Solicited Proposal Application

ANNOUNCEMENT OF CUBESAT LAUNCH INITIATIVE

Reference Number: NNH10SOMD001L

NASA/Goddard Space Flight Center NASA Headquarters Acquisition Branch Code 210.H Greenbelt, MD 20771



CubeSat Lunar Spacecraft Navigation System

Points of Contact:

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Proposal Abstract:

Lunar Lander / Orbiter CubeSats

We have received a NASA Consortium Development Grant (NNG05GH16H) for Vermont Technical College to build prototype CubeSats for travel from a geosynchronous satellite launch to the moon. One spacecraft will involve a two-unit CubeSat mono propellant booster to go from a geosynchronous transfer ellipse to the moon. It will enter lunar orbit while carrying a single CubeSat lunar lander. The second triple CubeSat will have a xenon ion drive to carry it from a geosynchronous transfer ellipse via a low-energy transfer through L1 to enter lunar orbit. The single-unit CubeSat lander is designed for landing on the Moon from a 100 km orbit. The 0.57 kg of propellant is a hypergolic combination of hydroxyl ammonium nitrate and methanol. Four 1.0 N radiation cooled thrusters are at one end, with the pair on each side canted slightly toward each other. This design allows for full three-axis control with differential use of the four thrusters. The mono propellant booster, a double-unit CubeSat, would have the same propulsion system, but with 1.62 kg of propellant. With the single unit lander attached, this package would be capable of generating a Δv of 2,000 m/s, which would be sufficient to leave a geosynchronous transfer ellipse at the apogee with escape velocity and to enter lunar orbit. A triple-unit CubeSat ion drive spacecraft will also be developed in parallel. The preliminary design for this spacecraft is based on the mission profile of the SMART-1 spacecraft of the European Space Agency. However, our design will use the CubeSat-sized NASA-JPL developed miniature xenon ion thruster MiXI with a specific impulse of 2,000-5,000 seconds. The thruster will be used as is, with only a gimbal added or grid beam steering, both have been developed for previous ion drives. With this thruster, a 0.5 kg propellant load of xenon would give a Δv of about 3,500-8,900 m/s. Power for the thruster will come from photovoltaic cells on the spacecraft and four fold out panels. The overall CubeSat mission will be completely robotic, as the spacecraft will be entirely autonomous. Navigation will be by the NASA Goddard developed GEONS (GPS Enhanced Onboard Navigation System) which uses GPS enhancement and celestial navigation via optical means using sun, moon and earth tracking. The GEONS system is written in C, and we will be rewriting the system in Ada (as used on the Cassini and other NASA missions) / SPARK. It has a record of producing extremely reliable software, with about 1% the error rate of C. The other control software for the mission will also be written in Ada/SPARK. We have developed extensive experience with this software system in our NASA-funded Arctic Sea Ice Buoy project. The optical sensor (used by the GEONS navigation system for celestial measurements and for attitude determination) development of both hardware and software will be done by faculty and students at Norwich University, who have extensive experience in this area with their NASA funded autonomous underwater robot. Low-energy transfer strategies and the effect of radiation exposure from the Van Allen belts and solar coronal mass ejections will be modeled by faculty and students at the University of Vermont. They will also study strategies for coordinating multiple spacecraft.

For this launch opportunity, we propose to use a single unit CubeSat to test the GEONS navigation system, rewritten in Ada/SPARK. This will create a new level of sophisticated navigation, available for all CubeSat mission, while increasing the reliability of the NASA developed GEONS system.

Proposal Detail

Introduction:

For this launch opportunity, we propose to use a single unit CubeSat to test the NASA Goddard developed GEONS navigation system, rewritten in Ada/SPARK. This will create a new level of sophisticated navigation, available for all CubeSat mission, while increasing the reliability of the NASA developed GEONS system. We are planning to use GEONS in our fairly substantial NASA funded Consortium Development Grant for our Lunar Orbiter/Lander Spacecraft. This is the first proposal to use self propelled CubeSats to go from a Geosynchronous launch to the moon.

This single unit mission will allow the testing and proving in flight of the navigation system which will be critical for our larger Lunar mission, before the much more expensive full Lunar mission.

A CubeSat is a payload package having dimensions 10cm x 10cm x 10cm. A recent revision (8/1/09, rev12) of the CubeSat design specifications allows for a mass of up to 1.33 kg. Prior development of launch technology for this payload format has resulted in a significant cost advantage over other types of satellite deployment. In particular, work at the California Polytechnic Institute (Cal Poly) has produced a standard, reliable, and flight proven deployment system. The Poly Picosatellite Orbital Deployer, or P-POD, is a tubular, springloaded mechanism taking up very little space. It can hold up to three CubeSats and be integrated into any launch vehicle, protecting primary payloads from the CubeSats and vice-versa.

New Capabilities: Although a number of CubeSat's have previously been developed and launched into Earth orbit, none have used high-energy mono-propellant thrusters or long duration ion thrusters, and none have done interplanetary navigation. The development of a Lunar Lander CubeSat would thus be an important contribution to NASA's mission capabilities and be useful for future CubeSat missions away from low Earth orbit. The faculty and students working on this project will develop expertise in the area of spacecraft design and navigation and forge links between research groups at multiple Vermont institutions as well as links with collaborators at NASA, already formed at NASA Goddard Space Flight Center, and NASA's Jet Propulsion Laboratory. The resulting opportunities for graduate thesis research and mentored undergraduate research, involving both individuals and groups of students at four Vermont colleges and universities, will make significant contributions to the development of the STEM (Science, Technology, Engineering & Mathematics) workforce.

Chemical Propellant Rocket: Preliminary results obtained in the CubeSat Laboratory of Vermont Technical College (VTC) have indicated the feasibility of designing a single unit CubeSat with a propulsion system capable of following the Apollo lunar landing profile and landing on the Moon from a 100km orbit. The propellant considered is a mixture of hydroxyl ammonium nitrate and methanol in a catalyst based mono-propellant thruster. According to preliminary design calculations, the propellant mass fraction for this lander will be within 0.2% of that used on the Apollo Moon lander. A preliminary design has also been developed for a two-unit CubeSat booster (20cm x 10cm x 10cm, 2 kg) using the same propulsion system, but with 1.5kg of propellant. With the single unit lander attached, this package would be capable of generating a Δv of 2,000 m/s, which would be sufficient to leave a geosynchronous transfer ellipse at the apogee with escape velocity.

Ion Drive Rocket: In addition to refining and prototyping these chemical propellant rocket designs, this project will consider in parallel the development of a two-unit CubeSat solar photovoltaic powered ion drive booster with a propellant load of xenon, giving a Δv of about 4,000 m/s. An ion drive would remove the flammable propellants from the booster, and the inert xenon propellant would present no danger to a primary geostationary payload. While emphasis will be on developing a lunar lander package, if launch permission for a chemically propelled lunar lander could not be obtained, with an ion drive booster the lander portion of the spacecraft could be replaced with an instrument package for making observations from orbit of the Moon. A spacecraft with ion drive booster would also be capable of reaching Mars.

Low Energy Transfer Flight Paths: To have sufficient leeway for lunar orbit insertion and lowering, a low energy transfer strategy will be developed. The required indirect transfer trajectories will have transit times of close to a year. However, indirect transfer can produce considerable savings in energy requirements, making the projected missions possible. The missions in this project will be completely robotic, as the spacecraft will be entirely autonomous. Navigation will be by GPS and optical images using sun, earth and moon tracking using the GEONS software. Optical means will also be used for attitude determination during the descent to the lunar surface, and for measurement of lateral velocity during the landing phase. Optical sensors might also be used for data collection on the lunar surface. The proposed lander will communicate with the booster/orbiter for relay of data collected to Earth through a wireless network involving both stationary and mobile stations.

With the low cost of the CubeSats compared with conventional spacecraft, a "swarm" of a dozen or more landers could be sent to the Moon and communicate among themselves and with the boosters/orbiters. The proposed project will include interactions with NASA colleagues in the Asteroids, Comets & Satellites group at JPL (Jet Propulsion Laboratory) and the Space Weather Laboratory, Heliophysics Science Division at GSFC (Goddard Space Flight Center) as well as assistance from industrial collaborators.

Project Description

Description of Project Elements

Preliminary Designs: The starting point for this project will be preliminary designs developed by Profs. Carl Brandon and Peter Chapman and their students in the CubeSat Laboratory of Vermont Technical College (VTC). The proposed lunar lander will be a single unit CubeSat having four 1 N thrusters at one end, with the pair on each side canted slightly towards each other. This design allows for full three-axis control with differential use of the four thrusters. The proposed mono-propellant booster, a double unit CubeSat, would have the same arrangement.

Rapid prototyping and manufacturing facilities at VTC will be used to construct prototypes of both the lander and the booster. Structural components will use graphite composite as much as possible to save mass. The prototype design will also strive to use or adapt available off-the-shelf components. For example, radiation effects above low Earth orbit will pose a significant risk to proper operation of spacecraft systems, and Prof. Brandon has identified an existing source of radiation hardened electronic boards that appear suitable for this project. Despite the 33% increase in mass allowed by Revision 12 of the CubeSat design standard, propellant mass will remain limited by tank volume restrictions. In the bi-unit booster, some propellant will be needed for course corrections. Consequently, the Δv remaining for lunar orbit insertion will be marginal. As described below, the development of non-standard trajectories that allow for low energy transfer will be a critical part of this project.

