Dartmouth Greencube 5 (2012 SURP)

Director's Research and Development Fund (DRDF)
Final Report
JPL Task # ####

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A. OBJECTIVES

The goals of the GreenCube project are (1) to maintain a scientifically interesting, student-driven CubeSat development and flight program in Dartmouth Physics; (2) to incorporate new design features into small payloads for Low Cost Access to Space (LCAS) auroral sounding rocket proposals by Professor Lynch; and (3) on a longer timescale, to incorporate designs into future plans for small orbiters, which potentially could include student-designed CubeSats. This has been the sixth continuous year of our JPL-funded GreenCube project.

The 2012 SURP proposal for GreenCube5 listed the following specific objectives for the GreenCube5 year: *For GreenCube5 we propose to focus on the concept of a "swarm" of sensorcraft: how to design, build, test, communicate with, and assimilate the data from 15-20 autonomous vehicles. Given the logistical difficulties of launching and recovering that many meteorological balloon payloads at once ... we propose this year to temporarily move away from our balloon-borne design and instead use a swarm of autonomous sensorcraft to study the transport of objects by river flows in the nearby junction of the Connecticut River and the White River, by making our sensorcraft buoyant and floating them down the river as an array. We will also continue our ongoing solar panel development work. The assimilation of these approximately 20 separated measurements of position, attitude, and temperature into vector field arrays of data that can be analyzed is an interesting physics problem with strong connections to the interpretation of vector fields of plasma physics data. ... The fabrication, test, and use of so many independent sensorcraft as an array of low-resource measurement points is an engineering project with strong connections to spacecraft design; note in particular the recent DARPA "F-6" initiative for clusters of low-resource spacecraft which are wirelessly-interconnected modules working together.*

And, as reported in last year's final report: *With GreenCube 4 the group began to look forward to technologies for orbital cubesat systems, and to investigate commercially available technologies to be exploited for low-resource spacecraft. These projects incuded (a) learning about solar panel power systems and control, (b) developing an Arduino-based "squidbee"-type spacecraft computer platform, and (c) investigating telemetry protocols for local networks among swarms of spacecraft. In addition, the students have investigated (d) the feasibility of a localized swarm of cubesats for ionospheric studies.*

During this past year, the specific goals of GreenCube 4 and GreenCube 5 have overlapped and merged in a highly constructive manner, as described below. The

GreenCube program has been funded yearly by JPL for 6 years now, and we hope to continue this constructive project.

Students involved in GreenCube this year (with their graduation year noted) are: Amanda Slagle (2012) (selected for a JPL summer internship, 2011; senior honors thesis, 2012), Jon Guinther (2013) (senior honors thesis, 2013), Patrick Yukman (2014) (Dartmouth Presidential Scholar, 2013), Peter Horak (2014) (Dartmouth Presidential Scholar, 2013), Ha Nguyen (2015), Ellen Weburg (2015), Todd Anderson (2014), Jake Nevola (2014), Jacob Weiss (2016).

B. APPROACH AND RESULTS

In the sections below the students summarize their contributions to the GreenCube project over the past year. Many of the reports are verbatim from the students' input; some have been edited, and the description of Amanda Slagle's "Ducks" project is written by the PI as Amanda has graduated.

(a) Amanda Slagle did her Dartmouth Senior Honors thesis on the particular version of GreenCube involving a flotilla of GreenCube payloads measuring the flow fields of rivers.

As described in the proposal, it seemed worthwhile to consider the measurement of the velocity field of a river as an expansion of our typically balloon-borne program. This enabled the investigation of design, test, telemetry, manufacturability, and data assimilation techniques for a far larger number of sensorcraft than the balloon platform allows. To enable this, the students developed an Arduino-based sensorcraft platform to replace their in-house processor board. They used a digital compass and a GPS system and an XBee radio system that were all available commercially and supported by the Arduino infrastructure. Thus they were able to design and fabricate a 20-payload suite of instrumentation in a remarkably short time (indeed, their enthusiasm for this project once the proposal was submitted rather took over some of the previous year's efforts); the concept was described in the proposal in early winter, and the flotilla was floated in the spring term of 2012.

