2.3 Global Environmental Micro Sensors Test Operations in the Natural Environment

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1 Introduction

Originally proposed in mid 2000, the Global Environmental Micro Sensors (GEMS) concept leverages technological advancements in micro and nanotechnology for the design and development of a new atmospheric in situ observing system. The initial idea was to deploy large numbers (> 10,000) of low-cost, disposable probes as small as 50-100 microns in one or more dimensions. At these sizes, the probes would have very small terminal velocities and be lightweight enough to pose virtually no threat to people or property including aircraft. ENSCO, Inc. has been defining and studying the major feasibility issues and enabling technologies for the GEMS system through various internally and externally funded projects since 2001.

During the course of a multi-year study on the GEMS system for the National Aeronautics and Space Administration (NASA) Institute for Advanced Concepts (NIAC; http://www.niac.usra.edu), the original idea to pursue miniaturization of the entire probe toward the micron-size was modified based on communication, power, and terminal velocity requirements (Manobianco 2005). First, radio frequency (RF) communication with probes of this size is not practical over the distances of at least several kilometers because their linear dimensions are too small in comparison with radio wavelengths. Second, power generation using solar energy requires areas on the order of hundreds of square centimeters which is impractical with dust-size devices. The final design trade-off favoring larger devices was the requirement to maximize the time probes remain airborne which is best achieved using a self-contained, super pressure balloon filled with helium to make it neutrally buoyant (i.e. with zero terminal velocity).

When the two-year NIAC phase II project was completed in August 2005, ENSCO began developing GEMS prototypes using commercial-off-the-shelf components as part of internal research efforts. In January 2006, ENSCO and the National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC) Weather Office responded to a solicitation for dual-use projects implemented through the KSC Technology Transfer Office Innovative Partnerships Program (IPP). The project funded by the IPP was called the GEMS Test Operations in the Natural Environment (GEMSTONE). The goal of the GEMSTONE project was to build and field test prototype probes in the natural environment of the Earth's atmosphere.

The current GEMS super pressure balloons are neutrally buoyant and carried passively by the wind at various predetermined levels in the atmosphere. Each probe is self-contained with a power source to provide sensing, data processing, geolocation, and communication functions. The probes use one-way RF communication with low-earth orbiting satellites which relay data to ground stations. Each probe contains a micro global positioning system (GPS) unit for accurate wind velocity measurements and micro electro mechanical system sensors for pressure, temperature, and moisture measurements. These sensors are similar to the ones used in dropsondes and radiosondes so GEMS probes can achieve the same measurement precision and accuracy as commercially available instruments. The measurement and communication frequencies are configurable within certain limits depending on the specific application and the desired time/space scales of interest.

This paper summarizes key aspects of the GEMSTONE project. Section 2 describes the GEMS probe and system engineering while Section 3 focuses on data analysis from different laboratory and field tests conducted during the project. Section 4 concludes with a summary and roadmap for future system development.

2 Probe and System Engineering

2.1 Mechanical Design

The GEMS probe features a helium-filled super pressure balloon that is designed to maintain a constant volume when inflated to maximum capacity at sea level pressure. Except for the sensor board, the remaining electronics were initially encapsulated within the helium-filled probe shell. The shell is constructed by placing two pieces of 48-gauge (12-µ) thick Mylar™ together using heat sealing glue. A plastic valve is affixed to one side of the balloon with a combination of heat sealing glue and rubber cement. The seams are then heat rolled and pressed to meet glue manufacturer's suggestion of 180 - 240 °C cure temperature.

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When inflated the balloon is pumpkin-shaped measuring ~1.2 m in width by ~0.6 m in height. Initial tests showed that when the electronics were housed within the balloon, the probe was prone to leaking at the seam where the sensor cable passed through shell material. Therefore, the decision was made to place the electronics below rather than inside the balloon. This design modification maintains the integrity of the helium-filled probe but still protects the electronics from water.

The electronics are attached to the bottom of the balloon using a separate piece of shell material with adhesive after inflation and prior to launch (Fig. 1). The antenna boards are positioned at the edges of the material and secured from slipping below the electronics package which would obstruct them from transmitting and receiving signals during flight. The sensor board and cable pass through a small opening in the extra shell material so that they are suspended 2-3 cm below the probe and exposed to the free atmosphere during flight.

Based on buoyancy calculations, the balloon can lift a 170-gram payload when fully inflated with helium at sea level pressure and temperature in east central Florida. The level of neutral buoyancy can be adjusted using an approximate density profile from a nearby radiosonde to estimate the changes in lift with increased mass. During flight, the level of neutral buoyancy is expected to vary several 100 meters due to turbulence, horizontal/vertical variations in air density, and radiative heating/cooling of the helium inside the balloon. Similar altitude excursions have been observed during past constant altitude balloon flights.