Ion Drive Justification: A triple unit lander-booster CubeSat spacecraft with two propellant powered drives may have problems obtaining launch permission because of the danger it might pose to a primary launch payload. Consequently, the VTC component of this project will also develop a double unit CubeSat ion drive booster. The preliminary design for this booster is based on the mission profile of the SMART-1 spacecraft of the European Space Agency (ESA). However, our booster design will use the CubeSat sized NASA JPL-developed miniature xenon ion thruster MiXI with an Isp of ~2,000-5,000. With this thruster, a 0.5kg propellant load of xenon would give a v of about 3,500-8,900 m/s. Power for the thruster will come from photovoltaic cells on the spacecraft. The 357kg ion-drive SMART-1 spacecraft had a thrust of 68mN operating for a total of 5,000 hours. In contrast, our projected spacecraft will have a thrust of 0.5-1.0mN for 2,500-5,000 hours. Although the MiXI thruster has already been developed, we will need develop the five-part power supply/control unit for our booster. Xenon pressure must be reduced from 150-300 atmospheres in the graphite tank to about 2.0 atmospheres. The xenon flow control unit will be another technology challenge, because of the very low flow rates (0.1-0.2g/hr or 0.25-0.50 sccm). Both the miniature xenon pressure regulator and flow control unit will need to be developed for our ion drive booster.

Software: The control software for the mission will be written in Ada (as used on the Cassini and other NASA missions) / SPARK, which yields very reliable software (about 1% of the error rate of C). Profs. Brandon and Chapman have developed extensive experience with this system in their Arctic Sea Ice Buoy prototyping project, which was funded by a previous NASA CDC (Consortium Development Competition) award. The CPU for the spacecraft will use the Texas Instruments MSP430 processor, which has the lowest power consumption of any available processor and has been used in a number of CubeSat missions.

Low Energy Transfer Flight Paths Analysis: Because of the available energy restrictions imposed by the CubeSat format, the development of low-energy transfer strategies will be a crucial part of this project. Prof. Jun Yu at the University of Vermont (UVM) will lead this project component. He will be assisted by a full-time UVM graduate student assistant and, in the summer, by undergraduate student researchers from both UVM and St. Michael's College (SMC). Three types of indirect trajectories will be considered and analyzed using mathematical modeling and numerical simulations. These studies will examine spacecraft maneuvers, fuel use, and other parameters affecting the transfer and landing trajectories, including the effect on the spacecraft of radiation exposure from the Van Allen belts and solar coronal mass ejections. Indirect trajectories to be studied include the so-called weak stability boundary (WSB) transfer, which was used by the Hiten mission in 1991. This transfer trajectory leaves the Earth with an apogee around 1.5x10 km and falls back into Earth orbit, but with a radius of perigee increased by the Sun's perturbations, so that it co-orbits the Earth with the Moon. On this trajectory, the spacecraft can enter lunar orbit with no maneuvering, although the orbit is highly unstable and must be firmly controlled. The second type of trajectory provides a transfer to the Moon through a Lissajous orbit at the Earth-Moon L1 Lagrange point. This strategy takes advantage of the complex dynamical behavior of the trajectory near the L1 point, and from a Lissajous obit about L1 it is possible to access various lunar orbital planes with different inclinations and ascending nodes using a minimal Δv . The third type of indirect trajectory utilizes a geostationary transfer to the Moon of the type used by the ESA SMART-1 mission in 2003. The

spacecraft is first put into a geostationary transfer orbit (742 x 36,016 km, inclined at 7 degrees to the equator for the SMART-1 mission). It then elongates its Earth orbit and utilizes lunar resonance maneuvers to minimize propellant use. A final continuous thrust maneuver can be used to perform a lunar orbit capture at a distance of about 60,000 km from the lunar surface. For this type of transfer, there will be greater demands on spacecraft navigation due to the timing of the lunar resonances. With the ion drive booster, navigation will also be done with the GEONS system by GPS and optical celestial means during the expanding spiral orbit. This enhancement will allow for accurate determination of the latter stages of a transfer trajectory. *Autonomous Mission:* The overall CubeSat mission will be completely robotic, as the spacecraft will be entirely autonomous. Navigation will be by the GEONS system with GPS and optical images using sun and star tracking.

Optical means will also be used for attitude determination during the descent to the lunar surface, and for measurement of lateral velocity during the landing phase. The optical sensor development of both hardware and software will thus be a significant part of the project. Profs. Ronald Lessard and Danner Friend at Norwich University, as well as undergraduate engineering students on the Norwich Autonomous Underwater Vehicle (AUV) Design Team, will work on the artificial perception and vision-based capabilities of the spacecraft and as well as robot navigation control and robot autonomy design for the proposed lunar mission. We anticipate that the navigation by vision and artificial perception innovations the AUV Team has already developed to allow their robot vehicle to navigate below the ice on Europa can be adapted for use in the present missions.

Coordinated Multiple Spacecraft: With the relatively low cost of a CubeSat lunar mission, laying the groundwork for projects involving multiple landers is an intriguing component of this project. Controlling and communicating among multiple landers and orbiting boosters can leverage recent advances in wireless sensor networks (WSN. WSN deploy numerous low-cost, energy-efficient sensor nodes, which form a communications network through which data can be wirelessly relayed to the end user. While major advances in WSN research have been made in the past decade, little work has considered a symbiotic relationship between static WSN and mobile resources, such as will be needed for the present application. WSN are typically statically deployed within an environment (i.e., in situ) and collect multiple parameters of environmental data at arbitrarily fine temporal resolutions. In contrast, mobile resources can provide arbitrarily fine spatial resolution albeit with diminished temporal resolution. Furthermore, while orbiting devices serve as an ideal platform for remote sensing, the collected data suffers from the lack of *in situ* ground truth. In short, we contend that research in *symbiotic* sensing systems shows promise in best leveraging the proposed CubeSat platform. The CubeSat design enables an approach where resources can be first dynamic and then static. As resources land on the lunar surface, sensed data (relayed to the remaining orbiting resources) will assist in where the next lander should be located. This evolving nature of the proposed CubeSat lander network calls for new approaches. Networking between landers can occur directly (if they are in close proximity), via an orbiting relay (if horizon view is available), or via saved and retransmitted information (e.g., in the case where landers are antipodally located). In our proposed project, Prof. Jeff Frolik from UVM will leverage the ongoing work in complex systems and WSN to develop robust, energy and computationally efficient strategies that are readily integrated in the CubeSat design. He will be assisted in this research by a full-time graduate assistant and, in the summer, two summer undergraduate research students from UVM

and SMC.

Science Development: Given the limited funding and one-year performance period for a CDC award, science aspects of a lunar mission will largely need to postponed as follow-on work. While the emphasis in this proposed project will be primarily on developing the concepts, technology, and prototypes needed for a CubeSat mission that places a single-unit lander on the Moon or a instrument package in lunar orbit, possible science components will not be neglected. With a lander mission, the mass and space available for science instruments is quite limited. However, an electron or ion flux sensor would be feasible. Without a lander, an entire 10 cm cube, and over 1+ kg in mass would be available for the instruments. For the orbiter, more complex instruments, such as ion spectrometers or the recently developed ultra violet spectrometer would fit within the mass and space budget. In addition. Professor Danner Friend will mentor a team of Norwich mechanical engineering students in the summer of 2010 developing a preliminary design concept for a "CubeSat" lunar rover robot. Technology Development: The most difficult technical challenge, the ion engine, has been previously developed at NASA JPL. It will be used as is, with only steering via gimble or grid beam steering, both developed for previous ion drives. The pressure regulator and xenon flow control will be adapted (reduced in size) from the SMART-1 spacecraft. Navigation and deep space communication will be adapted from SMART-1 and Deep Space-1 ion spacecraft. Chemical mono-propellant radiation cooled thrusters and valves will be adapted from larger existing designs. The miniature power supplies for the ion engine will also need to be developed. NASA and Industrial Collaborators: Participants in this project will collaborate closely with NASA colleagues as well as industrial advisors. Jay Goguen of the Asteroids, Comets & Satellites group at NASA JPL has offered assistance with the design of the optical system for the project. Mr. Goguen has previously designed the optical system for determining lateral velocity on the Mars Pathfinder landing system. Doug Rowland of the Space Weather Laboratory, Heliophysics Science Division, NASA Goddard Space Flight Center has met with Carl Brandon and Jun Yu at Goddard. Mr. Rowland is currently working on the NSF/NASA 'Firefly' CubeSat Mission to study the link between lightning and terrestrial gamma ray flashes. In addition, Timothy Stubbs, Associate Research Scientist in the GEST Research Group, Heliophysics and Solar System Division, NASA Goddard Space Flight Center has given us suggestions for science instruments for use in lunar orbit or on the surface. Industrial advisors will include Michael Harris, Technical Director, Space Systems and Electronics Division, BAE Systems, Nashua, NH. (Among many other space products, BAE supplied the computers for the Mars rovers and Mars Reconnaissance Orbiter.) Mr. Harris has given us advice on various parts of this project (including navigation and radiation hardened electronics) and will continue to do so. William McGrath, CEO of LED Dynamics, Randolph, VT, which makes constant current power supplies, has also offered to help with the design of the constant current power supplies for the ion engine. Needs Being Addressed: Vermont is a state noted for its commitment to protecting the environment. The strategic vision developed to support this critical Vermont concern by encouraging the advancement of environmentally friendly, high-technology industrial and research activity is set out in the Vermont State Science and Technology Plan. The education and training of the next generation of the STEM workforce is a key element of this Plan. Support letters from Congressman Peter Welch (VT At-Large) and Vermont Lt. Governor Brian Dubie (who is also the current President of the Aerospace States Association) addressed the direct relevance of the proposed project to state needs. More locally, the University of Vermont,

