SEDSAT 1 Advanced Photovoltaic Power System Technology Demonstration Flight

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The University of Alabama in Huntsville Students for the Exploration and Development of Space, in cooperation with the NASA Marshall Space Flight Center, Boeing Defense & Space, and the Kopin Corporation, are designing an advanced electrical power system for a small satellite. This system incorporates recent advances in three areas: photovoltaic cell design, battery energy storage design, and DC-DC power conversion technology. Introducing these advances into a flight power system will produce a satellite power system with double the capability of similar systems utilizing current technology.

Introduction

Electrical power generation, delivery, and control is a primary driver in the design and application of small satellites. The intrinsic small size of these satellites limits the amount of area available for solar arrays. This, coupled with restrictions on deployable arrays placed on them by launch vehicle companies when flown as secondary payloads, places great limitations on the power available for use. This is frustrating to the designer and user of small satellites because advances in electronic packaging and high density integrated circuits allows the inclusion of capability in these satellites unheard just a few years ago. To take full advantage of these advances, and compensate for restrictions imposed, demands that a new high energy density power generation, storage, and control system be developed.

SEDSAT 1 is a technology demonstration small satellite potentially flying as a secondary payload as part of NASA's Small Expendable Deployer System (SEDS) flight demonstration project.[1] SEDSAT 1 is designed to be deployed into a 680 X 792 km orbit at a 39° inclination. SEDSAT 1 will be deployed from a McDonnell Douglas Delta II 7925 second stage by the SEDS via a 46 km tether (upward deployment). The objectives of SEDSAT 1 are to measure the SEDS tether deployment dynamics, demonstrate tether propulsion as a technology, serve as an Earth observation platform, demonstrate new power technology, and provide a dual transponder amateur radio communications system.

The power for SEDSAT 1 will be supplied primarily by the Boeing/Kopin lightweight GaAs/CuInSe$_2$ thin film tandem solar cells. The cell efficiency of these tandem cells has been tested to 23.1% AM0. In addition, at least one facet of the satellite will incorporate the latest, improved, mechanically-stacked, double-heterostructure (AlGaAs)GaAs/CuInSe$_2$ cells. The anticipated efficiency of this type cell is greater than 26% at 28°c. The batteries to complement the advanced cells are the Ovonic Battery Co. sealed nickel-metal hydride batteries now coming into use.[2] These batteries offer an energy density of twice that of conventional Nickel/Cadmium designs with no "memory" effect. These advanced components, coupled with high efficiency DC-DC power conversion components and load side power management under microprocessor control, comprise the heart of the electrical power system for SEDSAT 1.

In this paper, a conceptual design and specific features of the power system optimized for a successful SEDSAT 1 mission are described. An advanced design of solar panels utilizing high-efficiency GaAs(AlGaAs)/CuInSe$_2$ tandem solar cells will be discussed along with advanced features of energy storage and power conditioning.

Project Organization

The SEDSAT 1 project is organized and located at the University of Alabama in Huntsville (UAH). The lead organization is the UAH chapter of the Students for the Exploration and Development of Space (UAH SEDS). This project is being carried out under the guidance of faculty advisors Dr. Charles Lundquist, Director of the UAH Center for the Commercial Development of Space, and Dr. S. T. Wu, Director of the Center for Space Plasma and Aeronomic Research. Major participation from industry comes from Boeing Defense and Space, Renton, WA; Kopin Corporation of Taunton, MA; Trec, Inc.; and Optechnology of Huntsville AL. Other Support comes from the Institute for Aeronautics and Astronautics, National Chen Kung University, Tianan, Taiwan; Weber State University, Odgen, Utah; the Amateur Radio Satellite Organization (AMSAT/NA); and SEDS chapters from around the world. Figure 1 represents our team approach to this project.
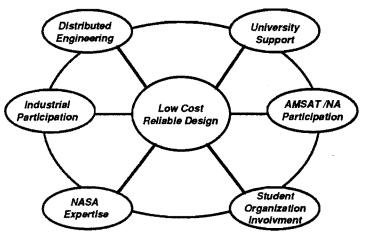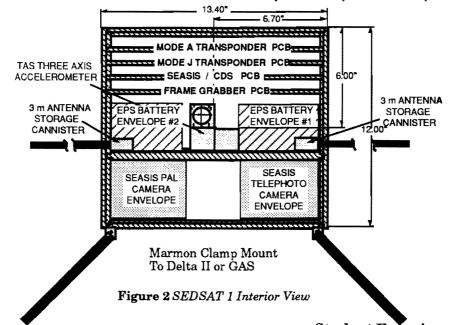

