

Thermal Management Integration Using Plug-and Play Variable Emissivity Devices

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ABSTRACT

The performance of mission-critical components and systems within spacecraft and satellites requires the ability to control the local thermal environment. Under conditions of relatively constant component and system loading, this would involve radiative dissipation of both internally and externally generated heat loads and altering thermal balances to provide heating where necessary. As the local thermal load changes with component use, the need arises to alter the heat transfer rates and dissipation within the spacecraft. It is also desirable to be able to evaluate, reconfigure or repair space-based thermal control systems using only ground station commands. These needs can be met using a Plug-and-Play variable emittance control system where operational analysis and reconfiguration is accomplished via an improved Universal Serial Bus (USB) or space-wire controlled architecture.

This paper presents a modular, USB/space-wire-driven thermal control system using a solid state thin-film infrared variable emittance device (EclipseVED™) from Eclipse Energy Systems, Inc. The paper discusses critical issues including connectivity, device control scale-up for the advancement of an integrated variable emittance system, comparison of device weight to other variable emittance systems, the capacity to replace or repair devices in-flight, the survivability of the system in space and the importance of individual device control.

I. INTRODUCTION

Typically, the design and configuration of a small satellite is a two or three year process, with each component optimized for the specific mission. Defense planners and executives hope to be able to drastically reduce this time and provide mission-specific satellite support by being able to configure and launch a satellite having responsive capabilities to a designated orbit within days of the recognition of an actionable need. This is one of the goals of the “Plan for Operationally Responsive Space”. Operationally Responsive Space (ORS) has been defined within the U.S. Department of Defense as “assured space power focused on timely satisfaction of Joint Force Commanders’ needs.” The requirements of this approach extend all the way from power generation to spacecraft thermal control to electro-optical imaging and analysis. One of the goals of Operationally Responsive Space is to reduce the time required for satellite design and development through the systematic integration of operational systems in a plug-and-play architecture.

The need for robust, modular and scalable next generation satellite thermal control systems is discussed in Ref. 1 where three main responsive system architectures were delineated. These included an isothermal architecture with high thermal conductivity inserts capable of achieving a consistent thermal state across the entire satellite. A second thermal isolation approach treated each sub-system separately with its own radiator and temperature control apparatus. In the third approach, variable heat transfer is used to achieve the desired operating conditions. Variable emissivity (VE) surfaces are a subset of the variable heat transfer approach.

Space-compatible VE technologies include macrolouvers, microelectromechanical systems (MEMS)-based approaches, micro-chemical techniques and those based on the change in absorption or transmission of a thin layer. Each VE approach has its individual strengths and weaknesses. Macrolouvers^{2,3} are generally too bulky for small satellites and require energy intensive actuation. With the emergence of MEMS technologies, microlouvers became available⁴.

A MEMS Variable Emittance device was flown aboard the Space Technology 5 (ST5) satellite providing a change of emittance of 0.03 while in orbit. The theoretical maximum emittance range is 0.40, based upon the configuration of the microlouver and the use of a five-layer polycrystalline silicon manufacturing process currently in place at Sandia National Laboratory (NASA Goddard Space Flight Center, US Patent 6538796). When the microlouver is closed, a reflective metal surface is exposed. Opening the microlouver exposes an emissive silicon surface. The performance is limited by the difference in emissivity between the metal and silicon surfaces and the fraction of the total surface where the change in emittance takes place. The need for a protective polymeric coating over the radiator may also limit the performance of the device.

MEMS technology has also been used by Sensortex, Inc. to develop an electrostatically-switched radiator, (ESR)^{5,6}. Here, a high emissivity cover film is attracted to the radiator surface by electrostatic forces. When in contact, the thermal conductivity across the radiator-film interface is high and the surface exhibits high radiative heat transfer. When released, the thermal conductivity across the radiator-film interface is negligible, causing the film to radiate to space at a much lower temperature. This technology has been in development for some time with results approaching a change of emittance of 0.80 under laboratory conditions. The efficiency of this process may be limited as ionizing radiation may cause the cover film (membrane) to stick to the satellite surface⁷.

