

# Design and Development of an Equipotential Voltage Reference (Grounding) System for a Low-Cost Rapid-Development Modular Spacecraft Architecture

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**Abstract**—This work describes the design and development effort to adapt rapid-development space hardware by creating a ground system using solutions of low complexity, mass, & cost. The Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft is based on the modular common spacecraft bus architecture developed at NASA Ames Research Center. The challenge was building upon the existing modular common bus design and development work and improving the LADEE spacecraft design by adding an Equipotential Voltage Reference (EVeR) system, commonly referred to as a ground system. This would aid LADEE in meeting Electromagnetic Environmental Effects (E3) requirements, thereby making the spacecraft more compatible with itself and its space environment. The methods used to adapt existing hardware are presented, including provisions which may be used on future spacecraft.

## I. INTRODUCTION

The Lunar Atmosphere and Dust Environment Explorer (LADEE) is designed to characterize the lunar atmosphere and dust environment from orbit. The scientific objectives of the mission are: 1) Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity; and 2) Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy. Further objectives are to determine the cause of Apollo astronaut sightings of diffuse emission at tens of kilometers above the surface, and to document the dust impactor environment, and to help guide design engineering for future missions.[1]-[2]

The orbiter will carry a neutral mass spectrometer, an ultraviolet/visible spectrometer, and a dust detector. There is also a technology demonstration, the Lunar laser Communication Demonstration [3], which is an experiment to provide the proof-of-concept test for laser-based communications from lunar orbit.

## II. THE MODULAR COMMON BUS ARCHITECTURE AND LADEE SPACECRAFT DESIGN OVERVIEW

The Modular Common Bus Architecture developed by NASA Ames Research Center (Ames) is a design philosophy which develops capability-based spacecraft from readily available off the shelf components in a “Plug and play” manner. By developing modules over time, capabilities can be established enabling new missions to be available to researchers which build off previous design efforts. Examples of the modular concept and vehicles types which are proposed for the future are shown in Figure 1. [4]



Fig. 1. The Modular Common Bus Concept

The LADEE spacecraft bus design, derived from the Modular Common Spacecraft Bus architecture, is a small, low-cost spacecraft designed to deliver scientifically and technically useful payloads to a variety of locations including lunar orbit. The spacecraft is a modular bus design that can be

configured for a variety of mission objectives. Figure 2 shows the spacecraft bus in the LADEE configuration, with the instruments attached



Fig. 2. The LADEE Lunar Orbiter

The spacecraft bus is a lightweight carbon composite structure designed for ease of manufacturing and assembly. The modular design also allows parallel development, assembly, and test of modules.

For LADEE, the spacecraft bus modules consist of: (1) the Radiator Module, which carries the avionics, electrical system, and attitude sensors, (2) the Bus Module, (3) the Payload Module, which carries the two largest instruments, (4) the Extension Modules, which house the propulsion system, and (5) the Propulsion Module. The bus design is shown schematically in Figure 3.

### III. FUNCTIONS SERVED BY AN EQUIPOTENTIAL VOLTAGE REFERENCE SYSTEM IN A SPACECRAFT.

There are four major functions served by the a spacecraft Equipotential Voltage Reference (EVeR) system; to provide a return path for currents in the power system, to provide a voltage reference for avionics, to provide a system to safely collect and distribute accumulated charge, and to serve as a safety system to shunt fault currents away from personnel and equipment. (Note: Some might refer to the EVeR system as the spacecraft's ground system, following a naming convention that dates back to Benjamin Franklin's experiments with lightning and rods driven into Earth's soil, or ground [5]. However with planet Earth a considerable distance away and completely unconnected electrically to the spacecraft by any means; "ground" is a most inappropriate

term to describe the EVeR system's purpose or function. That is the source of the acronym "EVeR", because "One should not EVeR call it a ground system")



Fig. 3. LADEE Bus Modules

The primary power system consists of two halves; the primary high side in which currents flow from a power source, and a primary return side in which currents return to the source. The primary power high and return sides are both isolated from spacecraft structure, preventing the structure from being an intentional carrier of current. The power system's return side is joined to the structure at a single point, referred to as "Single Point Ground" (SPG). The SPG is also the central point of the EVeR system, which provides the power system a reference so it does not "Float" from the spacecraft structure or the chassis of assemblies mounted to the spacecraft. [6]

The EVeR system provides a common voltage reference that is critical to ensuring proper interoperability of avionics boxes. It does this by providing a low impedance path across the structure between assemblies and the SPG. It also provides the voltage reference interface to the ground support equipment, test facilities, and launch vehicle ground reference. Without an established common voltage reference, circuit interfaces may not function as designed between boxes and assemblies.