2.2 Electronics Design

The electronics package for the GEMS system was designed to be very modular so that hardware and/or software capability could be easily added or removed depending on changing requirements and applications (Fig. 2a). The sensor board has been configured as a switch to activate the electronics once it is plugged into the system. As soon as the electronics are powered up, the system will transmit data at pre-determined time intervals that are software configurable. Each board has a male-female vertical connector that allows the electronics system to be stacked (Fig. 2b). A thin ribbon cable connects the microcontroller board to the sensor board. This cable is passed through the Mylar™ shell material. When completely assembled, the electronics stack weighs ~60 gm with the antenna boards and connector cables adding ~40 gm. The total system payload weighs between 130 - 145 grams depending on the power source as described in section 2.3.

2.3 Power System

The GEMS power board was designed to house primary and secondary power systems. The primary power source is either a standard 9-volt (9V) battery or a 9V thin film solar panel. The decision to use solar cells or batteries depends on requirements for flight duration and time of day as well as frequency of data acquisition primarily related to satellite communications.

The secondary power system consists of two rechargeable lithium coin cells. The batteries are connected in series and supply 7.2 V of backup power during night time and cloudy conditions. Two 3.6 V 120 mAh batteries connected in series provide the necessary 5 V required for satellite communication (SATCOM) transmissions during cloudy and night time conditions. The coin cells are used only in conjunction with the solar panels. A microprocessor controls the coin cell recharging circuit. During the day time, the coin cells are constantly charging in order to store energy for night time transmission. The solar/coin cell system relies on cycling GPS sleep states to conserve power for night time transmission.

The SATCOM transmissions are not powered directly by the batteries or solar cell but from two super capacitors connected in parallel at 5 V and 3.2 Farad (F) capacitance. The super capacitors can source up to 10 amps at 5 V for less than a second. This high current output is needed on quick demand for the SATCOM module. Tests conducted with a standard, plug-in power supply showed that during power cycling, an average of 9 mAh was needed at 15-minute intervals. The current system does not employ power cycling due to the GPS module and averages 65 mAh during 15-minute transmissions. The system can maintain this average current with a 9V battery or solar cells in full sun.

2.4 Microprocessor

The microprocessor board regulates the GEMS probe and uses a Texas Instruments msp430 microcontroller. The processor controls the timing, data acquisition, SATCOM, and power cycling. Included on the microprocessor board is an operational amplifier to read in the pressure sensor data. All other data are acquired through serial communication ports. Additional analog-to-digital conversion and control lines have been routed to the sensor board through the ribbon cable. This design feature makes it possible to include additional sensors and/or capability on the sensor board.

2.5 Satellite Communications

The GEMS probe uses the Axonn STX2 satellite transmitter which provides one-way communication to the Global Star network. The STX2 module is the largest electronics component with the SATCOM antenna and SATCOM boards encompassing 40% of the system weight. The SATCOM module has been designed to maximize board space utilizing both top and bottom sides which minimize excess board weight.

Data is compressed to meet the 144-bit STX2 single message requirement and sent via serial communication to the STX2 module. The STX2 uses 1.5 W of power from the super capacitors for 1.4 seconds while transmitting the data to low Earth orbiting satellites through a patch antenna. The STX2 module is configured to meet factory recommended transmission requirements. Axonn suggests that each transmitted message be followed by three subsequent backup messages to achieve >95% transmission rate. Bench top experiments were completed using a configuration of 5-, 10-, and 20-minute message intervals. Each transmission was accompanied by three backup transmissions as suggested by Axonn. Each test was conducted with a power supply, 9V battery, and solar cells. The three backup transmissions yielded over 90% success rate compared to <40% for a single transmission.

2.6 Geo-location

The GPS receiver board delivers all geo-location data to the microprocessor. The GPS receiver acquires heading, speed, position, and altitude data from GPS orbiting satellites. The Navman Jupiter 30 was chosen for its size, weight and performance characteristics. All tests with the GPS module ran the Jupiter 30 continuously to acquire hot start position fixes and did not conserve power using a GPS sleep mode. Given the focus on daytime probe demonstrations for the GEMSTONE project, this tradeoff does not affect the power cycling but will be important to address for continuous day/night operation in follow-on efforts.