Figure 1 *SEDSAT 1 Design Philosophy*

SEDSAT 1 Overview

SEDSAT 1 is a microsat class satellite with a projected launch weight of 37 kilograms. The satellite is a 34.04 X 34.04 X 30.5 cm flattened cube This size was chosen as the one that best supported the tether dynamics studies while still fitting within the allocated secondary payload envelope of the Delta II second stage.[3] There are two sets of antennas on SEDSAT 1 to support amateur radio satellite communcations. The lower turnstile antennas are 70 cm transmit antennas, and the upper antennas on the corner, support the 2 meter uplink and 10 meter downlink. Figure 2 is a diagram of SEDSAT 1 with the -Z face removed.

Attitude Control

SEDSAT 1 attitude control is similar to the passive spin/magnetic type used on the AMSAT microsat.[5] Either the 70 cm., or the 2/10 m antennas can be used for solar vanes, while the hysteresis rods and permanent magnets are mounted as with the microsats. The flattened cube shape will guarantee that the spin axis will remain aligned with the Z axis. This will support the remote sensing as well as the communications aspects of post tether deployment operations.

An alternative for attitude control being considered is the use of a 100 meter short tether with a mini end mass as a deployable gravity gradient boom. The gravity gradient tether would accomplish the same alignment with respect to the earth as permanent magnets but with the drawback of more system and operational complexity.

Figure 2 *SEDSAT 1 Interior View*

Structural Design

Modularity and testability is the key to the SEDSAT 1 design. A card cage design was chosen for the Electronic PCB's to simplify ground testing and enable quick disassembly in case of a late failure during satellite integration. The PCB's are mounted on a 6.35 mm square mounting plate that slides into the shell of the satellite. The experiments are also mounted on a slide out mount that will allow easy access to the experiments and the batteries.

The main structure of the satellite is made out of 1.27 cm (.5") 6061 T6 aluminum. Weight is not as much of a factor in the design of SEDSAT 1 as the requirement of making the satellite massive enough to keep tension on the tether during the deployment sequence.

This massive approach to structural design has a beneficial impact on thermal control. The thermal constant for the entire structure is on the order of 10,000 seconds. This large value will guarantee that the temperature of SEDSAT 1 will vary very little during operation of the satellite.[4] This is important due to the fact that the AlGaAs/CIS solar cells have greater absorptivity than silicon cells. Also at the inclination of SEDSAT 1's orbit, the shade time will vary from a maximum of 33 percent of orbit down to a minimum of 8 percent. The large thermal mass will help to keep temperatures within a range of values that allow us to characterize the power system in a thorough, systematic manner.

Student Experiments

SEASIS

SEDS Earth, Atmosphere, and Space Imaging System (SEASIS) is an imaging experiment that will visually record the attitude of SEDSAT 1.[6] SEASIS incorporates two Panasonic GPKD502 industrial video cameras with NTSC and RGB output. Each camera head has three Charged Coupled Device (CCD's) organized into a 492 X 682 array. Each CCD output, R, G, B, can be captured independently.

A flash analog to digital converter/frame grabber from Weber State University similar to the one used on WeberSAT is used to convert the cameras's NTSC or RGB output to a digital pixel array where each element is one byte in length. A dedicated Motorola 68020 microprocessor is used to transfer the image data from the frame grabber to memory. In image memory, it is compressed to allow the storage of up to 2000 images onboard the satellite for later downlink to the Earth via the Mode J digital transponder.

TAS

The Three-axis Accelerometer System (TAS) consists of a three axis set of very accurate, very temperature stable accelerometers (Sundstrand QA 3000-030). At the limit of their resolution, they can measure g levels on the order of one μg. These accelerometers will be used to measure the accelerations that the endmass is subjected to at the end of the tether.[7] The accelerometers are mounted at the exact center of mass and geometry of the satellite.

Command Data System

The command data system (CDS) design closely parallels the AMSAT microsat design in order to retain as much software compatibility as possible. This design consists of an NEC V.40 microprocessor with the following features.

