Interaction Notes

Note 264

October 1975

Evaluation of Present Internal EMP Interaction Technology: Description of Needed Improvements

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Abstract

This report presents a description of the state of the art in the area of internal electromagnetic pulse (EMP) interaction technology. Improvements in the modeling methodology are suggested and a number of specific problems are described which will permit more accurate solutions to problems in this area.

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I. Introduction

It is generally acknowledged that the weakest link in the analysis of complicated systems excited by a nuclear electromagnetic pulse (EMP) is the area of internal interaction. Not only because of extremely complicated and ill defined geometries, but also because of computational difficulties is this statement made.

A great deal of effort has gone into the studying and understanding of EMP production within the source region as well as how the EMP interacts with the exteriors of various objects, both inside and outside the source region. Simple geometries such as spheroids and cylinders have been analyzed, as have other more complicated structures such as crossed cylinders, which approximately represent a physical aircraft. Currently, more sophisticated external electromagnetic aircraft models are being developed and will be employed for future analysis.

Similarly, the field of circuit analysis is well developed and is capable of predicting the behavior (both linear and non-linear) of circuit elements, provided the appropriate driving functions are given. Such forcing functions are usually defined by a voltage or current at the input of a circuit.

The general area of internal interaction is that which links the external calculations to the circuit calculations. Any difficiencies existing in the analysis at this level will thus adversely affect the results at subsequent stages of analysis for the overall system behavior.

In terms of future efforts to better the state-of-the art in calculating responses of overall systems, it is most beneficial to concentrate the efforts in the areas where the uncertainties are the greatest. Thus, the area of internal interaction is one which deserves to receive more interest in the near future.

As described in detail in a previous note (1), the area of internal interaction can be divided into three overall categories: coupling, penetration, and propagation. Each of these sub-problem areas are encountered one or more times within the confines of a shielded system. For a complicated and/or well shielded system, there are a number of layers or levels of shielding, each of which requires separate calculations of coupling, penetration, and propagation.

The transfer of EMP energy from one topological volume to another is referred to as the penetration problem. The coupling problem involves determining the local sources which excite the transmission lines within the shielded region in question, and the propagation problem is the determination of the distribution of energy on the transmission lines as excited by the local sources.

Although it is possible that there may be some arbitrariness as to how a particular system can be divided into topological volumes and as to where the division between coupling and propagation should be made, these concepts provide a useful way of looking at the complex problem of internal EMP interaction.

Aside from the general topological and problem definition question mentioned above and discussed in more detail in Ref. (1,2), the present report goes on to suggest a number of specific improvements which could be made in the area of internal interaction.

Previous work in internal interaction has almost exclusively employed the single transmission line model to determine the energy transport within the interior of complex systems. In Section II of this report, a brief discussion of this approach, its assumptions, and limits of validity. It will be clear that additional work is needed to develop a more accurate prediction process.

Section III goes on to suggest a number of specific problems which should be considered to permit the development of a more accurate mathematical model for internal interaction problems. Because of the wide use of the single transmission line model by a number of groups engaged in EMP analysis, it is thought that any improvements made in that model could be readily incorporated in the various computer codes, thereby having immediate impact on the accurary of the analysis. Thus, a number of specific coupling and propagation problems are outlined for the single line model.

It must be kept in mind that the single line model, even with possible improvements, is inherently limited as to its ability to model complex, many wire transmission lines. An accurate treatment of this problem can be treated by developing a rigorous multi-wire transmission line model for internal interaction. Many of the specific coupling and propagation problems which arise in the single line case also are found in the multi-wire problem. Section III concludes with a description of these problems in relation to a multi-wire analysis program.

In Section IV a discussion of statistical methods and potential applicability to internal interaction problems is presented. Due to the extreme complexity of the interior cable geometry on airborne systems and due to the inherent randomness of many multi-wire cable bundles, this approach may have broad applicability as an analysis tool.

Finally, in Section V a summary of the program recommendations is presented and a suggested project plan is illustrated. The basic philosophy of the proposed plan is two fold: to better understand and improve upon the limitations of the single line family of internal interaction codes and also to develop technology in the multi-wire analysis code. As a result of successfully performing both of these tasks, we will also have indications of needed experiments to verify theoretical results and will be able to develop screening criteria or guidelines for simplified internal interaction analysis.

II. Current State of Internal Coupling Analysis and Possible Improvements

In attempting to perform an analysis on a complicated system, one of the most difficult tasks in proceeding with the internal interaction portion of the analysis is not the solution of a specific transmission line excitation or propagation problem, but is the simplification of the extremely complex internal geometry into a reasonable number of cables and loads which can be analyzed without exorbitant expense.

Presently there are no well defined and documented guidelines which indicate how the geometry simplification should be made. Clearly the effects of direct cable illumination, cross cable coupling and cable loading are important in understanding how to simplify the geometry, but are not the only ones which affect the choice. Often the simple observation of a cable bundle passing near a point of entry will cause that bundle to be labled as a critical coupling path.

As a first step in attempting to better understand the internal interaction problem, various "screening criteria" or "model simplification guidelines" should be developed and made available to the community. The topological concepts of the system previously monitored will assist in doing this, as will studies of specific cable problems.

One difficulty with many analysis methods is that a large number of calculations must be performed. Such calculations are usually done sequentially, and an error in any one calculation can have serious consequences in the final result. The development and use of the screening criteria should be done in such a manner to eliminate the need for extensive computation in the internal interaction area.

Generally speaking, however, there will be a tradeoff between computational difficulty and accuracy of the final results. The development of the screening requirements must attempt to minimize the computational difficulty and provide maximum accuracy within the tolerances deemed acceptable by the systems analysts.

The most widely used approach for analyzing internal interaction problems is to use a single transmission line model to calculate the total or "bulk" current flowing on a number of individual cables which are all oriented in the same direction. Thus, the complicated configuration of power and signal cables leading to the disconnect panel, as shown in Fig. 1, would be represented by one or more single transmission lines connected to simple, averaged loads. As will be pointed out, many of the assumptions which have gone into developing this model are of an empirical nature. This results in poor agreement between theory and experiment in many cases.

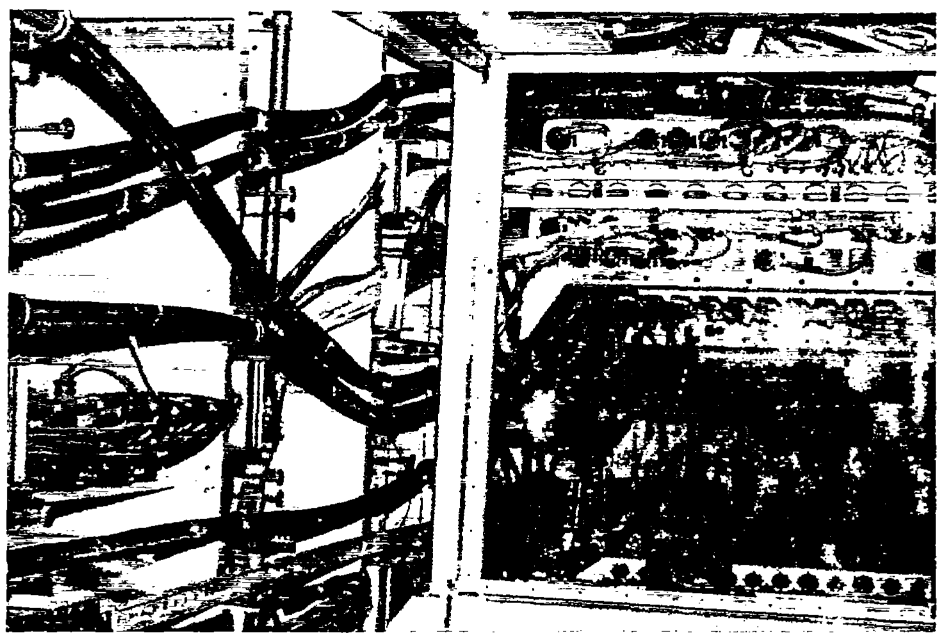

Figure 1. Power and Signal Cables in AABNCP.

Consider the schematic representation of a complicated cable network with various loads as shown in Fig. 2. Each wire pertains to a particular cable bundle and is loaded with a unique load impedance (usually complex) at both ends. Over some portion of the wire there are electric and magnetic fields which serve to excite the currents on the cable. These are not indicated in the figure. The analysis of such a multi-wire transmission line is indicated in Ref. 3 and 4.

The main arguments put forth by investigators against wide-spread use of a multi-wire model with proper individual wire terminations are:

1) The collection of wire configuration and termination data would be monumental and valid for only specific systems.

2) Computation time and memory requirements are prohibitive.

In view of these objections, a number of investigators have developed a single line common mode individual wire model, which can be implemented in a computer algorithm. Such an approach assumes that a wire of interest in a multiconductor cable can be represented as a single transmission line coupled to the cable common mode (bulk) current only at its terminals.

The transmission line per-unit-length parameters of inductance, capacitance, and resistance (or equivalently,

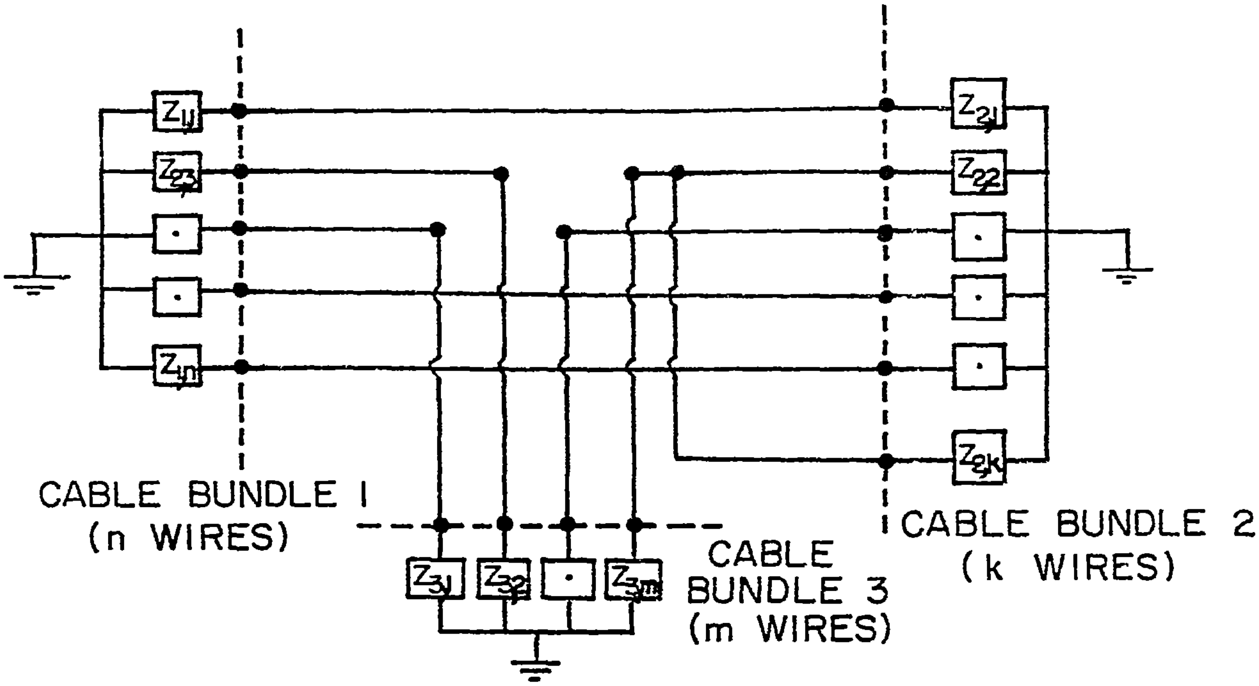

Figure 2. Generalized Multi-Conductor Cable Network.

