EMI ANALYSIS OF TRANSIENT EVENTS VIA METHOD OF MOMENTS

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Abstract

Expendable rockets constitute one of the delivery systems used for satellites and other space instruments. In such rockets, the electric power consumption during ascent and separation is supplied by several batteries located within the rocket's stages. Thermostats help keep a constant temperature range within the batteries during ascent to geosynchronous orbit. Large transient currents in the batteries due to the ON/OFF thermostats switching events, can produce significant amounts of conducted and radiated Electromagnetic Interference (EMI) which can adversely affect the normal operating environment of nearby electronics. This paper first conducts a brief review of the physics involved in the arcing process. Tlhe major portion of the paper will then be devoted to modeling the radiated EMI caused by thermostats' transients using the Method of Moments (MoM) . This paper will also address the validation of MoM data with obtained measurements.

1.0 INTRODUCTION

Since the middle 1980's new and upgraded launch vehicles have been acquired by the Air Force to deliver larger and heavier payloads to geosynchronous orbit (22,000 miles). The multi-stage launch vehicles contain, as the final stage, an Inertia Upper Stage (IUS) responsible for carrying the intended cargo (e.g satellite) into the required orbit. As part of a new design for the IUS, new batteries are being developed for supplying the needed electric power. Present new battery designs are capable of supplying 60 amps of uninter:rupted current for up to 5 hours. The IUS uses four of these batteries and the current demand during the first few minutes of IUS ascend can reach up to 75 amps. Each battery is made up of nine cells in series, each located within its individual cavity in the battery housing. The total supply voltage for the battery is 29 volts.

In order to meet the functional requirements of new batteries for the IUS, four thermostats are installed within each battery housing. Thermostats are needed to keep a constant operating temperature during large variations of ambient temperature during large variations of ambient temperature experienced by the battery during ascend of the IUS. The four thermostats are synchronized to operate at different temperature ranges as needed. Each thermostats is individually connected to a thermally radiating heating element. The heating elements are distributed on the walls of eight of the nine cavities where the battery cells are installed as shown in, Figure 1. The heating elements consist of teflon coated (ϵ_r=2.1), gauge 12 copper wiring which are laid out on the interior surface of the battery walls. Each thermostat connects to an RC network which serve as "arrestor" circuit for suppressing the arcing phenomena which occurs during thermostats ON/OFF switching operations., The figure also shows the schematic of the thermostats and arrestor circuits.

