Techniques for Magnetic Cleanliness on Spacecraft Solar Arrays

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Solar arrays can be designed to minimize generated magnetic disturbances in order to accommodate the needs of spacecraft with sensitive magnetometers. Techniques for minimizing the magnetic field include avoiding magnetic materials and applying magnetic field cancellation techniques. The avoidance of magnetic materials is usually possible by careful material selection, but the field induced by the magnetic dipole moment of current loops cannot be completely avoided. Several techniques are described that minimize and cancel these magnetic dipole moments. A finite element modeling technique was developed that accurately calculates the total magnetic moment of a solar array, and evaluates the resulting magnetic field at discrete locations. Using the model, it was shown that, even after application of magnetic cancellation techniques, there are limits to magnetic cleanliness for practical solar panel configurations.

I. Introduction

CERTAIN missions require solar arrays that are magnetically clean in order to minimize the disturbance of the magnetic field in the vicinity of the spacecraft. These requirements typically arise as a result of the need to make measurements by sensitive magnetometers. Solar arrays are a significant source of electromagnetic noise because of their size, the types of materials used, and the large number and size of current loops associated with the photovoltaic cells and their lead wires.

The acceptable magnetic field imposed by a spacecraft having sensitive magnetometers is typically budgeted to the various spacecraft subsystems. Often, to flow down this requirement to the solar array level, the requirement is expressed in terms of magnetic dipole moment. The magnetic dipole moment is defined as the vector cross product of the current contained in a wire loop and the planar area enclosed by the loop (see Figure 1), and is linearly related to the magnetic field, at least for the far field condition. The reason that dipole moment is often specified is because it is much easier to evaluate magnetic dipole moment on a preliminary solar panel design, and modify the design to minimize it, than it is to evaluate and minimize the resulting magnetic field.

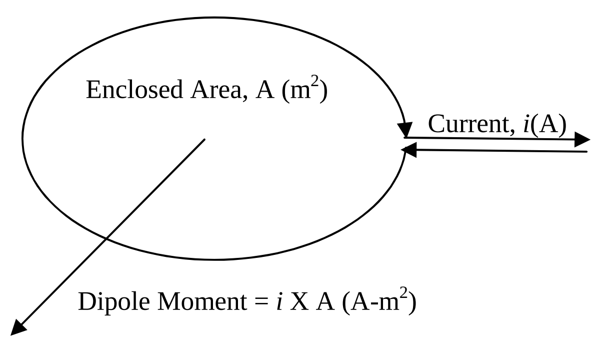

Figure 1. Definition of magnetic dipole moment

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II. Sources of Magnetic Fields and Their Mitigation

Magnetic fields from solar arrays can come from two sources - the residual magnetization of ferromagnetic and paramagnetic materials in the design and those induced from the current loops inherent to the electrical power generation of the solar cells and their associated wiring.

A. Magnetic materials in solar arrays

Ferro and paramagnetic materials in solar arrays are primarily those that contain iron and nickel. Most of the solar array materials are inherently non-magnetic. The panel structures use graphite composite and/or aluminum, with titanium or aluminum fittings. The cells are based on material systems using silicon, germanium or III-V compounds such as gallium-arsenide. Wiring is usually silver coated copper. This leaves the main sources of magnetism to be the solar cell interconnects, which are commonly constructed from Kovar, and other mechanical piece-parts (screws, washers, inserts, etc.) that may contain nickel or iron.

During the design process, these materials can be avoided. Molybdenum interconnects can often be substituted as an alternative to Kovar, and non-magnetizing materials and alloys can be used for other piece-parts. In cases where small amounts of magnetic materials are unavoidable, degaussing of the materials can minimize the residual field. Table 1 shows the results of an experiment performed on molybdenum and Kovar interconnects. Even though the molybdenum interconnect had a small amount of nickel cladding (used to enhance the solderability of the surface), it did not show appreciable residual magnetism. The magnetism exhibited by the Kovar interconnect was eliminated by degaussing, but it is desirable to avoid the need to degauss materials and there is also a risk that these materials may become remagnetized.

Table 1. Magnetism of Kovar and Molybdenum interconnects measured at 10cm.