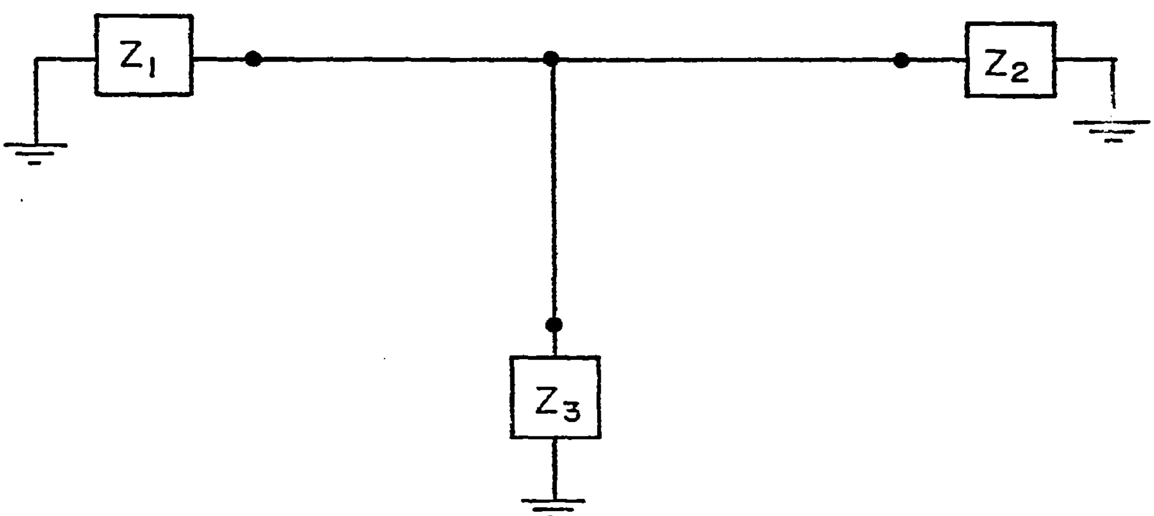

Figure 3. Single Wire Equivalent of Multi-Conductor Cable Network.

complex propagation constant and characteristic impedance) are often calculated by another computer program, which considers unshielded wire bundles over a ground plane, cables with braid shields, cables in conduits, controlled lay cables, or compound cables made of several internal cables.

Thus, the complicated cable system in Fig. 2 is simplified to yield that shown in Fig. 3. The main quantity of interest is the total or "bulk" current flowing on the line. This model presumes that it is possible to define some sort of an "average" load at the termination of a particular cable bundle and that the current on each of the n wires is the same. It is not clear under what circumstances these assumptions are truly justifiable.

The main quantity of interest in an analysis of a cable system is not really the bulk current, but how a particular wire in the larger cable can excite a circuit connected as a load. Using the equivalent circuit concept, the effect of the single wire can be expressed through an input load impedance seen looking into the wire and a Thevenin voltage source as shown in Fig. 4. If this approach is to be used, it would be desirable to relate these quantities, Z_{in} and V_{oc}, to physical properties of the line and give a rationale for how they are chosen. For many existing single line models, however, this is not done.

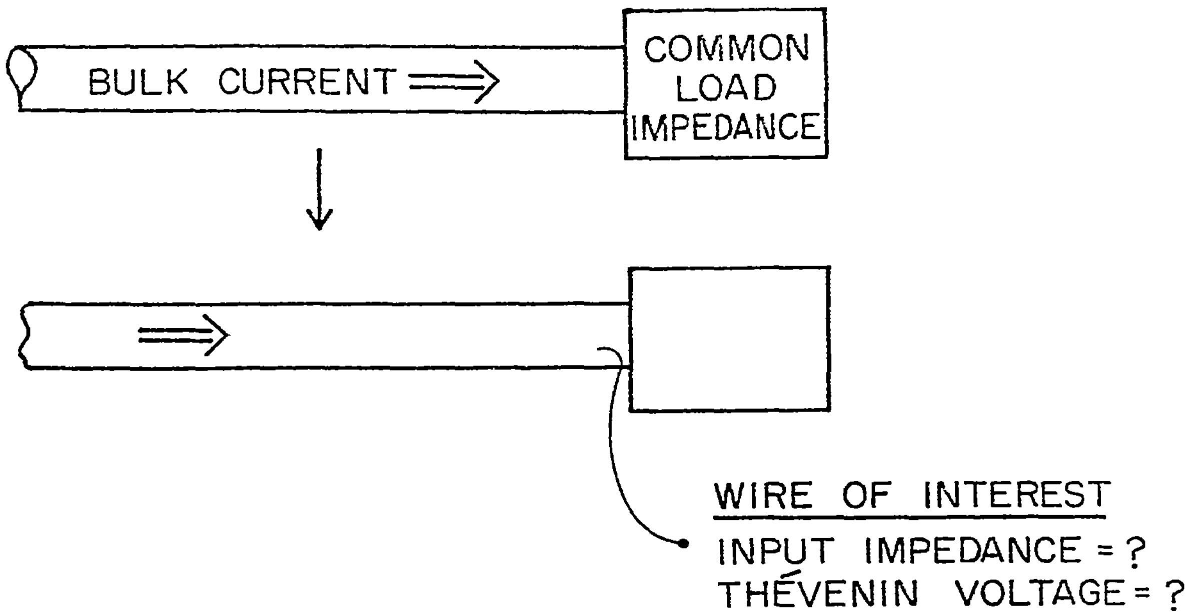

Figure 4a). Single Wire Isolated From Cable Bundle.

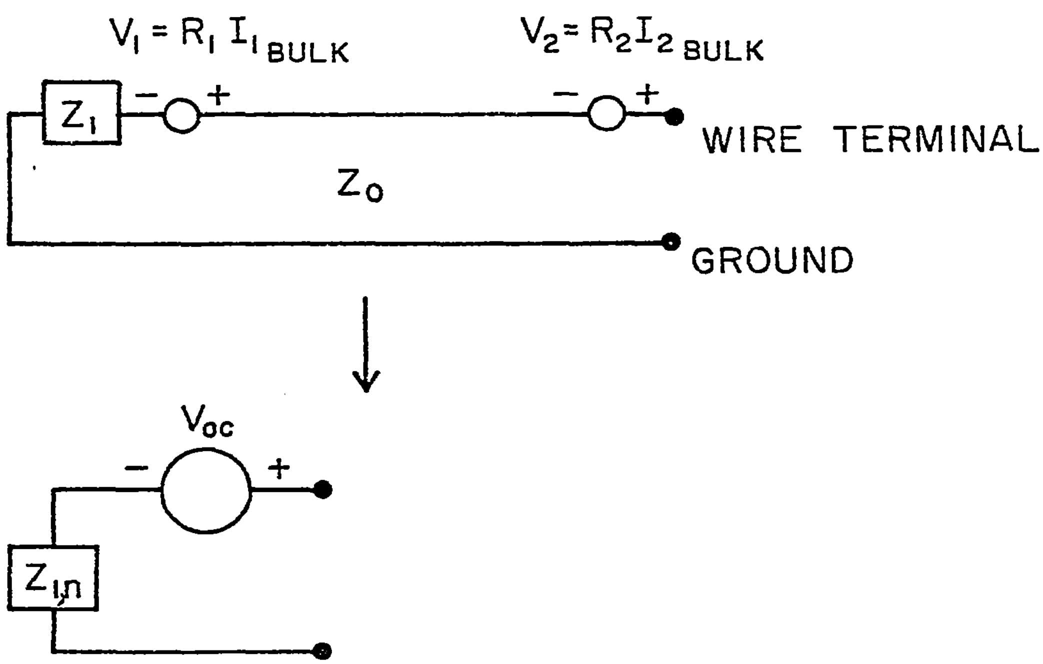

Figure 4b). Individual Wire Model with Driving Terms

As an example, in the SNGLIN code[5], the terminal impedance is assumed to be the impedance Z_1 connected to the input of the wire under consideration, transformed by the transmission line. In doing this, effects of cross coupling between transmission lines is neglected and the transmission line impedance for the wire under consideration, Z_o, is determined empirically.

Moreover, the excitation sources V_1 and V_2 are assumed to be located at only two positions on the cable and are related to the cable bulk currents at those points by real constants, R. These constants are not calculated, but are also determined empirically. As shown by King[6], generalized coupling between transmission lines requires three excitation sources not two. For a current distribution on the exciting line (the bulk current in this case) being an odd function about its center, only two sources are necessary. It is not clear at the moment that this will be the case for the problem under consideration.

During the course of development of the single line model, limited sensitivity studies have been performed to examine the effects of variations in height above ground plane, non-uniform spacing above ground plane, rib-structure ground plane, metallic bundle anchor straps, branched segment lengths, point excitation source position, and branch locations.

These studies usually lead to generalizations as in the case of rib structure where it was determined that such structure inserts a lumped capacitance into the cable and can be viewed as reducing ground plane spacing. But we might also expect frequency selective characteristics.

Another example is the conclusion drawn for non-uniform ground plane spacing that the common mode propagation velocity was decreased with a corresponding decrease in common mode frequency response. Since the single line model's strength lies in its high frequency predictions, quantitative statements are in order about frequency response degradation for various types of non-uniform ground spacing.

The preliminary sensitivity studies already accomplished should be expanded to include other geometrical configurations prevalent in aircraft, including bundle passage through metallic bulkheads, changes in bundle configurations near obstacles or anchoring structures, not only random conductor lay but also highly non-uniform conductor spacing and non-homogeneous dielectric around wires (especially important in differential mode calculations). More will be said about these areas in Sections III.

As mentioned earlier, a more rigorous approach to the internal interaction problem is to employ a multi-wire transmission line analysis. Kajfez[7] gives a particularly good description of the method of analysis and includes a number of examples. A more mathematical treatment is given by Frankel's recent reports[3,4]. Other reports are also available, such as Ref. (8), but may be more difficult to obtain.