Space contains with many sources of charge including ambient plasmas, charged radiation belts, solar wind, etc. These sources can result in two types of charging on a

spacecraft; surface charging and deep charging. Surface charging is charge deposited directly on upon spacecraft surfaces directly exposed to space, typically from low-energy particles (<50 MeV). Deep Charging, also known as bulk charging or deep penetration charging, results when high energy electrons and ions (>50 MeV) penetrate the outermost layers of a spacecraft then impact metal surfaces, depositing charge when they impact metal internal to the system.[7] Left unchecked charge from both these phenomena can build up until it reaches the discharge voltage point. The resulting discharge can upset or damage spacecraft systems. To prevent that from happening, the EVeR system provides a path to equalize the charge distribution across the spacecraft, preventing differential charge buildup from affecting systems and precluding breakdown events.

Every spacecraft is surrounded by personnel during its assembly, test, and launch operations phases. There is an absolute need to provide for the safety of the individuals performing these activities by providing a path for any fault currents to flow safely. Any fault current will travel from the fault location through the low impedance vehicle structure to the facility ground, thus minimizing the possibility the currents might pass through and harm personnel. As a secondary concern, it is desirable to limit the extent of structural, avionics, support equipment, and facility damage from a fault event. Providing a low impedance path for the flow of fault current limits the extent of damage, enabling a program to repair or replace affected components instead of replacing an entire spacecraft

#### IV. DESIGN GOALS AND CONSTRAINTS

The following design goals and constraints were used to develop the LADEE EVeR system. First the system had to meet all mission needs & requirements. The approach had to adapt to the existing modular common bus design, manufacturing, test flows, and philosophy, including allowing individual modules to be assembled and tested separately, then joined. Like most space missions it was necessary to minimize the impact of mass, cost, complexity, and to ease integration, assembly test and launch operations. The design had to be able to grow for future adaptations beyond LADEE so that future modular common bus architecture variants could build upon the LADEE EVeR system design. Due to the fact extensive design and development effort had already been made, the approach had to adapt to the existing Modular Common Bus Concept designs & philosophy.

To accomplish these goals the program's Electromagnetics Environmental Effects (E3) engineer and structural design engineer worked together closely to design, develop, and implement solutions acceptable to each other and the spacecraft community as a whole. The design team leveraged off past experience of NASA and commercial space missions, benefiting from previous publications, handbooks, test data, & analyses.

In keeping with the goals and philosophy above, it was deemed beneficial to have each module contain a complete self-contained EVeR system for its own use. This would allow individual modules to be assembled and tested separately, then joined. To facilitate final assembly and test the system was designed such that joining modules of the common bus module architecture would automatically link the EVeR of each module into the spacecraft-level EVeR system. The EVeR system was designed to be able to grow for future Modular Common Bus adaptations beyond LADEE so that single module craft, multi-module craft, landers, and variants not yet dreamed of could build upon this concept.

#### V. DESCRIPTION OF DESIGN

To address the multiple functions performed by the EVeR system, there are several facets within the system, including; the electrical power grounding system, the fault current protection system, the equipotential voltage reference plane, the structural grounding system, and the charge control & distribution system. Thus the parts of the design overlap and play multiple roles. For example, the charge control & distribution system also carries fault currents, and serves as the equipotential reference at the same time. For simplicity, we'll describe the EVeRS system in just two ways; 1) the primary electrical power ground system and 2) the structural grounding system

It was useful to break the EVeR system into zones, and develop impedance levels to meet the need in each of the zones. There are two levels of bonding defined in the EVeR system, described using terms that originated on MIL-B-5087 [8] as Class S and Class R. Class S (For static) bonding was used for areas in which the bleed off of accumulated charge was the only concern, with a bond impedance of 10 Ohms or less being sufficient to preclude buildup and discharge of any accumulated charge. Class R (for Radio Frequency) bonding of 2.5 Milliohms or less was used for all avionics assembly bonds, all module-to-module bonds, all solar array to module bonds, the SPG, and all major structural paths leading back to the SPG.

It was also useful to zone the system further in the Class S category by source of charging. The entire spacecraft surface directly exposed to the space environment had to control surface resistivity to allow charge to flow readily into and throughout of the EVeR system. No control of surface resistivity is required internal to the spacecraft, however the metallic items internal to the spacecraft must be tied to the EVeR system with a class S bond due to deep charging. [9]

The EVeR system is best described by describing its elements; the electrical power system, the bond strap, the radiator/SPG, the composite modules and panels, composite panel inserts, the small isolated metallic parts, the solar arrays, and the propulsion system

### A. Electrical Power System (EPS) Grounding

The LADEE electrical power system was designed using the Single Point Ground (PPG) approach. [6] In this approach the primary power return lines are isolated from the structure at all points except one, The SPG. Structure is not used as an intentional current-carrying conductor for primary or secondary power.