Figure 1 illustrates the suite of payloads and some of the resulting data. The data analysis of the position and velocity data (from the telemetered GPS data) became the start point for Jon Guinther's senior thesis project on data assimilation (described below.) Amanda's senior thesis is entitled "Vector Field Mapping and Analysis Using Finite Sensor Swarms"; Jon subsequently submitted an article on this project to the Dartmouth Undergraduate Journal of Science.

The Arduino-based sensor platform that was used so constructively in the "Ducks" project was then folded into our balloon-borne projects, and the "Dave" payload was born. Another version of the payload, called "Bob", is being used for an LCAS sounding rocket subpayload development study, as described below.

(b) *Jacob Weiss reports on improvements and electrical designs for the Arduino-based "Bob" payload, our autonomous sensor platform which is the most recent iteration of our payload design. The Bob payload uses an Arduino microcontroller board; supporting electronics are carried on a "shield" board which attaches to the Arduino and was designed by Jacob.*

Before the BobShield, the Bob payload contained an Arduino coupled to an Xbee Shield, an Accelerometer/Magnetometer breakout, an SD card breakout board, and a DNT support board. It became clear that this mess of electronics could be simplified and improved upon with a new PCB design. Over the past several months, I designed, produced, tested, and programmed this shield. I designed the Shield using the Eagle PCB design software from Cadsoft. The layout is shown in Figure 2.

The design of the BobShield was meant to incorporate all of the components listed above, but with one key improvement: the SD card would be replaced by a NAND Flash chip. We selected the Micron MT29F4G01AAADD, a small BGA chip with a 4 Gb (gigabit, not gigabyte) capacity. We selected this chip for its ease of use, quality of documentation, as well as the fact that it had already been field tested (by colleagues at Siena College). An Eagle library did not yet exist for the part, so I had to create one. I also created an Arduino code library that simplified reading from and writing to the memory. This way, the other members of the GreenCube team did not have to understand the low level interactions with the chip.

The other components of the BobShield did not need to be modified, but only consolidated. The DNT, accelerometer/magnetometer breakout, and the required circuitry from the Xbee Shield all fit nicely into the allotted space. The BobShield also contains the required circuitry to support the Pip sensor and a hardware ID tag.

(c) *Todd Anderson reports on STK studies of ionospheric swarms of small spacecraft, as well as mechanical design for the "Bob" payloads. Todd is our operations manager for the balloon campaigns.*

Last fall I ran a number of CubeSat swarm simulations using Satellite Tool Kit 9 (STK) to determine the limits of deployment altitude, deployment velocity, drag area and other parameters that would result in a swarm with the desired lifetime and cohesiveness in the auroral zones. Over the last 12 months I also organized multiple sounding balloon launches, and updated our balloon launch procedues. More recently, I have worked on CAD modeling and manufacturing of the foam core of our "Bob" sounding rocket payload. Figure 3 illustrates these STK efforts, and Figure 4 shows the mechanical configuration of the (spin stabilized) Bob payload for sounding rocket subpayload use.

(d) *Jon Guinther's senior honors thesis projects is a study of data assimilation tools that are necessary for interpreting data from multiple sensors.*

A defining feature of the GreenCube lab is the use of multiple, identical, measurement payloads in order to observe large geophysical phenomena. Each experiment requires a slightly different data assimilation and analysis technique. However, data from these types of studies take a nearly identical form--a list of locations and times plus the observed values at these points. By leveraging these similarities, a recent goal of the lab has been to implement a generic tool to assimilate and analyze data of this type. Currently, a Support Vector Regression (SVR) method is being used to create a model from the observed data samples. Then, this model can be queried for points where no samples were observed. Finally, these results can be visualized through a highly customizable routine that supports animation and the ability to switch coordinate systems on the fly.

Figure 5 illustrates the input and output to this Matlab tool in its current state. We will continue to evolve this extremely useful application for a variety of data analysis tasks, which can be used in the future to justify and define the required number of spacecraft in our ionospheric swarm.

