Puerto Rico's First CubeSat: Multidisciplinary Research Project to Attract STEM Students into the Area of Aerospace Systems

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Abstract **– The purpose of this paper is to present an interdisciplinary research project using Cubesats to attract engineering students to the area of aerospace systems. CubeSats are miniature satellites designed for space science explorations. Due to their low cost and reduced size, not only have they earned an eminent position in the field of space exploration but they have also become a reliable tool for space education. This project is the first low-cost cubesat developed in Puerto Rico as a joint program between the University of Puerto Rico-Mayaguez (UPRM), the Inter American University of Puerto Rico- Bayamon (UIPRB), the University of Puerto Rico-Rio Piedras (UPRRP), and the University of Turabo. It is financially supported by the Puerto Rico Industrial Development Company (PRIDCO) and the Puerto Rico National Aeronautics and Space Administration (NASA) Space Grant. The main objective is to promote interdisciplinary research in the area of aerospace systems with the collaboration of graduate and undergraduate students from electrical, mechanical and computer engineering departments. The multidisciplinary process consists of the design, simulation, and construction of each subsystem of the Cubesat. Each university is responsible of building at least one subsystem. Focus is given to the Cubesats Electronic Power Supply (EPS) constructed by the UPRM. Once the project is finalized, the expected end result is a working Cubesat capable of space science exploration.**

Index Terms – Interdisciplinary Research, Study Program, Electrical Power Supply, CubeSat

I. INTRODUCTION

It is evident that research and development has become an essential part of a large number of engineering universities for its significant contributions to society [1]. Despite the global impact research conveys, it is mostly a closed group effort. Specific groups (Companies, Organizations, Universities, Departments, etc.) work towards achieving an objective. Engineering research should no longer be constrained to single agencies; interdisciplinary efforts should aid in accomplishing global objectives. Recently universities have adopted interdisciplinary approaches collaborating with other institutes in order to expand ideas and improve teaching methods [2]. As part of the Puerto Rico NASA Space Grant, different universities have merged together in order to design and construct Puerto Rico's first Cubesat. Fig. 1 illustrates a diagram of the different universities, agencies and departments collaborating in this project.

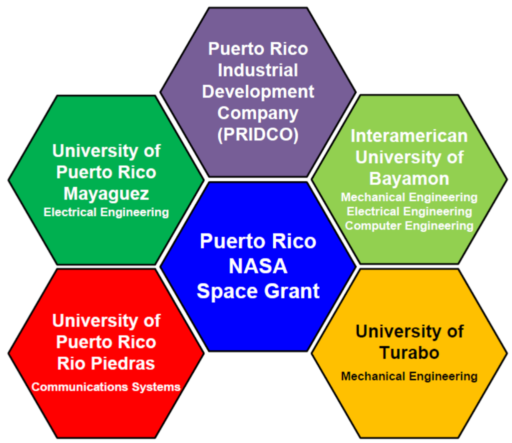

Fig 1: Project Interdisciplinary Scheme

This project is an opportunity to encourage collaboration between with different universities in Puerto Rico while at the same time promoting a higher degree of learning. The objective of the Puerto Rico Space Grant Consortium (PRSGC) is to enhance Puerto Rico's research, education and workforce in the fields of Science, Technology, Engineering and Mathematics (STEM). With this in mind, the participating universities are assigned a part in the CubeSats construction. The University of Puerto Rico-Mayaguez is tasked with building and testing the electronic power supply (EPS). The Inter American University of Puerto Rico-Bayamon will focus on the structural and mechanical design of the CubeSat. As an example of the progress obtained through interdisciplinary research, this paper will focus on the EPS developed by UPRM and how the collaboration with other institutions and disciplines made it possible.

This article is organized in the following manner: section II describes the CubeSat project in general and how the EPS gives functionality to the system. Section III details the results obtained from the UPRMs EPS. A short description of the history of UPRM and its ECE department is given in section IV. Section V describes the collaborations made with other institutions. Section VI focuses on the educational impact this project has had on students, universities and Puerto Rico. Finally section VII presents the conclusion obtained.