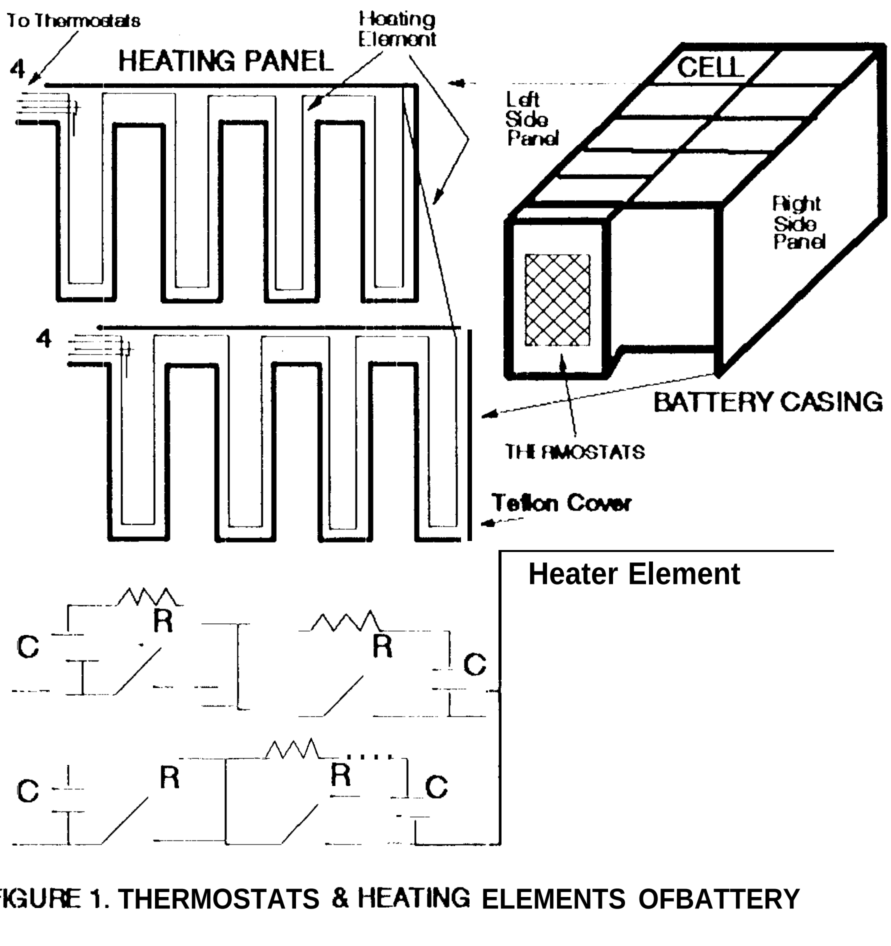

FIGURE 1. THERMOSTATS & HEATING ELEMENTS OFBATTERY

Each of the four thermostats draws about 1.6 amps of nominal current. However, transient currents of up to 4.7 amps can be measured across the thermostats during the ON/OFF switching cycles. Transient currents constitute one the major sources of conducted and radiated Electromagnetic Interference (EMI) [1] which can adversely affect the behavior of nearby electronics. Conducted EMI is of importance to eliminate because such conducted noise can be propagated to other electronic devices which are connected to the same battery. Radiated EMI is of importance to eliminate because the propagated noise can be pick up by sensitive receiver circuits through antennas and other electromagnetic field sensors commonly used in spacecraft. While considerable effort has been done in the past in analyzing conducted emissions through network representation of transient phenornenae and associated circuits [2-4], less effort has been invested in analyzing the radiated EMI due to transients because of the complex nature of the transient-caused radiate emissions phenomena. There is a need to understand better and predict the amount of radiated EMI from transient circuits such that the proper electronics can be develop to avoid interferences among sensitive spacecraft instruments.

2.0 RADIATED EMI FROM TRANSIENT EFFECTS.

Radiated noise from transient current events, such as those found in thermostats ON/OFF switching, are the results of two different types of events: a) arcing processes (e.g across thermostats contacts) , and b) "temporal" behavior of transient circuit elements as an antenna.

Arcing occurs is the result of mechanical switches ON/OFF operations. When the voltage across the contacts of mechanical switches is large enough it can cause the breakdown of the intervening gas. This is known as the "long arc". For smaller contact spacings, in a vacuum, the arc can be initiated by a "field-induced" emissions wherein the electric fields at the highest and sharpest points on the cathode liberate electrons. The voltage across the contacts divided by the contact spacing exceeds the breakdown field strength of the gas.

In a transient event the resulting transient current is responsible for the temporary antenna behavior of the heating elements. Though small in duration (only a few microseconds) , such transients can be large enough to cause significant fields to be radiated as the wiring of the heating elements behave as a radiating antenna. In this paper we will first discuss briefly the physics of arcing phenomena. The major portion of this paper will then be devoted to modeling the antenna behavior of the thermostats/heating element, during ON/OFF switching operations using the method of moments.

2.1 RADIATED EMISSIONS DUE TO ARCING

In the arcing process the external circuit has a pronounce effect on the type of discharge or even whether a discharge occurs. Switches are frequently used to interrupt loads that are resistive and inductive (e.g heater elements in a thermostat circuit) in nature as shown in Figure 2.

Interruption of these types of circuits leads to an interesting phenomena called "showering arc." An inevitable parasitic capacitance is in parallel with the inductive load. When the switch is closed, a steady-state current $I=V_{dc}/R$ is established in the inductor. When the switch open, the inductor attempts to maintain this current. It is therefore diverted through the capacitance, charging the latter. The switch voltage $V(t) = V_c+V_{dc}$, therefore increases. As this switch voltage increases, it may exceed the switch breakdown voltage, whereby a short arc forms and the switch voltage drops. The capacitor discharges through the switch, with the current being primarily limited by the local resistance and inductance of the wiring diagram. If the switch current exceeds the minimum arc-sustaining current, the arc is sustained. If not, the arc is extinguished and the capacitor begins to recharge. The switch voltage once again exceeds the switch breakdown voltage, and the switch voltage drops again. If the arc is not sustainable, the capacitor begins to recharge once again. Eventually the energy stored initially is dissipated, and the capacitor voltage decays to zero, leaving $V=V_{dc}$. This leads to a sequence of rising (as the capacitor charges) and rapidly falling (as the switch breaks down) voltages across the contact separation, which has been referred as the showering arc.