(e) *Peter Horak reports on the application of the "Ducks" Arduino-based sensorcraft to the development of the balloon-borne "Dave" payload, requiring longer-range telemetry than the Xbee radio can support. This development is also being used for the sounding-rocket version called the "Bob" payload.*

This past fall I focused my efforts on improving the Greencube payload's telemetry system. I began by making the Arduino micro-controller code faster. This involved changing the settings of the compass board and built-in ADCs and transmitting data in binary rather than ASCII text. With these and other improvements, I was able to make the telemetry rates, for everything except the GPS, over 100 times higher than before. The next steps involved the DNT radios. I learned about many radio settings in the process of balancing their power consumption with their throughput. The DNT power consumption plot (shown in Figure 6) describes the relationships between throughput, RF power, and power draw on the batteries. In general, sending data faster resulted in a higher duty cycle and greater power consumption. The DNT power settings are important because they will enable the payload to communicate at longer distances than before. We have yet to see the DNTs successfully operate through an entire balloon flight. However, range test results are auspicious. The DNT range plot (also Figure 6) shows data from the most recent configuration. The received signal strength indication (RSSI) remains above -100 dBm, the noise level, for the entire test, and the trend suggests that it may remain so at larger distances.

Some of the next steps for our telemetry system are handling multiple sensor payloads and reducing power consumption when inactive. The DNTs share the same 900MHz (ISM) radio band. Eventually, we will need to determine how best to allocate our limited bandwidth for multi-point measurements. In an orbital mission, it would be helpful to reduce the DNT power draw when they are not in a region of interest. One potential approach could be to use their sleep mode, which we have yet to explore.

(f) *Peter Horak also reports on the remainder of the solar panel development project, a continuation from the previous year's efforts.*

Last spring, I had just finished designing a solar panel board to be tested on a balloon flight. Since then, I fabricated one copy of the board with the help of the Dartmouth Science Division electronics shop (Figure 7). The board flew on the subsequent GreenCube flight with the intent of testing it in a more realistic environment. The resulting data showed large variations in the output voltage and power of the panel. This is undesirable in the solar panel. However, strong correlations between the panel output, onboard photometers, and compass board, proving the payload's orientation, suggest that payload motion and shadowing from the balloon may be the causes. I investigated the dependence of the output power on the incidence angle of light (Figure 7) and the effect of partial shadowing. My results indicated that the shadowing or motion could account of the output variations. The next step is to fly the panel again with a better load match, to increase the overall power output, and a video camera to confirm the source of the output variability. Hopefully, the motion and shadowing effects can be accounted for in order to investigate any other dependencies, such as temperature.

We plan to do our next balloon flight in the spring term of 2013, incorporating the improved Arduino payloads and BobShields, as well as this solar panel development. (We can not launch during the late fall and winter terms because of wind and weather constraints.)

(g) *Jake Nevola reports on balloon payload recovery team efforts. This past year we have had a nearly complete turnover in our student staff on the recovery team, but the overlap of students is sufficient to hand over the acquired experience to the new group. Jake also works on mechanical design.*

With Greencube, my primary focus was on the mechanics of Bob, and on participating in the balloon payload recovery team. With Bob I helped organize the layout of the payload while also creating SolidWorks models for it. I also learned how to use the foam crafter (a prototyping machine which generates foam objects by removing material; we use these to support the Bob components) to create several iterations of inner supports for Bob's electronics. On the recovery team, I'm responsible for driving the long drives and helping to physically recover the payload once it has landed. During my first recovery, after about an hour and half of searching, we found the Dave payload 60 feet up in a tree. I climbed said tree and ended up cutting off the branch to free the payload. For Dave's second recovery for the next flight, I drove to Maine. We discovered right after launch that of the ham radio, the DNT radio, and the emergency beacon, only the ham radio was transmitting. Thus, because it is difficult to receive the ham radio signal once the payload passes the tree line, we drove around Maine, trying to predict where the payload would land from the few pieces of data that got through. Fortunately we tracked it down around half an hour after landing due to some good predicting tools which estimate the landing position based on the received data. Figure 8 illustrates a treed payload.

(h) Patrick Yukman reports on planning for more complex telemetry systems.