One of the radiator mounted assemblies, the Integrated Avionics Unit (IAU) performs the Command and Data Handling (C&DH) functions as well as the Electrical Power System (EPS) functions. Internal to the IAU resides the Solar Array Charging Interface (SACI) card, which contains the single point at which the electrical power system is joined to the structure; the Single Point Ground (SPG). All other avionics on LADEE have their primary returns isolated from structure

LADEE secondary power was isolated from primary power. Secondary power also followed the SPG concept for each circuit, with each secondary circuit tied to structure in just one location. Secondary power returns did not need to be tied to structure at the same location as the primary power SPG.

### B. The Bond Strap

The bond strap is the lowest level element for joining parts of the EVeR system. The bond strap design is a lightweight hybrid design of aluminum foil wrapped over Mylar. The foil provides conductivity with minimal metal mass, and the Mylar provides mechanical strength. A thin layer of metal foil is sufficient since current flows on surface of metals, thus the center material need not be conductive. This allows one to maximize surface area, minimize impedance, & minimize mass with a flat strap that saves mass. The front and back sides of the strap are a single piece of foil wrapped once around the Mylar with a fold line that runs the length of the strap. This provides a low-impedance from front to back sides of the strap. A 5:1 length-to-width ratio is used to insure the strap has low inductance from one end to the other. This same design used throughout the LADEE EVeR system. While it may vary in length to meet special needs, the 5:1 ratio always met. Throughout the system redundant bond straps are utilized to make the system one fault tolerant and to reduce impedance via parallel paths

### C. Radiator/SPG

The radiator panel at the top of LADEE is a large single piece of aluminum that serves as the mounting point for multiple electronics assemblies. Assemblies structurally mounted to the radiator are electrically bonded to the radiator via redundant bond straps. The radiator itself is electrically bonded to its adjacent module's EVeR system via a series of parallel bond straps. The remainder of the structure is bonded to the radiator through the rest of the spacecraft's EVeR system as described in the sections below.

As mentioned previously one of the radiator mounted assemblies, the IAU and its SACI card, contains the single point at which the electrical power system is joined to the structure; the Single Point Ground (SPG).

### D. Composite Modules and Panels

The spacecraft body is composed of interconnected carbon composite modules. Some of the modules contain a Cruciform (crossbeams) and additional internal panels. While carbon is conductive, carbon composite exhibits a more complex behavior due to the nonconductive resin used to bind the fibers. Depending upon the tooling used, surfaces can be insulative or semiconductive making them unsuitable for a Class R or S bond. Due to the resistive nature of carbon composites have limited current carrying capacity before becoming degraded. [10] These properties make untreated carbon fiber unsuitable for use as a reference path.

The LADEE solution is to provide a thin layer of foil to serve as a low impedance path across the composite panel surface in places where a reference path is needed or where low surface conductivity for charge control is necessary. While it would have been possible to co-cure the foil in the layup of the composite structure, NASA Ames had invested a lot of previous effort into the common modular bus and did not wish to alter composite manufacturing processes and tooling. The EVeR system had to be added to composites post-cure. For this reason, thin layers of aluminum foil are adhesively bonded to the composite after curing using a structurally strong, nonconductive adhesive. Handling needs force the foil to be applied in sections, so bond straps are used to bridge between foiled sections.

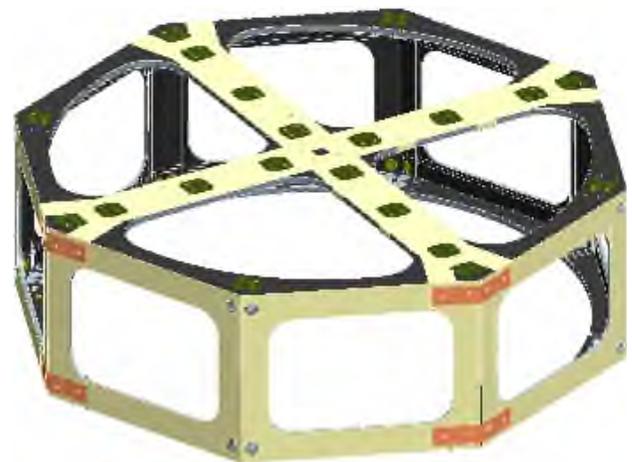


Fig. 3. LADEE Bus Module Showing EVeR System Panel Foiling, Cruciform Foiling, and Bond Straps