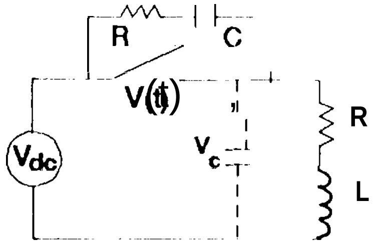

FIGURE 2 THERMOSTAT SWITCH AND ARRESTOR CIRCUIT

Showering arcs clearly have significant spectral content, and may therefore create EMI problems [6-8]. The wiring carrying these currents may cause significant radiated emissions, thereby creating interference problems. These signals may also be directly conducted along interconnected wiring paths, creating a potentially more troublesome effect, since the signal levels that are directly conducted to other points will be of the order of the switch voltages. Since these potential effects are recognized, various suppression measures are usually employed in conjunction with a mechanical switch.

A suppression technique for the arcing process is to prevent the switch voltage from exceeding the breakdown voltage of the switch. This can be implemented by placing a sufficiently large capacitor in parallel with the inductor, thereby reducing the peak available circuit voltage and also reducing the initial rise of the available circuit voltage. This scheme has the drawback in that contact damage can occur during switch closure because of large capacitor charging currents. A solution is to limit the discharge current that occur on contact closure by adding a resistor in series with the capacitor as shown in Figure 2. The minimum value of R is chosen to limit the discharge current during switch closure to below the minimum arcing current: $V_{dc}/R < I_{min}$.

To obtain an estimate of the amount of radiated EMI from arcing a thermostat was removed from the battery and place on a wooden platform inside a shielded room in order to measure the radiated emissions for several samples of ON/OFF switching. The thermostat was fed from a DC battery and a broadband antenna was used for the measurements. A resistive load to simulate the heater was used while keeping wiring to a minimum. The small load was selected to draw 1.6 amps of continuous current from the thermostats. Figure 3 shows the results of arcing-induced broadband emissions as compared to MIL-STD-461 EMI broadband (BB) emissions limits.

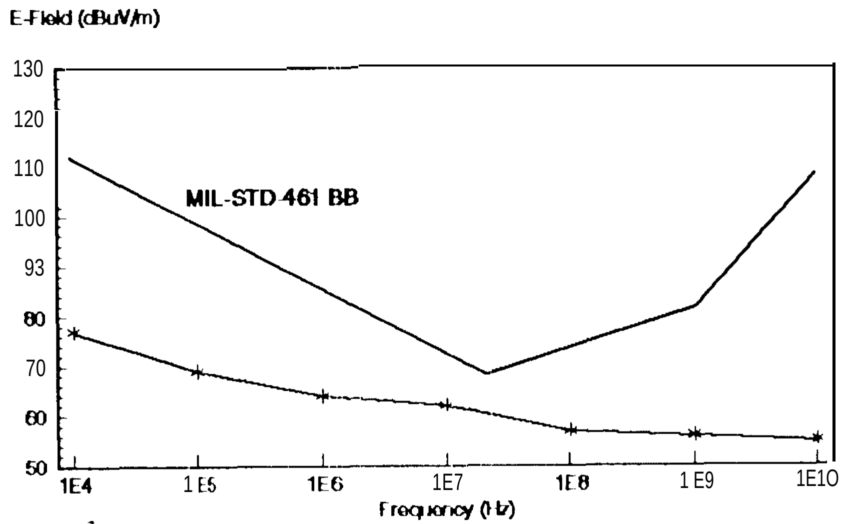

FIGURE 3. E-FIELD EMISSIOSN DUE TO ARCING

2.2 RADIATED EMISSIONS FROM ANTENNA BEHAVIOR

One of the major objectives in this work is to simulate the amount of radiated electric field emissions from the heater element as it behaves temporarily as an antenna from thermostats' ON/OFF switching transients. This task will be accomplished by using the method of moments for modeling the thermostat switch/heater element as a radiating structure.