The past year has led to some serious development of our telemetry systems, since many of our mission goals became related to the use of fast, reliable, high-throughput (but also cheap!) radio communications. I became heavily involved with integrating a brand new radio - the DNT900 - into our already existing setups in order to meet the kinds of data goals we had in mind. Working with the new radios has definitely taught me a lot about the iterative design process: not only did I get the chance to design a custom printed circuit board to interface our existing hardware with the new radios, I got the chance to revisit the design and make it better, and even work with Jacob Weiss on upgrading the board to meet tighter restrictions and offer more capabilities. Working with Peter Horak on maximizing our payload's data cadence and throughput gave me a great deal of experience with optimizing communications setups, in addition to experience with analyzing and debugging communication protocols that can be dense and unfamiliar. Along these same lines, I've begun working on using the DNTs to configure different kinds of wireless networks (with an eye towards eventually implementing GomSpace's "Cubesat Space Protocol" as our basic communication protocol) for the purposes of building up the telemetry technology for our hypothetical "fleet" of satellites. Having a good handle on our telemetry capabilities is crucial for any further development of our payloads, which I'm excited to continue working on.

Figure 9 shows a diagram of a data-forwarding tree network formed with a set of DNT900 radios.

(i) Rob Clayton reports on developing low-resource supporting electronics for our future plasma sensor, a thermal ion retarding potential analyzer called a PIP (Petite Ion Probe), that are compatible with the Arduino.

The PIP instruments can generate a current/voltage graph (IV curve) of the surrounding plasma. In order to do this, the PIP must receive a retarding potential (voltage) sweep from a controlling circuit. Previously, an FPGA was used to provide a step function stepping up the voltage to the pip from 0 to 5 volts, and back from 5 volts to 0, in small precise box steps. In an effort to use widely available inexpensive parts, the FPGA can be replaced by an Arduino microprocessor for this task. Since the Arduino does not have the ability to output an analog voltage (it is only capable of digital on +5v, or digital off 0v), the desirable step up or down in voltage can be approximated by an RC circuit. The RC circuit provides an exponential decay from the provided voltage down to 0, unlike the even steps of the FPGA setup. However, it still provides the needed sweep by the PIP as long as resistors and capacitors are chosen to allow for a sufficiently slow decay. This sweep screen control of the PIP was tested in our thermal plasma facility.

C. SIGNIFICANCE OF RESULTS

The GreenCube team met and exceeded its GreenCube5 technology development goals by extensively expanding the use of the Arduino platform in several iterations to support various autonomous sensorcraft. This has been so successful that it has become a seed project for larger projects in the Lynch Rocket Lab, including the development of a version for use as a sounding rocket subpayload. The team "launched" a fleet of 20 sensorcraft on two separate river flow investigations, and continued the balloon flight program that we have had for multiple years. We plan another flight later this spring term.

The GreenCube program addresses JPL's interests in enhancing student preparation for a professional career in space systems/science at JPL or elsewhere. The students have gained experience with instruments of particular interest to JPL, such as GPS; magnetometers; and solar panels, as well as with analysis techniques for multi-point in-situ geophysical observations. Last year's senior thesis project student, Amanda Slagle, is now working as a research engineer for a sounding rocket project at University of California Berkeley's Space Sciences Lab.

D. NEW TECHNOLOGY

GreenCube5 is being a pathfinder for the Lynch Rocket Lab in terms of finding and making use of commercially available technologies which can be eventually used for low-resource spacecraft. It will be very interesting to discover how far the Arduino platform can be pushed in this direction. Our overall goal this year is a trade study between embedded systems which we design in house, and commercial subsystems which can be purchased whole.

E. FINANCIAL STATUS

The total funding for this task was $20,000, all but $xxx of which will be expended by the project end date. We have requested an NCE for the remaining funds given the delays in implementing the grant.

F. ACKNOWLEDGEMENTS

This report was assembled by Professor Lynch using input from the named students.

G. PUBLICATIONS and PRESENTATIONS

[A] Amanda Slagle, Dartmouth College Senior Honors Thesis, May 2012, "Vector Field Mapping and Analysis Using Finite Sensor Swarms"

[B] Jon Guinther, Dartmouth Undergraduate Journal of Science (DUJS) submission, 2013, "GreenCube5: Mapping River Flow with Sensor Swarms"

[C] Group Wiki page, including "launch list": http://northstar(dash)www.dartmouth.edu/~klynch/pmwiki(dash)gc/index.php?n=Main.HomePage

H. REFERENCES

None.