Once at the level of neutral buoyancy, the GEMS probe is assumed to be a passive tracer moving with the wind. Therefore, the instantaneous GPS-derived heading and speed are used to infer horizontal wind velocity. This assumption will not be valid in turbulent flow so it will be necessary in the future to average several high frequency GPS measurements as well as account for vertical probe displacement in order to retrieve accurate wind velocities under diverse weather conditions.

The accuracy of the position, speed, altitude, and heading sent as part of the 144-bit compressed data packet along with the Jupiter 30 specifications for the same quantities is shown in Table 1. The current compression method clearly sacrifices some accuracy that could be obtained using the full resolution measurements from the Jupiter 30. However, the GEMS data record still provides heading and speed measurements accurate to 1 degree and 0.5 m s^{-1}, respectively, that is deemed sufficient given the current application and stage of prototype development.

2.7 Sensors

The sensor package is equipped with an Intersema MS5401-AM analog pressure sensor and a Sensirion SHT14 14-bit temperature/relative humidity (RH) sensor. The Intersema pressure sensor has an accuracy of +/- 0.3 hPa and an operating range of 0 to 1000 hPa. Future projects should explore a pressure sensor with a dynamic range exceeding 1000 hPa to record useful data near the ground when the probes are first launched. The Sensirion temperature (RH) sensor has a resolution of +/- 0.02 ^{o}C (+/- 0.03%) and a range of -40 ^{o}C to 125 ^{o}C (1% to 99%) as stated by the manufacturer's data sheet. The sensor board also features a connection where the microprocessor could be reprogrammed after assembly as needed to adjust or troubleshoot firmware settings, functionality, etc.

3 Testing and Analysis

3.1 Static Outdoor Test

A static outdoor test was designed to identify any biases in the GEMS Sensirion temperature and RH sensors over the range of ambient conditions near ground level. A National Institute of Standards and Technology traceable sensor was purchased from Vaisala to provide accurate validation of the Sensirion sensors during a diurnal cycle. Both the GEMS and Vaisala sensors were located 2 m above ground level adjacent to the ENSCO's Coastal Technology Center facility in Melbourne, Florida. Acquired data were analyzed for any bias over three-day periods during November and December 2006. The validation of the GEMS sensors required placing the sensor board in a louvered plastic housing. Such an arrangement exposed both the GEMS and ground truth sensors to the same environmental conditions and provided radiation shielding and aspiration. A computer workstation was set up to record data from the GEMS sensors.

The diurnal RH tests revealed a bias above 95% and below 65%. As can be seen in Fig. 3a, the Sensirion RH measurements are low when the Vaisala sensor reports RH above 95% and the Sensirion measurements are high when the Vaisala sensor reports RH below 65%. The repeatability of the biases suggests that a systematic difference exists between the Vaisala and Sensirion RH sensors. However, no such bias is present with the temperature measurements as the two traces overlap for the same three-day period in November/December 2006 (Fig. 3b). At the end of the test period on 1 December 2006, a rain shower deposited water directly onto the Sensirion sensor that was located close to the edge of the louvered housing. The wetting of the sensor would account for the increase in humidity and decrease in temperature drop relative to the Vaisala measurements.

3.2 Pressure Sensor Calibration

Tests were conducted over a three-day period from 11-13 December 2006 at the NASA KSC environmental testing facility. The facility provided access to a 1.2 x 1.2 x 1.8 m altitude chamber. The chamber was needed to calibrate both the Intersema pressure and Sensirion temperature/RH sensors. The results from the Sensirion sensors are presented below.

The pressure sensors required calibration at multiple values of temperature and pressure to generate realistic calibration curves that would be consistent with conditions at various altitudes and temperatures. The sensors are based upon a resistive bridge coupled to a flexible membrane that deforms as the pressure changes. This deformation is measured as a voltage change across the resistive bridge. The sensor is rated for operation from 0 to 1000 hPa so pressures greater than 1000 hPa generate a nonlinear response. In order to calibrate the sensors, measurements were taken at eight different pressure levels and four different temperatures. Due to limitations of the KSC altitude chamber, it was not possible to record the voltage at or near a zero pressure reading. Therefore, the zero pressure reading was extrapolated from the data acquired. Fig. 4 illustrates the sensor response as a function of pressure.

The temperature in the NASA chamber was varied to measure the thermal coefficient of the resistive bridge. Although the pressure variation induced by temperature is small, it still has an impact on the pressure as seen from the data spread in Fig. 4. The bridge's thermal coefficient produces a change in both the slope (delta) and y-intercept of the pressure data. Since the y-intercept/zero pressure reading could not be obtained empirically, an extrapolation was performed. As shown in Fig. 4, the spread in the data is also not uniform so regression was used to determine the best fit for both the slope and y-intercept values of the regression line.