II. THE CUBESAT PROJECT

A CubeSat is a miniature satellite originally designed for space science. Conceived as an educational tool, they have managed to challenge traditional satellite standards and are recognized for their potential utility by space and research agencies around the world [3]. These projects are primarily led primarily by universities and non-US space groups. Government agencies have sponsored the development of these projects through organizations such as; National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), and through the Department of Energy (DoE) [4]. CubeSats are mainly composed of several units; an on-board computer, control and communication systems, among other measurement devices. In order for these units to operate it is essential that their power is supplied by an EPS. Fig. 2 shows a standard CubeSat design, illustrating some of the most vital parts of the Electronic Power Supply (EPS).

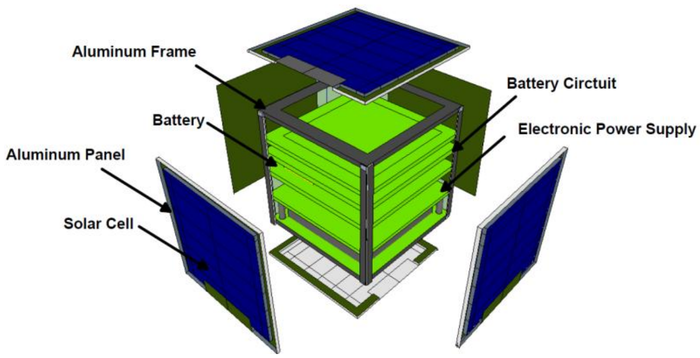

Fig 2: Standard CubeSat Diagram

The goal of the project is to help develop an aerospace engineering experience for students in Puerto Rico and to provide a system engineering experience for the students. The Space Plasma Ionic Charge Analyzer (SPICA) CubeSats main objective is to acquire relevant space weather data in order to understand the effects the sun has on our planet. The UPRM is tasked with designing the EPS system. The Power Electronic courses in the university cover a wide range of power supply designs using DC/DC converters with a variety of applications, including aerospace. A CubeSat is powered with solar energy; solar panels located on each one of its sides. The six solar panels are constructed with 24 Triangular Advanced, Improved triple-junction Gallium Arsenide (GaAs) solar cells. Individually each solar cell has a V_{oc} and the I_{sc} of 2.52V and 0.031A respectively. When the series and parallel connections are made between the solar cells, the end results are six 10cm x 10cm solar panel possessing a V_{oc} and the I_{sc} of 5.04V and 0.372A respectively. The solar panel supplies the power to the necessary loads as well as to power the microcontroller while at the same time charging the battery source of the CubeSat. It is essential to maximize the available electrical energy gained from the minimal solar cell area available. In order to accomplish this, the maximum power point tracking (MPPT) methods is used [5]. The considered MPPT technique to maximize power output is the optimal duty cycle method. The proposed EPS design for the CubeSat is illustrated in Fig. 3.

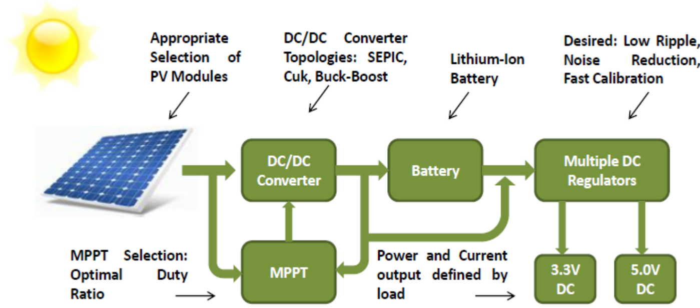

Fig 3: CubeSat EPS Design

The EPS must provide power to the CubeSats peripherals so it can maintain its functionality. The power supply design will accommodate an onboard computer, ADS Sensor, ACS actuator, several scientific instruments, as well as the communications system. The design consists of a primary DC/DC converter that will perform the MPPT, in order to obtain the maximum power from the solar cell array. In order to regulate voltage at the loads, two voltage regulators also constructed with DC/DC converters are used. For these DC/DC converters, the chosen topology is the Single-Ended Primary-Inductor Converter (SEPIC). A Lithium (Li) battery is used due to its compact size and light weight [6]. The battery is connected to the output of the SEPIC as well as to the input of two DC/DC converters used for voltage regulators.