the VTSGC's Lead Institution, is placing increased emphasis on complex systems and research of an interdisciplinary nature. Contributions this project will make to promote this objective are noted in the included support letter from Prof. Domenic Grasso, the past Dean of UVM's College of Engineering and Mathematics and UVM's new Vice President for Research. Finally, his project will increase NASA's capabilities by developing the science and technology base needed to extend CubeSat spacecraft missions beyond low Earth orbit. Included letters from NASA collaborators attest to NASA's need for the proposed development and support this project.

Review of Technical Merit:

The Vermont CubeSat Lunar Lander Project formed the entire basis for Vermont Space Grant's proposal to the 2009 Space Grant Consortium Development Competition (CDC09). Vermont's CDC09 submission was one of five proposals chosen for funding in the 2009 Competition by NASA's National Space Grant College and Fellowship Program. In coming to this affirmative decision, the National Program conducted an extensive competitive review of the proposed project, including its technical merit, relevance to new and continuing NASA research priorities, and the extent to which the proposed project would provide benefits to NASA by addressing components of the NASA Education Strategic Coordination Framework. CDC09 proposals were reviewed and evaluated by a combination of NASA Space Grant staff, Designated Space Grant Directors, and other qualified personnel selected by the National Program. Criteria that were used in proposal evaluation included the technical merit of the proposed project, including feasibility to achieve the stated project goals, the extent to which the project would contribute to Outcome 1 of the NASA Education Strategic Coordination Framework, the relevance of the project based on a compelling need for both the Vermont institutions involved and NASA, the project's partnerships and prospects for sustainability, plans for project management and program evaluation, and the contribution of the project to increasing the STEM workforce and promoting diversity. The relevant section of the CDC09 announcement dated 7/8/09 on "Proposal Review and Evaluation" is included in the current proposal's Appendix as a supporting document. The National Program's competitive review of this project produced no findings that needed to be addressed by the Vermont project team.

Review of Feasibility:

We have \$195,000 from the lunar spacecraft grant, including about \$34,000 for hardware, and \$10,000 for hardware remaining from prior space grants, which will provide sufficient funding for the development of the CubeSat payload proposed for participation in the current pilot project. We also have on hand, the \$3,500 power supply board from Clyde Space and the photovoltaic cells from Spectrolab, and satellite flight module and cpu from CubeSatKit. As noted above, an examination of the feasibility of the CubeSat Lunar Lander Project was carried out as one component of the National Program's competitive review of Vermont's CDC09 proposal. However, as part of the preparation for the current proposal, two additional expert reviews of project feasibility were solicited. Douglas Rowland of the Space Weather Laboratory, Heliophysics Division (Code 674) at NASA GSFC carried out the first review. Prof. Brandon discussed the CubeSat Lunar Lander project with Mr. Rowland in detail during a recent visit to Goddard. Mr. Rowland was also given the CDC09 proposal and preliminary project data

to provide an additional basis for his review. Mike Harris, Technical Director, Space Systems and Electronics, BAE Systems (Nashua, NH) was asked to carry out a second feasibility review. Mike led technology development and developed risk mitigation plans for key programs, technical lead for major development programs, subcontractor technical oversight, new business concept development for various spacecraft classified and unclassified systems for the military and NASA. BAE Systems, with 106,900 employees worldwide, delivers a full range of products and services for air, land and naval forces, as well as advanced electronics, security, information technology solutions and customer support services. Letters from both of these experts giving the results of their reviews are included as documentation in the Appendix.

Finally, a further indication, albeit indirect, of the technical merit and feasibility of the Vermont CubeSat Lunar Lander Project is that a paper by Prof. Brandon on this project has been accepted for presentation at the CubeSat Developers' Workshop at Cal Poly (San Luis Obispo, CA), April 21-23, 2010. The abstract for this presentation is included in the Appendix. Also, a paper on our software experience with Ada/SPARK, "Use of SPARK in a Resource Constrained Embedded System", was presented by Prof. Chapin at the SIGAda Conference in St. Petersburg, FL, November 1-5, 2009 and is included in the Appendix. A paper, "Use of Ada in a Student CubeSat Project" was presented by Prof. Brandon at the 13th International Conference on Reliable Software Technologies - Ada-Europe 2008, 16-20 June 2008, Venice, Italy. It was published in the *Ada Users Journal* September, 2008 and is included in the Appendix.

Schedule

April 2010 Receive GEONS software from NASA May 2010 Order new CPU board, GPS receiver, Sony camera modules June 2010 Design & fabricate photovoltaic panels July 2010 Design additional electronics and interfaces August 2010 Design any additional hardware for the CubeSat September 2010 Breadboard electronics and camera system October 2010 Rewrite GEONS software framework in Ada/SPARK, write camera software November-December 2010 Rewrite GEONS modules in Ada/SPARK, write camera software January-May 2011 Rewrite GEONS modules in Ada/SPARK, test and debug camera software June 2011 Test and debug GEONS software August 2011 Test and debug all other software

September 2011 Integrate and test software

October 2011 Assemble all hardware

November 2011 Test integrated CubeSat

December 2011 Final test, thermal, vacuum and vibration

Budget

We have most of the expensive hardware in hand: CubeSat Kit CubeSat structure, Clyde Space electrical power system, Spectrolab TASC photovoltaics

Other items:	
New CubeSat Kit Motherboard (MB)	\$1,200
Pluggable Processor Module A3 (PPM A3), with TI's MSP430F2618TPM	\$ 500
GPS board	\$1,000
Camera modules	\$1,000
Clyde Space CubeSat Battery Daughter Board (two stack)	\$1,700
Miscellaneous hardware	<u>\$1,000</u>
Total	\$6,400

Management/Project Plan

The team assembled for the Vermont CubeSat Lunar Lander Project involves faculty, graduate, and undergraduate student researchers from four Vermont colleges and universities. Indeed, all academic affiliates of the VTSGC are involved in this effort. The plan developed to manage this project has been modeled on a management structure that has been used by Vermont Space Grant with considerable success in other supported projects. Overall direction and oversight will be provided by Managing Principal Investigator William D. Lakin, Director of the VTSGC. Prof. Lakin will act as the liaison between the project, the VTSGC, and the National Program at NASA Headquarters. He will provide oversight on budget matters, coordinate professional evaluation of research results, student enrichment, and the extent to which scientific milestones are achieved, and will insure that appropriate progress reports are submitted in a timely manner to the National Space Grant Program. Prof. Carl Brandon, Head of the CubeSat Laboratory at Vermont Technical College and the PI for the present proposal, is the Science Principal Investigator for the CubeSat Lunar Lander project. He will coordinate the development and integration of the CubeSat payloads for both the present launch opportunity and the more extensive Lunar Lander. Prof. Brandon will be assisted by local coordinators at Norwich University, the University of Vermont, and St. Michael's College. The present management plan also includes a planned series of regular meetings involving all project personnel, whose

locations will rotate among the participating institutions, to keep all participants fully informed on progress in all aspects of the overall project.

Compliance checklist and required documents

o The proposer is a U.S. not-for-profit or U.S. educational organization

Yes.

o Proposal includes a payload from a CubeSat development effort conducted under

an existing NASA-supported activity

Yes

o Proposal includes documentation of the relevant NASA-supported activity

Yes

o Proposal includes demonstration of the benefits to NASA

Yes

o Proposal includes a description of the merit review process and outcome

Yes

o Proposal includes a description of the feasibility review process and outcome

Yes

o Proposal includes a schedule for remaining CubeSat development that supports a

launch in 2011 or 2012

Yes

o Proposal includes a management/ project plan for remaining CubeSat

development

Yes

o Proposal includes funding commitment letters demonstrating sufficient financial support for remaining CubeSat development

Yes

Appendix

April 13, 2010

CubeSat Laboratory Vermont Technical College P.O. Box 500 Randolph Center, VT 05061-0500

Attn: Dr. Carl Brandon

Re: Request for Feasibility Review

Dear Dr. Brandon:

Ref: (1) NASA Consortium Development Grant (NNG05GH16H)
(2) Proposed Single Unit CubeSat Test of GEONS Navigation System

I have reviewed your Reference (1) NASA Consortium Grant and your proposed Reference (2) test of the GEONS navigation system in a representative CubeSat orbit and assessed the feasibility of the projects.

