A coordinated balloon observation system for sustained in-situ measurements of hurricanes

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Abstract— **In this paper, a low-cost balloon observation system is proposed for sustained (week-long), broadly distributed, in-situ measurements of hurricane development. The high-quality, high-density (in both space and time) measurements to be made available by such a system should be instrumental in significantly improving our ability to forecast such extreme and dangerous atmospheric events. The present paper focuses specifically on developing the overall requirements and specifications of the balloons making up such a system, including a rough budget of the mass, energy, and cost of the key components of each balloon. A brief review of the specific balloon technology and control strategies to be used in the system is also included; both of these topics are discussed much further in our companion publications included in the references.**

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1. Introduction

In-situ observations of the inner regions of hurricanes (a.k.a. typhoons, tropical cyclones, etc.) are difficult to obtain, yet are essential for developing the forecast accuracy [12] needed to provide critically valuable lead time to protect lives and property, and to prepare emergency responses. Current operational approaches are very expensive, and significantly limited in duration and spatial resolution. For example, aircraft-deployed expendable dropsondes acquire vertical profiles of wind speed, humidity, pressure, and temperature during their short 10-20 minutes fall. Since 2014, small expendable UAVs called Coyotes [3] have also been deployed from NOAA aircraft, providing only an hour of operation. Additionally, aircraft-mounted Doppler radars provide high-frequency, high-resolution measurements, but are limited to about 9 hours of mission duration.

In contrast, atmospheric balloons have repeatedly proved their capability of surviving difficult environmental conditions, including high winds and high turbulence levels, for sustained periods of time. While many balloon flights have been performed in the low atmosphere [6], only a few have attempted to intercept hurricanes.

In the 2007 VASCO experiment [9] [11] in the Indian ocean, two Aeroclippers (dirigible-shaped balloons tethered to an instrumented gondola floating just below the ocean surface) survived being trapped in the eye of tropical cyclone Dora for more than a week, while a superpressure balloon captured by the inflow of tropical cyclone Gamede circled the storm center close to the maximum wind radius multiple times at almost zero radial velocity. These balloons were designed to fly at fixed pressure altitudes without feedback control, and established that balloons can indeed be constructed to survive and persist within hurricanes for sustained periods of time.

The groundbreaking work of Businger et al. [2] reports promising tests, in 2002 and 2005, of "smart" altitude-controlled balloon systems, leveraging constant-volume balloon designs with internal air ballast tanks to control the balloon density. Unfortunately, these tests were unsuccessful at intercepting their desired meteorological targets due to various technical malfunctions. Follow-up tests in thunderstorms, performed in collaboration with Smith & Williamson, provided more reliable altitude control of such constant-volume balloon designs. These smart balloon experiments established that accurate altitude control of atmospheric balloons is viable, even in inclement weather conditions.

The goal of the present work is to develop small, rugged, mobility-controllable sensor balloons, which may be deployed in large numbers via a single aircraft flight over a hurricane early in its development, and coordinated to autonomously and strategically position themselves within the hurricane, and moving with it until well after landfall. The sensor balloon system will be in satellite radio communication with weather forecasting centers to provide real-time data of the hurricane event, supporting significantly improved capability to forecast the storm path and intensity, and to improve predictive modelling capabilities for future storms.

The lighter-than-air platform for the proposed hurricane observation system is provided by the patent-pending, constant-mass, buoyancy-controlled balloon design developed by Thin Red Line and reported in [4], [5], to which the reader is referred for details. This design is markedly different from all other approaches to controllable balloon tecnologies, such those explored by Businger et al. and developed further by their collaborators at Smith & Williamson. Thin Red Line's accordion-like, volume-adjustable design is a constant-mass balloon that achieves rapid vertical mobility by simultaneously manipulating balloon density and altitude-adaptive volume by mechanically adjusting the length of an internal axial tendon running along the centerline of the balloon and attached to the balloon's polar extremities, as depicted in Figure 1.

The system to be developed will be capable of a one-week mission duration and a 0-8 km altitude range. This requires a 4:1 volumetric compression ratio of the balloon, which the design mentioned above is readily capable of achieving [4],

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Figure 1: Constant-mass buoyancy-controlled balloon design developed by Thin Red Line (see [4], [5]).