I. FIGURES

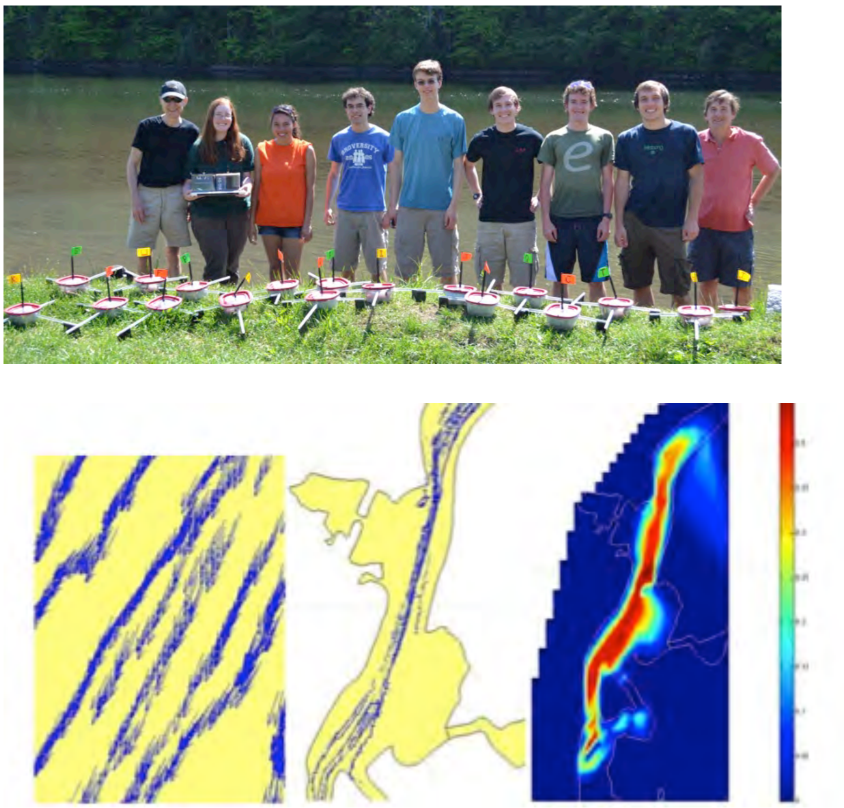

Figure 1. The Arduino-based platform used by the "Ducks" project, and the resulting assimilated data.

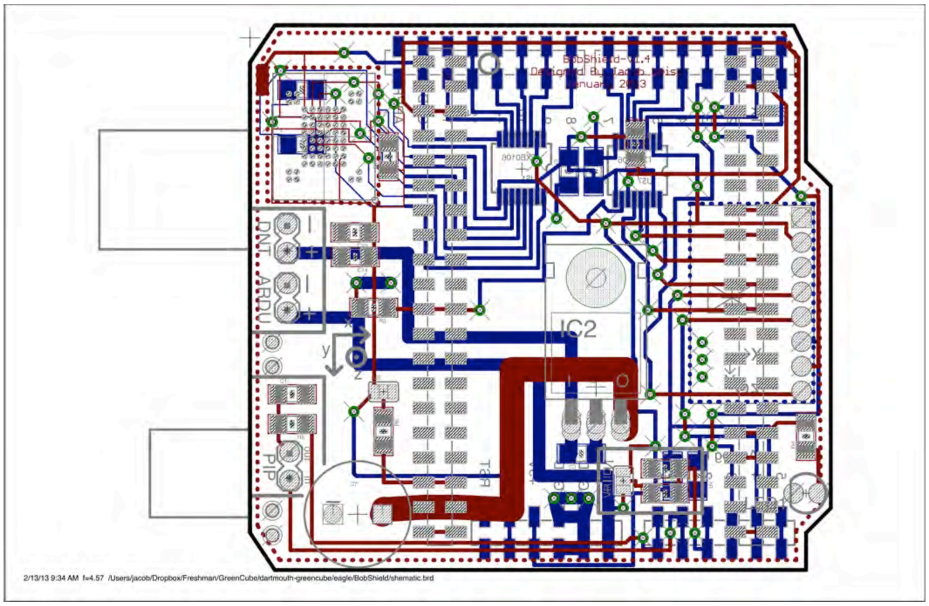

Figure 2. BobShield design.