I have evaluated the technology readiness level and the risks associated with the proposed program plan and the technologies proposed for use. I find the project to an exciting one that will **demonstrate a new path to achieve future robotic scientific exploration goals at a cost target that will enable university researchers (including students) to conduct space experimentation and exploration.** I believe your approach to integrate existing technologies into a CubeSat format will provide a platform and open the way forward for future researchers to conduct exciting scientific missions.

I believe your approach to integrate existing technologies rather than to depend on 'invention' or new technology development is a sound one, but not without its own risks. The challenge of providing a navigation system with sufficient fidelity to achieve Lunar orbit insertion from an Earth geosynchronous orbit is not a small one. After discussing your proposal to use the NASA GEONS navigation system with our engineers who work with the GPS signals, it is our conclusion that it is feasible to navigate as you propose in space using the far side GPS signals. Your proposal to develop the navigation system and test it in space in a representative CubeSat GEO orbit, which will serve as the staging orbit for your Lunar mission, will allow you to verify the challenging navigation aspects of your system prior to embarking on the Lunar mission and thus elevate that system level integration aspect of your system to a high TRL prior to the actual mission.

The feasibility of your CubeSat GEO demonstration of the navigation system will be enhanced by the pre-launch, ground based simulation and test that you propose. Your approach to software verification is also innovative and should contribute significantly to reducing the risk of your onorbit demonstration.

In summary: I find your project plan to have a moderate risk, which will be worked down to a low risk by your ground simulation and test plan. Given accomplishment of your risk burn-down approach I find the probability of success for your on-orbit test of the NASA GEONS navigation system using far side GPS and horizon sensing in a CubeSat to be high (70 - 90%).

Sincerely,

Under Haring

Michael Harris Technical Director, Space Systems and Electronics

National Aeronautics and Space Administration

Goddard Space Flight Center Greenbelt, Maryland 20771

Reply to Attn. of: Rowland / 674



April 14, 2010

Dr. Douglas Rowland Code 674 NASA/GSFC Greenbelt, MD 20771

Dr. Carl S. Brandon Vermont Technical College 3071 South Randolph Road Randolph Center, VT 05061-9734

Dear Carl,

9.

On March 1, 2010, I learned the details of the Lunar Orbiter/Lander CubeSat project from you and Dr. Jun Yu during your visit to NASA Goddard Space Flight Center.

From our discussions, I understand that you are proposing to test a navigation system developed by Goddard, GEONS (GPS Enhanced Onboard Navigation System), in orbit with a new single unit CubeSat. The following technologies will be used in the spacecraft:

• The GEONS software (TRL-9) will be rewritten in Ada/SPARK for enhanced reliability. The Vermont team has extensive experience with Ada/SPARK. They completed the software for their NASA-funded Arctic Sea Ice Buoy in Ada/SPARK, and should therefore be successful in the rewriting of GEONS.

• The same CPU board from the Pumpkin CubeSat Kit used in the Arctic Sea Ice Buoy will be used in the CubeSat. This CPU board is TRL-9.

• The CubeSat structure is also from the Pumpkin CubeSat Kit and is TRL-

• The Clyde Space Electrical Power System, and Li-Polymer batteries which are TRL-9.

• The Microhard 2.4GHz MHX2400 spread spectrum modem for communication is TRL-9, used on NASA's GeneSat-1, among others.

• The camera modules for the celestial navigation part of GEONS will be developed by the Norwich University team. They have successfully developed an artificial vision navigation system for a NASA funded autonomous underwater robot.

• The Novatel OEMV-1 GPS, for use by GEONS has been used in several

CubeSat projects.

The feasibility of this project is **good** based on the following considerations:

• Most of the hardware is TRL-9 COTS technology. The critical development technologies are:

- The software component, which will be implemented by a team experienced with Ada/SPARK from their NASA funded Arctic Sea Ice Buoy project.
- The camera system, which will be developed by a team experienced with this technology from their NASA funded Autonomous Underwater Robot.

• The management team has shown success in their previous NASA funded projects above. The roles, experience, expertise, and the organizational structure of the team are solid and likely to lead to success.

• The technical development risk associated with the overall CubeSat mission is small due the extensive use of TRL-9 COTS components, and the experience of the two teams in the new technologies (software porting of GEONS to Ada/SPARK and camera system for GEONS).

• These critical technology developments required for flight readiness are within the demonstrated abilities of the two teams.

• The development of the CubeSat for flight, is well within the demonstrated abilities of the teams on previous NASA funded projects.

• The feasibility review gives a high probability of success of this project.

• The team responded to comments during their discussions with myself and others they met with at NASA Goddard by incorporating GEONS as their navigation system and switching from bipropellant to advanced monopropellant thrusters (not part of this launch opportunity, but for their more extensive lunar spacecraft).

• There is sufficient financial support for the development of the CubeSat payload and for all other costs. The expensive hardware: CubeSat flight module structure, CPU board, Electrical Power System, radio system and photovoltaic cells are already in hand, and there is \$44,000 in hand from the previous CubeSat grants as well as the Lunar spacecraft Consortium Development Grant for any additional hardware purchases.

I wish you success in this exciting endeavor, which will help to advance small satellite technologies, and prove their utility for the kinds of small science missions we want to pursue in the Heliophysics Science Division, here at NASA GSFC.

Sincerely,

Fareface & Browland

Douglas E. Rowland

Dear Prof. Brandon,

The Vermont CubeSat Lunar Lander Project formed the entire basis for a proposal the Vermont Space Grant Consortium submitted to the 2009 Consortium Development Competition, held by NASA's National Space Grant College and Fellowship Program at NASA Headquarters. This proposal was awarded, and the National Program provided us with \$195,000 in augmentation funding from NASA to support development of the CubeSat Lunar Lander by you and your multidisciplinary team of faculty and students. In addition, the CDC 2009 proposal's budget included \$150,197 in local matching funds committed to this project. This email will confirm that this funding is in hand and there is sufficient financial support available for remaining CubeSat development.

Sincerely yours,

William D. Lakin, Ph.D.

Professor of Mathematics, Statistics and Biomedical Engineering, Emeritus The University of Vermont Director, Vermont Space Grant Consortium State Project Director, VT-NASA EPSCoR

(802) 324-8206 wlakin@together.net

National Aeronautics and Space Administration

Headquarters Washington, DC 20546-0001

Reply to Attn of: Office of Education

September 16, 2009

Dr. William D. Lakin, Director Vermont Space Grant Consortium Dept. of Mathematics and Statistics The University of Vermont 16 Colchester Avenue Burlington, VT 05401-1455

Dear Dr. Lakin:

Congratulations! It is a pleasure to inform you that the Vermont Space Grant Consortium has been selected as a recipient of a Consortium Development Competition award. The award has been approved for a total amount of \$195,000.00 for a one-year period. Please note, equipment purchases are not permitted with this award.

We received a total of 8 proposals for this solicitation. From these, 5 were recommended for funding. The evaluation was conducted according to the criteria described in the Consortium Development Competition notice.

We look forward to continuing the productive partnership between you and NASA. Please feel free to contact me at (202) 358-1069 or by email, diane.d.detroye@nasa.gov, if you have any questions or concerns.

Sincerely,

Dare DiDemoze

Diane D. DeTroye Manager, National Space Grant College and Fellowship Program Office of Education



National Space Grant College and Fellowship Program Consortium Development Competition

Office of Education 8 July 2009

B. Proposal Review and Evaluation

Proposals will be reviewed and evaluated by a combination of NASA Space Grant staff, Designated Space Grant Directors, and other qualified personnel. The following criteria will be used in the evaluation process:

1. Merit

• Overall Merit: Merit of the proposal including feasibility to achieve the proposed project(s); support of the purpose, and intent and scope of the announcement; innovative strategy. If multiple projects are proposed, there should be a sound rationale for the mix of projects. Demonstrates **quantitatively** that the proposed work will contribute to Outcome 1.

• **Relevance:** Project(s) responds to a need identified by the higher education community; based on a compelling mutual need for the institution and NASA; and can make an effective content contribution to the realization of NASA's mission.

- 6 - 7/8/09

• **Partnerships/Sustainability**: Education investments leverage and achieve sustainability through their intrinsic design and the involvement of appropriate local, regional, or national partners in the design, development, and dissemination. Involves a strategic and diverse range of institutions and is designed to attract and stimulate a cross-section of highly qualified individuals.

• Evaluation: Appropriate evaluation plan(s) is in place to document outcomes and demonstrate progress toward achieving the objectives of the proposed activities; projects have goals and SMART (specific, measurable, appropriate, realistic, and time-specific) objectives expressed in objective, quantifiable, and measurable forms; and evidence that forms of evaluation are based on reputable models and techniques appropriate to the content and scale of the project(s).