The first step in the analysis of this type of EMI emissions problem is to calculate the transient currents and voltages across the thermostats switch, hence, across the heater load, using the pSPICE network analysis program [5]. Figure 4 shows the pSPICE model for two thermostats (S7, S8 in the figure) and the heater load (87 ohms). The figure also shows the RC arrestor circuit for each thermostat and system's switch. In the calculations it is assumed that the system switch in conjunction with one of the thermostats are already close at $t=0^+$ before the other thermostat switch closes. This is consistent with the fact that during most ON/OFF switching cycles at least two thermostats will be conducting at a time. In the simulation the first thermostat (S7) closes at t=O with a rise time $t_r=1.0\mu S$. The other thermostat switch closes at $t=40\mu S$ ($t_r=1.0\mu S$ also) and stays closed for $30\mu S$ before it opens. The parasitic inductances for each of the switches are also shown in the figure (L_2 & L_3 of $1\mu H$) likewise the parasitic inductance of the connector between the system switch and the thermostat is shown ($L_1=4\mu H$) . The terms V_3-V_4 in the figure are used by pSPICE as voltage controllers to simulate the times ON/OFF in the thermostats. For the pSPICE run we assume $R_{ON}=0.1$ ohms and $R_{OFF}=1000$ Mega-ohms. "Dummy" voltages V_5-V_6 are used to monitor the thermostats' currents when the switch closes (V_6-V_5) and the current toward the heater load. The transient currents can be calculated at any point in the circuit. Figure 5 shows the results of simulating the transient current and voltages at several locations in the circuit. Of special interest is the transient current across the thermostat switch, which from the figure can be observed to be of magnitude 4.7 amps with a rise time $t_r=0.2\mu S$. This transient current is responsible for the antenna behavior of the heating element. By multiplying the magnitude of the transient current by the impedance of the heater element we can obtain the equivalent transient voltage across the thermostat as a function of time.

To establish a benchmark for method of moment modeling, a series of electric field measurements are usually made to determine the spectrum profile of the radiating structure during ON/OFF switching. For these measurements the shape of the heater element must be constructed to resemble that in the battery (i.e same shape and material) . The thermostats are usually encased using a shield cover, the shield is then grounded so that the effects of possible arcing will not become part of the recorded spectrum. The two thermostats and heater assembly can then be positioned on a wooden platform inside an semianechoic chamber. Ambient temperature is changed to simulate the needed switching cycles. During the ON/OFF switching operations a broadband antenna is used for recording the emissions of the heater element as it temporarily behaves as an antenna fo:r a period of about $1.5\mu s$ for each ON/OFF switching operation. Measurements can then be made in the 1OOKHZ-5OMHZ frequency range using a spectrum analyzer. Figure 6 shows a typical set up for obtaining the measurements.

Modeling the radiating structure was accomplished using the method of moments. Figure 7 shows a thin-wire representation of the heater element. The thermostat switch is represented as a transient

Modeling the radiating structure was accomplished using the method of moments. Figure 7 shows a thin-wire representation of the heater element. The thermostat switch is represented as a transient voltage source. Important information concerning the modeling can be described: total length of heater element is 4.52m, number of segments used for the radiating structure is 10, length of segments (minimum of $\lambda/10$ criteria was used) is 45 cm, radius of wire segments (same as radius of heater element) is 2.03 mm, and conductivity is 5.8 x 10^7 S/m. Furthermore, since the heater elements were wrapped with teflon, the modeling included an insulating dielectric (ϵ_r=2.1) sleeve around the wire conductor of 2.0 mm in thickness. Since the measurements were made over a wooden platform (1.5m x 1.5m) with a metal ground plane on top, the modeling in the Figure 7 also shows a thin-wire representation of the ground plane (40 segments) and the image of the radiating structure. The transient voltage sources (i.e transient voltage magnitude vs frequency) shown in Figure 7 were obtained by calculating the FFT of the transient current across the thermostat in Figure 5 multiplied by the heater element's impedance. In order to calculate the radiated electric field emissions at a particular frequency, the corresponding transient voltage at that frequency is used as the source input in Figure 7.

A series of transient voltage sources, whose frequencies fall within the frequency spectrum of the transient voltage were used as the driving inputs for the radiating structure of Figure 7 and they are given in Table 1. Table 2 shows the calculated values of the emitted electric fields at the six frequencies of interest using the driving inputs in Table 1. Comparison of the calculated results with measured ones shows very little agreement between the measured and calculated data (an average of 25dB) due to the fact that the measurements were performed in a shielded room where multiple reflections and resonances can cause errors of as much as 40dB. However, it was observed that both sets of data track each other in a constant decreasing trend with smaller discrepancies at higher frequencies (above 24 MHz). For frequencies below 24 MHz the difference goes up considerably.

3.0 CONCLUSION

Radiated EMI in 'the form of arcing and antenna radiation, due to transient events, can contribute significantly to the noise which can threaten sensitive receivers in a spacecraft. The method of moments can be used for estimating the amount of radiated EMI as a result of transient currents produced by circuit elements. Though the example described in this paper is for a thermostat circuit and its associated heater elements, the modeling principles herein discussed are applicable to other types of circuits where transients are observable and measurable. Two important principles to follow in transient modeling are: a) understand the physics of the transient phenomena taking effect for that particular circuit, and b) exercise care in the method of moments modeling.