The regression yielded excellent results for a linear approximation of slope with a correlation coefficient of 0.99 for both sensors. However, the correlation for the intercept was not as high especially for sensor 1 although the results are acceptable given the minor correction that the intercept actually applies to the pressure calculation (not shown).

3.3 Temperature Sensor Calibration

During the pressure sensor calibration process, the Sensirion sensors were also tested to determine their accuracy compared with thermocouples placed throughout the KSC altitude chamber. The initial plan was to test the sensors from -40 to +40 °C; however, the Sensirion sensors are operationally rated to -30 °C and as the temperature descended below -30 °C, the sensors began to fail. The sensor failure was due to icing and resumed correct operation once the ice melted. Due to this constraint, the sensors were tested from -20 to +40 °C with results of the temperature calibration summarized in Fig. 5.

Both GEMS sensors performed well from 0 to +40 °C over a wide range of pressures with respect to the thermocouple (Fig. 5). However, at -20 °C, sensor 2 began to deviate from the reference thermocouples by a substantial amount below 500 hPa. This condition worsened as the pressure decreased. The presence of water on the surface of the sensor could have caused this degradation. As the temperature was lowered, any water on the surface would have frozen and formed a thin ice layer on the sensing element. As the pressure was decreased, this ice could have applied stress to the temperature element which would have been interpreted as an increased temperature. Further tests would be needed to validate this hypothesis but were not performed since probes deployed during any GEMSTONE free flight tests at altitudes of 1 - 2 km would not experience such low temperatures or pressures.

3.4 Free Flight Testing

The free flight tests were designed to examine system functionality and robustness in the relevant environment, record sensor data, and document SATCOM reliability. Two free flight tests were attempted during the last week of March 2007 with little success. Problems with the GPS unit not updating position and the balloon having insufficient buoyancy to lift the payload caused premature test failures. The initial GPS problem was linked to using the Callisto receiver that was replaced by the Jupiter 30 module.

A third free flight test was conducted on 19 April 2007 around mid afternoon using a 9V battery as a power source. For this test, the GEMS probe was released from Melbourne Beach, Florida and traveled in a south, southeast direction (~140 degrees) along the coast for more than 7.5 hours with SATCOM reliability around 75%. The GPS data stopped updating near Ft. Pierce, Florida after drifting approximately 60 km at average speed of 7 m s^{-1}. The loss of real-time GPS data is likely to have occurred when the GPS antenna board came loose and slipped below the main electronics stack preventing the GPS module from acquiring any further signals from the satellite constellation. Before GPS data were lost, the probe altitude ranged from 470 - 1300 m. The limited data from this first successful flight of a GEMS probe are summarized in Fig. 6 and Table 2.

4 Summary and Roadmap

The GEMS concept leverages technological advancements in micro and nanotechnology for a new atmospheric in situ observing system based on an ensemble of self-contained, low cost disposable probes. During the course of a two-phase study funded by the NIAC, ENSCO, Inc. and collaborators identified the major feasibility issues for the GEMS system and mapped pathways for system development in a technology roadmap.

Follow-on work after the NIAC study included prototype development funded by ENSCO and a cost-sharing project called GEMSTONE sponsored by the KSC Technology Transfer Office. The goal of the GEMSTONE project was to build and field-test a small system of prototype probes in the Earth's atmosphere. This paper summarized highlights from the GEMSTONE project that included probe and system engineering as well as laboratory and field tests from September 2006 through May 2007.

The various laboratory and field tests conducted during the GEMSTONE project were designed to characterize the sensor suite, the micro GPS, SATCOM capabilities, and overall system performance. Chamber testing was performed to calibrate pressure and temperature sensors. Two free flight tests were attempted during the last week of March 2007 but failed due to problems with the GPS unit not updating position and the balloon having insufficient buoyancy. The third and final free flight test in April 2007 was successful in demonstrating system functionality and robustness in the relevant environment including capability to acquire and transmit useful data in real time.

This section concludes with a roadmap for future development efforts that would be required to yield a fully functional and reliable prototype system (Table 3). The roadmap covers areas related to sensors (dynamic range, aspiration, shielding), SATCOM reliability and coverage, GPS power management / cycling and data processing, balloon construction, and electronics miniaturization. Note that not all of these issues were discussed in the current paper but are covered in the GEMSTONE final report (Manobianco et al 2007). The successful single-probe flight test provides a solid foundation to move forward and address these outstanding issues in follow-on projects.