Very little work appears to have been done in applying multi-transmission line theory to practical problems of interest. Results of a recent literature search[9] indicate that the current problems being treated using this approach are still rather academic in nature. Some computer codes are reportedly in existence, such as the TEQUILA code at Boeing[10], a frequency domain and time domain code at Harry Diamond Laboratories*, and a similar frequency domain code at Mission Research Corp.**, but they do not seem to be widely employed.

In order to promote the further use of the multi-wire approach, there are a number of steps which should be taken. A critical examination of the existing analysis codes should be made to determine which code is the most accurate and flexible for internal interaction purposes.

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* Private Communication with Dr. Dave Merewether, Mission Research Corp.

** Private Communication with Capt. Doug Wilson, DNA.

This effort is similar to the study of existing wire computer codes by investigators at the Lawrence Livermore Laboratory which resulted in the Ohio State University code being selected for future external interaction calculations.

Second, the selected code should be made available to every investigator in the field along with a user's manual, or a similar document which illustrates the use of such a code on practical problems.

Finally, a number of improvements over the conventional multi-wire analysis can be made which will enhance the accuracy of the analysis. These are similar to the propagation problems for the single analysis to be described in Section III.

Another approach for treating the internal propagation problem is available for use. This is the lumped parameter network model (LPN) which permits the representation of a complicated transmission line network by a large number of lumped (discrete) curcuit elements, such as capacitors, inductors, or resistors.

Although this method is very powerful for treating the complex geometries typically found in internal interaction geometries, its use is not widespread. The reason is that a large computer and a circuit analysis code (like TRAFFIC) must be used to obtain a solution to the problem.

Such an analysis requires substantial computer time and storage. In addition, it requires much effort simplifying and modeling the system before the analysis is effected.

For these reasons, the LPN model has not been looked upon as a serious contender for the internal interaction area. However, the interesting possibility of combining both the distributed, transmission line methods with the LPN method has been suggested by some investigators and would be one way of treating geometries which are uniform for some distance but which then become very non-uniform or perturbed for a short distance.

The remainder of this report will concentrate on the possible application and improvements of the transmission line models to internal interaction.

III. Needed Transmission Line Model Improvements

In the area of internal interaction analysis there are a number of possible improvements in both the energy coupling area (the determination of local sources) as well as in the internal propagation area. As will be seen, similar coupling and propagation problems arise in both the single and multi-line cases.

The two major sources of coupling in an EMP vulnerable system such as the AABNCP are direct illumination by equivalent aperture sources and coupling from nearby transmission lines. For a single transmission line, the coupling analysis is usually formulated in terms of distributed transmission line voltage and current sources that are generated by the incident longitudinal and transverse electric fields as shown in Fig. 5. The longitudinal E-field generated distributed sources can be viewed also as originating via the incident magnetic flux linkages between conductors.

The differential section equivalent circuit for a lossless line is shown in Fig. 6 where the distributed voltage and current sources are generated by the arbitrary spatially distributed incident longitudinal and transverse E-fields, respectively. An excellent and detailed development of the coupling analysis for such a balanced two conductor lines, (or single conductor over a ground plane), is given by K.S. H. Lee,[11]. A related paper by Latham is found in Ref. (12).

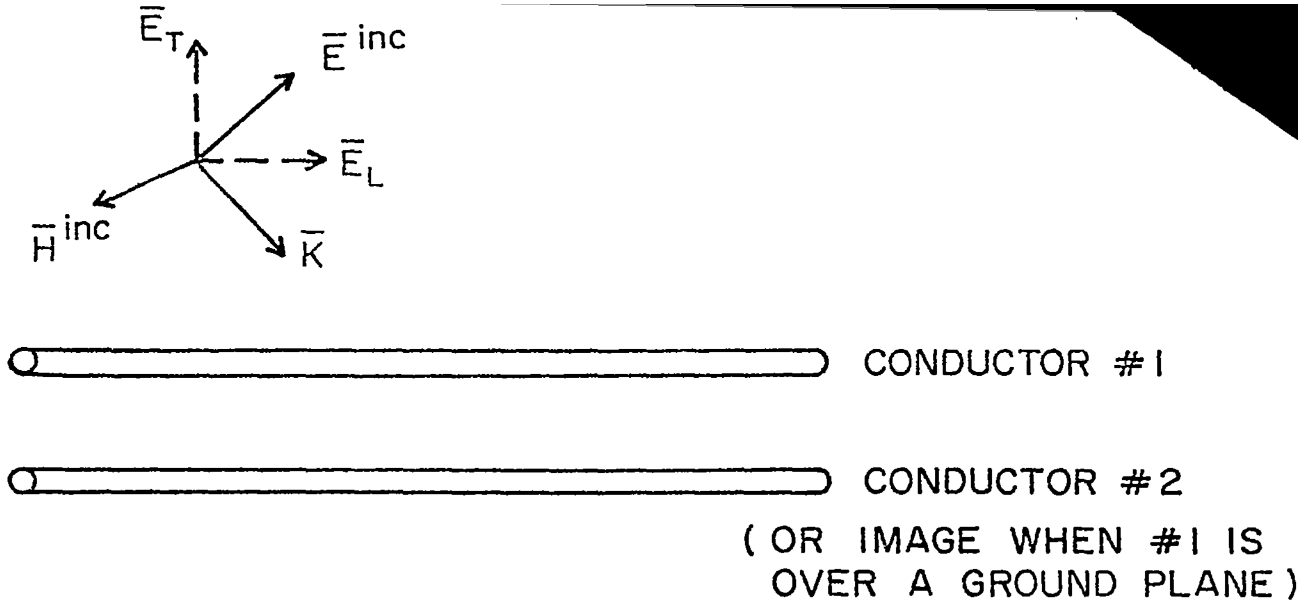


Figure 5. Single Line and Incident Field

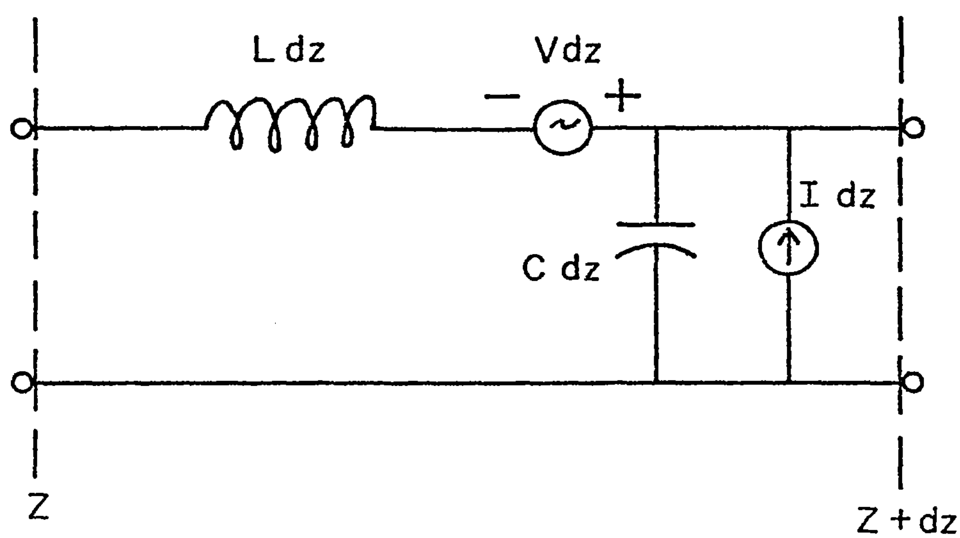


Figure 6. Differential Section Equivalent Circuit

It would be desirable to extend these calculations to cases where there are losses in the cable structure. It is well known that in this case we obtain a resistance per unit length in series with L and a conductance per unit length in parallel with C in Fig. 6. The variations of the sources should be calculated for this case.

For more general applicability of this theory, its formulation for use in non-uniform lines would also be a desirable task. Moreover, it would be desirable to numerically investigate the effects of non-uniform fields on the source terms as done theoretically in Ref. (11) for some specialized types of primary sources, such as diple moments.

For example, the dipole moments (due to an aperature, perhaps) shown in Fig. 7 will produce exciting sources on the transmission line which vary as a function of position along the line. Although the peak could occur at $Z = Z_d$, the same transverse position in which the dipole is located, it may occur elsewhere on the line, depending on the dipole orientation. It would be interesting to know how rapidly such source terms decay in amplitude along the line for various orientations of the dipole moments. The results of such a study would be useful in understanding and developing the various screening criteria previously mentioned.

Aside from energy flowing directly from apertures to the transmission line, there is energy coupling from