Type of Interconnect	As received	After 15G field exposure	After degaussing
Kovar loop interconnect	3nT	14nT	0nT
Mo loop interconnect	<1nT	<1nT	0nT

B. Current loop magnetism and mitigation

Although careful material selection can avoid or even eliminate residual magnetism in the solar array, the current flowing in solar cells and their associated wiring always generate some magnetic field. Several techniques are available, which, in combination, can minimize and cancel these current induced fields. The objectives of these techniques are to minimize the enclosed current loop area, and then to run equal size loops in opposing directions to cancel the magnetic moment vectors and therefore the resulting field.

The most common heritage approach to solar panel wiring assembles the wiring harness on the backside of a solar panel structure. This allows for easier manufacturing and maximum usage of the panel frontside for solar energy collection. Each solar cell string has an associated set of lead wires that go from a connector on the back side of the panel to the front-side string termination through-holes in the panel. Between the connector and one end of the solar cell string, the lead wires can be twisted to eliminate their magnetic field, but at that point, the current path splits up as it runs through the solar cells themselves and returns by the positive lead wire.

To minimize the loop area of the solar cells and their lead wires, one approach is to run the positive lead wire as close to the solar cells as possible. This technique, know as back-wiring, mirrors the path of the solar cells on the front side with the positive lead wire on the backside. Figure 2 shows the approach for a notional configuration of four cells in series. In Figure 2, two positive leads wire are shown returning from the positive end of the solar cell strings. It is typical for reliability reasons to have redundant lead wires, leading to both the positive and negative termination strip of the solar cell. In Figure 2, the two positive lead wires are shown separated on the back side when mirroring the solar cells. Because the solar cells carry a sheet current that is evenly distributed, as long as the wires run symmetrically along the center-line of the solar cells, there is no difference on magnetic moment whether both wires are run in the center, or they are separated by some distance.

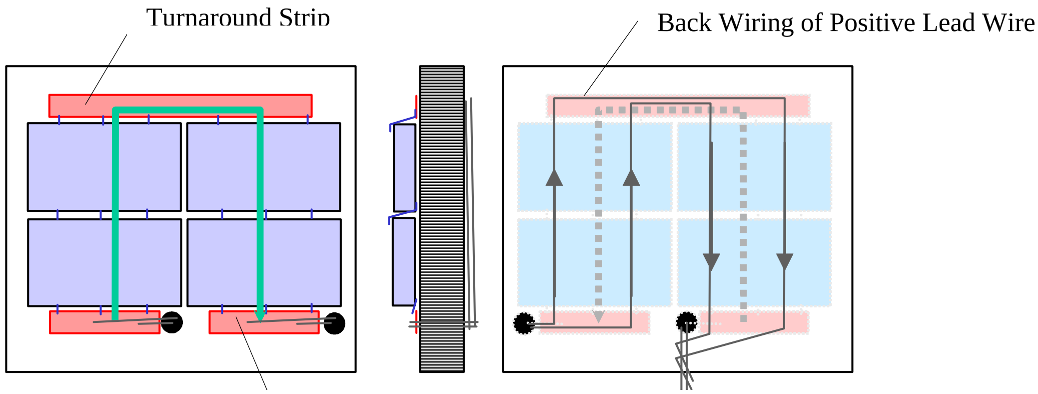

Figure 2. Notional solar panel string showing back-wiring technique for magnetic moment minimization.

Because the solar panel depth is significant for structural reasons, (typically 0.5 – 2.5cm), the back-wiring approach still encloses significant areas of current loops and therefore has significant magnetic dipole moment. The layout of the strings in a back-wired solar array can be arranged so that these loops cancel to a large extent. This is also shown in Figure 2, whereby the four solar cells are arranged in a serpentine pattern of two columns of two cells per column. It can be shown that if the solar cells and their associated wiring create a simply enclosed "fence," as shown in Figure 3, that the resulting magnetic dipole moment cancellation is zero, at least in the ideal case.