Modules can be hollow, or contain crossbeams and internal panels. In both cases, the exterior surface is foiled, but the internal surface is not. Due to the fact the foils is being added post-cure of the composite, it must be added in sections. Thus two faces of module are foiled at a time, and electrically

bonded to the adjacent face sheets via bond straps. For modules with a cruciform, the cruciform foil is extended and folded upon itself to form an integral bond strap to the face sheets. Thus each module has a complete self contained EVeR system, as shown in Figure 3. Avionics can be mounted and tested in modules, allowing for parallel assembly and test in a flight configuration. Once assembled and checked out modules can be mechanically and electrically joined together without disturbing a module's individual EVeR system connections.

Provisions for interfacing with the solar panel ground straps are built into each module, allowing the panels to be placed on or taken off the spacecraft at any time. This is especially important because all solar panels act as access doors to the interior of the spacecraft.

#### E. Composite Panel Inserts : Structural and Grounding

There are two type of inserts in the LADEE composite panels; structural and conductive. Structural inserts, intended to carry mechanical loads, are adhesively bonded into the panels utilizing high strength epoxy that is an electrical insulator. Conductive inserts are adhesively bonded with a conductive epoxy that lacks mechanical strength, and can not carry significant mechanical loads. Both types of inserts may extend above the composite surface, and are not necessarily flush mounted. Items mechanically joined to inserts float above panel surfaces, isolated electrically from them and any foil on the surface. For this reason, a means of joining items mounted on inserts to the EVeR system is required. This is accomplished by the use of a bond strap and a series of flat "Fender" washers to shim any gaps and hold the strap in compression to the foiled surface

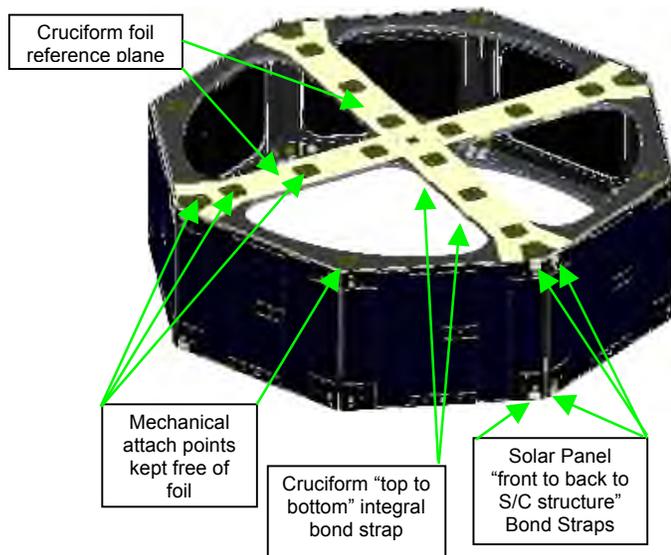


Fig. 4. LADEE Bus Module Showing EVeRs Solar Array Bond Straps and Cruciform Foiling

#### F. Small Isolated Metallic Parts

Every spacecraft is filled with an assortment of metallic odds and ends, ranging from clips to hold wire harness ties to support brackets providing strain relief. Some small metallic parts mounted internal to the spacecraft had no easy path to the EVeR system. For these small elements the surface of the composite will be prepped by lightly scuff-sanding the surface to expose carbon fiber, then a small amount of conductive epoxy applied to provide a path between the part and the composite surface.

#### G. Solar Array Panel Grounding

Each solar array panel has redundant EVeR system attach points at all four corners. As mentioned previously, each module's attach point has built in EVeR attach points for the solar panels. The act of mechanically attaching a solar panel to the spacecraft automatically ties it into the EVeR system, a process less complicated than making the actual power connections to each panel. Installed solar panels and their attachment to a Modules EVeR system is shown in Figure 4.

#### H. Propulsion System Grounding

The majority of the propulsion system is interconnected via a series of welded connections, insuring low impedance across the system. These portions of the propulsion system only require a class S bond. If measurements show they fail to reach Class S, they will be tied into the system using the same method as other tiny internal parts. The Control Avionics boxes for the Propulsion system are Class R bonded, using the same methods used on the modules. Foil will line the composite panel the boxes are mounted upon, and this will be tied into the rest of the EVeR system via bond straps

### VI. JOINING MODULES INTO A SPACECRAFT

Modules are joined to each other using bond straps. The bond strap attach points are different from the structural attach points. This prevents the bond straps from experiencing excessive mechanical loads, and allows the use of existing structural design analyses and test data. It also allows for replacement of any bond strap without affecting the structural assembly, useful in the event a repair or replacement is required. Bond straps are not only redundant, but also paralleled multiple times across the module-to-module interface to lower impedance between modules. An overview of the EVeR system showing only the foiled surfaces and bond straps is shown in Figure 5, not that this level of the design is still being worked may change.