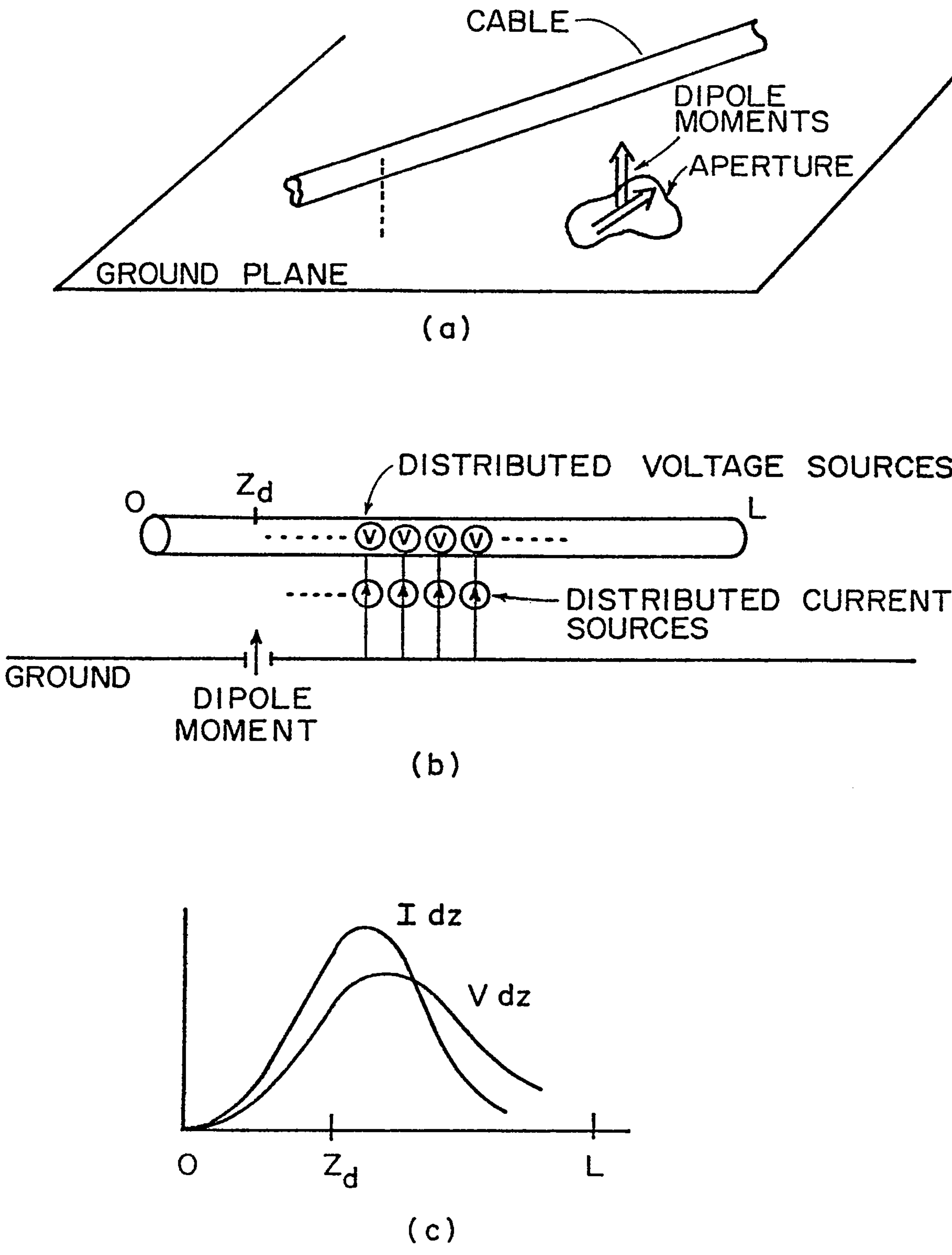


Figure 7. a) Localized excitation of Cable by Aperture.
b) Equivalent Excitation Sources Along Cable.
c) Hypothetical Variation of Sources Along Wire.

scattered fields within a given penetration level as well as from waveguide or cavity type fields that propagate or resonate within closed structures such as interior hull sections of an aircraft. Such scattered, waveguide, and cavity mode fields are believed to play only a minor role in the complete interior interaction process, with the possible exception of a few special cases where the processes of penetration, coupling, and propagation are difficult to consider separately. In attempting to simplify an actual system for analysis, however, this effect should be kept in mind as a possible coupling mechnaism and included in the tasks of developing screening criteria for systems.

The topic of parallel transmission line coupling is considered in detail by King.[6] The simple two line case is shown in Fig. 8. Note that this problem does not fall within the realm of multi-wire transmission line theory since the source or excitation current is assumed to be not affected by the presence of the nearby transmission line.

The results for this simple case indicate that in general the effect of the exciting line on the excited line can be summarized by placing three sets of oppositely polarized voltage sources with appropriate magnitudes and locations on the excited line as in Fig. 9. As previously mentioned this theory is seemingly at odds

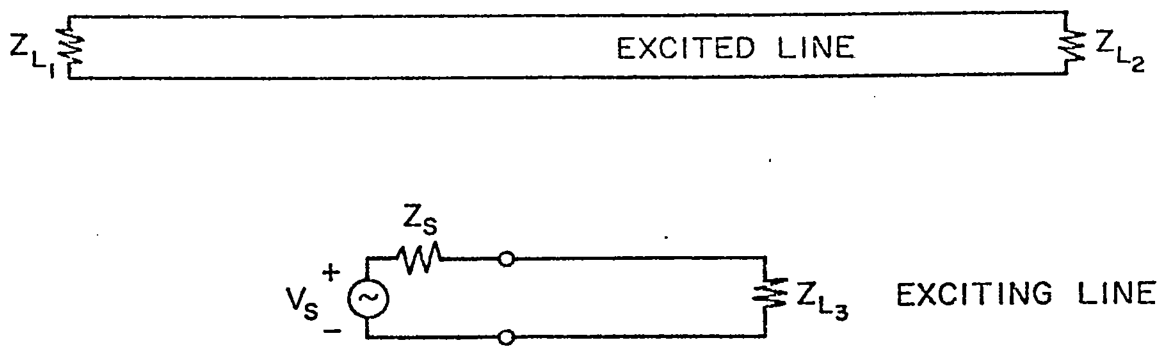


Figure 8. Simple Parallel Driving and Driven Lines.

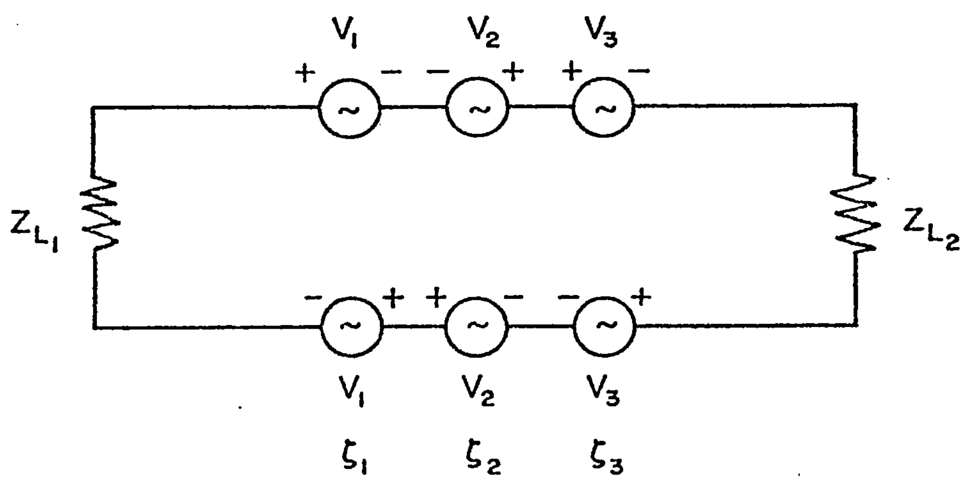


Figure 9. Equivalent Driving Generators.

with what is done in the single line analysis for determining the excitations of a single wire within a larger bundle.

A very important topic, with respect to EMP interaction analysis which should be investigated as soon as possible, is the coupling between both parallel and non-parallel meander lines for the general case of one exciting line and N coupled excited lines. As before, studies should be made with the idea of trying to understand when a particular cable can be considered as being uncoupled from another and when it is necessary to consider the coupling for an accurate analysis.

The second area of possible improvements lies in the propagation model. As has been mentioned, the accuracy of a single line, bulk current model presumably could be increased by taking into account perturbations in the local geometry which may affect TEM wave propagation along the line. After visiting the AABNCP and inspecting the internal wiring, it became apparent that there are a number of specific problems which could be solved to better the transmission line models.

The basic idea behind such a procedure is shown in Figure 10 where a uniform line over a ground plane passes by some form of an obstacle. The simple single line analysis neglects the presence and subsequent effects

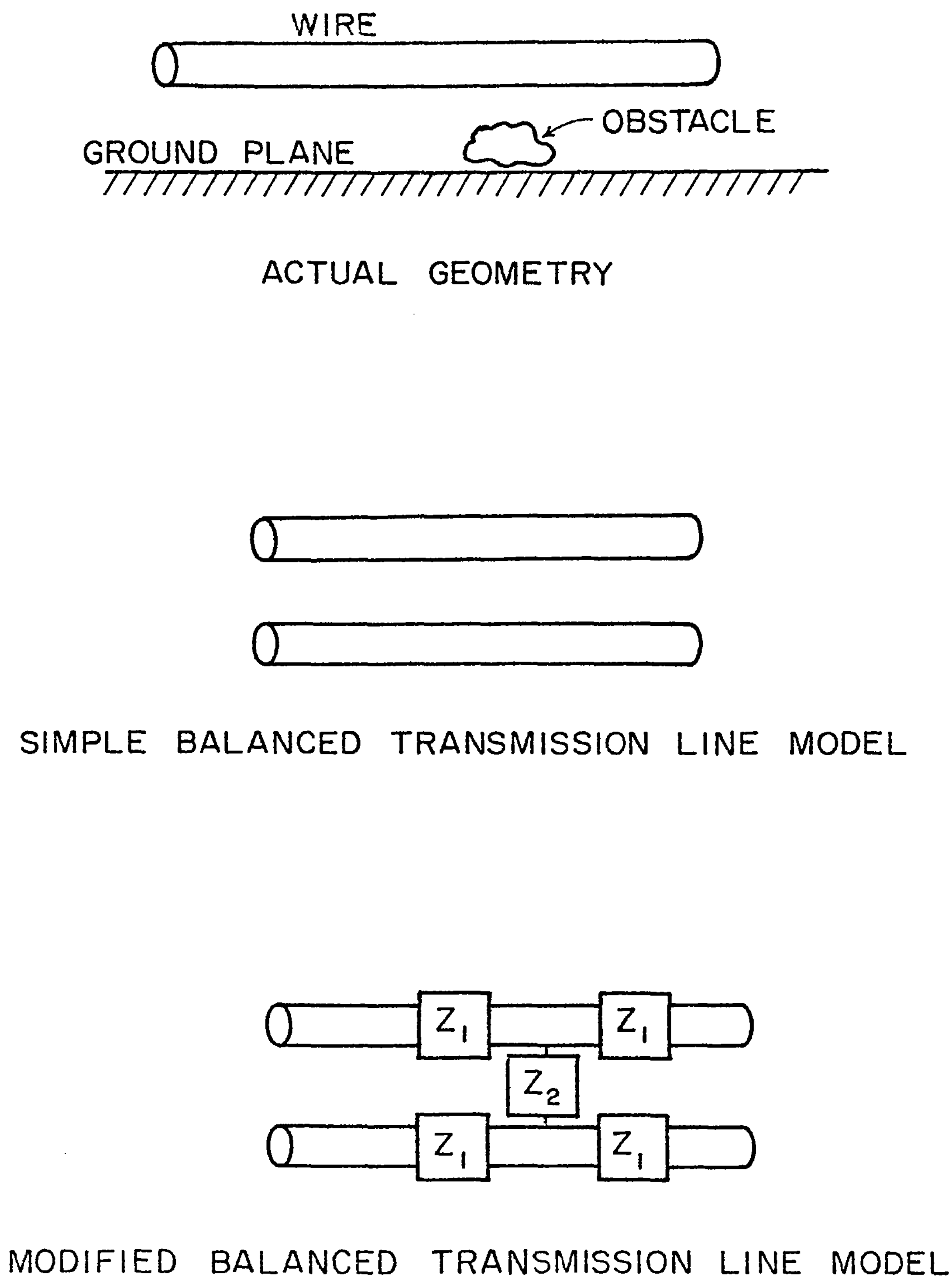


Figure 10. Effect of Obstacle on Transmission Line Model.