The analysis of solar panel behavior is performed using methods developed by professors from the UPRM [7]. These models are taught and discussed in ECE power electronics and renewable energy courses. This mathematical model makes use of a series of equations that take into consideration the useful data given by the manufacturer's data sheet that are given at standard test conditions. The developed mathematical model that represents the output current of the photovoltaic module is shown in equation (1).

$$I(V) = \frac{I_X}{1-exp(^{-1}/_{b})} \cdot \left[1 - exp\left(\frac{V}{b \cdot V_X} - \frac{1}{b}\right)\right] \quad (1)$$

In these equations, V is the output voltage of the panel and the variable b is the characteristic constant of the photovoltaic model that describes the I-V relationship. The expression used to obtain the parameter V_x is shown in equation (2).

$$V_x = \frac{E_{iN}}{E_i} TCV(T - T_N) + V_{max} - (V_{max} - V_{min}) exp\left[\frac{E_i}{E_{iN}} \ln\left(\frac{V_{max} - V_{oc}}{V_{max} - V_{min}}\right)\right] \quad (2)$$

This expression uses the maximum and minimum voltage values, where V_{max} is the open-circuit voltage at 25°C and more than 1,200W/m^2, V_{min} is the open-circuit voltage at 25°C and less than 200W/m^2. E_i is the effective solar irradiation in W/m^2. TCV is the temperature coefficient of V_{oc} in *V/°C*. The variable T is the solar panel temperature in °C. T_N is 25°C and the nominal effective solar irradiation E_{iN} is 1,000W/m^2. V_{oc} is the open-circuit voltage at 25C and 1000W/m^2. The variable I_x in equation (1) can be calculated by using equation (3).

$$I_x = \frac{E_i}{E_{iN}}[I_{sc} + TCi(T - T_N)] \tag{3}$$

The variable I_{sc} is the short circuit current measured at standard test conditions. In this equation, TCi is the temperature coefficient of I_{sc} in A/C. These are just examples of how mathematical models developed by universities are being implemented in order to aid in the development process.

III. CUBESAT ELECTRONIC POWER SUPPLY RESULTS

The EPS prototype is an example of how interdisciplinary research can aid the achievement of a common objective. The EPS was constructed based on the needs of the SPICA CubeSat established by the UIPR-Bayamon. The EPS is constructed on a 9cm x 9cm PCB, with a total weight of 0.071kg in order to comply with the CubeSat size and weight limitations. The constructed CubeSat EPS is shown in fig. 4. Fig. 5 illustrates the obtained output voltages of the CubeSats EPS.

