# THEMIS
# Electrostatic Cleanliness Specification

thm_sys_003e_ESC Specification
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Revision E

John Bonnell
University of California, Berkeley

Ellen Taylor, U.C.Berkeley, THEMIS Mission Systems Engineer

Tom Ajluni, Swales Aerospace, THEMIS Spacecraft Systems Engineer

Peter Harvey, U.C.Berkeley, THEMIS Project Manager

## Document Revision Record

| Rev. | Date | Description of Change | Approved By |
|---|---|---|---|
| - | 7/28/03 | Preliminary Draft expanded from ISEE ESC specification. | - |
| A | 8/11/03 | Change from 1 V to to 0.1 V uniformity requirement; addition of verification section; removal of editorial comments from Preliminary Draft. | |
| A.1 | 11/2/03 | 1-V requirement/0.1-V goal; 8-nA/$cm^2$ jmax. | |
| B | 11/5/03 | Added ESC Subcommittee names and verification responsibility | |
| C | 11/7/03 | Changed 2.5x10^3 in Verification section to 1.25x10^4 for meeting the requirement, and 1.25x10^3 for meeting the goal. | |
| D | 2/17/04 | Changed conductivity specification from bulk resistivity and thickness (ohm-cm) to surface resistivity (ohm/sqr); expanded and clarified discussion of apertures and exposed insulators. | |
| D1 | 2/25/2004 | Added further derivation of patch served by central ground for tutorial purposes in Section III. Corrected errors in text and tables as noted in ESC telecom, 18 Feb 2004. Turned on change tracking. | |
| E | 5/7/2004 | Modified Distribution List | |

## Distribution List

| Name | Email |
|---|---|
| Vassilis Angelopoulos, PI, U.C. Berkeley | vassilis@ssl.berkeley.edu; |
| Peter Harvey, Project Manager, U.C.Berkeley | prh@ssl.berkeley.edu; |
| John Bonnell, EFI Scientist, U.C. Berkeley | jbonnell@ssl.berkeley.edu; |
| Paul Turin, Mechanical Lead, U.C.Berkeley | pturin@ssl.berkeley.edu; |
| Ellen Taylor, Mission Systems, U.C. Berkeley | ertaylor@ssl.berkeley.edu; |
| Tom Ajluni, System Engineer, Swales Aerospace | tajluni@swales.com; |
| Don Jarosz, Swales Aerospace | djarosz@swales.com; |
| Rob Eppler, Lead Probe Mechanical, SA | weppler@swales.com; |
| Chris Lashley, Lead Mechanical, SA | clashley@swales.com; |
| David Jeyasunder, Electrical Systems, SA | djeyasunder@swales.com; |
| Kevin Brenneman, Systems, SA | kbrenneman@swales.com; |
| Rommel Zara, Thermal Lead, SA | rzara@swales.com; |
| Forrest Mozer, EFI Scientist, U.C. Berkeley | fmozer@ssl.berkeley.edu; |
| Stuart Bale, EFI Scientist, U.C. Berkeley | bale@ssl.berkeley.edu |

## ESC Subcommittee

Vassilis Angelopoulos, UCB
Ellen Taylor, UCB
John Bonnell, UCB
Paul Turin, UCB
Tom Ajluni, Swales

# I. RATIONALE

In order to make high-quality electric field and low energy plasma measurements in the terrestrial magnetosphere, the THEMIS probes must conform to an electrostatic cleanliness specification, or ESC. This ESC specifies a maximum tolerable variation in the electric potential over the surface of the spacecraft, a grounding requirement on exposed surfaces, and a symmetry requirement on deployed elements. The reasons for these requirements are threefold:

1. Asymmetries in the electrical potential distribution on and around the spacecraft lead to systematic errors in the DC electric field measurement. Insulating surfaces and poorly grounded conductors contribute directly to such asymmetries, and thus the presence of such surfaces needs to be minimized in order to insure high-quality DC electric field measurements.
2. Proper operation of the electric field sensors requires biasing to optimize the coupling between the electric field sensors and the ambient plasma. Biasing of the electric field sensors requires the use of the spacecraft surfaces for current collection. Insulating surfaces and improperly grounded conductors will reduce the area available for current collection as well as lead to asymmetries in the electric potential distribution when the biasing system is in operation. Thus, the presence of such surfaces needs to be minimized in order to insure high-quality DC electric field measurements.
3. Asymmetries in the electric potential distribution on and around the spacecraft distort the trajectories of low-energy plasma particles. These distortions are difficult to account for, and lead to errors in the estimated angular distribution of the low-energy plasma. As noted in (1) above, insulating surfaces and improperly grounded conductors contribute directly to such asymmetries, and thus the presence of such surfaces needs to be minimized in order to insure high-quality low-energy plasma measurements.