- Enhanced 80C186 CPU
- Clock Generator
- 2 Independent DMA Channels
- Programmable Interrupt Controller
- 3 Programmable 16-bit Timers
- Dynamic Ram Refresh Controller
- Programmable Memory & Chip Select Logic
- Programmable Wait State Generator
- Power Save Mode
- On Board Serial Port

The CDS also incorporates three serial controllers (NEC 72001's). These controllers will handle all communications with the ground as well as some interprocessor communications with the SEASIS processor. Also there will be 512k of 12 bit error detecting and correcting memory that will be used as the applications software operating memory. Another feature will be the inclusion of up to 128 analog inputs to twoA/D converters, with 12 for TAS and 116 available to monitor the state of the onboard systems. While for normal operation this is "overkill" in telemetry, these channels will be used to support the accurate in–flight characterization of the power system. Finally, there will be 512k of dual ported ram for image transfers between SEASIS and the CDS, with the AMSAT AART bus being used for controlling the communications transponders.

The operating system software for the CDS system is the Quadron QPS real time multitasking system that executes in a round robin fashion. This system gives each task a time slice in proportion to the time necessary to complete its task. The drivers for the digital communications are a variant of the CCITT X.25 protocol known as AX.25.

The primary task of the CDS for the elctrical powe system is the operation of the charge control system via software. Figure 3 shows a functional block diagram of SEDSAT's electronic systems.
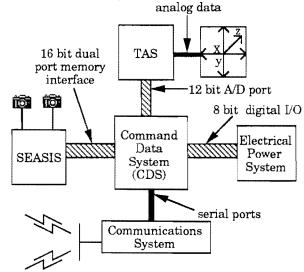

Figure 3 *SEDSAT 1 Electronics Systems*

Communications System

The communcations system for SEDSAT 1 is intended for the use of amateur radio satellite operators worldwide. There are two transponders onboard. The first transponder is a mode A linear transponder with a tentative frequency allocation on the downlink side of 29.300-29.360 Mhz. The uplink frequency is set at 145.820-145.880 Mhz. The second transponder downlink is set at 435.990-435.930 inverting with the uplink also in the two meter band. This transponder will be a digipeater similar to the six AMSAT microsats currently in orbit.

Electrical Power System Concept

In an effort to both broaden the scope and enhance the effectiveness of the SEDSAT 1 mission, UAH SEDS approached Boeing Defense and Space regarding the possibilities surrounding the use of their leading edge technology planar photovoltaic cells on SEDSAT 1.[8] In the ensuing negotiations with Boeing, and their subcontractor Kopin Corporation of Taunton, MA, it was mutually agreed that the (AlGaAs)GaAs/CIS thin-film, tandem cells jointly produced by the two companies would be the optimum solution in powering SEDSAT 1. In the course of technical discussions about the satellite, it was realized by all parties involved that not only would the cells be the optimum solution for SEDSAT 1, but also a flight demonstration of these cells on a microsat class satellite would be greatly beneficial to the rapidly developing field of small, low-cost satellite systems.

These (AlGaAs)GaAs/CIS cells coupled with new high-energy battery technology and a unique power system developed by UAH SEDS with the support of NASA Marshall Space Flight Center, offer the small satellite industry a doubling of available power and a decrease in system complexity compared to currently used approaches. This combination of new technologies opens up new and exciting possibilities in the further development of small satellites and their applications.

To complement the vastly increased performance offered by the incorporation of the thin film tandem cells, it was decided by the SEDSAT 1 design team to pursue the inclusion of batteries with a performance to match that of the solar arrays.[9] While weight is not a problem with SEDSAT 1, internal volume and center of mass is. Use of C size NiMH batteries affords SEDSAT 1 a doubling of energy storage with no increase in either weight or volume. Two batteries with an energy storage capacity of 150 watt hours were chosen. These batteries fit within the allocated volume and enable SEDSAT 1 to run full power with a very low depth of discharge on the batteries.