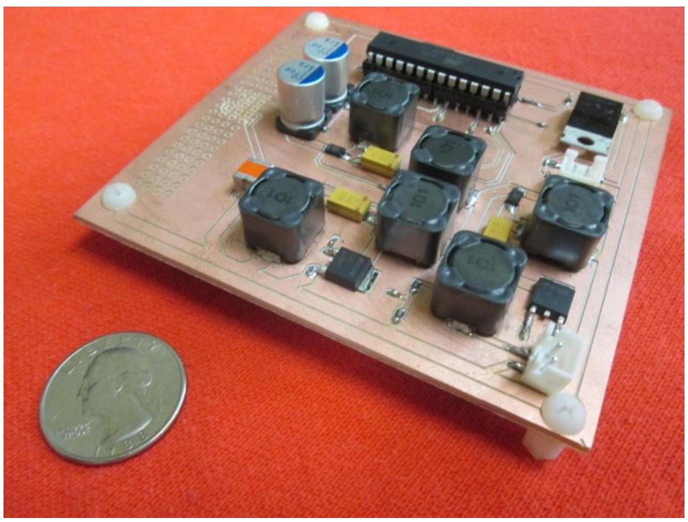

Fig 4: CubeSat EPS PCB Prototype

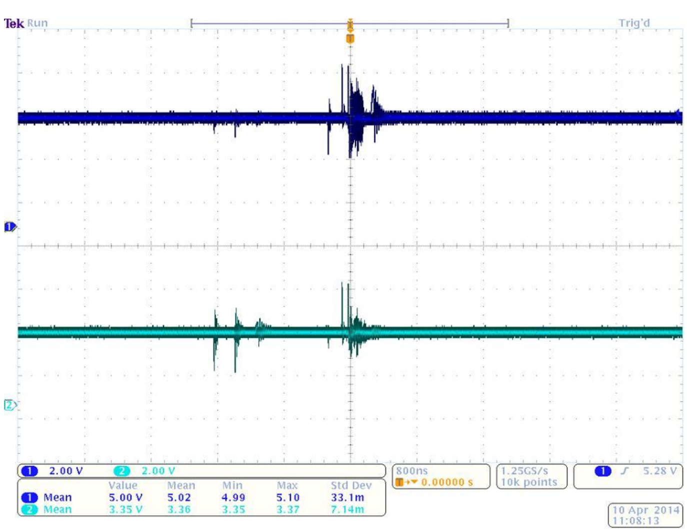

Fig 5: EPS Output Voltages

The EPS prototype is built using an Arduino Uno microcontroller. The microcontroller is tasked with controlling the MPPT of the SEPIC as well as adjusting the duty cycle of the regulators accordingly. The EPS is also designed to provide regulation for both output voltages. Both regulators are designed using the SEPIC Topology. In order to test functionality the output voltages of the EPS where measured. Notice how the experimental results show that the EPS is able to regulate 5V and 3.3V at its respective outputs with little signal distortion. The 3.3V regulator reached a maximum voltage of 3.37V and a minimum voltage of 3.35V with a standard deviation of 0.0331V. The 5V regulator reaches a maximum voltage of 5.10V and a minimum voltage of 4.99V with a standard deviation of 0.00714V. Both regulators are able to regulate voltage properly.

IV. UPRM ECE DEPARTMENT

The University of Puerto Rico-Mayaguez is a public university located in the municipality of Mayaguez; Puerto Rico established in 1911.UPRM offers 52 bachelor's programs, 28 master's programs and five doctoral programs. Moreover, it has been accredited by the Middle States Commission on Higher Education (MSCHE) since 1946 and by ABET, ranking among the top 10 U.S. universities in the field of engineering.

The Electrical Engineering Program is fully accredited by the Accreditation Board of Engineering and Technology (ABET). The curriculum provides a general education in mathematics, science, and humanities and emphasis in selected areas. Currently, the UPRM's ECE Department has nearly 1,100 students which represents nearly 10% of the whole UPRM's student population and more that 20% of the UPRM College of Engineering' student population. Also, the ECE Department's research and graduate programs involve 14 laboratories, groups and centers, more than 40 graduate-level courses, 49 faculty members with PhD degree, 2 adjunct professors, nearly 1,100 undergraduate students and over 60 graduated students. At the present, the ECE department offers BS and MS degrees in electrical engineering and computer engineering and a Ph.D. in Computer Informatics Science and Engineering. By the year 2015, the ECE department expects to start two new academic programs in addition to the existing ones. These two new programs will be: 1) the first Ph.D. program in electrical engineering in Puerto Rico and the rest of the US Territories; and 2) BS program in Computer Informatics Science and Engineering. The ECE Department offers several areas of specialization that could be applied to aerospace systems: control systems (e.g. trajectory optimization), electronics (e.g. IC for energy harvesting), power electronics (e.g. high density power supplies for satellites), computing systems (e.g. cyber security), and communications (e.g. wireless communications). The ECE department has a variety of existing courses at the undergraduate and graduate levels. Over the years the ECE department has shown a growth in interest in the field of aerospace technologies. Table I shows examples of ECE courses that could be used for education on aerospace systems.

TABLE I: UPRM ECE AEROSPACE RELATED COURSES

Field	Course	Description
Communications	INEL 4301	Communication Theory
	INEL 4307	Communication between Computers
	INEL 5327	Image Processing
	INEL 5316	Wireless Communications
Computing Systems	ICOM 5018	Network Security and Cryptography
	ICOM 5026	Computer Networks
	ICOM 6005	Database System Design
	ICOM 6025	High Performance Computing
Control Systems	INEL 4505	Introduction to Control Systems
	INEL 5505	Linear Control Systems
	INEL 6000	Nonlinear Control Systems
	INEL 6001	Optimal Control
Electronics, Hardware and Embedded Systems	INEL 4201	Electronics
	ICOM 5217	Microprocessor Interfacing
	INEL 5265	Analog Integrated Circuit Design
	INEL 6048	Advanced Microprocessor Interfacing
Power Electronics	INEL 4416	Introduction to Power Electronics
	INEL 5417	P. E. for Renewable Energy Systems
	INEL 6066	Control of Electric Motors
	INEL 6085	Advance Power Electronics