Two other approaches have been occasionally used for magnetic moment cancellation, both of which run the solar cell wiring on the front side of the structural panel. In one approach, the wires from the positive terminal strip of the solar cell string is run along the sides of the solar cells, until it reaches the negative terminal strip, where the lead wires can be twisted together to lead to the connector. In this approach, the distance between the solar cells and the back-wiring is reduced to less than 0.1cm, since the solar panel structure does not get in the way.

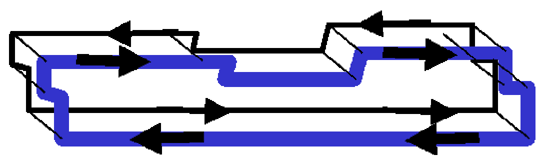

Figure 3. Current flows from solar cell and back-wiring that form a simply enclosed fence result in zero moment.

In the second approach, a printed flex circuit is run directly underneath the solar cell. This approach is both the most effective and most difficult to implement. It has the lowest inherent dipole moment, since the return current is a sheet current which can mirror the sheet current in the solar cell string, and its separation from the solar cells can be as little as 0.02cm. This approach has been implemented on a couple of spacecraft in the past, but the flex-circuit wiring approach is difficult to implement, not amenable to design changes, and not reliably qualified for long term thermal cycling environment.

III. Magnetic Field Modeling

A magnetic field finite element model was developed to analyze the induced field and calculate the total magnetic dipole moment of a set of solar panels. The model uses Matlab to directly load the geometry from a CAD based model of the solar array, and calculates the magnetic moment and induced field of each incremental wire loop. The model was used to show that, using the techniques described here, the magnetic moment of a typical solar panel can be minimized to achieve a value with an order of magnitude of <1E-04 amp-meter-squared, while the field at a point 1 meter away from the solar panel can be limited to much less than 1 nanotesla.

Wiring on the panels is laid out in CAD, and selected points along the wires are given unique names to indicate their relative position along a given current loop. These point names and their coordinates are then exported to a custom Matlab program where they serve to define the start and finish of individual current segments.

The solar cells themselves are modeled as groups of parallel wires running the length of a string to simulate a sheet current, as shown in Figure 4. The CAD model provides the coordinates of the beginning and end of each string, as well as the typical cell width. The Matlab program then generates the associated current segments, based upon a pre-defined value for the number of wires needed to simulate a sheet current. The number of wires which were used to model the sheet current is easily varied. Doing so had no affect upon the magnetic moment, and beyond a value of 20 wires per string, the calculated field did not change appreciably. In models that were developed, 20 wires per string was the standard value used.

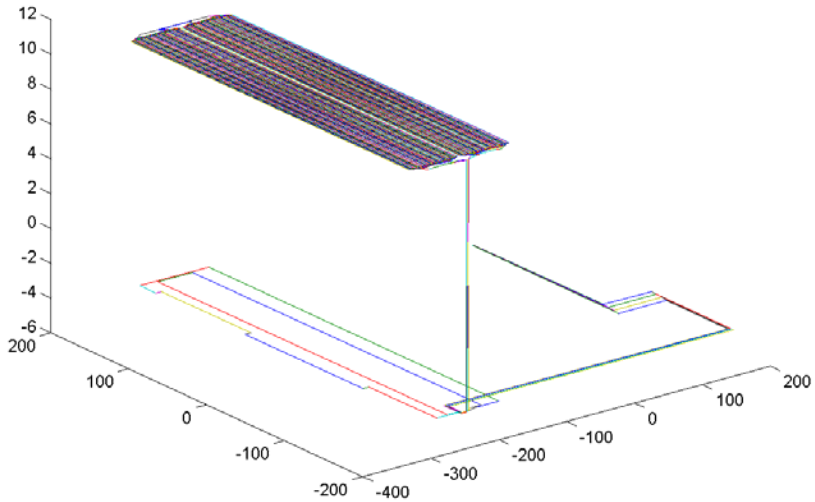

Figure 4. The solar cells were modeled using parallel wires. (Dimensions in mm - z-axis not to scale)

With all the current segments defined, the coordinates of the desired field measurement are entered, and the program then calculates the magnetic moment and field contributions from each segment, summing their vectors. The result is the total magnetic moment of the panel and the total field at the point of measurement.