A novel MEMS-based approach is described in Ref. 8. The approach relies upon the use of electrowetting, applying a surface potential to alter the wetting characteristics of a substrate, to change the shape and size of conductive liquid droplets separating the satellite surface from high emissivity surface (Figure 1).

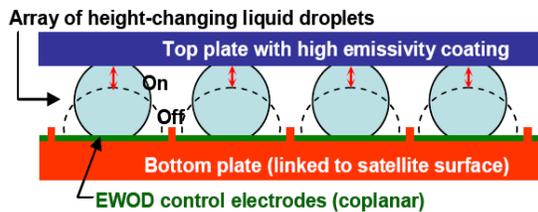


Figure 1. Variable Emittance Approach Proposed in Ref. 8

Variable emittance approaches involving changes in absorption or reflection of infrared radiation have been developed for use with small satellites. The Smart Radiation Device (SRD) supported by the European

Space Agency is based on the change in infrared emissivity accompanying a metal-to-insulator transition in the lanthanum strontium manganate and lanthanum calcium manganate material systems⁹. The total spectral emissivity can be altered from 0.25 to 0.75 accompanying a change in temperature from 175 K to 375 K. The SRD approach is being considered by the European Space Authority as a means of satellite thermal control. Other materials that undergo a metal-insulator transition that affects infrared emissivity include the vanadium oxides¹⁰ (Paradis, Laou, and Alain, 2007). Another fluidic technology is the reversible electrodeposition infrared modulator originally addressed by McDonnell Douglas (US Patent 5774255) and Rockwell Scientific (US Patents 6,798,556 7,022,210) and later described in Ref. 11. This approach involves the reversible electrochemical transfer of metal (copper) from a working electrode to a counter electrode. The maximum emittance modulation was reported to be 0.32 with a decrease in modulation depth of 15% after 300 cycles.

Electrochromic approaches to VE systems have advantages in terms of long-term stability in the space environment and amenability to redundant configurations through multiple layered devices and individual pixel control. Issues of system stability under oxidizing conditions need to be addressed prior to the use of polymer-based electrochromic systems of the sort described in Ref. 12. Eclipse, under the direction of Hulya Demiryont has been actively working on its All Solid State Variable Emittance Electrochromic Device (EclipseVEDTM) technology^{13,14} for several years now. The EclipseVEDTM technology has an aerial density of 180g/m² when deposited on 5 mil thick poly(ethylene terephthalate) substrate, not including buss wiring and can provide change in emittance in excess of 0.80 with no moving parts^{15, 16}. In addition, no working liquids are required as in the case of reversible electrochemical deposition or electrowetting technologies.

II. ECLIPSE VEDTM SYSTEM

The morphology of the layers comprising the EclipseVEDTM is controlled during fabrication to produce a system exhibiting a wide range of infrared emissivity under low external voltage conditions. A simple illustration of an EclipseVEDTM is shown in Figure 2. The modulation of the emittance occurs upon the injection and removal of ions from the two active layers, which change their optical properties. The primary components of the thin film emittance device include the IR transmissive or reflective electrodes and

the active layer system. The structure of EclipseVED™ exhibits the following properties:

- Electrode 1 (the bottom electrode) is an electrically conductive and optically reflective mirror film.
- Electrode 2 (the top electrode) is an electrically conductive, but optically IR transparent film.
- The bleached mode of the EclipseVED™ is its reflective mode.
- The colored mode of the EclipseVED™ is its absorbing, non-reflective mode which exhibits high emittance.
- In the bleached mode, all layers of the active element are non-absorbing in the IR region and exhibit low emittance.

