apply for the emerging solar power markets. Teisberg et al. (2005) claim that U.S. utilities could save $59M per year with a 1 ^{o}C improvement in temperature forecast accuracy for scheduling day-ahead electricity generation from gas, coal, and other conventional power plants. Their analysis did not consider multi-day forecasts in scheduling maintenance or include other countries so it represents only a fraction of the total potential benefit to this market segment from more accurate temperature forecasts.

Table 4.2. Estimated annual revenue potential (U.S. dollars) for commercialization pathways.

Description	Assumptions and Estimates	Annual Revenue (millions)
System sales (Path 1) Aircraft deployment	Vaisala global dropsonde market ~3000 units/year 100 times more probes/unit x 3000 units/year = 300,000 probes Revenue = 300,000 probes x $7.50/probe	2.25
System sales (Path 1) Balloon deployment	800 sites globally x 2 launches/day x 365 days/year = 584,000 25% x 584,000 launches x 20 probes/launch = 146,000 probes Revenue = 146,000 probes x $7.50/probe	22
Product sales (Path 2) Wind energy forecasting	Single client savings $36M/year with 20% accuracy improvement 7.5% of U.S clients (5) invest 5% savings ($36M x 5% x 5) = $9M Revenue = $9M / 20% (U.S. nameplate capacity worldwide)	45
Total	----------------	69.25

Another portion of the energy sector with weather sensitivity is short term trading used to balance electricity supply (generation) and demand (load) in the U.S. and abroad. For example, power purchased on spot markets (near real time) typically costs more per megawatt hour than day-ahead bids so underestimating load based on weather forecasts could require utilities to incur higher costs to cover generation deficits. These few examples help to illustrate that there are potentially many more clients for path 2 commercialization with enough weather sensitivity who would be willing to pay for even marginal improvements in forecast accuracy. The challenge is to validate these markets and develop a complete business model that accounts for costs to routinely deploy probes, retrieve data, and then leverage those data to create value added products.

4.3. Estimated Investment for Commercialization. Past and ongoing discussions with potential government (NOAA), industry clients, and investors have revealed interest in the concept once a prototype system has been built and tested. Therefore, prototype development is a critical milestone that must be met to commercialize the system. A Phase II project on the order of $750,000 would provide sufficient funding for probe design and component integration, development of external packaging for balloon deployment, and a limited network of fixed or mobile ground receivers. The prototype system would be demonstrated in a relevant environment as part of a field experiment to test deployment mechanisms, probe functionality, and successful communication with at least an ensemble of 100 probes.

Additional investments would then be required to address any issues with various subsystem components resulting from field testing and accommodate aircraft deployment mechanisms if required by the initial customer base. Assuming path 1 commercialization path of selling systems, the required investment is estimated to be between $1.5M - $2M, which is at least twice the Phase II award. For commercialization following path 2, the amount is projected to be on the order of $4M (or two times higher than the path 1 strategy) to cover costs involved with deploying probes using some targeted observing strategy, setting up a network of receivers, and effectively assimilating probe data to generate more accurate forecast products.

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6. References Cited

Aberson, S., M. L. Black, R. A. Black, R. W. Burpee, J. J. Cione, C. W. Landsea, and F. D. Marks, 2006: Thirty years of tropical cyclone research with the NOAA P-3 aircraft. *Bull. Amer. Meteor. Soc.*, **87**, 1039-1055.

Ahlstrom, M., and Coauthors, 2011: Atmospheric pressure: Weather, wind, forecasting, and energy market operations. *IEEE Power Energy Magazine*, **9**, 97-107.

Atchison, J. A., 2008: A passive microscale solar sail. Proceedings, *SPACE 2008 Conference and Exposition*, American Institute of Aeronautics and Astronautics, San Diego, California, 1961-1978.

Atchison, J. A., Z. R. Manchester, and M. A. Peck, 2010: Microscale atmospheric re-entry sensors. Proceedings, *7th International Planetary Probe Workshop*, Barcelona, Spain. [Available online at http://www.planetaryprobe.eu/IPPW7/proceedings/IPPW7%20Proceedings/Papers/Session6A/p390.pdf].