The model was used to determine the magnetic field that would be seen by a magnetometer that was positioned at a point "P" one meter away from a spinning spacecraft with a body-mounted solar array as shown in Figure 5. Each face of the solar array was sized at 0.5X0.5m and assumed to have four strings, each generating 0.38A at full sun. The four strings were physically divided into 8 balanced serpentine rows of cells. Conventional back-wiring was assumed, using the technique described here with wires mirroring the center of the solar cell strings.

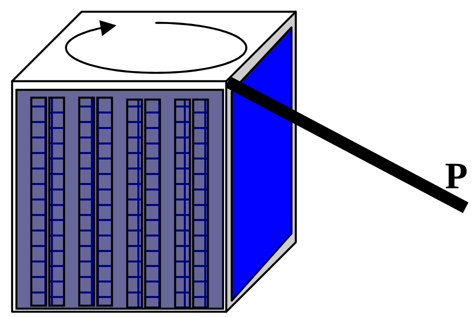

Figure 5. Magnetic analysis of the field at the end of a boom attached to a spinning spacecraft.

The model calculated the field generated as a function of current for each of the eight strings on the two panels. Since this is a spinning spacecraft, the current varies as the cosine of the angle of the normal of each of the two sun-facing panels as they turn into and then out of the sun. A separate calculation of current over time was used to operate on the results of the magnetic analysis, providing the results shown in Figure 6. As the spacecraft spins, the currents in the two panels vary, giving the dynamic field result shown. When the first panel is at 0 degrees, it has the highest current, while the second panel has zero current. When both panels reach 45 degrees, the total current from the combined set is maximized, but cancellation of the fields in the two panels is seen to minimize the field. Finally, as the first panel turns out of the sun, the second panel's current increases and the field increases again. The slight asymmetry in the results is a result of the two panels being identical, and not mirror images.

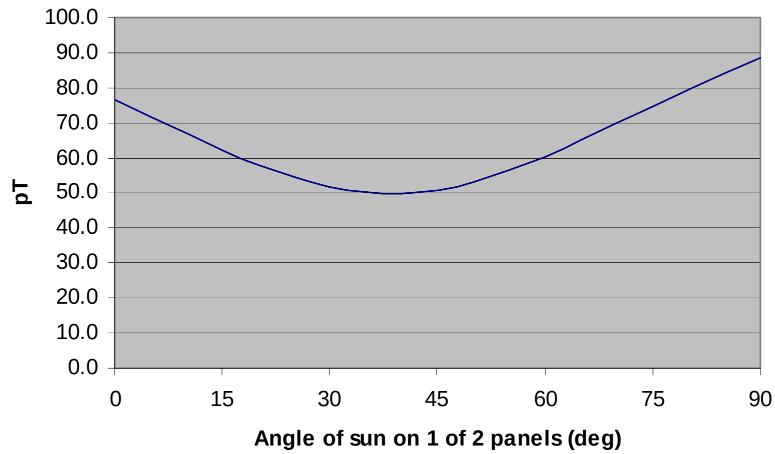

Figure 6. Field at 1m away from a spinning spacecraft.

Although the design that was modeled attempted to balance the solar cell strings perfectly, the field is still non-zero for two reasons. At one meter away from panels 0.5m in dimension, we still see some near-field fringe effects. The separation of the balancing current loops is several centimeters, and this has a significant effect. Also, there are details in the CAD model representative of a real solar panel which includes separation of wires near the terminal strips and at the diode board diode-boards. These wire separations exist on solar panels for practical reasons of manufacturability and reliability. Even so, it was shown that a back-wired panel could limit fields to the less than 100 picotesla.

IV. CONCLUSIONS

Methods exist which allow the magnetic fields generated by a solar panel to be minimized. However, even designs that eliminate magnetic materials, minimize enclosed current loops and make maximum use of moment cancellation result in some magnetic fields generated by the solar array. Even the best cancellation techniques cannot remove all of the near-field contributions, and there are practical requirements for wiring that cause minor irregularities. Still, with relatively short booms, experiments with magnetometers can expect that carefully designed solar arrays can provide a magnetic environment which is clean down to the picotesla range.