Space

| |
|------------------------------------|
| IR Transmissive “Window” Electrode |
| Active Layer 1 (EC) |
| Electrolyte (IC) |
| Active Layer 2 (IS) |
| IR Reflective Mirror Electrode |
| Satellite or Substrate Surface |

Figure 1. Eclipse Variable Emittance Device (EclipseVED™) with the active element composed of Ion Storage (IS), Ion Conductor (IC), and Electrochromic (EC) layers sandwiched between an IR transparent electrode and an IR reflective mirror electrode.

III. RESULTS AND DISCUSSION

Figure 3 shows the performance of the EclipseVED™ as it is cycled from bleached to colored modes.

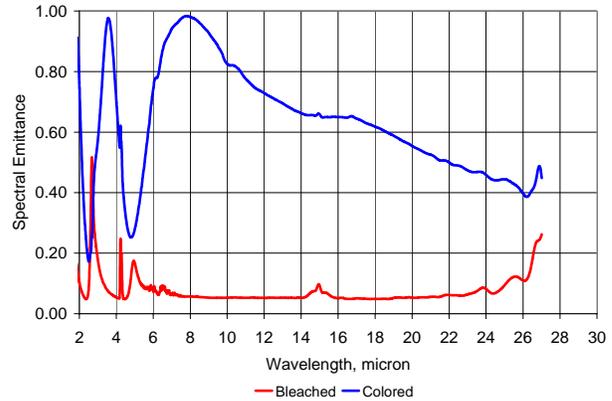


Figure 3. Spectral Emittance of EclipseVED™: The average bleached emissivity is 0.06 and the average colored emissivity is over 0.77

An EclipseVED™ system capable of modularization for Plug-and-Play integration was recently demonstrated by Eclipse Energy Systems, Inc. This unit was flown aboard the Midshipman Space Technology Applications Research (MidSTAR-1) Satellite launched March 9, 2007 (Figure 4). The flight testing has been successful with emittance changes successfully demonstrated on orbit (Figure 5).



Figure 4. MidSTAR-1 Heat Dissipation Test Module with High Emittance (black), Low Emittance (gold) and two VED devices fully integrated.

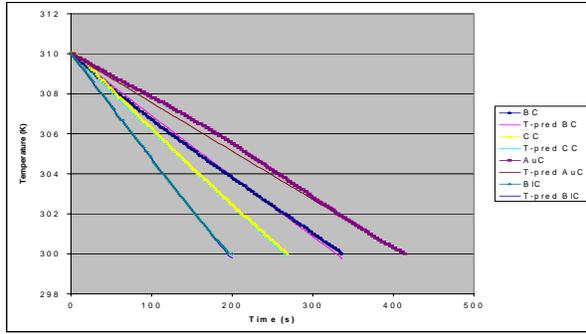


Figure 5. Results of the MidSTAR1 experiment to measure heat dissipation rates of colored and bleached EclipseVED™ devices are shown. Reference gold plate and black surface present low- (emissivity=1) and high-e surfaces respectively.

From figure 5, it can be seen that the gold plate has the slowest heat dissipation and the black the fastest. The heat dissipation rate of the colored EclipseVED™ is closer to that of the black surface and the heat dissipation rate of the bleached EclipseVED™ is closer to that of the gold surface.

This demonstrates the EclipseVED™ devices function in the space-based conditions and were remotely controlled from the earth.

In a SBIR program for the U.S. Air Force, the MidSTAR-1 system was reconfigured for USB control and the number of devices simultaneously controllable was expanded to 8 per controller module. The unit connects directly to a standard PC USB port, receives DC power from the port and communicates with the host over the USB serial bus. In addition, the controller software is being tailored to detect the characteristics of each panel and sub-component and compensate for any loss by monitoring the current across the samples. In the simplest form, if the current is zero the device is not detected (offline) and if a short is detected, then the device is considered damaged. In addition, the system will be integrated directly onto a satellite panel and size and surface area covered maximized for maximum control and or emittance modulation. The specifics of the needs for the configuration, device size, and sub-paneling structure (Figure 5) will be discussed.