Acknowledgements

The ENSCO team would like to thank Dr. Francis Merceret (NASA KSC Weather Office Chief Scientist) for his enthusiastic support of the GEMS concept beginning in 2001 and his contributions to the GEMSTONE project as co-investigator. The entire project team acknowledges Rosemary Baize (NASA KSC Technology Transfer Office) for her guidance and support throughout the project as well as ENSCO, Inc. for significant cost sharing that made it possible to complete the effort

References

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Fig. 1. The GEMS probe prior to deployment for the first successful free flight test. Note the electronics mounted on the bottom of the probe with the sensor board hanging below the balloon.

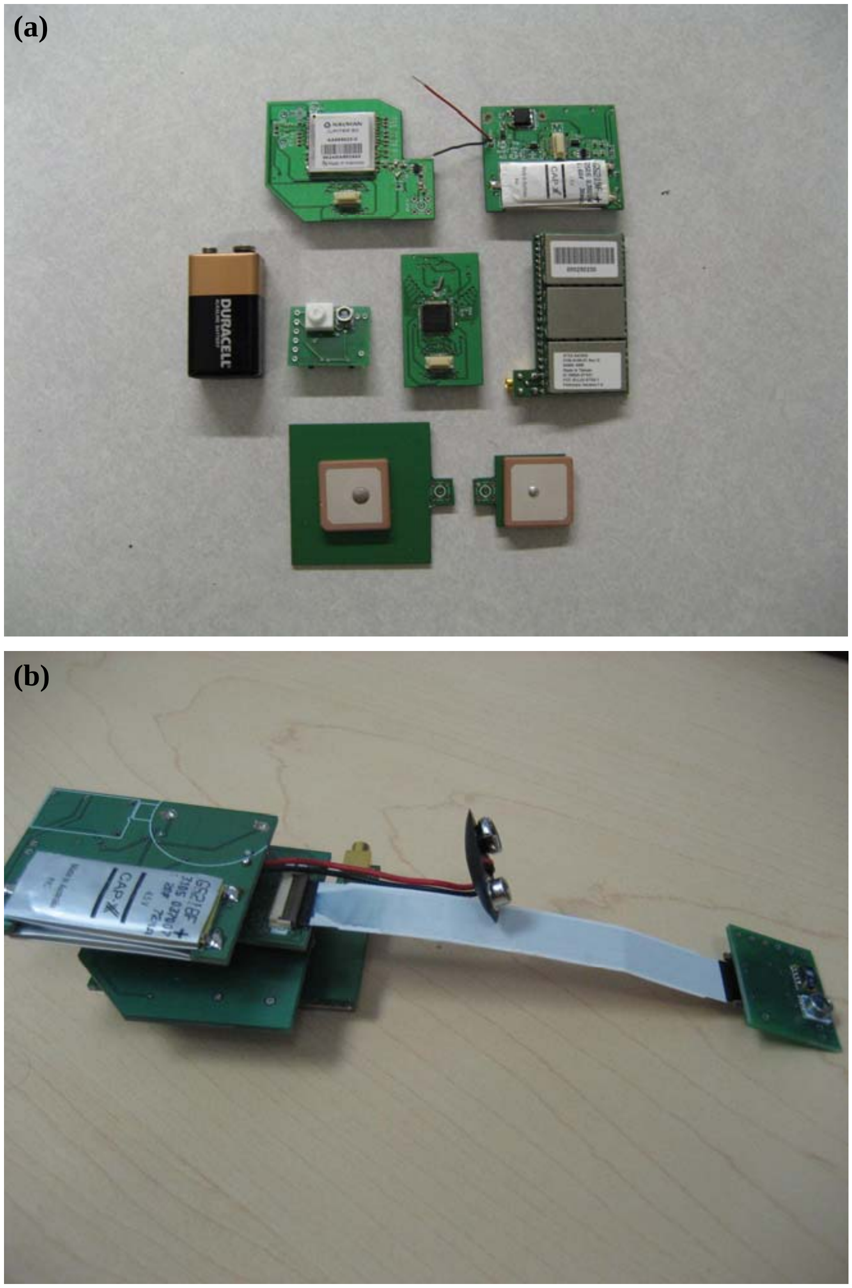

Fig. 2. (a) Complete GEMS electronics system with 9-volt battery included for scale. The modules shown from left to right and top to bottom are the global positioning system (GPS), power, sensor, microprocessor, satellite communication (SATCOM), SATCOM antenna, and GPS antenna boards, respectively. (b) Complete electronics stack assembled including sensor board cable that passes through the shell material.

Table 1. Comparison between the accuracy of GEMS data record and Jupiter 30 manufacturer specifications for GPS position, speed, altitude, and heading.