With the goal of reducing the manufacturing cost and complexity of SEDSAT 1 a distributed power architecture was selected. This architecture provides a smaller size, lighter weight, more efficient operation with battery power, and more efficient subsystem isolation and redundancy than a centralized design. The number of cables required to carry power is decreased by having only a single distribution voltage with local conversion to the needed voltage.[10]

Until recently this approach was not optimum due to the inefficiencies in the DC-DC converters in use. SEDSAT 1 is using the Interpoint MTR series DC-DC converters. These converters offer efficiencies of power conversion in the 78% to 84% range. It was decided that the efficiencies provided by the converters were good enough to justify the trade off of decreased system complexity, increased reliability, and lower manufacturing cost. Figure 4 is a functional block diagram of the SEDSAT 1 Electrical Power System.
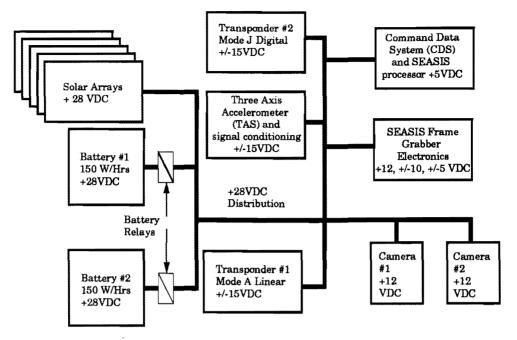
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Figure 3 *Electrical Power System Functional Block Diagram*

Electrical Power System Components

Following is a description of each of the major components of the SEDSAT 1 Advanced Power System (APS).

Solar Cells

The power for SEDSAT 1 will be supplied primarily by the Boeing/Kopin lightweight GaAs/CIS thin film tandem solar cells.[11] In addition, at least one facet of the satellite will incorporate the latest improved mechanically stacked (AlGaAs)GaAs/CIS cells. Both types of cells are mechanically stacked tandem cells consisting of GaAs thin-film (5 micron thick) top cells, or GaAs on AlGaAs CLEFT for the (AlGaAs)GaAs/CIS cells, and CuInSe$_2$ polycrystalline thin film (6 micron thick) bottom cells. A schematic of a GaAs/CIS tandem cell is shown in Figure 5.
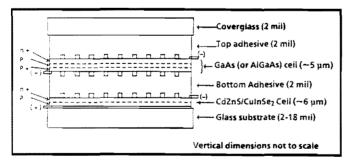

Figure 5 *Schematic of Boeing/Kopin Tandem Cell*

As indicated in Figure 6, the primary GaAs or (Al) top cell responds to the short wavelength portion of the solar spectrum, and transmits the longer wavelength portion onto the CuInSe$_2$ bottom cell which is responsive to the long wavelengths. To date, the GaAs/CIS design has resulted in a cell efficiency in testing to 23.1% AM0. Individually, top cell efficiencies of 20.6% and bottom cell efficiencies of 3.0% have been measured. These cells give promise of efficiencies of 24%. In addition, CY '91 IR&D work, replacing the GaAs material with AlGaAs, is yielding results promising efficiencies of over 26%. The efficiency of the (AlGaAs)GaAs/CIS cells will allow an >80% increase in

power delivered to the power bus when compared to the best available silicon technology, and even a 35% increase over traditional GaAs cell designs. A cell-coverglass specific power of over 400 W/kg has been demonstrated for (AlGaAs)GaAs/CIS.

The GaAs/CIS cells have also gone through a number of generic space qualification tests and have satisfied all of the standard requirements. The GaAs top cell is more radiation resistant than silicon cells and the CuInSe$_2$ bottom cell is almost impervious to radiation damage. Thus, the end-of-life performance of the tandem cell exceeds that of GaAs cells alone. Cost modeling of the current baseline cell fabrication process indicates that, due to material savings, increased efficiency and radiation resistance, the tandem cells will be more cost effective than either GaAs or GaAs/Ge cells.
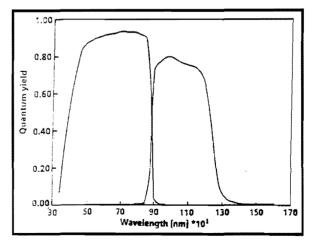

Figure 6 *Spectral Response of A Tandem Cell*

Solar Array Design

The cell design will be a voltage-matched, two-terminal configuration based on 2 cm x 4 cm cell area. The cell design will be optimized for SEDSAT 1 operational conditions. Boeing will build one side panel using

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(AlGaAs)GaAs/CIS, and GaAs/CIS thin film tandem cells on the other panels depending upon the progress of Boeing's internal IR&D work. A decision will be made whether to provide all (AlGaAs)GaAs/CIS prior to start of cell fabrication. The solar panel, made of solid aluminum plate, will contain high efficiency (AlGaAs)GaAs/CIS solar cells, bus terminals, and interconnect wiring. The solar panel will also contain an optical surface reflector to control thermal load.