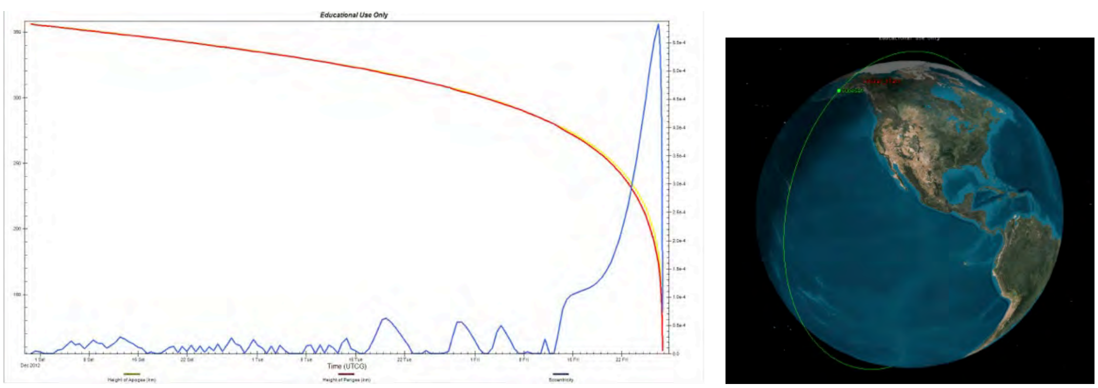

Figure 3. STK studies

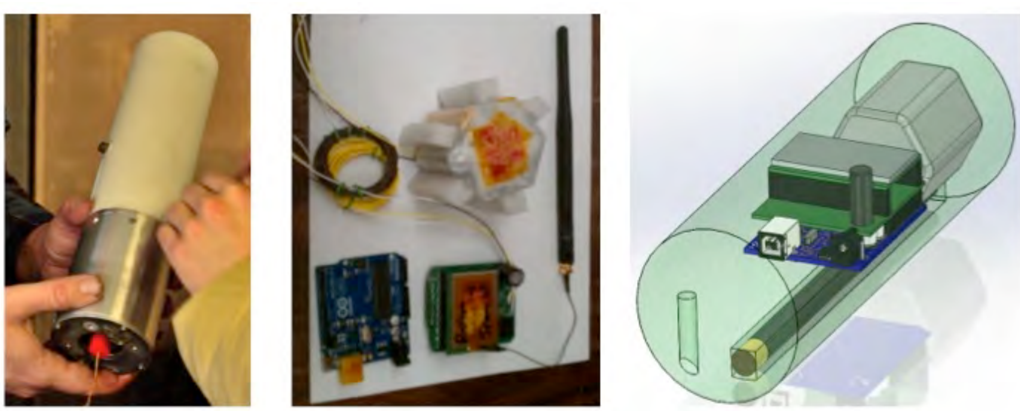

Figure 4. Bob payload mechanical design.