• **Project Execution:** Plan and structure for efficient operation of the project(s). Involves a creative, innovative approach that can serve as a model to other institutions or Space Grant consortia.

CARL S. BRANDON, Ph. D.

3071 South Randolph Road Randolph Center, VT 05061-9734 Phone: (802) 728-9947 Cell: (802) 356-2822 E-mail: carl.brandon@vtc.edu

EXPERIENCE: 1977-Present, Full Professor, Chair - Aeronautical Engineering Technology Vermont Technical College (Vermont State Colleges)

Randolph Center, VT 1969-77, Graduate teaching assistant University of Massachusetts

1967-69, Junior Physicist IBM Components Division East Fishkill, NY Computer modeling and computer aided design of transistors and integrated circuits (co-designer .of IBM's first memory chip.)

1966, Junior PhysicistIBM Thomas J. Watson Research CenterYorktown Heights, NYComputerized data collection and analysis of the magnetic properties of rare earth compounds.

1963-67, Programmer and Computer Operator Cyclotron Laboratory, Michigan State University East Lansing, MI Assembly language and FORTRAN programming for the design of cyclotron components.

EDUCATION: 1979 Ph. D., University of Massachusetts 1974 M. S., University of Massachusetts 1969-70 Graduate Physics courses: University of Massachusetts 1966-7 Graduate Physics courses, Michigan State University 1966 B. S., Michigan State University, Physics.

LICENSES: Commercial Pilot (Airplane Single Engine Land and Sea, Instrument Airplane, Glider) Flight Instructor (Airplane, Instrument and Glider), Pilot since 1964, Instructor since 1969, Amateur Radio Extra Class License (N1BCD)

POST Ph. D. COURSES: SPARK programming, Airline Transport Pilot written exam course (TWA), Microprocessors, Microprocessor Troubleshooting, Pascal Programming, Ada Programming (several), Compilers, Data Communications, Java, Linux (several).

PUBLICATIONS: "Lunar Lander / Orbiter CubeSats", CubeSat Developers' Workshop Proceedings, April, 2010
"Use of SPARK in a Resource Constrained Embedded System", SIGAda Proceedings, November, 2009
"Use of Ada in a Student CubeSat Project", Ada Users Journal, September, 2008
"Ada Language Moving Closer to Market, Control Engineering, 31(12):89-90, November 1984
"High Speed Photography of Animals: A Strobe Design", Journal of the Biological Photographic Association, 1978

RESUME Peter C. Chapin P.O. Box 317 Randolph Center, Vermont 05061 Phone: 802-522-6763 Email: PChapin@vtc.vsc.edu Web: http://vortex.cis.vtc.edu/pcc/ GENERAL:

I am a versatile technical individual who learns quickly. I have the following expertise:

1. Programming languages—C, C++, Ada, SPARK, Java, Scala, .NET, and many others.

2. Software development—Application programming (both GUI and console), network programming, parallel programming, and system programming.

3. System administration—Linux and Windows, including troubleshooting network problems at the packet level.

4. Sensor and embedded systems—Wireless sensor networks, nesC and TinyOS programming, and the CubeSat platform.

EMPLOYMENT HISTORY:

2009–Present, CubeSat Laboratory Software Director at Vermont Technical College.
 2007–Present, Maintainer of the Open Watcom open source C/C++ and FORTRAN compiler suite.

3. 1986–Present, Professor, Vermont Technical College.

4. Conceived, developed, and delivered courses in computer engineering technology, software engineering, and information technology. Some examples include: C/C++ programming, network protocols, algorithms, compiler design, system administration, computer security, operating systems, parallel programming, microprocessor systems, digital electronics, and analog electronic devices.

5. Proposed and developed four year program in computer engineering technology.

6. Provided on-line courses to both internal and external communities.

7. Provided industry workshops.

8. Actively participated in the development of VTC's distance learning offerings.

9. Acted as system administrator for the VTC's NetWare and Unix systems.

10.Designed, coded and deployed user specified software for Vermont Interactive Television.

11.Served on X3J16 (1990–1993), the technical committee charged with standardizing C++.

EDUCATION:

 Currently a student at the University of Vermont pursuing a PhD in Computer Science with a focus on programming language based security in wireless sensor networks.
 2004–Present.

2. University of Illinois, MSEE, 1985

3. Western New England College, BSEE, 1982. Graduated with a GPA of 3.93/4.0. Member of Σ BT honor society.

EDUCATION

- **Doctor of Philosophy, Aerospace Engineering**, Texas A&M University
- 1991 Master of Science, Engineering Mechanics, Clemson University
- **Bachelor of Science, Mechanical Engineering**, Virginia Military Institute

EMPLOYMENT

- 2008-Present Associate Professor, Mechanical Engineering Department, Norwich University
- 2003-2008 Assistant Professor, Mechanical Engineering Department, Norwich University
- 2000-2003 Senior Engineer, Applied Research Associates, Alexandria, VA.
- 1999-2000 Staff Engineer, Applied Research Associates, Alexandria, VA.
- 1997-1999 Teaching Assistant, Aerospace Engineering Department, Texas A&M University.
- 1993-1997 Research Assistant, Aerospace Engineering Department, Texas A&M University.
- 1991-1993 Instructor, Mechanical Engineering Department, Virginia Military Institute.
- 1989-1990 Teaching Assistant, Mechanical Engineering Department, Clemson University.
- 1987-1989 Instructor, Mechanical Engineering Department, Virginia Military Institute.

PROFESSIONAL ACTIVITIES

<u>Undergraduate Research Activities</u>: Mentored undergraduate research projects focusing on robotics, materials, and computer aided design and manufacturing.

2009 "Robotic Navigation by Vision" (NASA funded)

2009, 2008, and 2007 "Autonomous Underwater Vehicle" (NASA funded)

2008 "Multiphysics Analysis of a Sample Holder for an Inductively Coupled Plasma Torch Facility." (NASA funded)

2006 "Computer Aided Design and Prototype Development of a Rod Clamping Mechanism for a Light Duty Cone Penetrometer" (sponsored by Applied Research Associates)

Course and Lab Development Activities: Redesigned the Introduction to Engineering course for engineering freshman.

Lead the development of a new course on Turbomachinery under a Curriculum Development Fellowship. The course was developed and taught jointly with Concepts NREC, a company specializing in turbomachinery design and development.

Incorporated new technologies and expanded the use of the Computer Integrated Manufacturing (CIM) Lab. Integrated new computer aided manufacturing software, SURFCAM and subsequently CAMWorks, for improved and more advanced machining capabilities. Expanded the utilization of the CIM Lab in the ME358 Metallurgy and Manufacturing course, ME499 Turbomachinery course, and senior projects involving industry and NASA related applications.

Consulting Work: Performed consulting work for Applied Research Associates from 2005 to 2006 validating and improving methodologies for predicting damage inflicted by underground detonations against tunnels. The

work included a review and analysis of extensive groundshock propagation and tunnel damage data from underground explosion tests.

PUBLICATIONS

M.W. Prairie and R.D. Friend, "Machine Shop Training with a Musical Note," 40th ASEE/IEEE Frontiers in Education Conference, Washington, D.C., (October 2010). (In review)

G. Wight, R. Friend, W. Barry, and J. Beneat, "A Project-Based Introduction to Engineering for Freshmen Engineering Students at Norwich University," 2008 American Society of Engineering Education Annual Conference and Exposition, Pittsburgh, PA, (June 2008).

R. Danner Friend, "A Review and Analysis of the Underground Explosion Tests (UET Program) for Improving Rock Mass Characterization Algorithms", internal technical report submitted through Applied Research Associates to the Technology Development Directorate of the Defense Threat Reduction Agency, (June 2006).

