N93-19403

1992 NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

JOHN F. KENNEDY SPACE CENTER
UNIVERSITY OF CENTRAL FLORIDA

DETERMINATION AND REPRESENTATION OF ELECTRIC CHARGE DISTRIBUTIONS ASSOCIATED WITH ADVERSE WEATHER CONDITIONS

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DATE:	August 7, 1992
CONTRACT NUMBER:	University of Central Florida NASA-NGT-60002 Supplement: 8

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ACKNOWLEDGEMENTS

This participant in the NASA/ASEE Summer Faculty Fellowship Program extends thanks to all those associated with the program for this opportunity for creativity and education. Special thanks are offered to NASA representative Ms. Carol Valdes for helping us all gain a complete picture of operations at KSC and for assisting us fulfill our individual objectives. Special thanks to University of Central Florida representatives, Dr. Loren Anderson and Ms. Kari Stiles for their assistance in making participation in the program a unincumbered experience.

The support, advice, direction and encouragement given to the participant by his colleague, Ms. Launa Maier, is greatly appreciated.

Much is owed to many others for their contribution to this summer's effort. The support given by Mr. Nicholus Schultz and his colleagues was of special value. Thanks to all my fellow participants in the program for their camaraderie. Their support will be long remembered.

Support in preparation for this summer's investigation was given to the participant by his home institution, the University of Wisconsin-Stout. That support comes in the form of a Faculty Research Initiative Grant. The success of the current investigation is due in good measure to the preliminary work carried out under that grant. That support is greatly appreciated.

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ABSTRACT

Algorithms are presented for determining the size and location of electric charges which model storm systems and lightning strikes. The analysis utilizes readings from a grid of ground level field mills and geometric constraints on parameters to arrive at a representative set of charges. This set is used to generate Three dimensional graphical depictions of the set as well as contour maps of the ground level electrical environment over the grid. The composite, analytic and graphic, package is demonstrated and evaluated using controlled input data and archived data from a storm system. The results demonstrate the packages utility as: an operational tool in appraising adverse weather conditions; a research tool in studies of topics such as storm structure, storm dynamics, and lightning; and a tool in designing and evaluating grid systems.

INTRODUCTION

1.1 ELECTRIC FIELD MILL

An electric field mill is a device used to determine the size of an electric field component. The device consists of two metallic coaxial disks of the same radius separated by a fixed distance. The axis of these disks is pointed in the direction of the field component to be investigated. The lower disk is radially segmented and fixed in position. The upper disk has similarly segmented but has alternate segments removed. This upper disk is rotated. As that disk rotates the electric field flux to the lower segments undergoes continual change. This changing flux between the disks induces a voltage between the plates. Knowledge of this voltage and the distance between the disks permits the determination of the electric field component (reference 1).

1.1.1 KSC/CCAFS GRID OF ELECTRIC FIELD MILLS. The Kennedy Space Center and the Cape Canaveral Air Force Station are spanned by a grid of more than thirty vertically directed ground level field mills. With the earth acting as a nearly perfect conductor of electricity, these mills monitor the full ambient field. The current study deals with data obtained through that system and the interpretation of that data for operational uses at the station and center and the potential use by investigators.

1.1.2 OPERATIONAL USE OF FIELD MILL DATA. Information from these mills is gathered and recorded. The real-time data is used to appraise the potential for a lightning strike. If conditions warrant, a warning is issued and precautions in the threatened area are taken to minimize any damage or injury which might occur due to a strike.

1.1.3 SCIENTIFIC USE OF MILL DATA. The data generated by these mills is also archived. This stored information represents an invaluable data base for investigating the storms which frequent this area. Real-time data has also been used to monitor the region's electric field during experimentation.

1.2 FORMATS FOR INTERPRETATION OF FIELD MILL DATA

Two formats for presenting field mill data are currently employed. contour maps and strip charts. Each format emphasizes a different aspect of the available data. Each represents a different tool used by observers in appraising the situation and ezch impacts the decision making process.

1.2.1 STRIP CHART. The data stream from the field mills is continuous and finds its most immediate represention in strip charts. This presentation emphasizes the time development of the electric field but, of necessity, is focused to the output of a small number of mills. The investigator's attention is directed toward the behavior of the electric field over a limited region of the grid.

1.2.2 CONTOUR MAP. The information from the entire working grid can be digitalized and the representative readings from the various mills over a particular time interval can be accumulated. This time interval can be made short enough so as to represent nearly instantaneous data. With knowledge of the field level at the various grid mill sites, algorithms can be employed to determine the approximate field values at other locals within the grid. Lines can be constructed connecting those locals which, according to the algorithm, experience the same field strength. Contours constructed in this way give a quick overview of the regional electric field at a particular time. Continual updating is needed to provide an investigator with an impression of the time development of the field over the region.

