# A PHYSICAL BASIS FOR EMPIRICAL ELECTROMAGNETIC EFFECTS RESEARCH

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## ABSTRACT

The goal of susceptibility analysis is to predict the outcome of an illumination of a complex electronic system by an electromagnetic wave. This paper describes the process of designing susceptibility tests and interpretation of those tests in physical terms. Significant use is made of regression analysis, but physical laws are used to constrain the analysis. In the end, we develop the means to verify the chosen physics-based approximations with empirical results from susceptibility tests. The results can then be used to design future tests and to estimate the susceptibility of systems that cannot be tested.

## INTRODUCTION

The foundation of science is experiment. The goal of science is to discover laws that relate the various physical quantities with each other. A difficulty in learning physics is that we do not know all of the physical laws and are continually improving the quantitative picture of the universe [1]. Maxwell's equations form one of the most successful physical laws discovered by man. However, it took more than one hundred years to take some of the early measurements and turn those measurements into a coherent theory. Cavendish, for example, established the $1/r^2$ force law to about 10% in 1772. Maxwell did not publish his results until late in the 19$^{th}$ century. As reported in 1975 [2], this same law was shown to be accurate to better than 1 part in $10^{15}$.

One of the physical relationships that we do not presently understand is that of relating an external environment to the failure of electronic systems. Complex electronic systems are very difficult to describe and just the description of the coupling of the fields into the system is difficult without the further complexity of the operation of the electronics. To properly establish an equation or other relation that will predict a failure of an electronic system as a function of its environment we must consider all of the tools we have available, including all established physical laws that might apply and the results of carefully crafted experiments. In the end, we must be able to generalize the prediction of failure so that it applies to a definable, but meaningful class of systems.

Available information for this determination includes various scaling laws, solutions to Maxwell's equations (analytic and numerical), circuit description and solution, and most importantly the results of experiments on the equipment of interest and supporting equipment. Analytic results might include the use of the decay of power density with range or peak field ($1/r^2$) or the decay of peak field with distance ($1/r$). Either might be important to the damage or upset model. Other configurations might have other decay rates with distance or material properties in the presence of material interfaces or other norms of the incident waveforms. More complex solutions might include the acceptance geometry of an aperture as related to the incident fields. For digital electronics the analysis might include the failure probability of a system for various coding schemes and error correction techniques. Empirical results might include the state of a system of interest due to a particular illumination. Effects experiments might include many such illuminations and descriptions of the results in varying levels of detail.

All of the parameters mentioned above are important to the outcome prediction and this technique treats all of them on an equal basis to assure all we know about the system effects is used as part of the analysis. This technique departs from the common practice of assuming that failure responds to a threshold peak electric field or power density. This single variable technique has been shown to be inadequate. In this work, we describe the system configuration as a vector in a linear vector space. Likewise, the parameters of interest are described in another linear vector space. The various relationships described above are linked to the outcome through a single set of equations. These equations are an extension of the General Linear Model used in statistics. Full use is made of the freedom in choosing the transformation variables to support the best use of the "physics" of the problem.

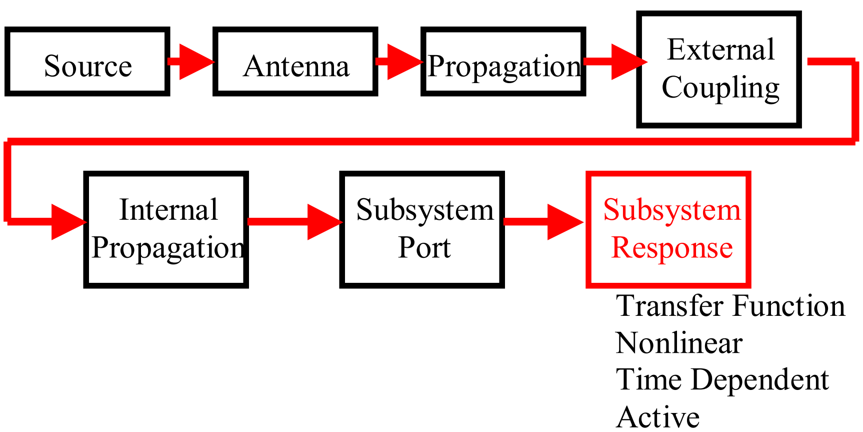
The outcome or prediction is that of the state of the system with an estimate of the uncertainty of that outcome. A typical type of outcome is that of a threshold value for, say, an electric field for a particular type of failure. For that case, the model will determine a transition curve or fit for the failure probabilities. Many other models are possible. Illustrations will be given. Alternate physical models can be applied and tried to find the best fit (e.g., compare both 1/r and $1/r^2$, if the dominant failure mechanism is not known. The main limitation of the model is that the probability estimates must be locally linear in the transformed variables.