Based on a 34cm x 34cm solar panel, whose array packing factor and multiplication factor for the spinning satellite will be up to 81% and 1.414 respectively, the projected powers of solar array are summarized in the table. As shown in the table, power outputs of 35.43 W, 38.65 W, and 41.87 W are projected for the Boeing/Kopen tandem cells with the efficiencies of 22%, 24%, and 26% at standard test conditions. This represents a significant increase (up to 73%) from the base-line power output of 24.15 W when conventional silicon Back Surface Field Reflector cells of 15% are used.

15% Silicon	24.12 Watts
22% GaAs/CIS	35.43 Watts
24% AlGaAs/CIS	38.65 Watts
26% AlGaAs/CIS	41.87 Watts

Table 1 *Comparative Efficiencies of cell types*

Batteries

The batteries to complement the advanced solar cells are the Ovonic Battery Co. sealed nickel-metal hydride (NiMH) cells now coming into use. These battery cells offer an energy density of twice that of conventional Nickel/Cadmium designs with no "memory" effect. By eliminating the memory effect, the operational complexities involved in reconditioning the batteries onboard satellites is eliminated. This decrease in operational complexity will allow the satellite to operate in a more autonomous manner than otherwise would be the case.

Also, Ovonics currently has a set of the NiMH batteries under life test that have demonstrated an accelerated life test of over 8,000 charge-discharge cycles at at a Depth of Discharge (DOD) of 30%. This indicates that these batteries are much more robust in reliability than their NiCad counterparts. Further testing will be undertaken at the Marshall Space Flight Center to characterize the cells, and operate them in a simulated SEDSAT 1 electrical power system. This increase in energy density, coupled with operational simplicity, and greater reliability, make these batteries ideal for the APS flight demonstration.

Power Conversion and Charge Control

The APS power components, coupled with high efficiency high reliability, DC-DC power conversion components from Interpoint, allows the SEDSAT 1 design team to build a distributed power system. These DC-DC converters offer power conversion efficiencies typically on the order of >80%, with an input voltage range of 16-40 Volts DC. These efficiencies, coupled with large input voltage tolerances, allows the SEDSAT 1 team to design a robust distributed power system that will allow the direct matching of the solar arrays to the battery system with no further regulation of the main power bus. This approach will allow SEDSAT 1 another benefit, which is to operate the satellite with a load side power management system. The onboard microprocessor will monitor voltages, currents, and temperatures of the batteries and other onboard systems.

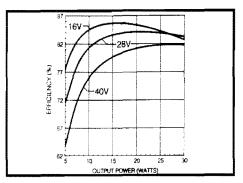Figure 7 illustrates DC-DC converter efficiency vs. line and load for the MTR 2815S converter.

Figure 7 *SEDSAT 1 typical DC-DC converter efficiency*

When the batteries are fully charged, after the satellite emerges from the night side, the CDS processor will divert the power going to the batteries from the arrays, in a linear fashion, to the experiments and the communications transponders. This will allow the satellite to operate at a near one hundred percent power factor utilization which has never been accomplished before according to engineers at NASA Marshall Space Flight Center. It is to be noted here that this approach will allow the complete elimination of hardware associated with a traditional satellite charge control system. We call this our Virtual Charge Control (VCC) system.

To implement the VCC, we will gather data from the ground based prototype power system, and manufacturers data regarding the voltage vs. temperature curves of the batteries and solar cells (V/T curves). These V/T curves will be stored in EE prom for to be referenced by the CDS system as part of the charge regulation system. Autonomously, the CDS will monitor the temperature of the batteries and solar cells and modify the charge rates accordingly. The charge control algorithm itself will be voltage based, with secondary input from the temperature sensors allowing optimum adjusting of the charge rate.

Ground Based Validation Testing

To support the preflight testing, as well as to validate the concept used for the SEDSAT 1 APS, a program of validation testing is being implemented. Testing will be carried out on a subsystem as well as at a system level for the individual NiMH cells, completed batteries, solar arrays, along with cell and battery telemetry, and for the VCC.