[5]. This design will be ruggedized to sustain cold, wet, turbulent, electrically-active conditions. Recovery of many of the balloons after landfall, and reconditioning for reuse, is also planned. The balloon payload will include low-power satellite communication equipment as well as environmental sensors for monitoring the local pressure, temperature, and humidity, in addition to the balloon's location and velocity via GPS and an IMU. A key design objective is for the balloons (which may be compactly stowed and are about 3 kg each) to be deployable from Sonobuoy (AXBT) launch chutes, which are already implemented in NOAA WP-3 Orion aircraft for launching the Coyote UAV system mentioned previously. These chutes are 13 cm in diameter and 91 cm long.

Novel control strategies for efficiently maneuvering such balloons within hurricanes with remarkably little stored energy will be implemented, as reviewed briefly in §3 and discussed in detail in [1] and [8]. These control strategies leverage estimates of the stratified flowfield characterizing the hurricane (that is, a strong inflow in the planetary boundary layer at low altitudes, and a weaker outflow at higher altitudes), permitting the balloons to remain close to target radii and at optimized azimuthal separations using limited (that is, energetically inexpensive) changes in altitude. Larger altitude changes may be used for sweeping through different regions of interest in the hurricane as necessary.

Advantages of such balloon-based monitoring platforms for observing hurricanes include:

- operational life of a week or longer, as compared with 10-20 minutes (dropsondes) or one to several hours (aircraft),
- accurate horizontal wind measurements, by acting as a Lagrangian tracers at constant altitudes within the flowfield,
- low production and operational cost, leveraging heavily COTS cellphone-grade electronics, and
- high spatial and temporal measurement resolution, via a coordinated swarm of sensor balloons.

2. System requirements

A hurricane is characterized by a relatively calm core with clear skies, known as the eye, surrounded by a strongly convective region beginning approximately $40\,\mathrm{km}$ from the center, known as the eyewall [7]. The region outside the eyewall, where the hurricane intensity decays with distance, is characterized by the presence of spiral rainbands and, in certain cases, the formation of new eyewalls which can rapidly affect the hurricane's evolution [10].

Table 1: Typical hurricane scales.

Horizontal length	$1000\,\mathrm{km}$
Maximum wind radius	$50\,\mathrm{km}$
Vertical length	$10\,\mathrm{km}$
Characteristic Time	$16\,\mathrm{h}$
Azimuthal velocity	$60\,\mathrm{m/s}$
Radial velocity	$10\,\mathrm{m/s}$
Vertical velocity	$0.06\,\mathrm{m/s}$
Vertical velocity gradient	$0.001\,\mathrm{s}^{-1}$
Horizontal eddy diffusivity	$10^3\,\mathrm{m}^2/\mathrm{s}$

As the coordination strategy to be used in this work (see §3) relies on partial knowledge of the hurricane's flowfield, we present in Table 1 the characteristic length, time, and velocity scales of hurricanes (see, e.g., [7]). This data is valuable, both for specifying the control and system requirements, and for verifying the feasibility of the control approach to be used.

The horizontal extent of a hurricane is often of the order of $1000\,\mathrm{km}$. However, we are interested here in sampling the region of the hurricane extending horizontally up to about four times the maximum wind radius, or up to $200\,\mathrm{km}$. This is the most dynamic and hazardous region of the hurricane, and is where subtle, difficult-to-observe-from-space, and only partially-understood fluid-dynamic phenomena take place; these phenomena can rapidly alter the course of the hurricane. System design considerations on both weight and operating temperatures (see §5 and §4) suggest an operational service ceiling of about $8\,\mathrm{km}$ for the balloons; again, below this maximum altitude is the most dynamically significant region of the flowfield, as the hurricane itself is driven by evaporation at the air-sea interface.

Characteristic velocities in a hurricane are of the order of $60\,\mathrm{m/s}$, $10\,\mathrm{m/s}$, and $0.06\,\mathrm{m/s}$ in the azimuthal, radial, and vertical directions respectively. The rotational period at a radius of $50\,\mathrm{km}$ is about two hours, and the rotational period at a radius of $200\,\mathrm{km}$ is about five hours. It is important to note that, while a $0.06\,\mathrm{m/s}$ characteristic vertical velocity seems quite low (and, easily managed by a balloon having a controllable vertical velocity of up to about $1\,\mathrm{m/s}$), updrafts as strong as $10\,\mathrm{m/s}$ are occasionally present in the vicinity of the eyewall of a hurricane. We will not try to counteract such violent updrafts with feedback in the present work; rather, our coordination approach is, by design, somewhat "lazy", and allows balloons to occasionally diverge from the desired formation. When this happens, the coordination approach we have developed adjusts in a smooth, energetically efficient fashion to disperse the sensor balloon swarm into a new distribution within the hurricane.