When we consider the disruption, upset, or damage of an electronic system due to an incident electromagnetic environment, we want to know the general conditions for the disruption, upset or damage to occur. In other words, we want to predict the outcome of an illumination of an electronic system by an incident wave. Further, we want to know the uncertainty of our prediction as well as the conditions under which the prediction is valid.
Prediction for just the test system is not sufficient, but we want our prediction to be valid for *similar* illuminations and systems. Most analysts take the predicted peak electric field or the peak power density (fluence), compare that value from a derived threshold and use that information to predict failure of an electronic system. That approach leads to very large variance in the various predictions and therefore reduces the value of the prediction [3].

Many other variables affect the outcome of an illumination like the other characteristics of the waveform, the angle of illumination, the topology of the target electronics system, filtering of various elements of the incident spectrum by various elements, rectification efficiency and many others. In this analysis these other parameters will be treated on an equal basis with characteristics of the incident field. Much of the work here is designed to allow the introduction of empirical results into the analysis and trends. Electronic failure is sufficiently complex that models of the function of electronic systems, particularly digital systems do not exist. All of the parameters of interest are examined and important elements are selected for further analysis. Further, there are various physical models for the parameters that aid and limit the analysis. The goal of this work is to provide a framework that will allow locally linear predictions of trends in the variables. The end result of the analysis is prediction of effects, not just the intermediate values of currents and fields.

**A TRANSFER FUNCTION APPROACH**

An illumination of an electronic system takes the following form shown in Fig. 1 that is adapted from [4] and used at length in [5].




Each of the blocks in Fig.1 represents a transfer function. The source has an initial spectrum and the antenna filters that spectrum and provides directivity toward the target. The propagation block represents the decay of the fields as they travel from antenna to object. In common practice in electromagnetic compatibility and in high power microwave effects analysis the effects prediction occurs here. The analyst applies a threshold that is derived from analysis, data or a combination [5]. The threshold is typically a peak field, but may be some other norm [4]. This type of analysis is insufficient to describe the entire failure process and requires further consideration of the behavior of the circuit at risk. The circuit at risk is shown as the subsystem response block in Fig. 1. Its sensitivity to injected currents, and in some cases fields, has a large variance [3]. The purpose of this analytic framework is to determine the variables causing the variance. A circuit of interest is usually active and always acts as a further filter/transfer function at its input. Its response and sensitivity is time dependent with its internal operation and is often nonlinear. Finding the failure characteristics requires that we execute and documents experiments to support our conclusions. We find empirically that such a circuit can respond unfavorably to even very small fields and currents if those fields and currents couple very efficiently to the operating parts of the circuit or directly affect the operation of the circuit.

To use the large number of analytical and empirical tools to complete the prediction, we require a framework where all of the models and any empirical information can be applied compared and extended. The goal is difficult and the model is conceptually complex so we will appeal to a series of examples to illustrate the various facets of the model.