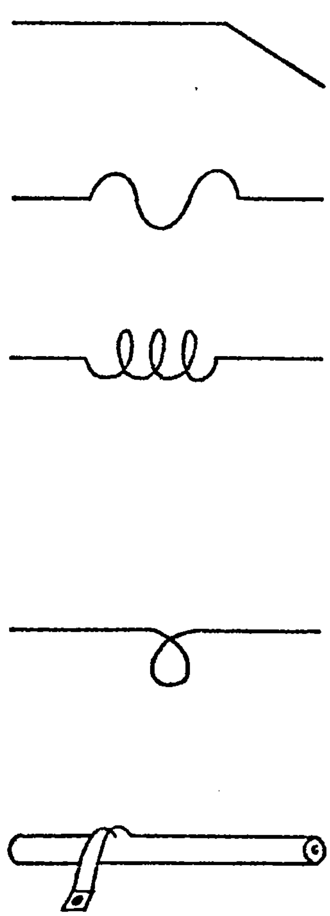
of the object. However, by inserting lumped elements in the transmission line, the effect of the obstacle on the wave propagation can be calculated. For obstacles of a more extended nature, a distribution of lumped elements would be needed.

For cases such where a single lumped element is not sufficient to represent the perturbing effects of the obstacle or line non-uniformity, it is necessary to calculate the transmission line parameters L, C, R, and G as a function of position and use non-uniform transmission line theory, LPN modeling, or another approach to compute the wave propagation along the section

Figure 11 shows pictorially a number of typical propagation problems whose solutions would provide a more accurate propagation model. Some of these may have been examined previously, such as a wire with a bend as in case A), which was investigated by King[6]. Nevertheless, the existing literature is extremely weak in providing adequate detailed analytical consideration of propagation on most of the single wire structures that are shown. Investigation of the propagation on such geometries should be initiated as soon as possible to permit accurate overall system evaluation using the solutions to these propagation subproblems.

As has been mentioned previously the application of the single line common mode model to multiple con-

(O.G.P. ⟹ Over a Ground Plane)



A) Angle Bend/O.G.P.

B) Meander Line Section/ O.G.P.

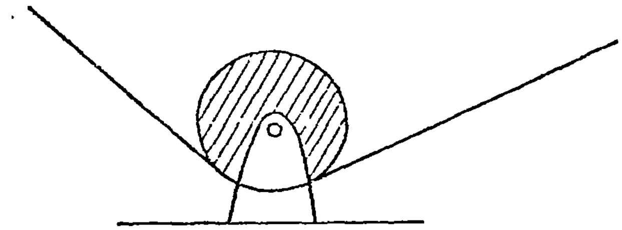
C) Helical Line Section Either O.G.P. or Wrapped Around Cylindrical Ground Post

D) Single Planar Loop (Arbitrary Orientation O.G.P.)

E) Cable Clamps Metallic and/or Dielectric (e.g. Metal Clamp with Dielectric Ring)

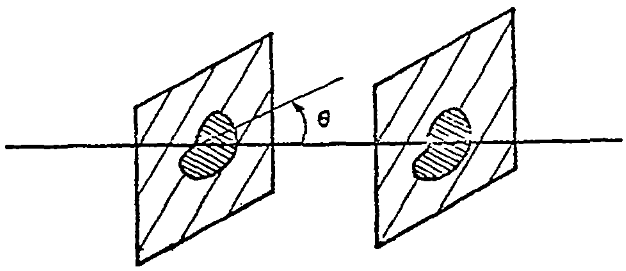
Figure 11. Some Relevant Single Line Propagation Geometries

F)



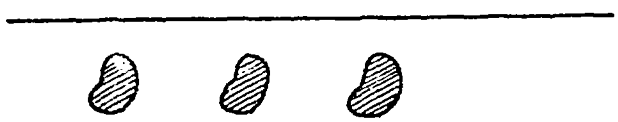
Cable With Insulated
Pulley Guide

G)



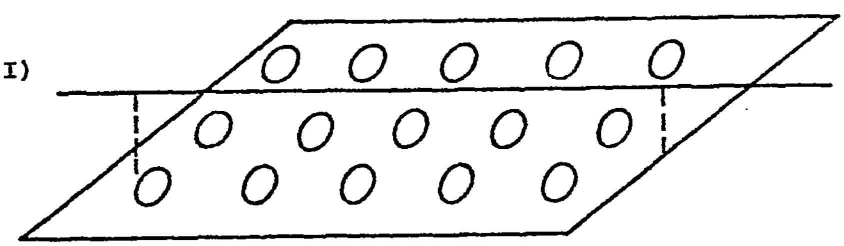
Single and Periodic
Feed Throughs/O.G.P.
(e.g. Bulkheads)
Arbitrary Hole Shapes,
Perhaps with Dieletric
Ring

H)



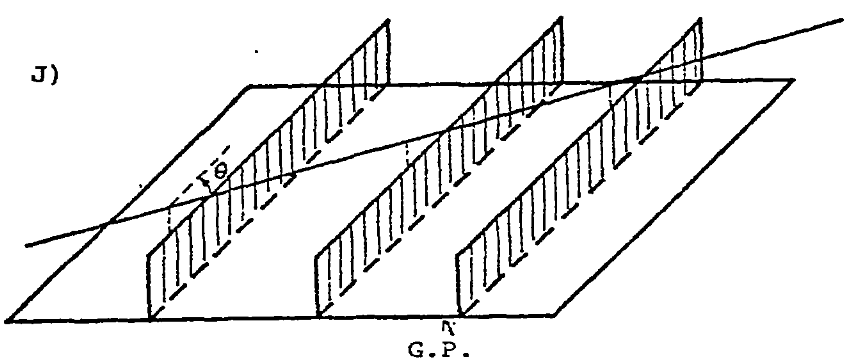
Single and Periodic
Nearby Metallic or
Dielectric Obstacles
O.G.P.

I)



Single and Periodic
Holes in the Ground
Plane

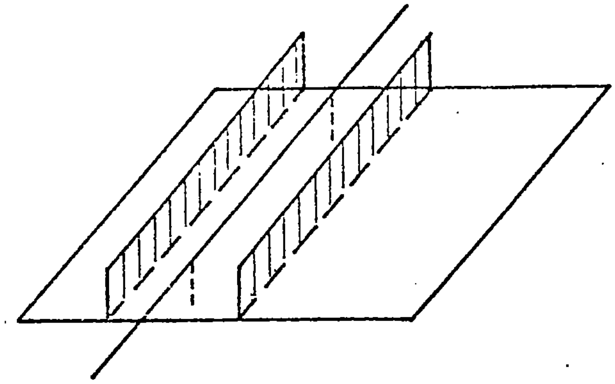
J)



Single and Periodic
Vertical Plates/O.G.P.
Line Passing Above

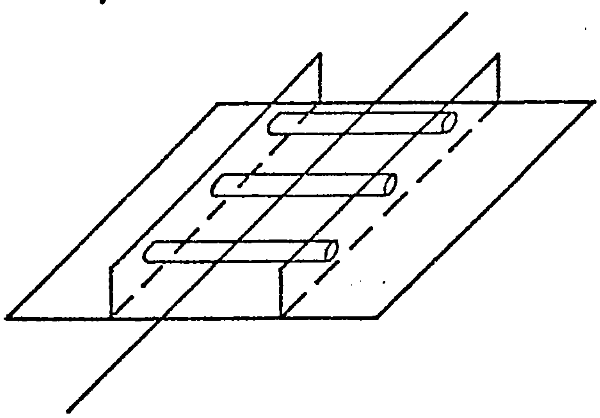
Figure 11 (continued)

K)



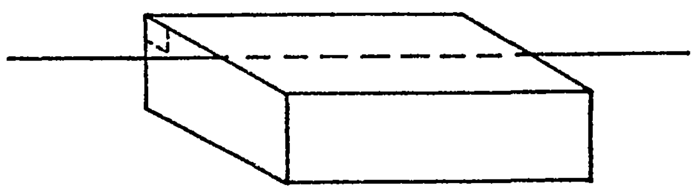
Line Near One or Two
Parallel Vertical Plates
/O.G.P.
(e.g. Line in a Trough)

L)



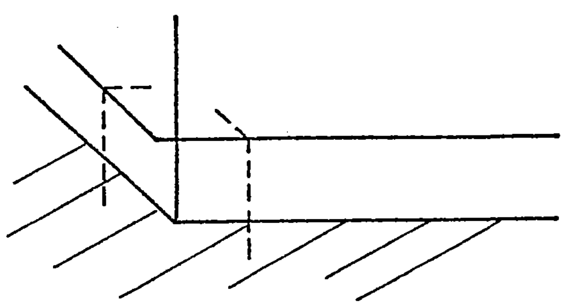
Line Above Periodic
Circular or Rectangu-
lar Cylindrical Posts

M)



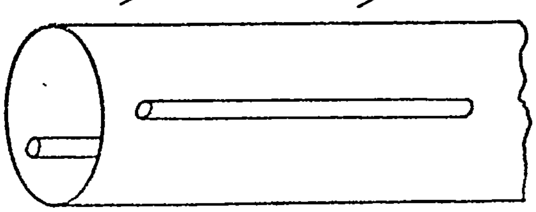
Line Inside or Out-
side of General
Cylindrical Pipe/
Duct (Non-Circular)

N)



Line Around a Corner/
O.G.P.

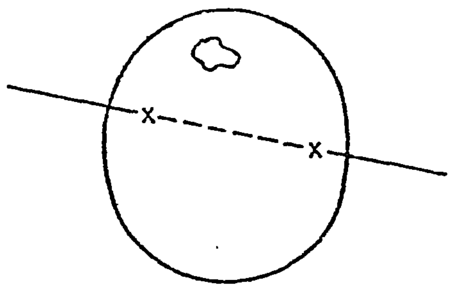
O)



Wire Inside (Outside)
Very Large Cylinder.
When is infinite
ground plane accurate.

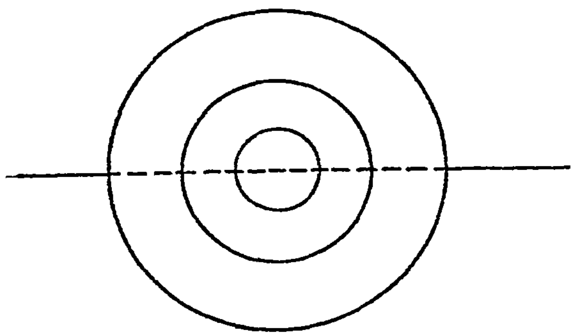
Figure 11. (continued)

P)



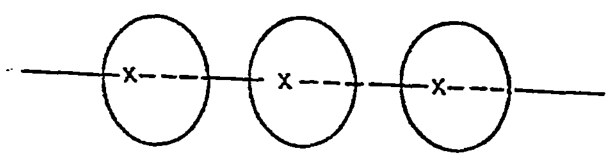
Line Passing Through Cavity. Excitation Either by Injection of Current or Through Aperture

Q)



Line Passing Through Multiple Cavities in Parallel

R)



Line Passing Thorugh Multiple Cavities in Series

Figure 11. (concluded)

ductor cables and cable bundles having individually different loads on each line often leads to completely erroneous estimates of load voltages and currents. The basic error in the common mode model is the oversimplifying assumption that differential potentials between conductors are negligible.