1.3 CHARGE DISTRIBUTION FORMAT

Presently, contours are generated by a linear approach which generates a highly reliable surface contour map. That approach is not well suited to investigation of other physical aspects of a storm system. It makes no attempt to mimic the physical charge distribution. A model which is based on a presumed system which is closer to the physical system would yield much more information regarding the system. A successful model would still be able to generate surface contours. In addition, it would be able to show the relative size, polarity and position of representative charges. This information could be used in developing approximations for the total energy of the system. Monitoring of the time development of this distribution would give information on the mechanism involved in storm dynamics. Information on storm development and activity would become tractable. Combined with other meteorological information, the role of surface charge and wind convergence on storm activity and lightning strikes could be studied.

1.3.1 THE RELATION OF ELECTRIC FIELD TO ELECTRIC CHARGE. Each electric charge can be considered as having its own electrical environment. It is through this electric field that it interacts with other charges within its environment. The size and direction of that environment at any point about a charge is given by Coulomb's law (ref 2,3). An accumulation of charges produces a more complex environment, but the composite is still a vector sum of the effect of the contribution of individual charges. Given a charge distribution it is possible, though perhaps tedious, to determine its unique electrical environment at all locations.

1.3.2 THE UTILITY OF A CHARGE DISTRIBUTION REPRESENTATION. In order to gain as much information from a data set as is possible it is reasonable to construct a mathematical model which resembles the physical system as closely as possible. In the field of electrodynamics the formalism for such an undertaking is complete and well tested. The potential for interpretation and applications of a functional model are extensive. The depiction of a storm system by a charge distribution would be progress in that direction.

1.3.3 THE LIMITATION IN DETERMINING THE REPRESENTATION. The traditional problem in electrodynamics involves the study of a given charge distribution in a setting of conductors and dielectrics. It is commonly agreed that the field for such systems is unique and can be determined using the most expedient mathematical approach available, of which there are many. The analysis of a storm system considers the opposite approach. A field over a limited region is known and the charge responsible for that field is to be determined. Due to this limited knowledge the charge distribution determined is not unique. Many charge distributions can have the same environment over a limited region. It has been this shortcoming which is primarily responsible for the lack of effort to formulate algorithms for finding any charge distribution to fit the data.

1.4 BASIC PREMISE

The current investigation attempts to initiate a search for a charge distributions which corresponds to distributions found in storm systems and involved in lightning strikes. The initial candidate distribution is determined by field mill readings only. It is presumed that confirmation of the results can gained by including limiting information apart for field. This other information would include restrictions on the physical systems probable dimensions. It would also include information based on insight gained through other means such the general models for charge distributions which are considered viable. The level and distribution of the energy in the system would also result in a strong restrictions on form of possible candidate distributions.

1.5 PRELIMINARY ALGORITHMS TO GENERATE REPRESENTATIVE CHARGE DISTRIBUTIONS

This investigator began such developments during work in the summer of '91 as a NASA/ASEE Summer Faculty Fellow. . These efforts consisted of an analysis of past modeling techiques and the introduction of innovations (ref. 4).

1.5.1 MODEL_A. This investigator reformulated the algorithm used by operations to construct field contours. It was found that the model used in that original process transforms the relationship between the electric field and the charges producing the field to a linear one. This is achieved through a dramatic reduction in the degrees of freedom in the problem. The assumed charge system is taken as an array of charges agreeing in number to the number of operable field mills. The location of these charges is fixed. A single charge is taken as located at a given height above any particular mill. The size of the charges are the only variables to be determined. Since the number of unknowns agrees with the number of independent mill values, a linear set of equations results and the charges determined. In turn these charges are used to determine the field over a grid covering the region and generate contour maps.

1.5.2 MODEL_B. As an alternate approach, this investigator introduced a mathematical formalism for data analysis. The description of a single charge includes four variables, three for the location of the charge and a fourth for its type and size. Thus the field value of four mills is sufficient to characterize a charge. Coulomb's law provides a set of four coupled, but none linear, equations for the determination of the four charge parameters. This model was developed to verify that the technique used in obtaining a solution is correct and functional. A hypothetical test charge was considered and the field values generated by that charge determined. The model correctly located the hypothetical single charge based on the four field values.

1.5.3 MODEL_C. With the mathematical technique thus established, limited time was spent that summer constructing a model consisting of two charges. By determining a single charge and subtracting its effect from the overall field a second charge producing this residual field could be determined. An iteration process balanced the contribution of the two charges. Results were encouraging and work was continued on the mathematical process by which the mill values are to be used in the analysis. This continued effort was conducted independently and under a Faculty Research Initiative Grant awarded by the University of Wisconsin-Stout. By the time the current investigation resumed here KSC, this model was nearly fully functional.