As discussed further in §3, knowledge at the hurricane forecasting center of the large-scale flow features, including filtered estimates of the vertical gradients of the horizontal (radial and azimuthal) velocity components, can be used to optimize balloon trajectories via a (centrally-computed) Model Predictive Control (MPC) approach in order to coordinate the balloon distribution [1]. Departures from these optimized trajectories, which are expected to be significant and which arise due to both subgrid-scale fluid motions as well as forecasting errors, and for which only statistical models are available, will be corrected for with a clever new Three-Level Control (TLC) feedback strategy, which may be computed and applied locally on each balloon [8].

Thus, of particular interest in our balloon coordination approach are (a) the horizontal eddy diffusivity, (b) the vertical gradients of the horizontal velocity components, and (c) the uncertainty of 1-hour forecasts of the hurricane. A balance between these three quantities ultimately determines how well a swarm of balloons can be maintained in a specified formation. The larger the velocity gradients, the greater the effect of a small change of altitude on the horizontal balloon distribution (and, thus, the greater the controllability of the relative position of the balloons). The more accurate the forecast of these winds and their gradients, the more they can be leveraged via the MPC-based optimization approach, and the less they need to be corrected for via TLC-based feedback. Finally, the horizontal eddy diffusivity represents, in effect, the rate at which the "random walk" of the balloons in the horizontal directions, arising from subgrid-scale fluid motions, separates the balloons from their optimized trajectories before TLC feedback is applied; the larger the horizontal eddy diffusivity, the more feedback will be necessary to counteract this random walk.

3. Balloon coordination strategy

As discussed above, balloon coordination will be achieved via a combination of a (centrally-computed, at the weather forecasting center) MPC approach to account for the forecasted large-scale motions of the hurricane, and a (locally-computed, on the balloons themselves) TLC approach to correct, to some extent, for the inaccuracies of these forecasts, as well as for the unresolved winds within the hurricane, which are both expected to be pronounced. Energetically, both of these control approaches are specifically designed to be maximally efficient, using buoyancy control only in a manner which directly leverages the strong vertical stratification of the horizontal winds within the hurricane.

Model Predictive Control (MPC). As presented in detail in [1], on the largest length and time scales, information from short-term ($\sim$ 1 hour) hurricane forecasts is leveraged directly to plan approximate trajectories for the balloons that keep them (or, restore them) to time-evolving distributions which, on average, are fairly well spread over the areas of greatest interest within the hurricane. Before the sensor balloons have been well dispersed over the hurricane, the short-term forecasts of the winds within the hurricane are expected to be significantly less accurate than after the sensor balloons have gathered more in situ information. The process of successively using reduced-accuracy wind forecasts to roughly navigate the wind-driven balloons into distributions that facilitate higher-accuracy forecasts to be performed is commonly referred to as "bootstrapping".

Three-Level Control (TLC). As presented in detail in [8], on smaller length and time scales, a (nonlinear) feedback control strategy is used to compensate for the departure of the balloons from their planned trajectories, arising from both errors in the forecasts of the large-scale winds as well as the "random walk" of the balloons in the horizontal directions, arising from subgrid-scale fluid motions. A key feature of the TLC algorithm is that it doesn't waste energy "chasing" the small-scale movements of each balloon; indeed, the TLC algorithm simply leaves the tendon tension control winch that compresses a balloon *at rest* until the balloon deviates too far from the desired the position; it then moves the balloon up or down (as appropriate) a finite amount, for a short period of time, in order to leverage the local stratification of the winds to return the balloon to the desired azimuthal position.

Table 2: Breakdown of a 26-byte measurement message.

quantity	range	integer type	size
Time (s)	$0 - 1000000$	unsigned long	4
Latitude	± 90.00000	signed long	4
Longitude	± 180.00000	singed long	4
Altitude (m)	$0 - 20000$	unsigned short	2
Pressure (kPa)	$0 - 120.00$	unsigned short	2
Temperature (K)	$0 - 325.0$	unsigned short	2
Humidity (%)	$0 - 100.0$	unsigned short	2
Velocity x (m/s)	± 100.0	signed short	2
Velocity y (m/s)	± 100.0	signed short	2
Velocity z (m/s)	± 25.00	signed short	2
Total (bytes):			26

The overall balloon coordination strategy is, by design, "lazy" (that is, maximally energy conserving), and disruptions of the balloon formation are allowed when violent updrafts or downdrafts are encountered within the hurricane. The balloons will simply "ride out" these violent events, and the balloon coordination strategy will smoothly adjust the balloon swarm into a new, well-distributed formation thereafter. Note that the goal of the balloon coordination strategy is quite modest: simply keep the balloons moving along with the hurricane without hitting the ground, and generally keep them well distributed over the hurricane, while (most importantly) conserving battery power as much as possible.