II. REQUIREMENT

The maximum tolerable variation in potential across the surface of the THEMIS spacecraft, $dV_{max}$, shall be 1 Volt, with a goal of 0.1 Volts, under the assumption of a maximum current density to the spacecraft surface, $j_{max}$, of 8 nA/cm$^2$. Adherence to this specification shall be guaranteed through the actions of the ESC subcommittee, consisting of at minimum the Lead Scientist on the Electric Field Instrument (EFI), and the Mission Systems Engineer.

The purpose of this specification is to guarantee that no exposed spacecraft components charge to potentials in excess of the maximum tolerable variation with respect to the mean spacecraft potential, and that all exposed surfaces are tied together into a single conductive surface, as explained in Section I above. This requirement demands that the surfaces of all spacecraft components that are exposed to the plasma environment be "sufficiently conducting," and that all surfaces exposed to sunlight and/or the plasma are connected to spacecraft ground through conducting paths of "sufficiently low impedance" (These terms are defined in Section III). In particular, this requires that:

1. Solar cells must be covered with "conductive" material, and those conductive surfaces connected to spacecraft ground.
2. Thermal coatings or any other materials placed on the spacecraft surface must be electrical "conductors," and must be tied together and to spacecraft ground.
3. All booms, appendages and instruments mounted on them must have "conducting" surfaces that are tied together and then to spacecraft ground.
4. All exposed portions of all scientific instruments, spacecraft hardware, cables or cable harnesses, etc., must be "conducting," and connected to spacecraft ground.

If any of the above described exposed "conducting" surfaces are not connected through low impedances to spacecraft ground (a non-conforming conductor), then such surfaces shall be connected through low impedances to potentials that differ from spacecraft ground by no more than $dV_{max}$.

Further, all spacecraft booms must be mounted as symmetrically as possible with respect to electric field sensors and as far as possible from low energy plasma experiments.

If a given exposed surface does not comply with the above requirements on uniformity of potential, maximum grounding impedance, or symmetry requirements, then said surface must be accounted for under the classes of Exceptions noted in Section IV below, and tracked as part of the Exceptions Roster maintained by the ESC Subcommittee.

## III. DEFINITION OF REQUIRED CONDUCTIVITY AND LOW-IMPEDANCE PATHS TO SPACECRAFT GROUND

An exposed surface that is “sufficiently conductive” with respect to the above requirements must allow the photoelectron and/or thermal plasma current to that surface to flow to spacecraft ground without generating potential differences in excess of $dV_{max}$. For some spacecraft surfaces, the current collection and flow to ground occurs in a distributed fashion through the entire boundary of the conductive surface (e.g. solar cell coatings, thermal blankets, etc.); for others, the grounding occurs through a single point (e.g. conductive shields on cables grounded via resistors or inductors). In either case, the requirement that the potential difference between any two points on the surface of the spacecraft is less than $dV_{max}$ places an upper bound on the allowed bulk resistivity divided by the thickness of the conducting layer, or equivalently the surface resistivity of that conducting layer that depends upon the dimensions of that exposed area. The upper bound in terms of both bulk resistivity and layer thickness (i.e. ohm-cm of bulk resistivity and Angstroms of layer thickness), and surface resistivity (i.e. ohm/sqr of surface resistivity) is worked out for common surface and ground geometries in the paragraphs below.

For the distributed current collection case, four current-collection and grounding geometries are most relevant for THEMIS: (1) Conductor between two grounding strips; (2) Conductor within grounded circle; (3) Circular conductor served by circular patch; (4) Conductor on top of grounded plane. For the calculation of the upper bounds below $j_{max}$ is assumed uniform over the surface of the conductor; this assumption holds if the variation in potential across the surface is less than the characteristic energy of the particle population carrying the current; if the THEMIS requirement of a 1-Volt uniformity in potential is maintained, then this assumption will be satisfied, if the THEMIS goal of a 0.1-Volt uniformity is achieved, then even more so In cases (1) and (2), the potential is assumed to be uniform through the thickness of the conducting layer; this assumption hold true if the layer is sufficiently thin relative to its extent; i.e. T << S (spacing between grounds), or R (radius of patch).