R. D. Friend and V. K. Kinra, "Particle Impact Damping," Journal of Sound and Vibration, 233(1), pp. 93-118, (2000).

PROFESSIONAL LICENSURE

Registered as a Professional Engineer in Virginia since June 2001

2010 CubeSat Developers' Workshop abstract

Lunar Lander / Orbiter CubeSats

We have received a NASA Consortium Development Grant for Vermont Technical College to build prototype CubeSats for travel from a geostationary satellite launch to the moon. One spacecraft will involve a two-unit CubeSat bi propellant booster to go from a geostationary transfer ellipse to the moon. It will enter lunar orbit while carrying a single CubeSat lunar lander. The second triple CubeSat will have a xenon ion drive to carry it from a geostationary transfer ellipse via a low-energy transfer through L1 to enter lunar orbit. The single-unit CubeSat lander is designed for landing on the Moon from a 100 km orbit. The 0.53 kg of propellant is a hypergolic combination of mono-methyl hydrazine and nitrogen tetroxide. Four 1.0 N radiation cooled thrusters are at one end, with the pair on each side canted slightly toward each other. This design allows for full three-axis control with differential use of the four thrusters. The bi propellant booster, a double-unit CubeSat, would have the same propulsion system, but with 1.5 kg of propellant. With the single unit lander attached, this package would be capable of generating a Δv of 2,000 m/s, which would be sufficient to leave a geostationary transfer ellipse at the apogee with escape velocity and to enter lunar orbit. A triple-unit CubeSat ion drive spacecraft will also be developed in parallel. The preliminary design for this spacecraft is based on the mission profile of the SMART-1 spacecraft of the European Space Agency. However, our design will use the CubeSat-sized NASA-JPL developed miniature xenon ion thruster MiXI with a specific impulse of 2,000-5,000 seconds. The thruster will be used as is, with only a gimbal added or grid beam steering, both have been developed for previous ion drives. With this thruster, a 0.5 kg propellant load of xenon would give a Δv of about 3,500-8,900 m/s. Power for the thruster will come from photovoltaic cells on the spacecraft and four fold out panels. The control software for the mission will be written in Ada (as used on the Cassini and other NASA missions) / SPARK. It has a record of producing reliable software, with about 1% the error rate of C. We have developed extensive experience with this system in our NASA-funded Arctic Sea Ice Buoy project. The overall CubeSat mission will be completely robotic, as the spacecraft will be entirely autonomous. Navigation will be by optical means using sun, moon and earth tracking with GPS enhancement while near perigee. Optics will also determine attitude during the descent to the lunar surface and measure the lateral velocity during the landing phase. The optical sensor development of both hardware and software will be done by faculty and students at Norwich University Low-energy transfer strategies and the effect of radiation exposure from the Van Allen belts and solar coronal mass ejections will be modeled by faculty and students at the University of Vermont. They will also study strategies for coordinating multiple spacecraft.

SIGAda 2009 paperTITLE

Use of SPARK in a Resource Constrained Embedded System

AUTHORS

Chad Loseby Vermont Technical College CLoseby@vtc.vsc.edu

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Carl Brandon Vermont Technical College Carl.Brandon@vtc.vsc.edu

Abstract

We are constructing a remote sensing buoy that will be deployed on the Arctic sea ice north of Alaska. The buoy will gather environmental data and transmit that data back to home base via the Iridium satellite network. This data will then be used (by others) to refine models of ice movement. To enhance reliability the buoy software was written using SPARK Ada. SPARK was also helpful in reducing the memory footprint of the software to an

acceptable level. Note also that the construction of the prototype buoy is a student project. Thus our experience is in an educational context.

Introduction

This project is part of a collaboration between Vermont Technical College (VTC) and the University of Vermont (UVM). Professor Jun Yu, Associate Chair Department of Mathematics & Statistics at UVM, has been mathematically modeling the movement of Arctic sea ice as it melts. This movement is influenced by many factors include temperature, wind speed, and wind direction. Previous work used satellite photographs of the ice as model input [1]. However this work suffered from a lack of "ground truth" information.

Vermont Technical College's role in this project is to build several buoys that will be deployed on the Arctic ice sheet to collect environmental data and transmit that data back to Vermont. During the 2008-2009 academic year one of us (Loseby) began developing the software for a prototype buoy as a senior project.

The prototype buoy is built around a CubeSat Kit [2]. This platform is based on a TI MSP430 microcontroller. It has significant constraints in processing power, ROM, and RAM. Specifically our development system used MSP430F149 MCU at 8 MHz with 60 KiB of ROM and only 2 KiB of RAM. interested in using this platform primarily because of its extremely low power consumption, but also because we have hopes of launching a satellite based on it as a future project [3]. Thus a secondary goal of this project was to gain experience with this platform.

There are five environmental parameters that the buoy needs to gather. These parameters are location, temperature, wind speed, and wind direction. Because the ice rotates as it moves it is also necessary to record a magnetic bearing that, together with location, provides an absolute orientation of the buoy. These parameters will be gathered once every 30 minutes and transmitted to home base via a satellite modem using the Iridium short burst data service.

To simplify the design the buoys will be battery powered (instead of solar powered) using a Tadiran PulsesPlus lithium thionyl chloride 7.2V 19Ah battery. Experience by the Army Cold Regions Research & Engineering Laboratory [4] suggests that this power supply should be sufficient to run the buoy for up to several months provided care is taken with power management. Since the buoys are expected to fall into the ocean as the ice melts there is no need for very long term operation.

Because it will be infeasible to perform any maintenance on the buoy once

it is deployed, issues of reliability are of utmost importance in this application. In particular, a "crash" of the buoy software will cause a failure of the mission. Even worse than an outright crash, however, would be an error that allows the buoy to operate but return incorrect data. To help avoid these problems the software was developed using SPARK Ada. The extra level of reliability provided by SPARK will also be important when we use this platform in a future satellite project.

Software Overview

The overall structure of the software is rather simple as illustrated by the flowchart in Figure 1 [caption: Buoy software main loop]. The buoy spends most of its time in a deep sleep state. A hardware timer generates periodic interrupts that are counted by software to accumulate an overall sleep time of 30 minutes. After being awakened, the buoy collects data from the various sensors, including time and location information from a GPS unit. This process can take several minutes but it is done entirely sequentially. The software makes no use of concurrent tasks.

The gathered data is stored, along with associated time stamps in several buffers with one buffer for each type of reading. During the reporting phase, the buoy packs as many readings as possible into a single short burst data packet and transmits that packet to Vermont. It is possible to pack more data into a short burst data packet than can possibly be gathered in a single run of the data gathering phase. Thus even if the buffers are non-empty at the start of the loop they will eventually drain as the loop executes.

The buffers account for possible problems in either gathering data or reporting it. If a sensor malfunctions, no data for that sensor will be entered into the buffer but this will not cause any complications for the handling of other data. If the satellite link goes down, data will accumulate in the buffers until such time as the link is up again. Note that due to memory constraints the buffer sizes are small, but because of the low sampling frequency they can still hold several hours worth of data.

Each buffered data item is time stamped separately. This is because the time at which the data item is reported may be much later than the time when it was gathered. Since the buoy's location is one of the data items being reported, the returned (time, location) pairs allow a trajectory of

the buoy to be plotted. This trajectory forms a basis for the interpretation of the other (time, value) data item pairs.

Tool Chain

To our knowledge there is no Ada compiler available that specifically targets the MSP430 microcontroller. It may be possible to build a cross compiling version of GNAT using gcc's MSP430 target [5]. However, this would require specialized knowledge of gcc technology, which was outside the scope of this project. Instead we used Sofcheck's Ada to C translator, Ada Magic, to convert our Ada source into plain C [6]. We then used Rowley Associates' CrossWorks C compiler for the MSP430 to generate our final object code [7]. This tool chain is shown in Figure 2 [caption: Buoy software tool chain. Green indicates code. Red indicates tools.]

This approach has the advantage of using a back end C compiler that officially supports our platform. In fact, we used several small C functions for interacting with hardware resources. In order to keep as much of the code as possible in Ada, and thus visible to the SPARK tools, a significant effort was made to keep the C functions as simple as possible. For example our package that exposes the system timer to Ada has the following specification

```
package Timer
--# own Timer_Hardware;
is
procedure Initialize;
--# global out Timer_Hardware;
--# derives Timer_Hardware from ;
pragma Import(C, Initialize);
procedure Sleep;
--# global in out Timer_Hardware;
--# derives Timer_Hardware from Timer_Hardware;
pragma Import(C, Sleep);
end Timer;
```

Timer_Hardware is a SPARK own variable that stands for the state of the hardware used by the timer. We implemented these procedures in C as follows.

```
void Timer_Sleep(void) {
    // Enter Low Power Mode 3
    _BIS_SR(LPM3_bits);
}
void Timer_Initialize(void) {
    // Timer A: Source TACLK, Clear, Mode 1.
    TACTL = TASSEL0 + TACLR + TAIE;
    TACTL |= MC1;
    // Enable interrupts
    _EINT();
}
```

We also provided an interrupt service routine for the timer that awakens the processor when the timer overflows. Procedure Sleep returns when this occurs.

```
void Timer_A(void) __interrupt [TIMERA1_VECTOR]
{
    // If we are overflowing, wake up the system.
    if (TAIV == 10) {
        _BIC_SR_IRQ(LPM3_bits);
    }
}
```

This C code is by necessity very system specific. However, the Ada code that calls procedures Initialize and Sleep is free of system dependencies and thus does not require an Ada compiler with any knowledge of the MSP430 platform. We handled interfacing with other hardware resources (A/D converters, the serial port, and some LEDs for test purposes) in a similar way.

```
Advantages/Disadvantages of SPARK
```

Because our platform is extremely resource constrained, we are interested in using the smallest run time system possible. In fact, we are not using any part of the normal Ada Magic run time system provided by Sofcheck. In addition to reducing memory, this also simplifies the running software and enhances reliability by eliminating a large body of code that would otherwise be outside of SPARK's visibility.

This rather extreme approach was made possible by two factors. First, our system is relatively simple. The sensors are read one at a time, and the serial communication is all done with polled I/O. This is acceptable in our case because of the slow time frame in which the system operates. Most of the software complexity is in formatting and buffering the data, and in gracefully handling hardware devices that malfunction.