4. Electronics payload

The payload of the balloon will consist of atmospheric sensors, a microprocessor, communication equipment, a motor to drive the tendon, and batteries. Most of this payload, except for the atmospheric sensors, will be tucked inside the balloon, near the winch, in order to protect it from the wet external environment, and to scavenge any waste heat generated by the motor, thereby increasing (slightly) the efficiency of the battery. In this section, we consider the communication, sensors, and batteries. Note that specifications for electronics components often declare, conservatively, a minimum working temperature of $-40\,^{\circ}\mathrm{C}$, though many of these components (except batteries) function well at significantly lower temperatures. Regardless, the maximum operating altitude considered in this work is about $8\,\mathrm{km}$, which corresponds to temperatures down to about $-40\,^{\circ}\mathrm{C}$.

For remote scientific measurement systems like that proposed here, there are a handful of viable options currently available for satellite communications, including Argos, Globalstar, and Iridium. A few new systems have also been proposed, by OneWeb, SpaceX, Google, and Facebook. The best currently available option for the present system appears to be the Argos network.

Argos is a low-earth-orbit (LEO) satellite network specifically designed for environmental monitoring and tracking. The extremely low power requirements and mass of Argos transmitters, as well as the proven reliability of these transmitters in difficult atmospheric environments, renders this solution quite well suited for the present application.

Disadvantages of the Argos network include its limited bandwidth, as well as its incomplete coverage over the geographic regions of interest.

The bandwidth requirements of the present application are extremely low. When each measurement is transmitted efficiently (e.g., transmitting measurements as integers of the appropriate size, with the appropriate scaling factors applied after transmission), each measurement message is only 26 bytes, as specified in Table 2. Such measurements are easily handled by the Argos system, even when measurements are taken fairly frequently (once every minute or so) by a swarm of scores of balloons. Assuming one measurement message per minute, each balloon needs to transfer $26 \cdot 60 \cdot 24 \cdot 7 = 262$ KB over its week-long operational life. The total energy consumption for such communication is estimated at $7\,\mathrm{W\,h}$ over the week. Note that the numerical digits of precision for each measurement to be reported will be as follows:

- 1 s for time since a recent epoch,
- about $1\mathrm{m}$ for latitude, longitude, and altitude,
- 0.01 kPa for pressure,
- 0.1 degree for temperature,
- 0.1 percent for humidity,
- 0.1 m/s for horizontal winds, and
- 0.01 m/s for vertical winds.

As a point of comparison, the datasheet for the Vaisala RS92 sensor used in dropsondes today indicates a measurement uncertainty in each component which is significantly larger than the numerical precision to be used here. Note also that the sensor balloons will be buoyancy stabilized to fly at approximately constant altitudes for extended periods of time; this strategy will lend itself to measurement of the (low-pass-filtered) horizontal velocity components in a hurricane that are far more accurate than the measurements of horizontal velocity components that may be achieved with dropsondes.

The incomplete coverage of the Argos network implies that the atmospheric measurements taken by the satellites will not become available immediately at the hurricane forecasting center. This could become a significant issue if a tighter integration between the data assimilation and the (centralized) MPC-based optimization of the balloon trajectories is attempted. However, neither the overall long-term hurricane forecasting objective, nor the approximate short-term hurricane forecasts leveraged by our MPC-based coordination algorithm as currently envisioned, specifically need measurements to be fed back to the hurricane forecasting center in precisely real time. We thus do not currently expect this aspect of the Argos network to be a significant drawback for the present application.

In regions of intense electrical activity within the hurricane, communication with LEO satellites might be disrupted for extended periods of time. If this turns out to be the case, a viable alternative is to equip the balloons for balloon-to-balloon message passing, and to maintain an ad hoc mesh network amongst the balloons in order to pass messages to and from the balloons within such electrically-active regions, all the way out to the LEO satellites, via those balloons that are operating in the clear. The possible need for such a capability will be investigated, and such a system will be implemented if needed.