Note that the bound on the bulk resistivity of the exposed conductor in each case is a function of both the thickness of the layer and the area exposed to space. The thicker the layer, the less resistance it poses to the flow of current from its surface to ground, and the higher the bulk resistivity can be. Conversely, the larger the area, the more current collected by the surface, and the larger distance it has to flow to ground, both of which contribute to a higher potential between the ground and a point in the interior of the exposed surface.

1. For the case of a conductor between two grounding strips (e.g. A thermal blanket with conductive coating with grounds running along two opposing edges), if the spacing between the grounds is S, and the film thickness is T, then the upper bound on the bulk resistivity of the conductor is: $\rho_{max} = 8(dV_{max}/j_{max})(T/S^2)$.
2. For the case of a circular conductor surrounded by a ground (e.g. a cover slip on a solar cell served by a surrounding metal ground), for a radius of R and a thickness of T, the upper bound on the bulk resistivity of the conductor is: $\rho_{max} = 4(dV_{max}/j_{max})(T/R^2)$.
3. For the case of a circular patch served by a central circular ground, for a patch radius of R and a ground radius of $R_G$, the upper bound on the bulk resistivity of the conductor is: $\rho_{max} = 2(dV_{max}/j_{max})*(1/G(R/R_G))*(T/R^2)$, where G is a function that takes into account the relatively larger potential drop required to carry current into grounds of smaller radii; for $R/R_G<100$, $G<7.5$. $G(R/R_G) = \ln(R/R_G) - 2*(1+(R/R_G)^2)$.
4. In the case of a conductor on top of a grounded plane (e.g. lubricating or thermal control coatings), for a conductor of thickness T, $\rho_{max} = (dV_{max}/j_{max})(1/T)$.

For the single-point ground case, the maximum impedance to ground, $R_{max}$, for a surface with exposed area of A is: $R_{max} = (dV_{max}/j_{max})(1/A)$.

The resistivity of conductive coatings is usually quoted in terms of the surface resistivity, rather than bulk resistivity and thickness. The upper limits on the bulk resistivity of the conductive coating considered in cases 1, 2, and 3 above can be converted to an upper limit on the surface resistivity. In each case, the upper limit on the bulk resistivity is given by the formula, $\rho_{max} = G(dV_{max}/j_{max})(T/L^2)$, where G is a dimensionless constant determined by the geometry of the exposed conductor and the electrodes servicing it, and L is a relevant dimension of the exposed conductor. Under the assumption that L>>T, so that the collected current flows uniformly through the cross section of the conductive coating, the surface resistivity, $R_S$, of the coating is given by, $R_S=\rho_{max}/T$. Since the bulk resistivity, $\rho$, is measured in units of ohm*length, the surface resistivity, $R_S$, will be measured in ohms, or, bowing to industry convention, ohms/square. The upper limit on the surface resistivity is then, $R_{S,max} = G(dV_{max}/j_{max})(1/L^2)$. Note that this limit depends not only on the maximum potential difference allowed across the surface and the assumed current density incident on the surface, but the dimensions of the exposed surface as well; i.e. one can not make a global specification on the upper limit on the surface resistivity of exposed conductors without specifying the dimensions of those conductors as well.

For the two cases covered by this specification (1-V requirement, 0.1-V goal), the upper bounds on surface resistivity ($R_S$), bulk resistivity ($\rho$), or resistance (R) to ground are collected in Table 1 below for reference.

| Geometry | 1-V, 8-nA/cm$^2$ Requirement | 0.1-V, 8-nA/cm$^2$ Goal |
|---|---|---|
| Strip between Grounds, $R_S$ (S is spacing between grounding strips). | $(1(G\Omega/sqr)\text{-}cm^2)(1/S^2)$ | $(100(M\Omega/sqr)\text{-}cm^2)(1/S^2)$ |
| Circular Patch surrounded by Ground, $R_S$ (R is radius of patch). | $(500(M\Omega/sqr)\text{-}cm^2)(1/R^2)$ | $(50(M\Omega/sqr)\text{-}cm^2)(1/R^2)$ |

| | | |
|---|---|---|
| Circular Patch Served by Central Ground, $R_{S;}$ $R/R_G$<= 100 (R and $R_G$ are radius of patch and ground respectively. | $(33(M\Omega/sqr)\text{-}cm^2)(1/R^2)$ | $(3.3(M\Omega/sqr)cm^2)(1/R^2)$ |
| Conductive Layer over Ground, $\rho_{max}$ (T is thickness of conductive layer). | $(125\ M\Omega\text{-}cm^2)(1/T)$ | $(12.5\ M\Omega\text{-}cm^2)(1/T)$ |
| Single-Point Grounding of Collection Area, $R_{max}$ (A is exposed area). | $(125\ M\Omega\text{-}cm^2)(1/A)$ | $(12.5\ M\Omega\text{-}cm^2)(1/A)$ |