**THE ANALYTIC FRAMEWORK**

This model provides a new framework for analyzing susceptibility data for complex electronic systems that allows the use of both analytical and empirical information to draw conclusions about the data. The model depicts information about the illumination of the system, coupling to the system, and the response of the system electronics through the use of an n-dimensional linear vector space in the following form.

$$F_k(y_k) = \sum_{i=1}^{n} \beta_{ik} g_{ik}(x_i)\hat{x}_i \text{ , where} \qquad (1)$$

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|---|---|
| $y_k$ | Represents one of k categorical response variables, like y=1 might state that the subsystem is upset or y=0 might state that it is not. Several subsystems in the system can be upset. |
| $F_k$ | A function of the response variable, used later for fitting. For threshold analysis this is often the logistic function. |
| $x_i$ | A generalized physical variable representing a parameter in the illumination or describing the target system. Examples might be range, electric field at a point, wall thickness, or a parameter averaged over a range of frequencies. |
| $\hat{x}_i$ | Unit vector used to discriminate parameters. The coordinate is generalized in that we might consider behavior in the "pulse repetition rate" direction. |
| $g_{ik}$ | A function of the generalized coordinate. Important for use in the representation of analytical results. For a coordinate r representing range, g(r) might be 1/r. |
| $\beta_{ik}$ | Coefficient linking and weighting the function of the generalized coordinate to the response. |

This model is by its nature linear in the fit variables and cannot provide a good fit unless that relationship is true. Each of the physical variables may appear in a number of different forms, including non linear forms, but the fit function is linear in the fit variables. This form is limiting only in a local sense, since we can iterate the use of the model to follow more complex curves.

The effectiveness of the model is also limited by the ability of the analyst to plan the test. Typically, there are many more experiments than variables, so that the matrix describing the experiments and used to solve for the $\beta_{ik}$ is over determined. The solution is found using least squares or maximum likelihood techniques. Limitations in the test planning appear when an orthonormal basis set is found for the experiment matrix. Fits can only exist for those experiments spanned by that matrix. Further, the elements of the matrix must properly sample the experiment space since we are trying to describe, by sampling, the entire range of experiments within the range of parameters.

While it is difficult to use the information derived from these techniques outside the range of the experiment parameters, the very purpose of this analysis is to use the trends found here to plan additional experiments or to find opportunities outside the space that might interest a sponsor. Note that there often is no other information available that might provide scientifically sound means of making predictions of this type.

**THE FRAMEWORK BY EXAMPLE**

The model in equation (1) is very general and has a lot of freedom to solve a large number of problems. Rather than using a long explanation of each variable, we will use a simple example. The simplest effects test that we might do is to establish a range threshold for a particular object whose failures are independent of angle of incidence and depend exclusively on a threshold of peak electric field or power density. The purpose of this experiment is to decide which of the two is dominant in causing effects in the particular target system. Equation (1) for this case is

$$P = \frac{1}{1 + e^{-(\beta_0 + \beta_i / r + \beta_i / r^2)}} \qquad (2)$$

The $y_i$ are now the probability P of electronic failure of the single device. The F function is the logit and has been inverted for proper representation of the threshold. Each of the $\beta_{ik}$ can be found using failure experiments at various ranges. Note that this set of experiments assumes the absence of an interface since the leading term for the electric field may be something other than 1/r.

When we introduce data from effects experiments, we normally note the outcome categorically. That is, there is either an effect or there is not. For these tests, the probability of failure is either 0 or 1 for that particular example. The logit cannot be inverted for these values because it does not exist there. Equation (2) must be solved using numerical techniques.

## CONCLUSIONS

We have outlined a number of research areas that are basic to electromagnetic effects research and have identified some particular questions associated with those areas. We hope to develop a predictive capability for electromagnetic effects on complex electronic systems and hope that this discussion will stimulate additional research in these areas. The interesting research areas are:
Extension of the physical models of tubes to include system information and noise propagation with more general models than the current transmission line models for wave and signal propagation.
A. Determination of the required detail for effects modelling.
B. Determination of the degree of change that a particular model can tolerate.
C. Substantial improvement in numerical model resolution and data input interface.
D. Development of a more detailed and basic theoretical foundation for statistical electromagnetics.
E. Improvement in the range of applicability of functional analysis models.
F. Improvement in the techniques, goodness of fit prediction and efficiency of multivariate data analysis techniques.

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