Buizza, R., C. Cardinali, G. Kelly, and J.-N. Thepaut, 2007: The value of observations. II: The value of observations located in singular-vector-based target areas. *Quart. J. Roy. Meteor. Soc.*, **133**, 1817–1832.

Cook, B. W., S. Lanzisera, and K. S. J. Pister, 2006: SoC Issues for RF smart dust. *Proceedings of the IEEE*, 94, 1177-1196.

Douglas, M. W., 2010: Adaptive sounding arrays for tropical regions. Preprints, *29th Conference on Hurricanes and Tropical Meteorology*, Tucson, AZ, Amer. Meteor. Soc., 12B.7 [Available online at https://ams.confex.com/ams/29Hurricanes/webprogram/Paper168262.html].

Electric Light & Power (ELP), 2013: U.S. electric utilities investing heavily in wind energy. [Available online at http://www.elp.com/articles/2013/01/u-s--electric-utilities-investing-heavily-in-wind-energy.html].

Elston, J. S., J. Roadman, M. Stachura, B. Argrow, A. L. Houston, and E. W. Frew, 2011: The Tempest unmanned aircraft system for in situ observations of tornadic supercells: Design and VORTEX2 flight results. *J. Field Robotics*, **28**, 461-483.

Guo, P., Y.-H. Kuo, S. V. Sokolovskiy, and D. H. Lenschow, 2011: Estimating atmospheric boundary layer depth using COSMIC radio occultation data. *J. Atmos. Sciences*, **68**, 1703-1713.

Global Wind Energy Council (GWEC), 2013: Global Wind Statistics 2012. [Available online at http://www.gwec.net/wp-content/uploads/2013/02/GWEC-PRstats-2012_english.pdf].

Hamill, T., F. Yang, C. Cardinali, and S. Majumdar, 2013: Impact of targeted winter storm reconnaissance dropwindsonde data on mid-latitude numerical weather prediction. To appear in *Mon. Wea. Rev*.

Ikonen, I., N. W. S. Demetriades, and R. L. Holle, 2010: Vaisala dropsondes: History, status, and applications. Preprints, *29th Conference on Hurricanes and Tropical Meteorology*, Tucson, Arizona, Amer. Meteor. Soc., P2.4. [Available online at http://ams.confex.com/ams/29Hurricanes/techprogram/paper_168031.htm].

Kahn, J. M., R. H. Katz, and K. S. J. Pister, 2000: Emerging challenges: mobile networking for Smart Dust. *J. of Commun. and Networks*, **2**, 188-196.

Kim, D-H., and others, 2011: Epidermal electronics. *Science*, **333**, 838-843.

Lazo, J., M. Lawson, P. H. Larsen, and D. M. Waldman, 2011: U.S. economic sensitivity to weather variability. *Bull. Amer. Meteor. Soc.*, **92**, 709-720.

Lew, D., M. Milligan, D. Piwko, and G. Jordon, 2011: The value of wind power forecasting. Preprints, *Second Conf. on Weather, Climate, and the New Energy Economy*, Seattle, WA, Amer. Meteor. Soc., 2.1. [Available online at http://ams.confex.com/ams/91Annual/webprogram/Manuscript/Paper180566/LewForecastingFinal.pdf].

Lin, P-H., and C-S. Lee, 2008: The eyewall-penetration reconnaissance observation of Typhoon Longwang (2005) with unmanned aerial vehicle, Aerosonde. *J. Atmos. Oceanic Technology*, **25**, 15-25.

Manobianco, J., 2005: Global Environmental MEMS Sensors (GEMS): A revolutionary observing system for the 21st century, Phase II Final Report. [Available online at http://www.niac.usra.edu/files/studies/final_report/842Manobianco.pdf].

Manobianco, J., J. G. Dreher, R. J. Evans, J. L. Case, and M. L. Adams, 2008: The impact of simulated super pressure balloon data on regional weather analyses and forecasts. *Meteor. Atmos. Phy*., **101**, 21-41.

Marquis, M., J. Wilczak, M. Ahlstrom, J. Sharp, A. Stern, C. Smith, and S. Calvert, 2011: Forecasting the wind to reach significant penetration levels of wind energy. *Bull. Amer. Meteor. Soc*., **92**, 1159-1171.

New York Times, 2010a: Smart Dust? Not quite, but we're getting there. [Available online at http://www.nytimes.com/2010/01/31/business/31unboxed.html].