However, our ability to use a minimal run time system is also a direct consequence of our use of SPARK. For example, SPARK forbids user defined exception handling, so no run time support for exceptions is needed. The Ada Magic compiler outputs calls to certain run time library functions for exception handling, but we provided empty implementations of these functions to satisfy the linker.

SPARK helps us to justify this approach. For example, Ada Magic's output includes calls to a C function rts_elab_check that is used to verify that packages are elaborated in an appropriate order. However, under SPARK rules the semantics of a program are not affected by elaboration order; the check can never fail. Thus we are justified in providing an empty implementation for this function.

Ada Magic also emits calls to functions rts_stack_check and rts_raise_constraint_error. We are justified in providing empty implementations for these functions only if we can statically prove that our system will never run out of stack space or raise Constraint_Error. Doing this will entail using SPARK proof annotations. At the time of this writing we have not completed that step, but it is our intention to do so before actually deploying the buoy.

Notice that there is no danger of accidentally using a run time library function unexpectedly. Whenever Ada Magic attempts to call a new function from its run time library, our system fails to link. This forces us to evaluate each new function used. In some cases we changed the Ada source specifically to avoid using run time library functions we didn't want to implement. For example in one case Ada Magic called a function to compute the mod operation because C's modulus operator does not have the right semantics. Rather than provide this function in C, where SPARK is unable to analyze it, we modified the Ada source so that it was no longer necessary.

The main disadvantage of SPARK was the learning curve associated with it.

This was our first attempt at using SPARK in any capacity and extra time was required to understand the restrictions imposed by the language as well as how to properly use the annotations.

In addition, debugging the system was complicated by the fact that the CrossWorks debugger had no knowledge of the original Ada source. All our debugging needed to be done in C which was, in effect, the assembly language of our system. We are fluent with C and that was very helpful, even necessary, in a project of this nature.

We also encountered some interesting interactions between SPARK and the

Magic compiler. In one case Ada Magic produced a warning about a possible use of an uninitialized variable. However, the data flow was such that no uninitialized use was possible. When we included a spurious initialization of the variable to satisfy Ada Magic, the SPARK Examiner complained that the initialization had no effect. We eventually decided to disable all warnings from Ada Magic on the assumption that the SPARK Examiner would be able to detect a superset of the flow problems detected by Ada Magic.

Educational Opportunities

Vermont Technical College's mission is education. Thus all of our projects need to be evaluated in that context. Although Ada is not used as the primary language in any VTC courses, it is taught at the instructor's discretion as a supplementary language in several courses. In particular, Loseby was first exposed to Ada in a programming languages course taught by Chapin. In addition Ada has been used for the last two years in a sophomore projects course. None of these courses currently discuss SPARK; this is the first time anyone at VTC, instructors and students alike, has attempted to use SPARK in any capacity.

From a student perspective, SPARK was a welcome introduction to static code analysis. Loseby found the SPARK annotations much easier to understand and write after grasping the concept that

hardware states could be represented and described by those annotations. In many cases, the process of visualizing the desired behavior in order to write an annotation revealed logical errors or prompted the refactoring of the code to improve efficiency or maintainability. Chapin and Brandon intend to build on the experience of this project by using the same approach in the construction of software for a VTC satellite. This will also be done as one or more senior projects with the first project group anticipated in the 2009-2010 academic year. In addition Chapin intends to comment explicitly on SPARK during his fall 2009 delivery of the programming languages course, using examples taken from this project.

Current Status and Future Directions

The work reported here has been on the construction of a single prototype buoy to demonstrate the feasibility of our design and of our approach. At the time of this writing the development of the prototype is still in progress. We have demonstrated reading temperature and wind direction data, and sending that data back to Vermont via the Iridium network. However, we still need to implement support for gathering and transmitting wind speed and magnetometer data.

In addition we are currently only using SPARK flow annotations. While this has been helpful with finding bugs in our software, we still need to make use of SPARK proof annotations to show that certain exceptions can't occur. Our system depends on this because of the way we have eliminated exception handling support in the run time system.

Funding for the construction of the prototype continues through the end of this year and we anticipate completing the prototype in time to conduct field tests during the northern hemisphere 2009-2010 winter season. In the long term we hope to receive funding to manufacture ten to twenty buoys for deployment in the Arctic perhaps in March of 2011.

Conclusion

Using SPARK Ada in an educational setting to develop software for a highly constrained embedded system without a native Ada compiler is feasible. Although there are some aspects of our project that have yet to be completed, we are confident that we will be able to build on the success we have had so far. One interesting benefit of using SPARK was in the way it allowed us to eliminate significant amounts of run time support. This was essential in our case due to the very limited amounts of memory available to us.

Acknowledgments

This project is supported by grants from the Vermont Space Grant Consortium, a part of the NASA Space Grant program. Vermont Technical College also received generous donations of commercial software from AdaCore, SofCheck, Praxis, and Rowley Associates.

References

- 1. Yu, J., Liu, A. K. and Zhao, Y. (2006). "Sea Ice Motion and Deformation in the Marginal Ice Zone through SAR." Accepted for inclusion in a book: Advances in Geosciences 2005, (Hyo Choi, Editor-in-Chief), World Scientific Publishing Company.
- 2. http://www.cubesatkit.com/
- 3. Carl S. Brandon, "Use of Ada in a Student CubeSat Project," Ada User Journal, Vol. 29, No. 3, Sept. 2008
- 4. http://www.crrel.usace.army.mil/
- 5. http://mspgcc.sourceforge.net/
- 6. http://www.sofcheck.com/products/adamagic.html
- 7. http://www.rowley.co.uk/msp430/index.htm

Use of Ada in a Student CubeSat Project

Carl Brandon

Vermont Technical College, PO Box 500, Randolph Center, VT 05061 USA; Tel: +1 802 728 1350; email: carl.brandon@vtc.edu

Abstract

A student project to develop a CubeSat (10 cm cube, 1 kilogram satellite) as part of Vermont Technical College's Aeronautical Engineering Technology degree uses a Texas Instrument MSP430 processor for which no Ada compiler is available. Ada and SPARK offer a highly desirable combination for the reliability needed in a satellite. Since there is no Ada compiler targeted for the MSP 430, we decided to use SofCheck's AdaMagic compiler which generates ANSI C as its intermediate language. We then use an existing C compiler as a back end, generating code for the MSP 430. This allows the students to write the original source code in Ada/SPARK and have object code for the MSP430.

Keywords: CubeSat, SPARK, Ada.

1 CubeSats

A CubeSat is a pico satellite approximately the size of a 10centimeter cube, with a maximum mass of one kilogram. The particular specification for the satellite hardware was developed by California Polytechnic State University (Cal Poly) and Stanford University (http://CubeSat.calpoly.edu), so that multiple CubeSats could be easily integrated into a launch vehicle.

The CubeSat is an autonomous satellite. The software to run all its systems must be completely reliable. It will be powered by high-efficiency triple junction photovoltaic cells, backed up by batteries for high-power operations, such as transmitting and, if the satellite is behind the earth, out of the sunlight power supply.

The Vermont Tech CubeSat will have a 2.4 GHz Microhard (http://microhardcorp.com/MHX2420.htm) spread spectrum modem for two-way communications with our ground station. This radio has been used in two CubeSats so far. Although the radio has a lot of built-in autonomous functionality, it will be controlled by the flight module computer.

Another function, the attitude determination and control system, will have the largest software component of any onboard system. We plan to have an active magnetic attitude control system. This will be used to point the patch antenna for the transceiver, and the camera toward the earth. The position of the Cubesat after deployment is generally determined by calculation from the Keplerian two-line elements describing the orbit as released by the launch providers soon after deployment. A program, such as Satellite Tool Kit (http://www.agi.com/index.cfm) can give accurate position, assuming the two-line elements are correct. The position accuracy is important for antenna pointing of the ground station to establish communications with the satellite. We will achieve even higher accuracy by including a Global Positioning Satellite navigation module in the CubeSat to transmit a more precise location of the satellite, which will correct the orbital parameters of the Keplerian two line elements.





The CPU for the satellite will be a Texas Instruments MSP430 micro controller, chosen for its extremely low power consumption, the lowest of any processor. With power production from the photovoltaics being about 1.5 watts in the sunlight, low power is an absolute requirement. The primary disadvantage, in our view, is that there is no Ada compiler for this processor. As discussed below, Ada/SPARK is our choice for the satellite software.

Cal Poly has developed a deployment system called a P-Pod, which holds three CubeSats, and releases them via a spring from the launch vehicle at the appropriate time. Cal Poly negotiates with commercial launch providers for P-Pod space on commercial satellite launches (there has also been a CubeSat deployment from the Space Shuttle). They negotiate launch prices in the \$30,000-\$50,000 range for a one kilogram CubeSat.

2 Arctic Sea Ice Buoys

We have been funded for a cooperative NASA grant with the University of Vermont, for a prototype Arctic Sea Ice Buoy which will use the same CPU and some of the software used in the Cubesat. We have also submitted a second cooperative NASA grant application with the University of Vermont, which will fund the construction and deployment of ten Arctic Sea Ice Buoys. These would be placed on ice in the Arctic Ocean to monitor wind speed and direction, temperature and GPS position of the buoy, and relay the data via the Iridium satellite network. The buoys share some of the same characteristics of the CubeSat: low power availability, harsh environmental conditions and the need to be reliable and autonomous.