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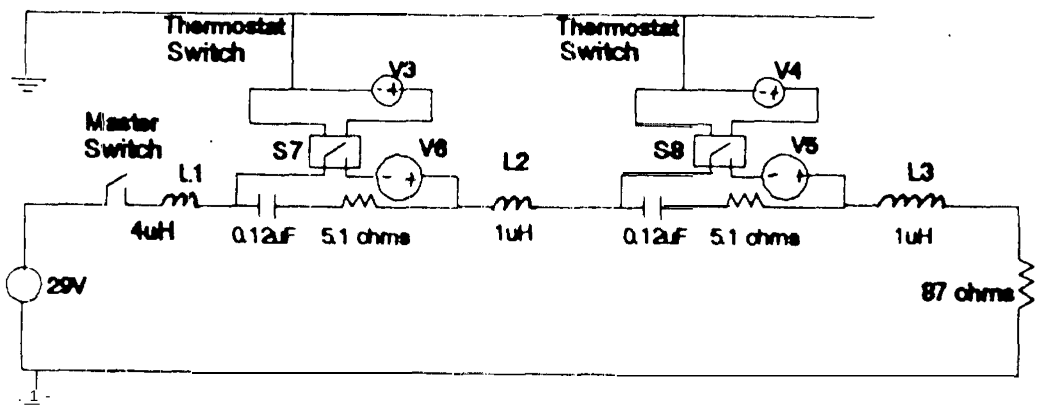


FIGURE 4. pSPICE THERMOSTATS SWITCHING MODELING

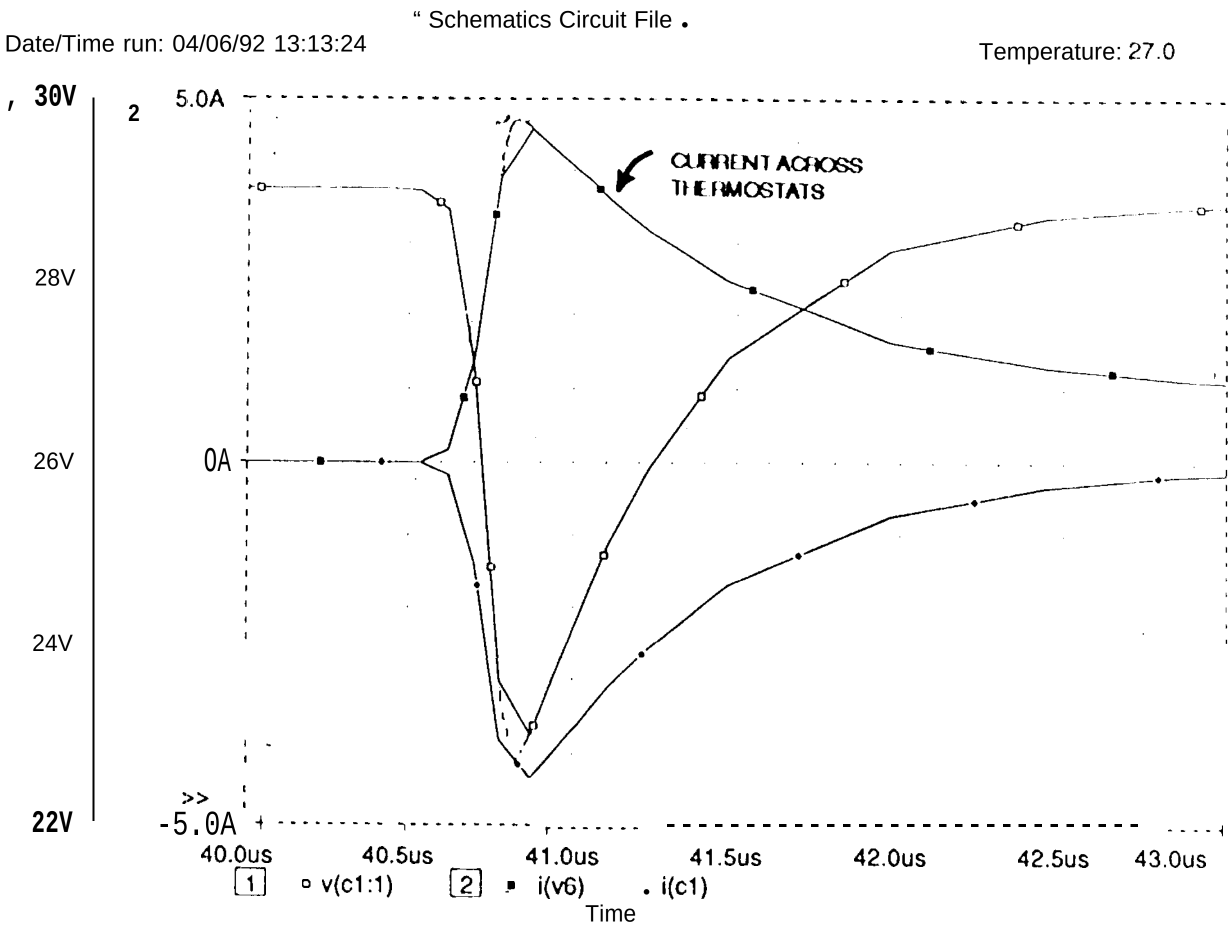
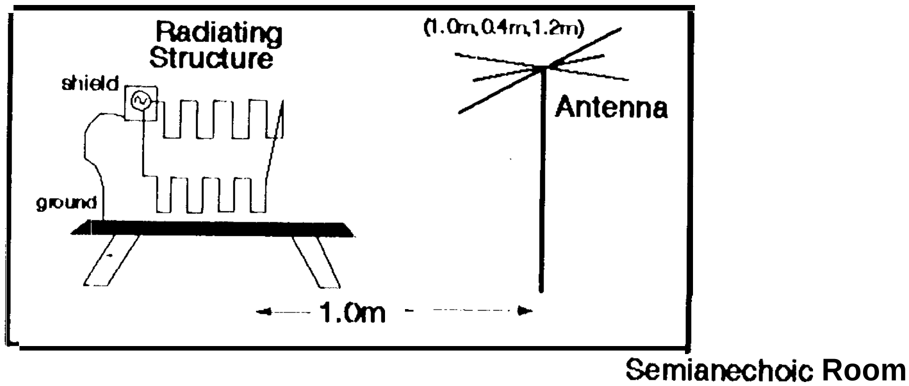