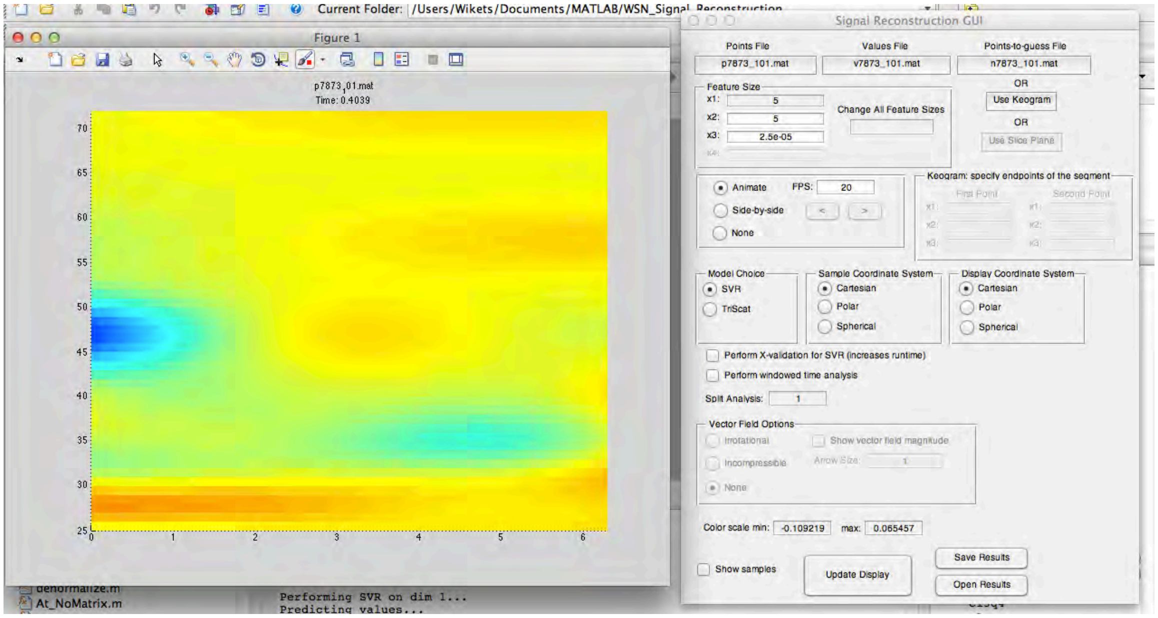

Figure 5. The graphical user interface for our data assimilation tool. The tool takes as input a set of observation places and times; a set of values recorded at those places and times; and a set of requested assimilated values (places where an estimate of the data value is requested.) The requested points can be, for instance, estimated values on a regular grid; or values along a rocket trajectory; or a slice at one altitude or position of the sampled volume.

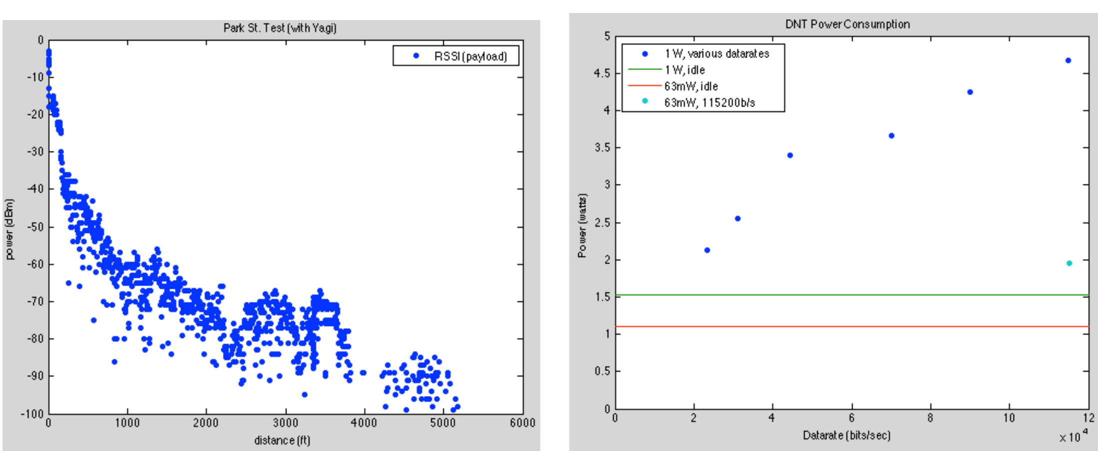

Figure 6. DNT studies: range test (left); power vs data rate (right).

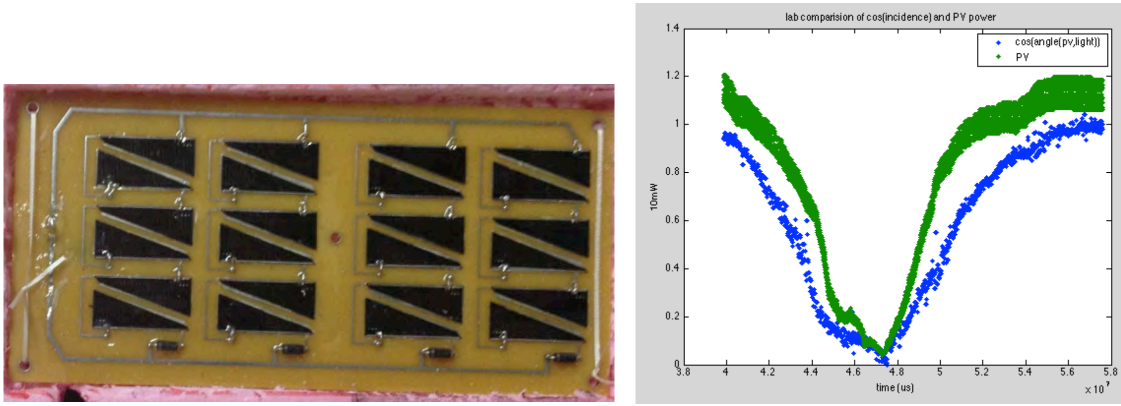

Figure 7. Solar panel development: TASC cells courtesy Tom Immel (UCB), on Peter's board layout design for the balloon payload (left); solar panel power vs incident angle (right).