	Position	**Speed**	**Altitude**	**Heading**
GEMS data record	30 m	0.5 m s^{-1}	10 m	1 degree
Jupiter 30 specification	2.2 m	0.05 m s^{-1}	0.1 m	0.1 degrees

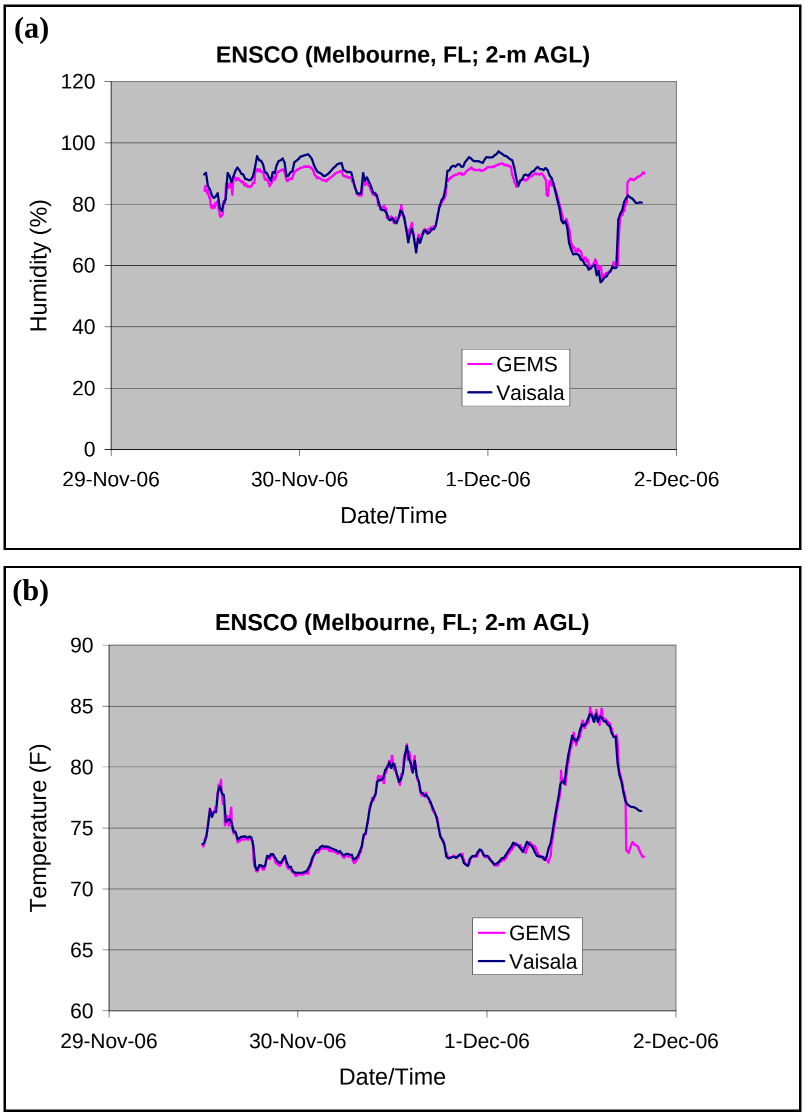

Fig. 3. Results comparing (a) relative humidity and (b) temperature measurements between the Vaisala and Sensirion sensors from 29 November 2006 through 1 December 2006 during the outdoor static test at ENSCO's Coastal Technology Center.