Solar Cells

The solar arrays delivered from Boeing will be tested at the Marshall Space Flight Center, at the array level, to characterize and verify operation as well as qualify the arrays for flight on SEDSAT 1. Several standard tests that are typically used for silicon technology will be applied to the Boeing/Kopin thin-film tandem cells.

Flash Test: Using Marshall's Large Area Pulsed Solar Simulator (LAPSS) the arrays will be measured for their voltage-current output characteristics at 28°c.

Vibrational Testing: The completed arrays and their mount, (a body panel of SEDSAT 1) will be vibration tested to 1.2 times the maximum specified loads for the Delta II. This will also qualify, them for shuttle due to the higher loads experienced on the Delta II.

Thermal Vacuum Cycle Testing: The arrays will be tested under space environmental conditions to validate, and qualify the structural and electrical integrity of the completed units.

Solar Cell Characterization: Using MSFC's thermal chamber, and a solar simulator, the voltage-current output of the arrays over the expected temperature range of operation will be measured. This information will be used in conjunction with the flash test data to predict the total solar array performance in the space environment.

Batteries

Parametric Testing: This testing will be done on a cell, as well as on a complete battery basis. This test will be conducted to determine the voltage-temperature characteristics of the cells, and complete battery, over the operational temperature range. This information will be input into the V/T model that will used by the VCC to determine optimum charge rates.

Environmental Testing: Tests to be conducted in this realm include battery overcharge testing, vibrational testing, and extreme temperature testing. These tests will be conducted in order to understand how this new cell and cell separator technology withstands launch environment, overcharge etc.

Life Testing: Ccompleted prototype batteries will be charged-discharged while running under simulated spacecraft loads. This testing will run from its start, through launch date and satellite life, and thereafter as desired.

Safety: Issues surrounding the safety of the batteries for spaceflight will be studied. Safety issues studied will be oriented toward shuttle qualification to support a SEDSAT 1 alternate deployment from the shuttle via the "GAS Program".

Power Conversion and Charge Control

To support the validation of the power conversion and VCC approach, a prototype of the entire electrical power system will be constructed. This will be done at Marshall Space Flight Center Electronics System Lab. In this prototype the CDS processor, distributed power bus, DC-DC converters, and simulated loads will be constructed. Also, the software for the VCC will be implemented, tested, and validated previous to flight. The simulated loads will have the ability to be commanded to various power levels in order to validate the load side power management hardware portion of the VCC. Any changes necessitated based on test information will be implemented, and the entire system will be built into the prototype structure of the satellite to verify form and fit.

APS Operational Scenario

After launch, and the tether deployment of SEDSAT 1 into its permanent orbit, the APS demonstration will commence. Up to 116 analog telemetry channels will be dedicated to the accurate characterization of the various components of the electrical power system. This telemetry information will be used primarily by the power system itself to optimize the operation of the VCC. The telemetry from the batteries, solar arrays and electronic systems will be sent down as normal engineering telemetry.

The operational lifetime of SEDSAT 1 , is projected to be up to five years; however, the orbit lifetime of the satellite will be much longer. Information about solar array degradation and battery deterioration will be plotted versus time throughout the lifetime of the satellite.

At the inclination of SEDSAT 1's orbit, i.e. 38-39°, the satellite will experience some unusual combinations of sun-shade times. With a maximum of 33% shade and a minimum of 8%, the satellite will give the elements of the power system a wide range of solar input to respond to. The transponders will be able to be commanded to very high power levels relative to the size of SEDSAT 1 in its low orbit. At times, levels of up to 20 watts input will be commanded to obtain deep depth-of-discharge rates on the batteries. Other variations in power utilization through running the experiments for varying amounts of time will be used in order to fully test the VCC software in compensating for various operating conditions.

Conclusions

The SEDSAT 1 Advanced Photovoltaic Power Demonstration Flight will be of great interest to any designer of flight power systems. This demonstration of the new design strategies and technologies incorporated into SEDSAT 1 overcomes many of the inherent limitations involved in low cost small satellites. The flight demonstration of new technologies and design methodologies such as those incorporated into SEDSAT 1 will open the door for new applications of advanced electronics for small satellites. Small satellites and their applications are still in their infancy, any design improvement that can be applied to the entire genre will help the industry to grow in the perhaps the same manner as the introduction of microprocessors and other high integration IC's fueled the explosive growth in the use and applications of microcomputers.

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