A third generation of the EclipseVED™ system is now being implemented and will further minimize the size and weight of the controller and VEDs while improving the ease of installation. The control bus structure for the Plug and Play satellite has evolved from USB to an adaptation of SpaceWire, and so the new controller has been adapted to accept this data path. The preferred method of SpaceWire bus connection is through the

program-developed ASIM (Applique Sensor Interface Module). Eclipse has duplicated the circuitry of the standard ASIM directly on the main controller PCB to reduce the overall height of the PCB and eliminate connectors. Since the circuitry is identical to the stock ASIM, any software improvements to the interface can be incorporated in the ASIM function without modification.

The analog portions of the controller incorporate a new VED drive system that improves power efficiency and provides additional redundancy and circuit reliability. This drive module is able to simultaneously drive eight VEDs and is also able to supply the increased surge currents associated with increased area VEDs. The current being supplied to each VED can be independently monitored and this data can be used to evaluate the charge storage and health of each connected VED.

Previous versions of the system fastened the VEDs directly to rigid panels that were then thermally coupled by mechanical fasteners to the spacecraft structure. While capable of excellent thermal performance, this concept did not lend itself to fast reconfiguration. The third generation EclipseVED™ system introduces the concept of peel and stick thermal radiators. Since the outer surface shape of the Plug and Play satellite is unknown until configuration and for small satellites there may or may not be spin stabilization, it is imperative that any thermal control structure be adaptable to any flight configuration. The EclipseVED™ system achieves this by supplying a variety of different VED tile sizes that can be tessellated onto any available flat or 2D curved surfaces. These tiles will be supplied with a pressure sensitive adhesive backing and can be applied in a manner similar to a Kapton foil heater.

A key factor in allowing the use of VEDs on non-rigid substrates is the use of a robust method of making electrical connections. The vacuum deposited VED conductive layers are extremely thin and thus subject to damage from excessive mechanical stress. Previous generations of devices employed a set of redundant mechanical finger contacts. These fingers were attached to the same rigid substrate as the VED, preventing any relative motion. While this method worked well, it consumed a significant portion of the available thermal transfer area and was unsuited for use in a flexing structure.

These contacts are being replaced with an alternate contact system using a small epoxy-glass printed circuit board mounted to the VED substrate for mechanical strain relief. The outgoing lead wires or connector is

attached to the PCB to transfer mechanical stresses to the device substrate, while a thin metallic ribbon is soldered to the PCB contacts and the other end is thermally bonded to the VED electrodes. The bonding is accomplished using a conductive epoxy tape normally used for bonding leads to liquid crystal displays. The electrical connection is made by a large number of silvered plastic particles in the tape that are squeezed into contact between the metallic ribbon and the VED while the epoxy cures under heat. The large number of particles makes a highly redundant connection while the particle's compliance prevents damage to the thin VED layers.

The VED tiles are applied to the spacecraft by first selecting the combination of tile sizes that will most fully cover the available surfaces. Installation consists of peeling the protective backing from the pressure sensitive adhesive rear coating and laying the VED down starting along one edge or corner. Once the device is attached, any remaining air bubbles are rolled out using a soft rubber brayer.

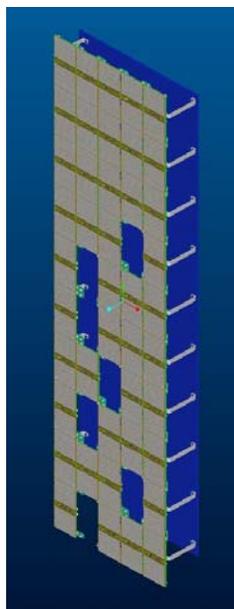


Figure 6. Example of tiled variable emittance devices, forming an interconnected panel. Holes demonstrate cutouts for components.