### VII. TESTING TO DATE

Test coupons of composite panels and prototype bond straps have been built and tested with acceptable electrical bonding results. This has given the team great confidence going forward, since the entire EVeR system is built upon these two simple concepts. However early vacuum tests on coupons have shown a need to perforate the foil to prevent trapped gasses from expanding and de-bonding the foil from the

composite. This will be accomplished by perforating the foil in a periodic pattern that will limit trapped gasses to a small area, which will then readily vent during ascent without detrimental de-bonding. This step could have been avoided by co-curing the foil in the composite layup, however it was a ground rule that the EVer system be an “add –on” system for the LADEE spacecraft.

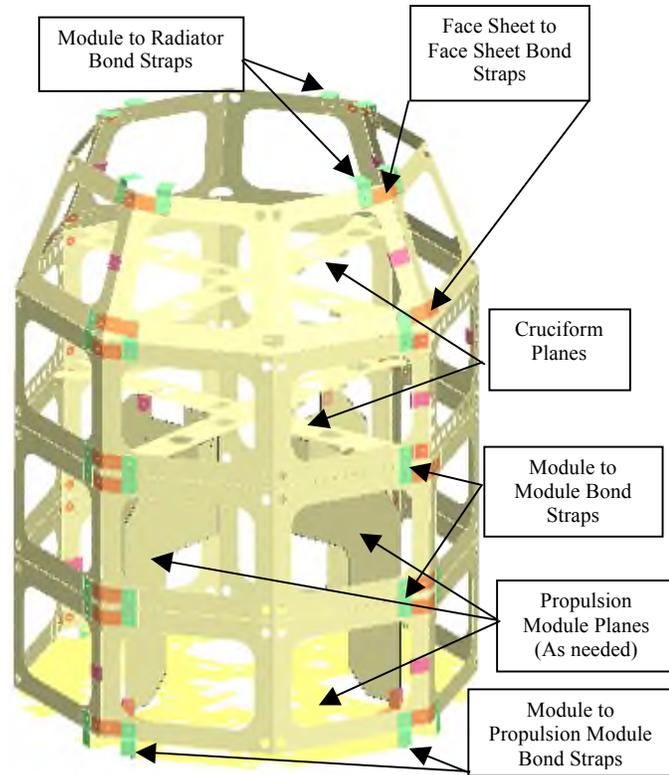


Fig. 3. The LADEE EVerS system illustrating a series of modules and panels joined by bond straps (Structure, solar arrays, avionics, harnesses, radiator panel, propulsion system, some bond straps and panel foiling omitted for clarity)

## VIII. DESCRIPTION OF FUTURE WORK

Much effort remains to be done on LADEE, including final detailed design work and further testing of the EVer system components and processes, followed by the assembly, test, and launch of LADEE and the successful collection of science.

In the future it is hoped to flow the EVer system & concepts into other spacecraft including, but not limited to, future variants of the Modular Common Bus Architecture.

## IX. CONCLUSION

To meet the severe E3 environments found in space flight spacecraft requires some form of EVer system to serve multiple critical functions. Traditional metallic spacecraft, which automatically had a built-in EVer system in the metal

structure, have given way to spacecraft built from nonconductive structural materials and bonds, which necessitates the EVer be explicitly designed. Working together as a team, LADEE’s E3 and Structures engineers have adapted existing rapid-development space hardware with an EVer while using solutions of low complexity, mass, & cost. The methods described can be used to design EVer systems for future spacecraft including but not limited to, future variants of the Ames modular common spacecraft bus

## ACKNOWLEDGMENT

The authors wish to acknowledge the support of the entire LADEE spacecraft program team, with special thanks to Stephan Spremo, Jim McKennon, Joe Camisa, Van Johnson, and Bill Reeve.

We wish to thank Albert Whittlesey of the Jet Propulsion Laboratory and Les Warboys (Retired) for their continued mentoring and support.

The authors also wish to acknowledge the pioneering work of Harry Lubcke, the first man to install and operate a television receiver on board an aircraft that was in flight. [11] Lubcke was among the first to encounter electromagnetic interference in avionics packages operating without a physical reference connection to the earth. Harry Lubcke’s legacy has been inspirational to the author

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