The sensor pack on the balloons will be composed of a GPS unit as well as pressure, relative humidity, and temeperature (P-RH-T) sensors. We will employ COTS cellphone-grade sensors for an economical, low-power, lightweight solution. Two P-RH-T sensors will be employed: one outside the balloon, for atmospheric data acquisition, and one inside the balloon, to provide data useful for the control algorithm. The total energy consumption for the sensor pack, including the GPS unit, is estimated at only $4\,\mathrm{W\,h}$ per week.

Table 3: Mechanical requirements on balloon design.

Altitude range	0-8 km
Compression ratio	4:1
Minimum temperature	$-40\,^{\circ}\mathrm{C}$
Maximum relative humidity	100%
Overpressure at maximum operating altitude	1500 Pa
Burst overpressure	7500 Pa
Maximum ascent/descent rate	$\sim 5\,\mathrm{m/s}$
Operational life (before reconditioning)	1 week

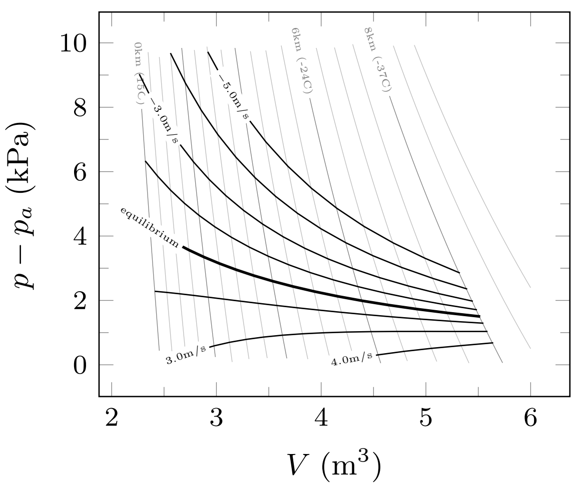

Figure 2: Pressure-volume diagram for a constant-mass (3 kg) balloon in thermal equilibrium with a standard atmosphere. See text for explanation.

The system proposed additionally requires a cellphone-grade microprocessor to implement the control algorithm, and to coordinate the communication. There are many low-cost and low-power options available here; power consumption for the microprocessor is estimated at no more than $5\,\mathrm{W\,h}$ per week.

For the battery, Li-SOCl2 chemistry appears to be the most promising, as it provides a high energy density (per unit mass), and performs reasonably well at operating temperatures down to $-40\,^{\circ}\mathrm{C}$. Though communication equipment, sensors, and microprocessors do not generally suffer at such low temperatures, battery performance does degrade somewhat. In particular, the high maximum discharge rates required for turning on the motor are difficult to achieve with small batteries even at room temperature; in this regard, low temperatures pose an even more significant challenge. We will thus opt for a solution which mates a battery with a super-capacitor, with the reserve in the supercapacitor providing the high power required for activating the motor when necessary.

5. Overall system design

Figure 2 presents a state (pressure-volume) diagram for the operating envelope of the balloon system being developed.

Table 4: Mass, energy, and cost estimates of the proposed system.

		Weight g	Power W	Week energy Wh	Price $
Balloon Envelope		900	—	—	500
Helium		420	—	—	50
Motor	EC-20 flat 351098 (0.56A-6V)	15	3	18	70
Gearbox	GP 22 C 44013 (1538:1)	94	—	—	120
Controller	367661	4	—	—	40
Battery (Actuation)	TLP-93111/A	140	—	19Ah @ 3.6V	NA
Communications	Argos system	4	0.025	7	NA
Sensors (P-RH-T)	Bosch BME280	NEGL	$< 15\,\mu$W	NEGL	5
GPS	EVA-7M	0.13	0.012	4	30
Computing		0.05	5	10	100
Battery (electronics)	Tadiran SL-2870	50	—	8.5Ah @ 3.6V	15
Other (frame, bearings etc.)		1400	—	—	500
Totals:		3000	—	50	1500

The horizontal axis denotes the volume of the balloon, which in the present work is accurately controlled by the winch. The vertical axis denotes the overpressure of the balloon (that is, the difference between the Helium pressure on the inside of the balloon and atmospheric pressure on the outside). The nearly vertical lines denote the altitude of the balloon (and, thus, temperature of the atmosphere). The solid lines sloping down to the right indicate the vertical velocity of the balloon. The dotted lines sloping up to the right indicate the tension on the central tendon, assuming a single tendon bears the entire load.

It is seen that, at any given altitude, the balloon can be made to ascend or descend at the desired rate by setting the volume of the balloon as indicated, via actuation of the central tendon with the winch.