To accurately describe propagation on multiple conductor cables, cable bundles, and parallel cable systems, a generalized multiconductor line capacitance matrix and inductance matrix approach should be utilized(3). Using this method, a section of cable shown in Fig. 2 can be represented by the equivalent lumped circuit of Fig. 12. The impedance matrix ($Z_{n,m}$) has in general a resistive component as well as an inductive component. Similarly, the admittance matrix ($Y_{n,m}$) has both capacitive and conductive components. For lossless cables, these matrices are related to the capacitive and inductive matrices for the cable.

The source terms V_n and I_n in Fig. 12 are determined by the incident electric and magnetic fields through the use of electric magnetic coupling vectors described in Ref. (4). Similarly, it is possible to represent a termination of a multi-line cable by a termination impedance $(Z_{n,m})_T$ as illustrated in Fig. 12.

For the branching regions of the multi-wire cable of Fig. 2, a branching impedance matrix $(Z_{n,m})_B$ can be

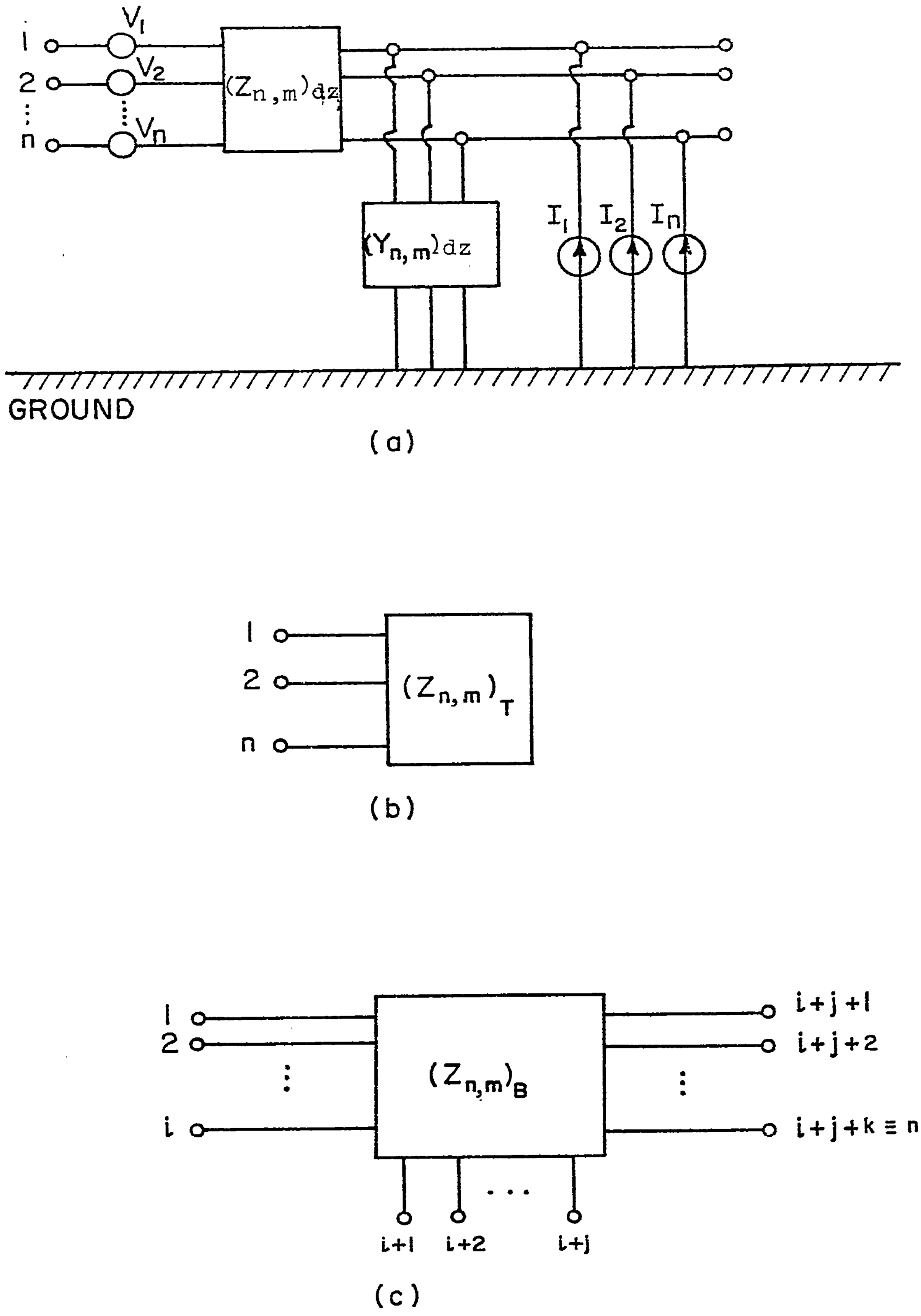
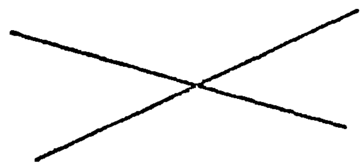


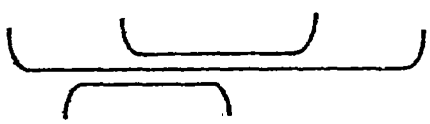
Figure 12. Multiconductor Transmission Line Models a) Section of Line, b) Load Impedance, c) Junction Impedance.

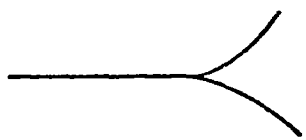
defined. Note that since one cable with i wires may enter the branching region and cables with j and k wires can exit, this impedance matrix serves to couple the solutions for each cable bundle together via the appropriate impedance elements. In all, there are n^2 elements in this branching matrix, with n being the total number of wires converging on the branch region.

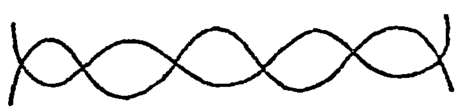
Most single line propagation geometries that were previously considered are also of importance for multiple line cases having either bunched cable or parallel run lines. Examples of these generally applicable geometries are bunched cable meander lines, parallel lines over periodic obstacles or over holes in a ground plane, and bunched cable planar loops. Some propagation geometries that are generated exclusively by multiple lines are shown in Fig. 13.

In each problem which is to be solved, the basic model should be that shown in Fig. 12. Thus it will be necessary to compute the matrices $(Z_{n,m})$ and $(Y_{n,m})$ for each problem, as well as the two source terms. Such a unified approach will permit the more rapid utilization of results for N-wire transmission line theory for internal EMP interaction studies.

A)  Crossed Wires/O.G.P.

B)  Short Parallel Run/ O.G.P.

C)  "Y" Branched/O.G.P. (including perpendicular branch "T")

D)  Non-Parallel Coupled Meander Line Section O.G.P.

E) Other cases in Figure 11 with multiwire line instead of single line.

Figure 13. Some Relevant Multiple Line Propagation Geometries

IV. Statistical Analysis of Random Line Structures: Requisite Modeling and Methodology Improvements

The internal interaction analysis of operational EMP vulnerable systems involves the consideration of many random parameters. These random parameters appear at all levels of the analysis, beginning with the uncertainty in the orientation and intensity of the primary drive illuminating field, and progressing into the various shielding levels where spatial configurations of coupled transmission lines fluctuate from system to system in a statistical manner.

In a previous report[13] an introductory discussion was presented concerning the statistical analysis of load excitations induced on a random N-wire cable by an incident time-harmonic field. The objective of this section will be to consider some requisite enhancements of knowledge and improvements of models related to the analysis of practically encountered random transmission line structures.

Non-Uniform N-Wire Line Theory Improvements

To develop a dependable statistical methodology presupposes the expertise to accurately solve, on a deterministic basis, the various problems encountered in the random sample space being considered. For the case of random coupled transmission line configurations the available deterministic analyses leave much to be desired.

The usual quasi-TEM transmission line approximation for uniform N-wire lines is not generally applicable to non-uniform lines undergoing rapid individual spatial oscillations, as shown in Fig. 14. A question of utmost importance is: what is the exact criterion for the failure of the distributed parameter transmission line model being characterized by the variable impedance and admittance matrices, $\underset{\sim}{Z}(x)$ and $\underset{\sim}{Y}(x)$? Another question that should be rigorously investigated is: under what specific conditions can wire to wire coupling be neglected and a strong coupling approximation be made for large-scale N-wire structures having a variety of relative wire orientations and proximities?

The questions above relate to establishing limits on the validity of the usual approximations that are made to describe propagation and coupling on N-wire structures. To develop models that are accurate for the variety of physically encountered N-wire lines the following investigations are proposed:

1. For the case of non-uniform lines having slow spatial variation and wire separation $<< \lambda$ (so the quasi-TEM approximation is valid) extend the 2 wire non-uniform line analysis given by Bergquist,[14], to the general N-wire case.
2. Also for the quasi-TEM case a stepwise uniform

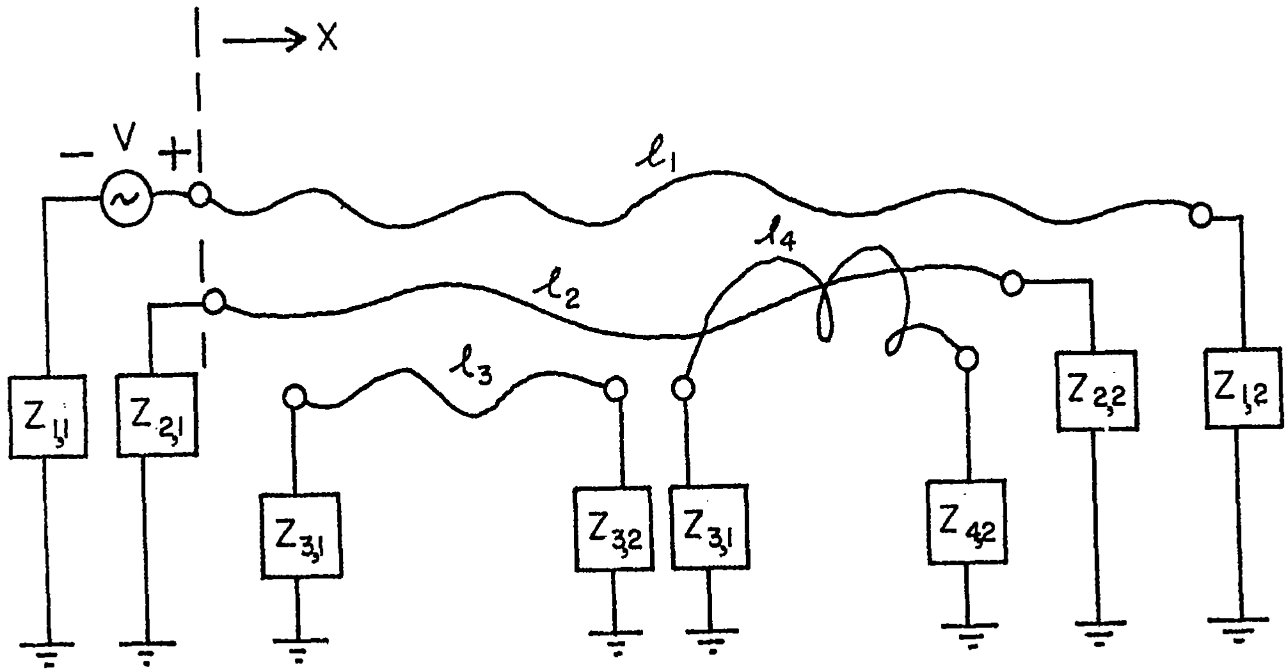


Figure 14. Random Meander Coupled Line.

section N-wire model can be developed and its range of validity checked.