New York Times, 2010b: Grab those billions! Why weather data is the next big thing in energy tech. [Available online at http://www.nytimes.com/external/venturebeat/2010/11/02/02venturebeat-grab-those-billions-why-weather-data-is-the-94976.html?ref=technology].

NOAA, 2013: NOAA's research aircraft. [Available online at http://www.aoml.noaa.gov/hrd/about_hrd/aircraft.html].

O'Grady, M. J., G. M. P. O'Hare, N. Hristova, S. Keegan, and C. Muldoon, 2007: Ubiquitous sensing: A prerequisite for mobile information services. *Proceedings of the 1st ERCIM Workshop on eMobility*, (WWIC2007), Coimbra, Portugal, 119-130.

PR Newswire, 2011: Advanced wind forecasts save millions of dollars for Xcel Energy. [Available online at http://www.prnewswire.com/news-releases/advanced-wind-forecasts-save-millions-of-dollars-for-xcel-energy-133624448.html].

Schenkman A. D., M. Xue, and A. Shapiro, 2012: Tornadogenesis in a simulated mesovortex within a mesoscale convective system. *J. Atmos Sci*., **69**, 3372-3390.

Seok, M., S. Hanson, Y-S. Lin, Z. Foo, D. Kim, Y. Lee, N. Liu, D. Sylvester, and D. Blaauw, 2008: The Phoenix processor: A 30-pW platform for sensor applications. *IEEE Symposium on VLSI Circuits*, Honolulu, HI, 188-189.

Skamarock, W. C., and Coauthors, 2008: A description of the advanced research WRF version 3. NCAR Tech. Note NCAR/TN-4751 STR, National Center for Atmospheric Research, 88 pp.

Stensrud, D., and others, 2009: Convective-scale warn-on-forecast system: A vision for 2020. *Bull. Amer. Meteor. Soc*., **90**, 1487-1499.

Swedberg, C., 2007: Gentag to commercialize super RFID technology. *RFID Journal*. [Available online at http://www.rfidjournal.com/article/view/3610].

Teisberg, T. J., R. F. Weiher, and A. Khotanzad, 2005: The economic value of temperature forecasts in electricity generation. *Bull. Amer. Meteor. Soc*., **86**, 1765-1771.

Uccellini, L. W., P. J. Kocin, R. S. Schneider, P. M. Stokols, and R. A. Dorr, 1995: Forecasting the 12-14 March 1993 Superstorm. *Bull. Amer. Meteor. Soc*., **76**, 183-199.

Uliasz, M., 1996: Regional modeling of air pollution transport in the southwestern United States. Environmental Modeling: *Computer Methods and Software for Simulating Environmental Pollution and Its Adverse Effects*, P. Zannetti, Ed., Computational Mechanics, 145–181.

U.S. Air Force (USAF), 2013: WC-130J aircraft factsheet. [Available online at http://www.403wg.afrc.af.mil/library/factsheets/ factsheet.asp?id=7482.

Vaisala, 2009: Vaisala to supply next generation dropsondes for National Oceanic and Atmospheric Administration in USA. Press release. [Available online at http://www.vaisala.com/EN/press/news/2009/Pages/Page_20100806032518.aspx].

Warneke, B., M. Last, B. Liebowitz, and K. S. J. Pister, 2001: Smart Dust: communicating with a cubic-millimeter computer. *Computer Magazine*, **34**, 44-51.

Wurman, J., J. M. Straka, E. Rasmussen, M. Randall, and A. Zahrai, 1997: Design and deployment of a portable pencil-beam pulsed Doppler 3-cm radar. *J. Atmos. Oceanic Technol*., **14**, 1502–1512.

Xcel Energy, 2013: Wind Power on Our System. [Available online at http://www.xcelenergy.com/Environment/Renewable_Energy/Wind/Wind_Power_on_Our_System].

Yankee Environmental Systems (YES), 2011: ARL-9000 Automated radiosonde launcher. [Available online at http://www.yesinc.com/products/data/arl9000/index.html].

Zussman, E., A. L. Yarin, and D. Weihs, 2002: A micro-aerodynamic decelerator based on permeable surfaces of nanofiber mats. *Experiments in Fluids*, **33** 315–320.