1.6 COMPONENTS OF AN APPLICATION PACKAGE

The intent of continued investigation is to design a new tool for the analysis of field mill readings for operational and scientific purposes. This application package will also include compatibility with traditional approaches, offer new approaches and provide for future modification.

1.6.1 DATA ACQUISITION. Data formats for projected models should include the input of archived information and for real-time input. The models presented have been formulated using a recorded set of data. Mr. Llyod Albright and Mr. Richard Neely of EG&G Florida, DPS have already introduced variations in the computer code developed for Model_A so that it gives real-time contours, and in another version, includes graphical information on wind velocity over the region.

1.6.2 DEVELOPMENT OF ALGORITHMS FOR DATA ANALYSIS. The computer programs written by the investigator are in FORTRAN. This language was chosen due to the principle investigator's familarity with the language and because it is a widely know and used in the scientific community (ref. 5-7). This will facilitate the use of the programs as a basis for modifications and innovations

1.6.3 PRESENTATION OF RESULTING REPRESENTATIVE CHARGE DISTRIBUTION. An essential feature of the models presented is the graphical representation of the resulting analysis. A graphical format facilitates the analysis of large data set, such as field mill data. This is carried out in an interactive framework.

1.6.4 INTEGRATION OF RESULTING PRESENTATIONS WITH TRADITIONAL FORMATS. The experience and insight gained from traditional presentations is a valuable asset in appraising the data. The models presented include the contour format of presentation.

1.6.5 INTRODUCTION OF TECHNIQUES FOR APPRAISING THE APPROPRIATENESS OF THE ALGORITHMS. Along with the introduction of analytical techniques the models presented were tested using controlled and specially formulated data sets. The development of computer programs to produce this data are part of the data handling system. They serve as a mechanism for appraising a model's utility. They can also be used to judge the effectiveness of the mill grid system.

THE APPLICATION PACKAGE: ANALYTICAL COMPONENT

2.1 THE PHYSICAL SYSTEM MODELED

The models presented are intended to represent an adverse storm system. Such systems contain continuous but variable distributions of positive and negative charge. One of the more popular depictions of a common system places a large positive charge at a high altitude, a counterpart large negative charge near the zero degree Centigrade level and a small positive charge at a lower level (ref. 8). The models forwarded do not attempt, at this stage of development, to suggest the structure of these continuous distributions. They take the initial step similar toward working models currently considered viable. In these models, large regions of a system are considered to have a single polarity and represented as a single point charge.

2.2 THE STRUCTURE OF MODEL_D AND MODEL_E

Model_C attempted to describe the charge system using two charges. This is a strong restriction an the model. The model did serve as a mechanism for fostering the analytical techniques use in the current effort. This summer's work has been devoted to the development of models which search out several charges.

2.2.1 CHARGE CHARACTERISTICS. Ten charges was taken as the working number but the programs are easily modified to permit variations in this number. The ten charges are assumed to be point charges. No restrictions are placed on their polarity or size. The only restriction placed on charges is that they be below the eighteen kilometers in altitude. No restrictions are placed on their horizontal location.

2.2.2 DETERMINATION OF A DOMINATE CHARGE'S SIZE AND LOCATION. The model ranks all the field mill readings in terms of intensity and selects the dominate polarity. The mill showing the largest reading in that set is selected as the central mill. Three other mills with high ranking readings in the vicinity of the central mill are chosen to complete the quartet needed to locate the charge. Once four such readings are obtained the locating algorithm developed with earlier models is employed to determine the charge size and location.

2.2.3 DETERMINATION OF A DOMINATE CHARGE'S INFLUENCE ON THE SYSTEM. With a charge so determined, its electric field environment contribution of that charge is calculated. In particular, the electric field contribution at the location of each field mill is determined and subtracted from the total field value to produce a residual electric field.

2.2.4 ITERATION PROCESSES APPLIED TO THE RESIDUAL ELECTRIC FIELD. The residual electric field is now used as the principal field and the augmented field mill values are re-ranked and the dominate influence in the residual field is determined. Four field mill values are selected using the process described above to determine the charge most likely responsible for this influence. The contribution to the field from this charge is then calculated. The role of the first charge and this second charge are reversed and the two re-evaluated in order to obtain a balanced combination. With these charges determined there combined environment is calculated and subtracted from the total field. This new residual field is used to determine a third charge and its electric field contribution. The process continues until ten charges are determined. Model_E employs an extended iteration process The balancing of charges is itself iterated several times in order to obtain a more representative distribution between the charges.

2.3 TECHNIQUES FOR SELECTING THE FIELD MILL VALUES USED IN THE ANALYSIS

The selection of the four field mills to be used in the determination of the four parameters associated with a charge, location and signed size, is a critical step in the analysis. Since all mills are under the environmental effect of many charges it is difficult to chose four mills which are dominated by the influence of a single charge. The process used in the formalism presented relies on guidelines based on the geometric considerations.