As a rule of thumb, one can use the specification for a circular patch served by a central ground to set the spacing between grounding points on a surface of given surface resistivity. This rule of thumb is shown in Table 2 below, and assumes that the ground radius is at least 1/100 of the patch radius:

| Surface Resistivity [ohm/sqr] | Maximum Spacing Between Ground Points [cm] | |
|---|---|---|
| | 1-V, 8-nA/$cm^2$ Requirement | 0.1-V, 8-nA/$cm^2$ Goal |
| $10^9$ | 0.18 | 0.06 |
| $10^6$ | 5.8 | 1.8 |
| $10^3$ | 183 | 56 |

As an example of the use of these specifications, consider grounding a 1-meter square thermal blanket at two opposite corners; what's the maximum surface resistivity allowed if the corner grounds have a radius greater than 1 cm? One can use the rule for a circular patch served by a ground to estimate the maximum surface resistivity. First, think of how each ground collects current; much like lawn sprinklers, each will draw from a circular wedge, as shown below:

[Picture to be added later]

Conservatively, each ground draws from an area with a radius of 1 meter; there is a region in the center that both grounds serve. Using the requirement that the surface resistivity can be no larger than $(33\ M\Omega/sqr)\text{-}cm^2*(1/R^2)$, the maximum surface resistivity of the coating on the thermal blanket is 330 kohm/sqr in order to achieve the ESC specification, and 33 kΩ/sqr to achieve the ESC goal (ten times smaller).

## IV. EXCEPTIONS

Exceptions to the rules of Section II or questions concerning suspected problem areas shall be presented to the ESC subcommittee for their evaluation, suggestions and concurrence.

Two common classes of exceptions are apertures that expose conductors maintained at significant potentials relative to spacecraft ground (e.g. apertures of electrostatic particle analyzers), and apertures that expose significant insulated areas to sunlight and the plasma environment. Explicit limits, or budgets, for such exceptional surfaces are detailed below.

In terms of the strictness of the budget on exposed area for THEMIS, the most stringent requirement is placed upon exposed insulators, followed by exposed apertures held at a fixed potential relative to spacecraft ground, followed by a general upper limit on the total area of all such exceptional surfaces imposed by current collection requirements for EFI biasing.

<u>Exposed insulators:</u>

The specification on exposed insulating areas is similar to that for apertures exposing high-potential surfaces (see detailed discussion in Apertures section below); the primary difference is that the potential of the exposed area is no longer fixed relative to spacecraft ground, but instead is determined in complex way by the illumination and exposure history of the insulating surface. An insulator continually in sunlight will charge to a potential on the order of several times the photoelectron characteristic energy, or a few tens of volts. An insulator in darkness will charge to a potential on the order of several times the ambient electron temperature, or a few hundred volts in the case of THEMIS's main operational region, the central plasma sheet and plasma sheet boundary layer in the magnetotail. Because of this possibility of charging to a very high potential relative to spacecraft ground and relevant bias potentials and particle energies, the Exposed Insulator budget is probably the most stringent requirement contained within the THEMIS ESC specification, after the requirement to make the entire surface a current collecting surface. Taking the worst case charging as 500 V, and applying the aperture specification, one has the following requirements on exposed insulator dimensions:

| Shielding Geometry and Potential Falloff | Requirement |
|---|---|
| $A_G$>20*A; dipole falloff. | $A < 1.2\ cm^2$ |
| $A_G$<=20*A; monopole falloff. | $D_{max} < 3.2x10^{-3}$ cm |

Exposed insulators shielded by collimators have their effective potential reduced in the same fashion as apertures (see discussion below in Apertures section).

Note that this specification does not take into account “deep dielectric charging” of insulators caused by penetrating high-energy particle fluxes; such charging can lead to kilovolts of relative potential between an insulator and nearby surfaces, but can not be mitigated readily using current technology, and so is not considered under this ESC specification

Apertures at high voltage:

There are two relevant limits for the case of an aperture or surface that exposes a conductor at a significant potential relative to spacecraft ground. In the first case, the aperture is surrounded by a sufficient area of grounded conductor so as to terminate locally nearly all the field lines emanating from the aperture, leading to a dipole-like falloff in electric potential away from the aperture. In the second case, the aperture is not surrounded by a sufficient area of grounded conductor, leading to a significant fraction of locally unterminated field lines, and a monopole-like falloff in electric potential away from the aperture. As a rough guideline, an aperture of area A must be surrounded by a conductive ground of area $A_G$, with $A_G$> 20*A in order to ensure the less-stringent dipole fall off case; if $A_G$<= 20*A, then the more stringent monopole fall off case must be used.