3. For N-wire lines having rapid spatial changes a possible model is to decompose the line into short sections (each of length << λ) which are individually represented by partial element equivalent represented by partial element equivalent circuits, (PEEC), using a technique similar to that given by Ruehi,[15]. The line would then be modeled by cascaded PEECs. This method is similar to the lumped parameter method but uses a rigorous integral equation solution, including retardation effects, to determine the equivalent circuit elements.

Statistical Modeling and Analysis

The ultimate objective associated with the statistical analysis of a complex random system is an estimate of the values of certain system variables that are of particular interest. The variables in an EMP vulnerability analysis are usually certain critical load excitations, while the statistical estimate is usually provided in the form of an average, or expectation, with an associated standard deviation which denotes, loosely, the expected spread of actual observations about the statistical average of the variable.

In considering the statistical behavior of random line structures certain fundamental questions require immediate and detailed investigation. These questions concern both the basic formulation of statistical analysis techniques and the general characteristics of the statistical estimate.

One such question concerns the diffusion of energy from a harmonically driven excited line into nearby randomly coupled lines, as illustrated in Fig. 15. At each cross section, given by constant X, the statistical description of the line currents and voltages will be given by the expectations and variances of $V_k(x)$ and $I_k(x)$ for k=1, N. Because of the rapid spatial configuration changes of the system does the random energy coupling from the driven line into the nearby lines tend to average out beyond a certain value of X, such that beyond this "diffusion length" the power in each line is invariant to X?

A second important question is related to the "propagation" of randomness as the internal interaction process is followed into higher and higher shielding levels. At each shielding level the internal interaction analysis is partitioned when possible, into propagation, penetration, and coupling subproblems where random driving terms generated from the previous level are exciting a propagation on random systems in the present level being

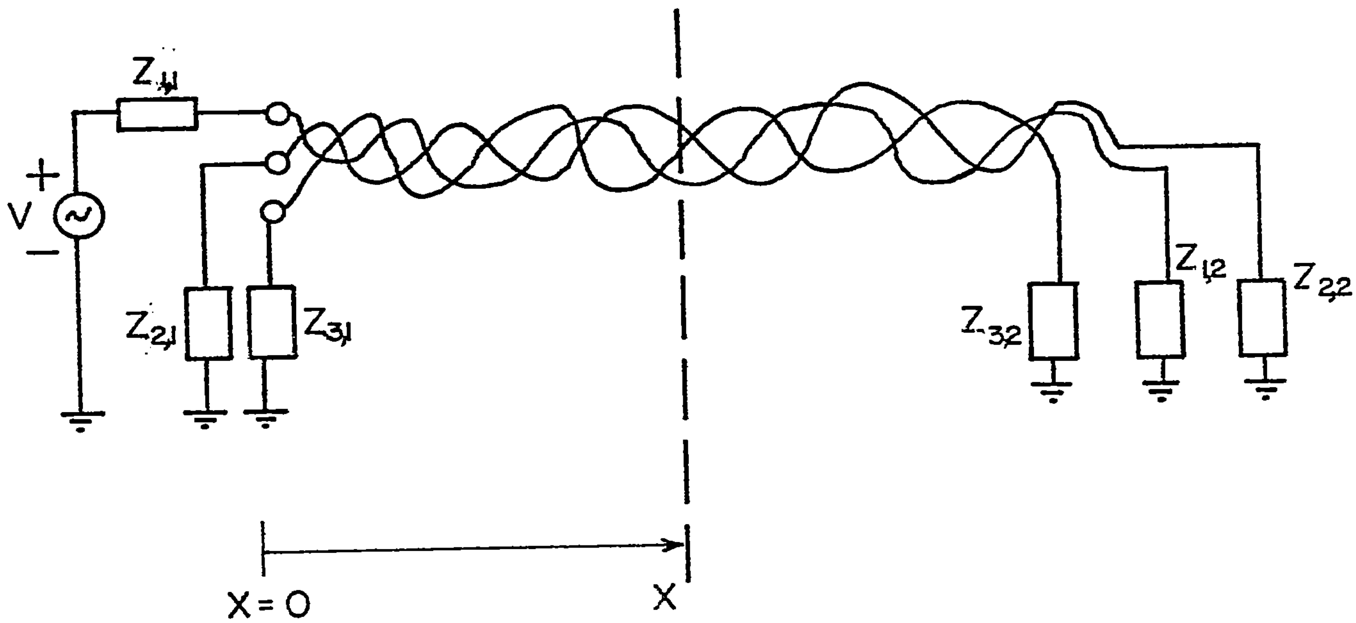


Figure 15. Energy Coupling Into Random Lines.

considered. If the present level systems were deterministic then the resultant excitations would only be as uncertain as the driving terms from the previous level. If the present level systems have their own independent randomness then the overall uncertainty of the excitations is enhanced beyond that of the driving terms. Hence, as the successive shielding levels of the system are transversed the excitations become less and less certain as the information entropy increases.

Other particular questions that should be resolved and statistical model improvements that should be implemented are listed below in a short format.

1. Under what specific criteria can statistical independence of individual wires be approximated for bunched cables and multiconductor cables?
2. How difficult is it to obtain probability distribution functions for the random positions of practical multiconductor cable systems?
3. What restrictions are there for the simple geometric subset representations for random cable systems as discussed in (1)?
4. In the N-wire transmission line model proposed in (1) the number of possible wire positions, Q, should be allowed, in general,

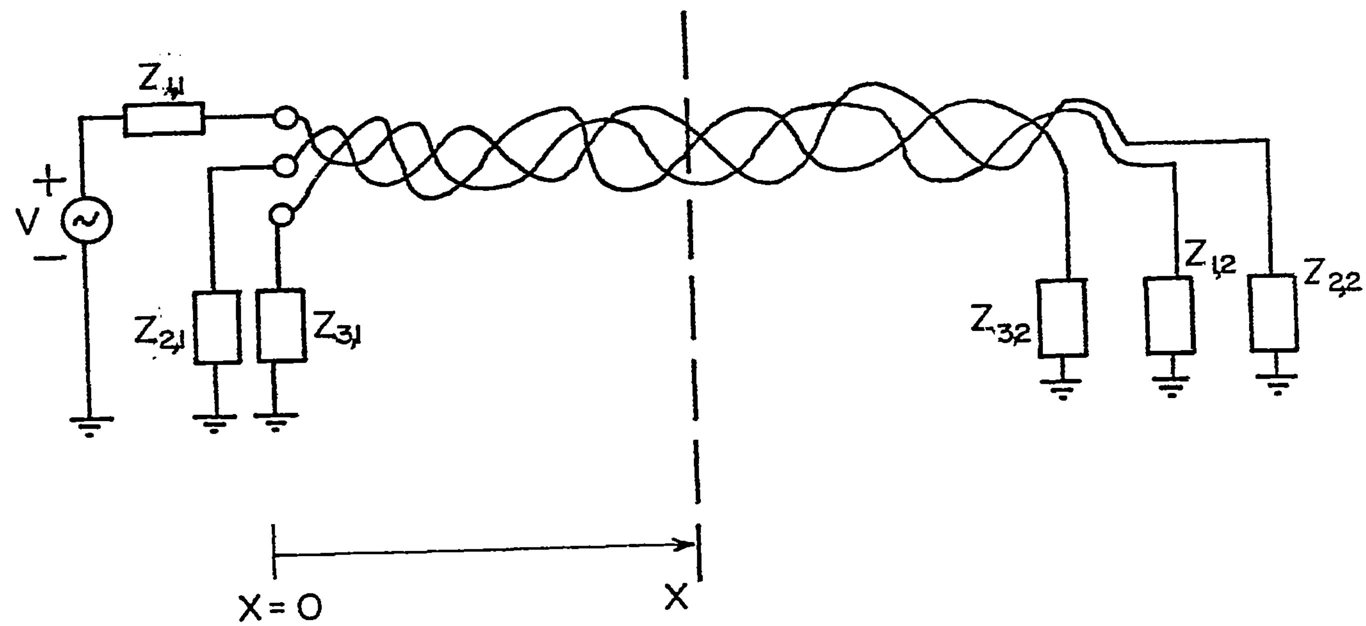


Figure 15. Energy Coupling Into Random Lines.

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3. What restrictions are there for the simple geometric subset representations for random cable systems as discussed in (1)?
4. In the N-wire transmission line model proposed in (1) the number of possible wire positions, Q, should be allowed, in general,

to be greater than N. This is a minor point but should be brought out.

5. The incident driving field which excites the random N-wire line should be considered to be non-deterministic, in general. In addition, in some special cases various load impedances on the line may be random in nature.

V. Summary of Recommendations

Upon reviewing existing technology in the internal interaction area, it is apparent that a number of improvements in both the models used for analysis, as well as in the numerical treatment of such models, can be made. These possible improvements are summarized below.

In order to permit the simplification of the very complex internal interaction geometries found in typical aircraft into a wave propagating structure which can be treated in a reasonable manner, the following tasks should be performed to define "screening criteria":

1) Continue studies pertaining to the topological decomposition of aircraft structures.
2) Study canonical problems which serve to better understand energy flow on complex transmission lines. These include the following:
    a) How far away from an aperture must a cable bundle be so that the direct excitation of the cable is negligible? Do a parametric study for various orientations and aperture dipole moments.
    b) How far away from another cable must a cable be to have negligible cross coupling?
    c) For only one wire in a cable bundle excited, how far down the line must one go to have large currents in the other lines?

3) Perform limited experiments to verify the theoretical calculations. At present, there are a number of specific experiments which can be performed to postulate and/or validate various screening criteria which may be suggested. In addition, experiments to validate the calculations for propagation models can be devised. A few of the possible experiments are as follows:

   a) Measure general transmission line parameters, such as inductance and capacitance (per unit length), impedance and propagation constant and how they vary with changing geometry around a specific line to validate mathematical model.

   b) Measure currents on a N-wire line excited at one wire only to see the effects of varying randomness on the current distribution far away from the exciting source.

   c) Using a complicated cable mock-up, consisting of multiple wires, branching segments, complex loads, etc., make measurements of various responses. Then using the screening criteria which are to be developed, simplify the physical cable system by removing unimportant cables, and again perform the measurements. Finally, simplified calculations should be made on the simplified cable system and results compared with the other two experimental results. This serves not only to validate the screening criteria but also indicates the overall accuracy of the calculational procedure.