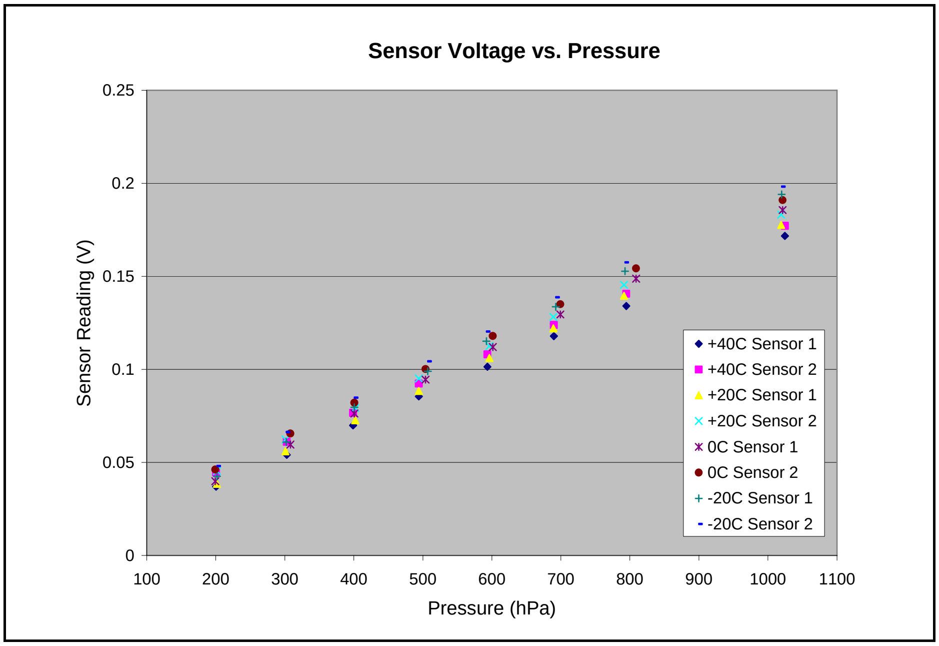

Fig. 4. Intersema pressure sensor calibration data from the NASA environmental test chamber.

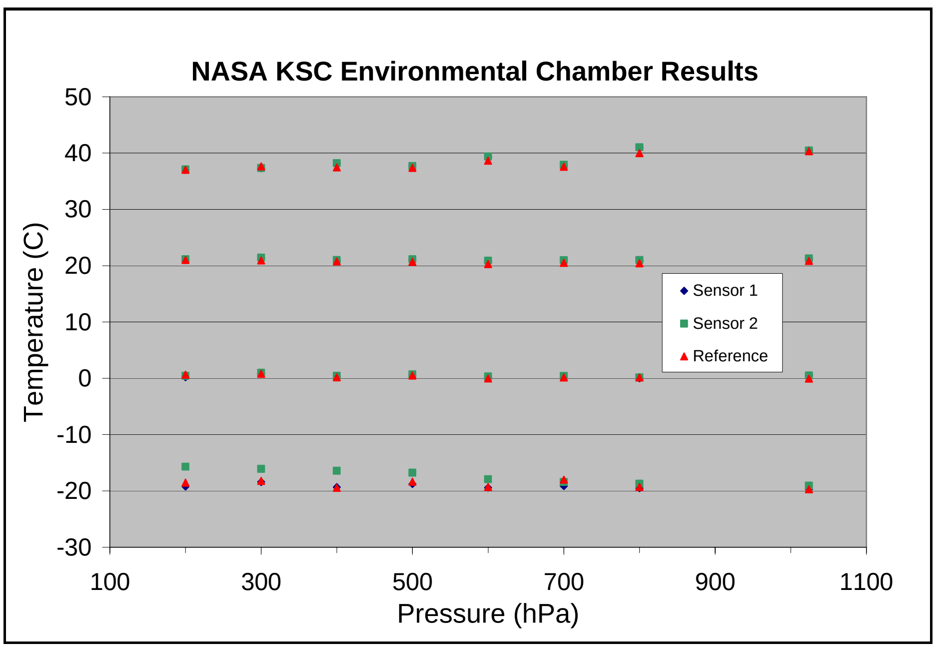

Fig. 5. Comparisons between two different Sensirion temperature sensors and the KSC altitude chamber thermocouple located below the test stand. Data were recorded at four different temperatures over a range of pressures from ambient to 200 hPa.