For the less-stringent dipole case, one has the requirement that $V*A*dL < E_{err}*L_{min}^4$; for the more-stringent monopole case, one has the requirement that $V*D_{max}*dL<E_{err}*L_{min}^3$. In each case, dL is the displacement of the aperture from the center of the spacecraft, $E_{err}$ is the allowed systematic error in the DC electric field measurement, $D_{max}$ is the maximum linear dimension of the aperture, and $L_{min}$ is the minimum relevant EFI boom length (half the tip-to-tip measurement; typically set by AXB). For apertures located on the surface of the THEMIS probe body, dL = 0.4 meters. $E_{err}$ is set by top-level science and boom alignment determination requirements as 0.1 mV/m. The resulting requirements on aperture potential and dimensions are collected in the table below:

| Shielding Geometry and Potential Falloff | Requirement |
|---|---|
| $A_G$>20*A; dipole falloff. | V*A < 640 V-cm$^2$ |
| $A_G$<=20*A; monopole falloff. | V*$D_{max}$ < 1.6 V-cm |

Note that these values constitute a budget for all such apertures, rather than limits on any one aperture; i.e. if all apertures are surrounded by sufficiently large grounded shields, then the total of V*A over all such apertures must be less than 640 V-cm$^2$.

Apertures nestled inside a grounded, conducting well, or collimator, are a special case. The walls of the collimator serve as more efficient shields than a flat surrounding area, and reduce the effective potential exposed to the plasma by the factor $e^{-Cd/Dmin}$, where d is the depth of the collimator and Dmin is the minimum linear dimension of the aperture, and C is a constant factor that depnedis upon the geometry of the surface: C=π for a rectangular collimator, C=2.2 for a circular collimator.

Limit on Total Excepted Area:

In order to maintain the spacecraft surface as a sufficiently large area for current collection, as well as to limit the total systematic error due to such surfaces, the total area of excepted apertures and insulators cannot exceed 1 percent of the exposed area of the spacecraft, boom systems, and other non-EFI sub-systems on THEMIS. Note that this specification will almost invariably be overridden by the budgets on exposed insulators and apertures at high voltages: if THEMIS is working up against this limit on total excepted area, then she is doing very well.

## V. VERIFICATION

Verification of the ESC requirement is straightforward, and should be done on both subassemblies (booms, thermal blankets, solar panels, etc.), and on the complete spacecraft. Responsibility for ensuring verification lies with the ESC subcommittee.

Grounding of Exposed Conductors:

Consider looking at the spacecraft with all its appendages deployed, covers released, etc. Anything that one can see will be exposed to the space plasma, and must conform to the ESC requirement. This requirement can be verified by measuring the resistance between any pair of surfaces. This measured resistance must be less than that found for the "Single-Point Grounding of Collection Area" case in Section III above, namely that resistance must be less than (125 MΩ)∗(1/A) for meeting the requirement, and (125 MΩ)∗(1/A) for meeting the goal, where A is the total exposed area of the two surfaces in square centimeters.

Exposed Apertures and Insulators:

As noted in the Requirement section above, all Exposed Apertures at significant potentials relative to ground, as well as Exposed Insulating Surfaces must be tracked as Exceptions by the ESC SubCommittee.

Notes on Implementation of the THEMIS ESC:

Since the bulk of the exposed surface of THEMIS will consist of thermal blankets, solar panels, and carbon composite spacecraft decking, special care needs to be taken to ensure that these items are built to the rules of Section II. This requires explicit implementation details, such as the conductive coatings on all solar cell cover slips being tied to ground,thermal blankets that utilize conductive coatings that do not fracture into independent, insolated domains when crinkled or otherwise stressed, and the possibility of additional conductive surface treatments on the composite deck material if the surface resistivity is not sufficiently low so as to meet the ESC specification outright. If the vendors of these items are unfamiliar with such requirements, and do not have previous experience with electrostatically clean spacecraft, the ESC subcommittee should be involved in implementation discussions and development of the vendor SOW .