While the tiles are applied to the spacecraft surface, small wire assemblies connect the VEDs to a controller module. Upon the application of power, the controller will test each output port for the presence of a VED, assess the area of the attached device(s) by measuring the device charge storage, and configure itself to provide appropriate control and telemetry. Since each VED module can also contain a precision temperature measurement device, the controller can provide

autonomous thermal control if desired or provide thermal data to the main spacecraft controller via the SpaceWire bus for external control.

If the control system detects a change in VED electrical characteristics, the condition can be reported via SpaceWire to the spacecraft controller and the device can either be disabled or a repair attempted. For a repair, the device is briefly driven with abnormally high voltages in an attempt to thermally disconnect an insulation fault, similar to the self-healing properties of some film capacitors. If the repair is successful and current returns to normal, the device is placed back in service.

Another component of thermal control in the presence of the sun is the reduction of absorption of a heat gain mechanism. The requirements on the EclipseVED™ to accomplish this and how in-sun thermal control will be integrated into the final system is a critical component for the future. This is particularly important to small satellites who do not have as large a heat sink area to dissipate excess heat from during in-the-sun conditions. In-sun control can currently be an issue as the high amount of heat energy gained through absorption of solar energy can offset any cooling done in the room temperature emittance range of the devices. To offset this, Eclipse has tailored a cold mirror. Cold mirrors are thin films coatings capable of transmitting IR energy, generally above 1-2.5 microns, and reflecting energy in the visible and NIR (Figure 7).

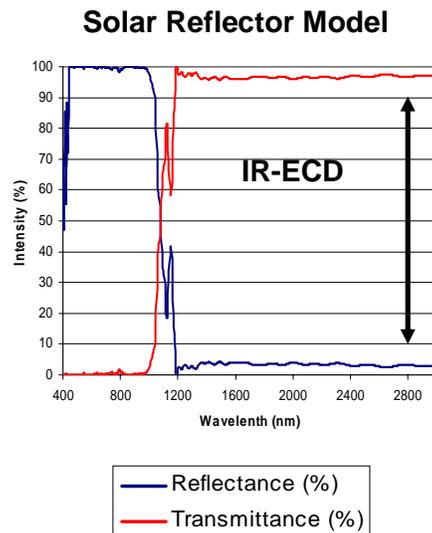


Figure 6. Example solar reflector cold mirror.

Initial work on cold mirrors will include a separate IR transparent substrate on which they are deposited. However for the realization of cold mirrors on small

satellite spacecraft, these devices will eventually be incorporated on the top of the EclipseVED™ stack. Once this final component is integrated, the total devices will be ready for use as active radiator components on small and plug and play based satellites.

IV. CONCLUSIONS

The Eclipse Plug-and-Play VED Thermal Control System (EclipsePET™) has the following capabilities:

- Rapid panel swapping capability with individual interchangeable panels/components which can be sizably increased, reduced or swapped out, and evaluation of system operational status via integrated system checks.
- The ability to actively modulate the emittance of each panel or sub-panel of the satellite to different emittance configurations, turning the skin of the satellite into a thermal management radiator capable of handling different heat loads adjustable during space operations.
- Identification of damaged panels and attempted self-repair of individual EclipseVED™ cells.
- Allow complex panel geometries while retaining control of the emittance modulation. Individual components can be cut or damaged and still function.
- Achieve dramatic weight savings by direct application of the EclipseVED™ to the satellite outer panels.

A critical requirement in the optimization of the technology is the resolution of undefined requirements. As the final tailored system is being realized, it is important to understand which factors are most important and when factors compete, what is the most effective method of maximizing the total system for satellite use. This paper discussed current requirements and compliance of the EclipseVED™ system, discussed the current state of the art through MidSTAR-1 results, and forecast the path to an integrated variable emittance thermal control system.

Acknowledgments

Eclipse Energy System, Inc. greatly appreciates the United States Air Force Research Laboratory for funding this project under contract FA9453-06-M-0176. The authors also would like to thank Dr. Billy Smith and the Naval Academy for their diligent efforts to realize the MidSTAR satellite project and make it a success.

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