FIGURE 5. TRANSIENT RESPONSE OF THERMOSTATS DURING SWITCHING



IFIGURE 6. MEASUREMENT OF E-FIELD FROM TRANSIENTS

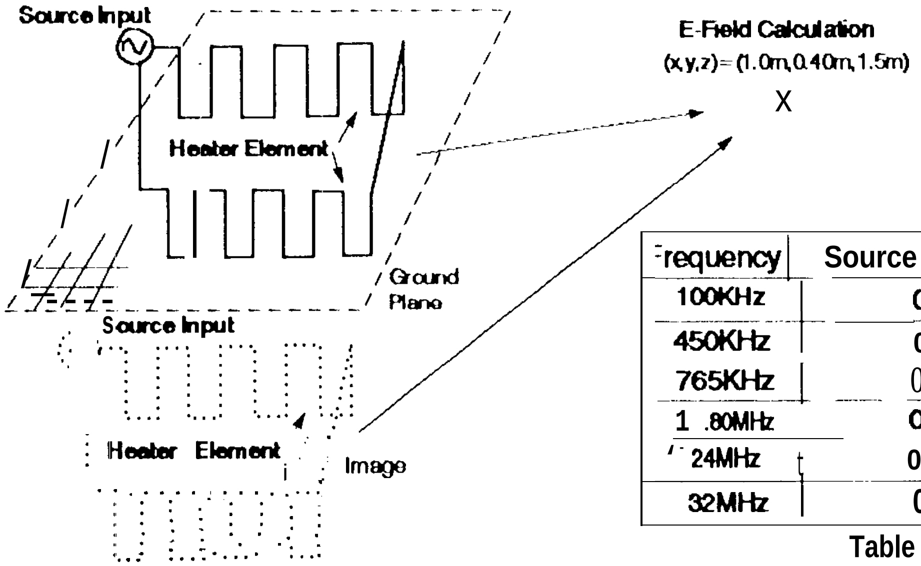


FIGURE 7. METHOD OF MOMENTS MODELING

Frequency	Source Input (volts)
100KHz	0.00082
450KHz	0.00076
765KHz	0.00069
1 .80MHz	0.00066
24MHz	0.00051
32MHz	0.00038

Table 1

Frequency	Calculated E-Fold (dBuV/m)
100KHZ	56.6
450KHz	52.0
765 KHz	48.5
1.80MHz	42.0
24MHz	23.0
32MHz	18.0

Table 2