As the environment to be encountered is both cold and wet, the accumulation of ice on the balloon is a significant hazard that must be dealt with appropriately. To combat icing, a hydrophobic coating such as fluoro-polymer will be applied to the entire exposed balloon surface to minimize condensation. Also, the compression of the balloon itself, which is used for altitude control, can also, if necessary, be used to deform the balloon surface to break up the ice as it begins to form, so that it subsequently flakes off. Finally, if/when a substantial amount of ice does accumulate on the balloon surface, the balloon will be reduced in altitude for a period of time, in a controlled fashion, where the warmer temperatures will melt the ice and the resulting water will bead up and fall off.

Key mechanical requirements on the balloon design for this project are summarized in Table 3. Some notes regarding the specific commercial technologies appropriate for such a system, which are necessary to develop accurate mass, energy, and cost estimates, follow:

- **Motor/Gearbox** The compression of the balloon requires high torque, low power motors. These motors are required to work in the helium filled, dry environment inside the balloon, for which special lubrication is necessary. A typical motor that is well suited for such an environment is the Maxon EC-20 flat 351098, with nominal performance values of 3 W, 6 V, 3030 rpm, 3.22 mNm, and 59% efficiency. A typical corresponding gearbox that is appropriate for the present application is the Maxon GP 22 C 44013, with a 1538:1 reduction ratio, a maximum torque of 2Nm and a 42% efficiency. A suitable motor controller for such a system is the Maxon 367661, which includes on/off control plus direction.

- **Tendon** A typical tendon material appropriate for this application is the Marlow Excel D12 Max 78, with a 2.5mm diameter and a 9170N breaking load. Note that the pulley and reel diameters on the winch must be about 10 times the rope diameter, or about 3cm.

- **Battery** Li-SOCl2 battery chemistry is specifically designed for the cold temperature range to be encountered in the application considered. At the same time, the high discharge rates required for activating the motor drastically limit their capacity, and a capacitor is necessary to overcome this issue. A typical battery-capacitor combination that is well suited for the present application is the Tadiran TLP-93111/A, which at 140 grams provides 3.6V and 19Ah, and is rated for operation from -40C to 85C. Similar Li-SOCl2 batteries from other manufacturers, such as UltraCell LLC, indicate that this battery chemistry actually functions down to -80C, albeit at reduced efficiency. Such batteries have negligible leakage discharge rates, especially at low temperatures.

- **Atmospheric sensors** Due to the explosion of interest in wearable electronics, high-quality, low-cost, low-power atmospheric sensors are now being mass produced. One example, which measures relative humidity, pressure, and temperature, is the Bosch BME280. Another representative example, which measures relative humidity and temperature, is the Sensirion SHT3x. The performance of such COTS environmental sensors at the low temperatures and high relative humidities to be encountered in this effort will be the subject of further investigation.

- **GPS** Typical all-in-one GPS units appropriate for this application, with highly efficient low-power modes, include the u-blox EVA-7M, which ships without an included antenna, and the u-blox PAM-7Q, which includes a patch antenna. The position accuracy of such units is about 2.5m, which well exceeds the requirements of the present application. It is noted here that it may be possible to use the same antenna for both the GPS unit and satellite communications.

- **Satellite communication** As discussed in detail in §4, the Argos system will be used for communication in the system proposed. Based on the data requirement shown in Table 2, the estimated power requirements is 7Wh over a week.

Leveraging the choices outlined above, a typical budget of mass, energy, and component costs for the primary components of the system under consideration is given in Table 4.

6. Conclusions

This work presents a novel atmospheric-balloon-based observational platform for in-situ, long term monitoring of hurricanes. The realization and utility of the proposed approach rest on two factors. First, the availability and use of low-cost, compact, lightweight electronics allows the production and deployment of large numbers of devices. Second, recent developments in data assimilation algorithms which can account for high resolution data establishes the utility of persistent and detailed measurements. The proposed coordination strategy, in conjunction with the 3kg, 50Wh, $1500 balloon design based on the patent-pending concept developed by Thin Red Line, should, in the near future, contribute to substantial improvements of real-time hurricane forecasts.

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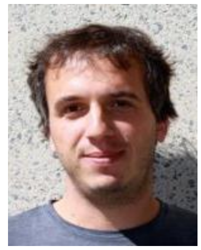
Biography



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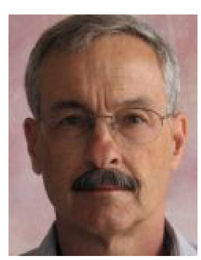

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