4) After the screening criteria have been thoroughly tested, issue a report with the compiled "screening criteria" and examples of how to use them for a complicated system. Such a document could be in the form of a Handbook.

For carrying out EMP internal interaction calculations, the present approach is to use a single line model. The results for this model are seen to be relatively poor and could be improved by using a multi-conductor analysis. Such analysis, however, is not commonly used. Future work in this area should be such that the multi-conductor approach is studied and implemented in a user oriented computer code.

This should not be done, however, at the risk of not being able to employ the existing single line models. Many analysts feel at ease with the single line model and may not readily accept the multi-conductor approach. In addition, the computer requirements for the single line approach are much less than in the more sophisticated case.

Thus, it is suggested that development of both single and multi-conducter interaction models continue.

For the single line improvements, the following should be performed:

1) Develop a better propagation model by determining the necessary shunt impedance elements to represent perturbations in the local geometry around the line. Such problems are outlined in Section IV.

2) Develop more accurate models for the behavior of a single wire within a larger cable bundle. This would entail using a multi-wire analysis procedure to correctly predict the effects of different loading on individual wires in a bundle, the line impedance of a single wire within a bundle, and the Thevenin or Norton sources for the single wire.

3) Provide accuracy estimates for single-line results by using multi-wire analysis procedures. This will answer the question of how accurate is the approximation that a single "bulk mode load impedance" can be made.

For the area of multi-line analysis, a number of similar tasks could be performed:

1) Execute a comprehensive study of existing multi-wire transmission line codes to see

which is most suitable for internal interaction purposes.

2) Select the most suitable code (or if needed, construct a new version which is suitable) and make it available to the EMP analysis community along with suitable documentation.

3) Increase the accuracy of the propagation model by considering discrete loading (actually in a matrix form) for geometrical perturbations near multi-wire transmission lines.

A number of other miscellaneous tasks are also suggested. They are as follows:

1) Continue the study and application of statistical methods applied to internal interaction. Specific tasks are suggested in Section IV.

2) Investigate field coupling effects for various classes of aperture dipole moments.

3) Investigate and implement a hybrid analysis approach using both the LPN approach and distributed transmission line theory.

Whereas the above list of possible tasks is by no means complete, it does provide a basic guide for future analytical efforts in the internal interaction area.

Figure 16 presents a proposed program plan for these efforts. This plan is based on an assumed 18 month duration

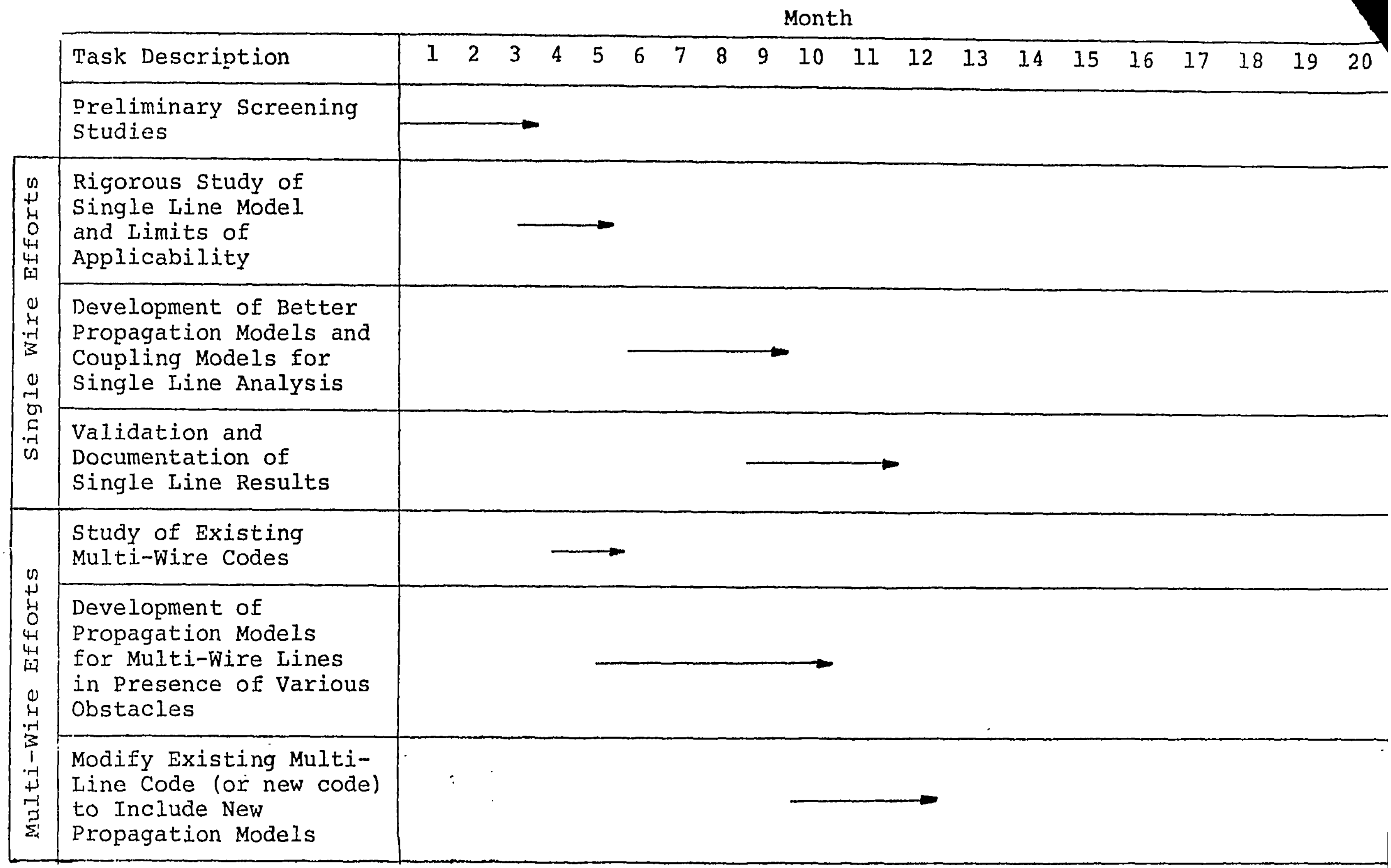

Figure 16. Possible Time Schedule for Future Technical Efforts in Internal Interaction Studies

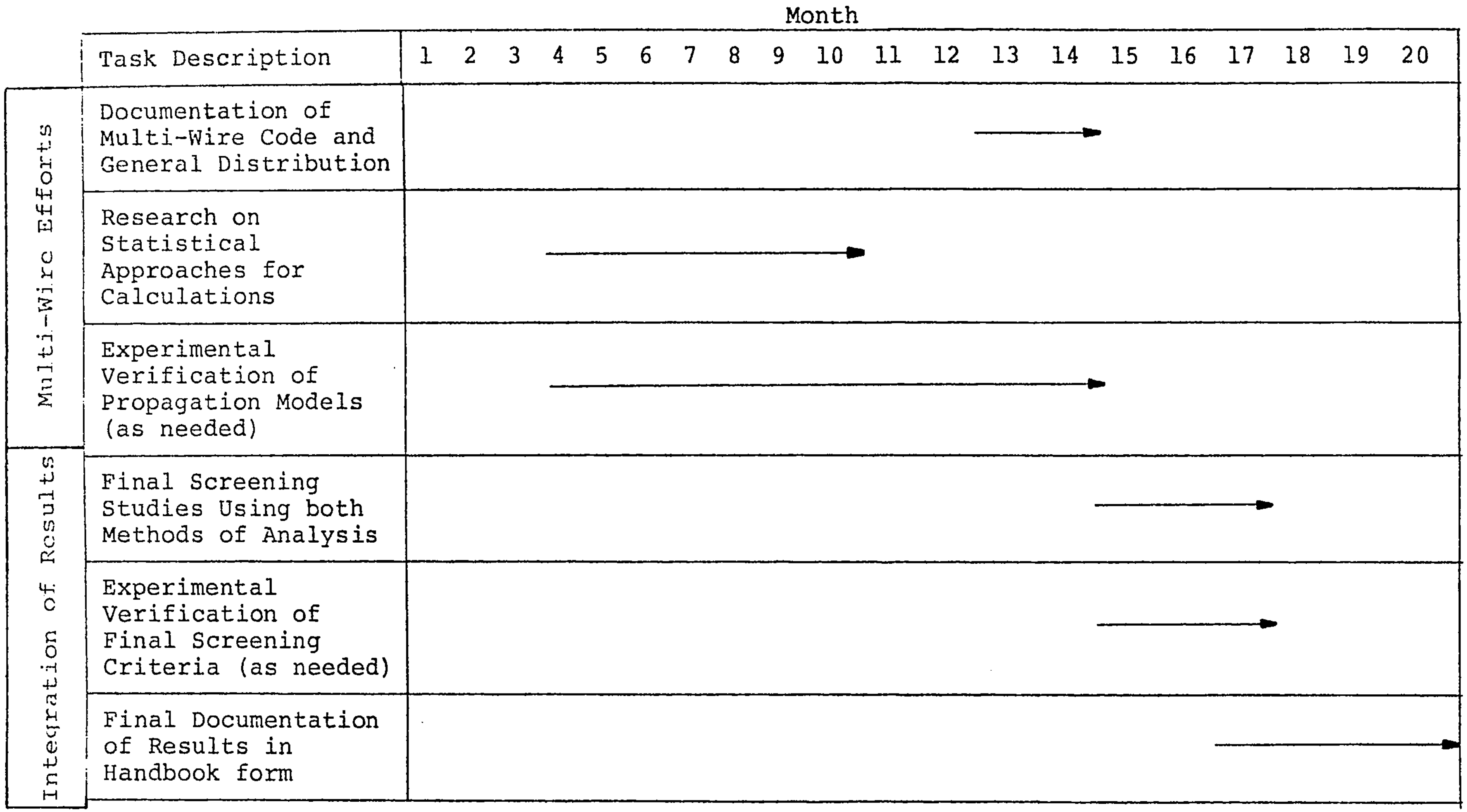

Figure 16. (cont'd)

of the research (exclusive of final documentation) and would permit the parallel developments of both single line and multi-wire analysis procedures. If a shorter period of time were available for this effort, the same schedule would hold, only the tasks would be performed in a shorter period of time. Thus the studies would not be as complete nor exhaustive, but nonetheless, would be extremely useful for furthering the state of the art of internal interaction analysis.

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