Software for control of the radio, power management, and telemetry will be shared from the CubeSat software development. The same necessity for extreme software reliability speaks for the use of Ada/SPARK.

3 Aeronautical Engineering Technology Degree Program

The general design of the CubeSat is being done by students in our Aeronautical Engineering Technology They take two semesters of Spacecraft program. Technology and a satellite design lab. In the lab, they look at the various satellite systems: command and control (CPU). attitude determination and control. communications, power and instrumentation. These associate degree students generate general specifications for the satellite, but the implementation will be done by bachelor students in our Electro-Mechanical, Computer Tech and Software Engineering programs during their senior projects.

4 Our CubeSat Project

With the somewhat limited personnel resources of a small college (Vermont Tech has about 1,500 students), we have chosen to use as much off-the-shelf technology in our spacecraft as possible. We have started with a CubeSat kit (http://www.CubeSatkit.com) which supplies the hardware chassis (flight module), the CPU board, real time operating system (Salvo), a number of software components, and a development board.

We are purchasing our electrical power system, which provides batteries, charging controller, and telemetry data from Clyde Space (http://www.clyde-space.com). The photovoltaic cells are TASC cells from Spectrolab (http://www.spectrolab.com). We will be fabricating our own PC boards for mounting the cells. These boards will also make up the outer shell of the satellite.

The spacecraft's attitude will be determined by a three-axis magnetometer to measure the direction of the earth's magnetic field, and a sun sensor to determine the direction of the sun. These two pieces of information, with a lot of computation, will enable the satellite to determine where it is pointing. To change its orientation, three mutually perpendicular torque coils will lie under the faces of the satellite, and computer controlled currents can be sent to any of them to create a torque against the earth's magnetic field, and thus rotate the satellite to the desired orientation. Although there is an off-the-shelf attitude determination and control system similar to what we want, it is much more complex (containing three torque wheels), adds a second ten-centimeter module, increasing the launch costs by \$30,000-\$50,000, and costs \$55,000 itself.

For the communication system, we will use the Microhard 2.4GHZ spread spectrum modem, and possibly a second radio beacon in the 440 MHz amateur radio band. Students will build a tracking dish antenna of three to eight meters, and a tracking dual yagi antenna for 440 MHz. Our ground station will become part of the GENSO (http://genso.org) network when it becomes operational in the fall of 2008.

The final instrument payload is yet to be determined, but will most likely include a camera for photographing the earth from space. Other instruments may be included, and all will have to be controlled, and data collected by the CPU.



Figure 2 CubeSat kit

5 MSP430 CPU Description

The Texas Instruments (http://focus.ti.com) MSP430 series of micro controllers are the lowest power micro controller/processors available. This makes them an excellent choice in an application where power is limited. They also contain a variety of peripherals on the chip, which also saves on complexity and power. The peripherals vary with the specific chip, but we are looking at a final choice of the MSP430F2618 which has 116 kb of flash, 8 kb of RAM, 12 bit SAR analog to digital converter, 2 12 bit digital to analog converters, analog comparator, DMA, Hardware Multiplier, 2 USCI interfaces. The CPU board can also take SD flash memory cards of up to 2 GB. It uses 2 μ A in low-power mode, and about 500 μ A at full speed. It can go from low-power mode to full speed in one microsecond. There is no Ada compiler for the MSP430.

6 Why use Ada

Although the CubeSat is not a safety-critical system, the software is mission critical. The small size of the CubeSat precludes uploading software patches as is sometimes done with NASA satellites and space probes. The cost of developing the CubeSat will be in the \$30,000-\$50,000 range, and the launch costs also in the \$30,000-\$50,000 range, so a non functional satellite because of a software error would result in a \$60,000-\$100,000 loss. Most of the CubeSats launched to date have been programmed in C, and admittedly most have generally worked.

Despite the general success of CubeSats programmed in C, Ada offers a number of advantages. Many large projects programmed in Ada have shown considerable reductions in error rates compared to C. In addition, finding and fixing the errors that do occur takes much less time. With the small size of our school, and thus fewer people resources for the project, efficiencies of this type are very important. In addition, having students involved in both the hardware and software for the project and using a language that makes use of the best of software engineering features has a great pedagogical advantage. This project is a realembedded system that must have very high-integrity software. Ada fits the bill for high-integrity software that is efficient to write and debug.

7 Ada and SPARK

The availability of SPARK makes possible a further increase in the integrity of the code over Ada alone. SPARK annotations allow the specification of the program, as expressed in the annotations, to be used by the SPARK toolset to check the code's compliance with the specification. Although this project is rather small compared to the projects that SPARK is normally used on, the fact that there is only one chance to get the deployed software right, and the high cost of failure in dollars and time, make it a good choice to help ensure the success of our project.

A second benefit of using SPARK is that this is an opportunity for some of our Software Engineering majors to work on a high-integrity real world project. This is a type of project not often done in an academic environment. SPARK allows the students to get experience with a particularly powerful method of achieving high-integrity software.

In the CubeSat, there is the need for real-time programming. There are interactions with the power system, the attitude determination and control system, the communications system, the navigation system and the camera and other instrumentation. The availability of RavenSPARK, the SPARK subset of the Ada Ravenscar Profile, will allow us to use SPARK to keep the real-time programming also very high-integrity. Thus the students will have a valuable experience in writing robust and clear software, that otherwise would not be available to them.

SPARK, being a subset of Ada, requires an Ada compiler. The only problem is that there is no Ada compiler for the processor we want to use.

8 AdaMagic

A solution to the compiler problem for this project required an unusual process. In talking with Tucker Taft of Sofcheck (http://www.sofcheck.com) at Ada Europe 2005, I learned about their AdaMagic compiler which produced ANSI C code as the intermediate language. This opened the interesting possibility of using an existing ANSI C compiler as the "back end" for the AdaMagic compiler. This is the route we have chosen, so we can develop software for our CubeSat in Ada/SPARK for high-integrity, check it with the Ada and SPARK toolsets, run it through AdaMagic, and then compile the resulting ANSI C version with our C compiler for the MSP430.

9 Crossworks C Compiler and the Salvo operating system

We have chosen the Rowley Associates (http://www.rowley.co.uk) CrossWorks for MSP430, which includes an ANSI C compiler, macro assembler, linker/locator, libraries, core simulator, flash downloader, JTAG debugger, and an integrated development environment, CrossStudio. This will provide the object code for our satellite CPU and download it into the processor. There is also an MSP430 core simulator, so code can be checked on the host Windows machine before downloading to the MSP430.

CrossWorks supports the Salvo Real-Time Operating System from Pumpkin, Inc. (http://www.pumpkininc.com), the manufacturer of the CubeSat kit. Salvo comes with the CubeSat kit, and will be the operating system in the satellite. Several in orbit CubeSats are running on Salvo.

10 GPS, GNAT Pro and SPARK

The development process is greatly facilitated by the inclusion of a set of Python scripts with the GNAT Programming Studio that allow invocation of the various command line tools in the SPARK toolset from within GPS. Having first used the SPARK toolset by invoking it from the command prompt window, this facility is extremely useful. One can now remain in the GPS development environment when using the SPARK tools.

11 Python Scripts for AdaMagic in GPS

At the moment, we are invoking AdaMagic from the command prompt window, as we used to do with SPARK. In our programming languages course, the students study both Ada and Python. In the coming semester, they will be assigned a Python project to create the necessary Python scripts to invoke the AdaMagic front end from within GPS. This will allow the programmer to remain in the GNAT Programming Studio environment for the entire development process for a much nicer overall process.



Figure 3 Software development process

12 Software workflow

Alongside is a diagram of the software development workflow with our various software tools. This shows the original development in GPS, use of the SPARK tools, compilation in GPS with GNAT, compilation again with AdaMagic with the production of ANSI C code and cross compiling with Crossworks for the production of the MSP430 object code.

13 Acknowledgments

This project at a school of our size would not be possible to undertake without a lot of outside support. For the satellite and supporting hardware, several grants have been obtained from the Vermont Space Grant Consortium, a part of NASA Space Grant (http://www.vtspacegrant.org). This would also be the source of funds for the satellite launch.

Analysis of the satellite in many aspects, from orbital analysis to thermal and communication link budget analysis, is being done in Satellite Tool Kit,. We have received a donation of thirty copies of this \$100,000-percopy software.

We have been a long time member of Adacore's GNAT Academic Program (GAP) (http://www.adacore.com/ home/academia) and have had the availability of GPS/GNAT for several years. We have also received a grant of GNAT Pro from Adacore for use in our grantfunded research.

Praxis (http://www.praxis-his.com) has donated the \$122,000-per-copy Spark toolset to us through our membership in GAP.

Rowley Associates has given us an academic discount for one license for Crossworks, and donated a second license.

We are very grateful to all these organizations for their extraordinarily generous gifts to Vermont Technical College. Without their support of academia, this project would have never launched.