V. COLLABORATION WITH OTHER INSTITUTES

The design and construction of a satellite is a multidisciplinary effort, involving aspects of all fields of engineering [8]. It is not expected that a single group should design and construct the entire CubeSat. For this task to be achieved it is essential to involve several groups, from different institutes [9]. The UPRM and the UIPR-Bayamon collaborate with UPRRP through the Puerto Rico NASA Space Grant Foundation as well as through PRIDCO. Through this grant, 15 graduate and undergraduate students are sponsored. UIPR-Bayamon collaborates in the CubeSat project by providing mechanical vibration and micro thruster tests. UPRRP is tasked with the CubeSats communication systems. The University of Turabo is also collaborating by supporting other universities; providing students skilled in different engineering fields. Fig. 6 illustrates the educational institutions that are collaborating in order to develop the CubeSat prototype as well as aerospace technology agencies that are widely distributed in Puerto Rico.

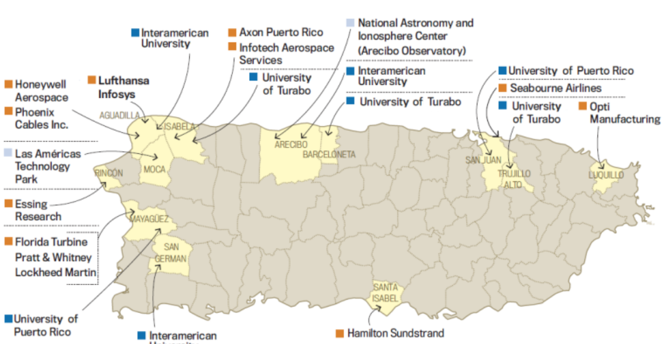

Fig 6: Puerto Rico Aerospace and Technology Cluster Map

One of the UIPR-Bayamon largest contributions is their Suggestion: "research facilities, which are designed for aerospace testing; ground Station laboratory for communications systems, thermal analysis laboratory equipped with thermal oven and a vacuum designed for testing space conditions. The university also possesses a control systems and electronics laboratory as well as a clean room. Table II illustrates the UIPR-Bayamon's aerospace programs and courses.

TABLE II: UIPR-BAYAMON AEROSPACE PROGRAMS

Program	Course	Description
Minor Aerospace Engineering	MECN 3974	Aerospace Experience I
	MECN 3973	Aerospace Experience II
	MECN 3975	Space Mission Analysis and Design
	MECN 4301	Aerospace Materials
	MECN 3545	Gas Turbines and Propulsion systems
	MECN 3350	Aircraft Design and Performance
Master of Science in Mechanical Engineering with concentration in Aerospace	MECN 6210	System Engineering
	MECN 6220	Advance Structure Engineering
	MECN 6230	Aerospace Dynamic
	MECN 6300	Advance Control System
	MECN 6260	Advance Mechanical Vibration

This program is designed to train students to develop the knowledge and abilities needed to function as an efficient professional in the fields of energy and aerospace. Specializing in aerospace gives students the opportunity to hone the necessary skills to be successful in the aerospace industry.

VI. EDUCATIONAL IMPACT

This project has provided student the experience of focusing on a single technical design while also teaching the students to coordinate work between groups from various departments at other universities [10]. It has motivated undergraduate students in the mechanical, electrical and computer engineering and computer science programs. Currently there are 42 students working directly on the cubesat project. It is expected that undergraduate students interested in pursuing a master's degree will base their thesis on this project. The majority of students that have worked in CubeSat related projects in the past have been employed by companies such as: Texas Instruments Honewell, Infotech aerospace services, Florida Turbine, Lockeed Martin and NASA. Other students have continued their studies at a PhD level at institutions such as: Michigan State University, Ohio State University and University of Minnesota among other high ranking universities.

Another beneficial impact obtained from this project is the experience students obtain from working with relevant software in the field of engineering: MatLab, Simulink, Multisim LabView among others. These different software tools help simulate stress and space conditions that cannot be easily verified with theoretical calculations. In the ECE of the UPRM, power electronics is generally applied to the subjects of motor control and renewable energy. This project has broadened the subject of power electronics applications in the field of aerospace. A variety of DC/DC converters topologies, microcontrollers (MSP430, ArduinoUno, Propeller, etc.) and MPPT techniques have been explored in order to meet the CubeSats specific needs. Another added incentive from this project is improving the students' hands-on skills and laboratory capabilities [11]. Students learn Printed Circuit Board (PCB) design and manufacturing. Once the PCB is manufactured, components are soldered and the CubeSats EPS is the end result. The final product is tested with the use of a solar array simulator that aids in emulating the CubeSats solar panels. Testing the constructed EPS involves verifying its ability to regulate both 5V and 3.3V output voltages as well as performing the MPPT.