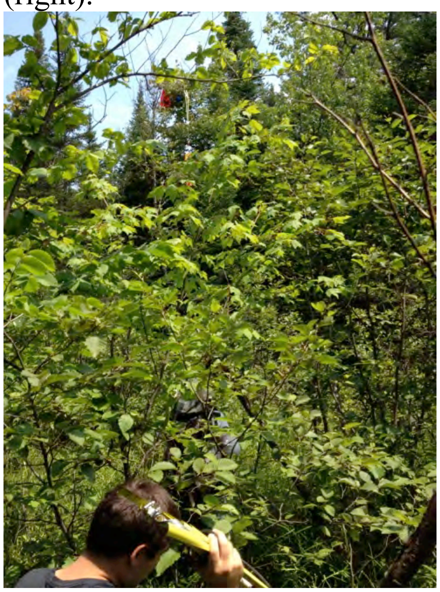

Figure 8. A treed payload, as found by the recovery team (small orange box near the top of the photo.)

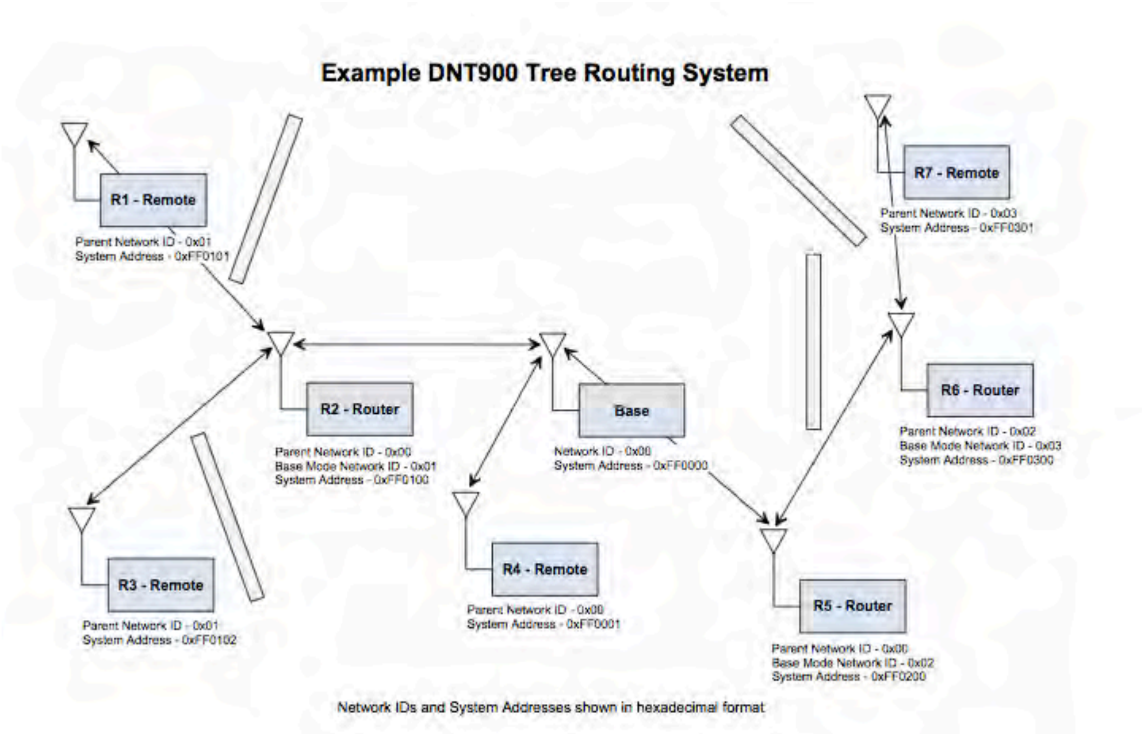

Figure 9. Telemetry plans.

K. COPYRIGHT STATEMENT