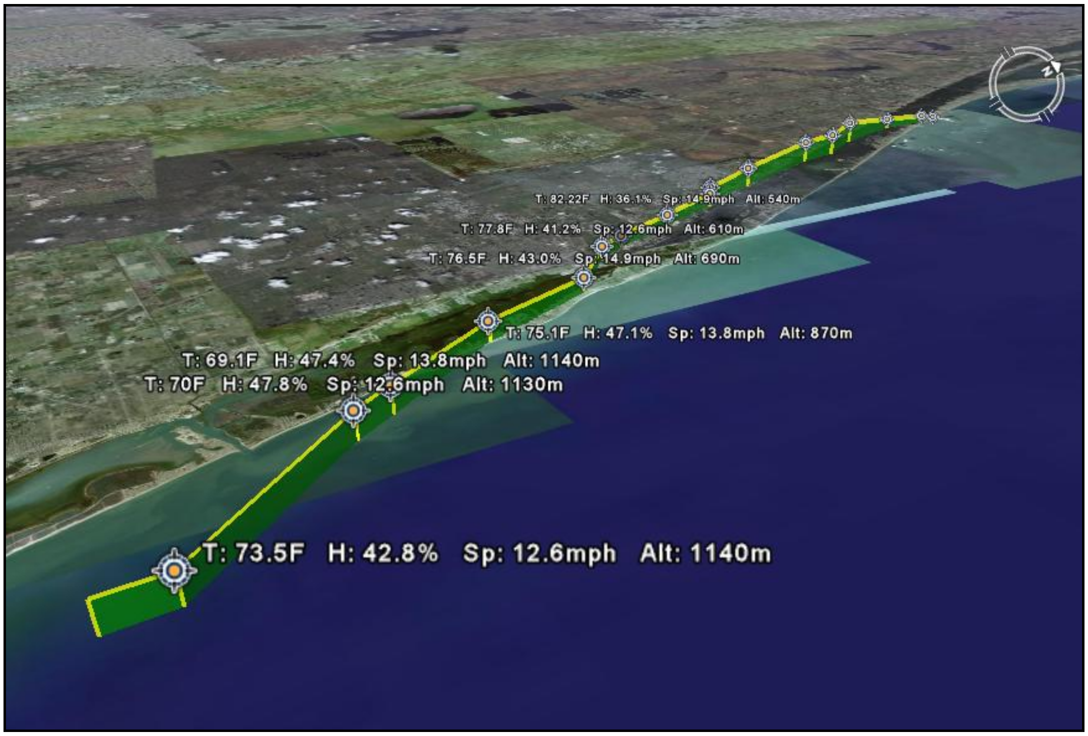

Fig. 6. Google Earth™ visual summary of free flight test on 19 April 2007. Data values were entered into the Google Earth™ image including temperature (T), humidity (H), speed (Sp), and altitude (Alt).

Table 2. Sample data from a free flight test on 19 April 2007 with deployment from Melbourne Beach, Florida.

Time	**Latitude (degrees)**	**Longitude (degrees)**	**Temperature (C)**	**Relative Humidity (%)**	**Altitude (m)**	**Speed ($m\ s^{-1}$)**
14:41	28.00	-80.52	26.2	51.3	10	0.0
14:53	27.96	-80.52	26.2	51.3	470	6.2
14:56	27.91	-80.50	22.8	52.2	620	7.2
15:16	27.87	-80.48	20.5	49.5	1300	5.1
15:39	27.85	-80.47	20.8	47.3	1240	5.6
15:58	27.78	-80.45	21.0	47.5	1050	6.2
16:10	27.75	-80.43	24.1	42.3	770	6.7
16:16	27.74	-80.42	23.1	44.5	670	6.7
16:24	27.70	-80.41	27.8	36.1	540	6.7
16:37	27.66	-80.39	26.2	39.8	620	6.7
16:40	27.65	-80.38	25.4	41.2	610	5.6
16:51	27.62	-80.35	24.7	43.0	690	6.7
17:12	27.56	-80.32	23.9	47.1	870	6.2
17:33	27.51	-80.28	20.6	47.4	1140	6.2
17:34	27.50	-80.27	21.1	47.8	1130	5.6
17:59	27.44	-80.21	23.1	42.8	1140	5.6

Table 3. Summary of issues, problems, and areas for future GEMS development along with possible solutions or recommended courses of action that constitute a technology roadmap.

Classification	Issue	Solution or Recommended Course of Action
Sensing	Intersema pressure sensor not rated above 1000 hPa	Research other pressure sensors and combine with or eliminate current device
Sensing	Sensors not aspirated	Complete testing and implementation of aspiration using small fans or other methods
Sensing	Sensors not shielded	Design and develop mechanical housing for shielding sensors – could be integrated with aspiration scheme
Sensing	Sensor cable passing through main shell material creates unacceptable failure point	Refine the current design for attaching electronics to the bottom of the probe or redesign the value to accommodate cable pass through
Communication	Unreliable Global Star communications	Explore other satellite providers (e.g. Iridium or ARGOS)
Communication	Global Star has limited coverage	Switch to Iridium or other provider with better coverage
Geo-location	Current microprocessor firmware not configured to use Jupiter 30 GPS sleep mode	Revise firmware so the GPS unit can use sleep mode to conserve power
Geo-location	Currently using instantaneous GPS heading and speed	Revise firmware to average higher frequency GPS measurements and account for altitude changes
Power	Continuous and reliable 24-h probe operation	Upgrade firmware, optimize power cycling, and test power subsystems
Flight termination	Hardware (mechanical system) not tested and firmware (GPS 'fence') not implemented	Complete hardware and firmware modifications, bench test, then field test
Balloon construction	Reliability of seams and values	Contract with balloon manufacturing company, optimize balloon design, new materials research
Miniaturization	Reduce system mass	Integrate separate boards, use flexible electronics and lighter components, redesign SATCOM hardware or choose alternate communication paradigm