VII. CONCLUSION

An interdisciplinary CubeSat project between the UPRM, the UIPRB, the UPRRP and University of Turabo is discussed. The EPS developed by the ECE department of the UPRM is used as an example of how multidisciplinary collaboration with other institutions aid in achieving a common goal. Results obtained from the EPS are presented. This EPS is able to take advantage of the SEPIC topology in order to perform MPPT to obtain the maximum power output of the solar panels connected at each side of the cubesat. Also, the EPS is able to successfully regulate the load voltages of 5V and 3.3V. This project has helped create ties between UPR system, UIPR-Bayamon and University of Turabo as well as with agencies like NASA and PRIDCO. This collaboration has influenced a growth in aerospace technologies in Puerto Rico. The effort of all the universities participating in this project has proven that interdisciplinary research can achieve a single goal, while at the same time influencing institutions into adopting new courses and teaching methods. In general the learned resources could not only be applied to this project but to any other project, including topics outside of aerospace and power electronics.

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REFERENCES

[1] Roberts, J.A.; Barnhill, R.E., "Engineering togetherness (an incentive system for interdisciplinary research)," Frontiers in Education Conference, 2001. 31st Annual , vol.2, no., pp.F2G,23-7 vol.2, 2001

[2] Polutnik, J.; Druzovec, M.; Welzer, T., "Interdisciplinary projects - Cooperation of students of different study programs," EAEEIE Annual Conference (EAEEIE), 2013 Proceedings of the 24th , vol., no., pp.215,218, 30-31 May 2013

[3] Rose, R.; Dickinson, J.; Ridley, A., "CubeSats to NanoSats; Bridging the gap between educational tools and science workhorses," Aerospace Conference, 2012 IEEE , vol., no., pp.1,11, 3-10 March 2012

[4] S.A. Asundi and N.G. Fitz-Coy, "CubeSat mission design based on a systems engineering approach," IEEE Aerospace Conference, March 2-9 2013, pp. 1-9.

[5] S. Padma Priya; A. Radhika and T. Deepika Vinothini,, "MPPT and SEPIC based controller development for energy utilisation in CubeSats," India Conference (INDICON), 2012 Annual IEEE, Dec. 7-9 2012, pp. 143-148.

[6] M. Obland, D.M. Klumpar, S. Kirn, G. Hunyadi, S. Jepsen, and B. Larsen, "Power subsystem design for the Montana EaRth Orbiting Pico-Explorer (MEROPE) CubeSat-class satellite," Aerospace Conference Proceedings, 2002 IEEE, vol. 1, pp. 465-472.

[7] E.I Ortiz-Rivera, "*Modeling and Analysis of Solar Distributed Generation*," Thesis submitted to the Department of Electrical and Computer Engineering at Michigan State University, 2006, pp. 12-17.

[8] Shiroma, W.A.; Ohta, A.T.; Tamamoto, M.A., "The University of Hawaii CubeSat: a multidisciplinary undergraduate engineering project," Frontiers in Education, 2003. FIE 2003 33rd Annual , vol.3, no., pp.S3A,7-11 vol.3, 5-8 Nov. 2003

[9] Larsen, J.A.; Nielsen, J.D., "Development of cubesats in an educational context," Recent Advances in Space Technologies (RAST), 2011 5th International Conference on , vol., no., pp.777,782, 9-11 June 2011

[10] Alminde, L.; Bisgaard, M.; Vinther, D.; Viscor, T.; Ostergard, K., "Educational value and lessons learned from the AAU-CubeSat project," Recent Advances in Space Technologies, 2003. RAST '03. International Conference on. Proceedings of , vol., no., pp.57,62, 20-22 Nov. 2003

[11] Swartwout, M.A.; Bennett, K.J., "Project Aria: space systems research, education and public outreach at Washington University," Aerospace Conference, 2001, IEEE Proceedings. , vol.7, no., pp.7,3671 vol.7, 2001