2.3.1 LIMITATIONS ON FIELD MILL RANGE. The first physical restriction placed on the model is based on distance from the central mill. It is presumed that the mill registering the largest absolute reading has a charge near its zenith. Using this field mill location as a hub, a radial range is established. Mills within that range are then investigated. Mills with the same polarity as the hub mill and which are high ranked in value are considered as candidates for the calculation process. Since the grid of field mills is irregular in orientation and span this process may not yield successful candidates. If this occurs the restriction on range is relaxed until four successful candidates are located.

2.3.2 LIMITATION ON CHARGE ALTITUDE. One of consequences of placing a restriction on range is that mills which are 'close' to the hub are also nearly below the charge to be located. As a result errors in determining the charge's altitude are increased. The error tends in the direction of large altitudes. If a calculation results in a charge altitude which is unreasonably large, the search for four other mills within the existing range is initiated. If after repeated searches, no physically reasonable results are achieved, the restrictions on range are relaxed until four successful candidates are determined.

2.3.3 INOPERATIVE FIELD MILLS. All values from active mills are included in the analysis. In ordinary operational situations not all mills will be functioning. In order to accommodate for this contingency the program provides for a flag to be assigned to inoperative mill. Flagged mills are withdrawn from the analysis. This is achieved by giving an inoperative field mill a value of absolute zero to the precision of the computer use. Once the grid of active field mills is determined care is taken so that active mills are not inadvertently eliminated if, at some time in the analysis, the residual value of the mill becomes zero.

2.3.4 SINGULARITIES. The calculations of the charge parameters takes several different paths should any combination of the four field values be identical. If a pair of values are equal, singularities in the calculation will result since division by the difference in field values is required at several points in the straight forward analysis. The programs presented consider all possible paths for the various combinations of identical values among the four-mills and provides alternate paths for each possibility. Each leads to a determination of the charge parameters. The possibility of mills having a common value is to be expected, especially since mills within a fixed range are sought out.

2.4 SUPPLEMENTAL FEATURES

Addition components have been added to the basic analytical framework of the analytical component to enhance its utility and facilitate its application. These features also serve as an illustration of how other innovations can be introduced into the program. This frame has been applied to two fundamental models, Model_D and Model_E. The resulting programs are labeled ANALYSIS_D and ANALYSIS_E.

2.4.1 COMPARISON OF ACTUAL AND MODEL FIELDS. With a distribution of representative charges so determined, a check on the reliability of that distribution can be applied to the results. The programs presented carry out such a calculation and incorporate the results in the output data file. The total field due to the entire set of charges is determined. In particular, the field at each field mill location is determined and compared to the input value for that mill. This variation is then compared to the inherent error for a mill according to a process suggested by Jacobson and Krider (ref. 9) and refered to here as Variation C.

2.4.2 INTERACTIVE FEATURES. In order to allow for applications to operation formats, the analysis programs also permits the user to direct the analysis to particular field mill reading files of interest. The user also labels the destination file. Since the input data usually includes a sequence of data sets, either real-time or archived, the program is structured to carry out an analysis of that sequence and store the results as directed by the user.

THE APPLICATION PACKAGE: GRAPHICAL COMPONENT

3.1 UTILITY OF GRAPHICAL REPRESENTATIONS

The output data of the analytic component is stored in files as labeled by the user. These files contain the designator for the data set, the four parameters associated with each of the ten charges and the results of the Variation C test for that data set. These files can be viewed directly, produced as hard copies or used in further analysis. In the current application this data presented graphically as a contour map or as a 3D distribution.

3.1.1 APPRAISAL OF DATA FOR USE IN OPERATIONS. The combined information from strip-charts, contours, and charge distributions should give an experienced observer a cleared picture of the electrical environment in the area. It is presumed that as experience with observed charge distributions increases and as the reliability of those models improves, observers will develop expertise in appraising the potential of cloud to ground, cloud to cloud, and triggered strikes (ref. 10,11).

3.1.2 ANALYSIS OF DATA IN RESEARCH. Expertise in appraising distributions is gained through direct comparisons on situations, events, and graphical representations. The archive data available here at KSC on a variety of meteorological parameters is extensive. The suggested analysis package can be applied to that data in a full scale research program to determine the storm development and activity is reflected in patterns depicted in charge distributions representations.

3.2 GRAPHICAL REPRESENTATION OF DATA

Two types of data representation have been developed to illustrate the utility and potential for further types of representations. The first of these is the familiar two dimensional contour of the electric field at ground level. This is done to establish a link with existing expertise and as means of comparing the results of the suggested models to those generated by the traditional Model_A. This representation also served as a guide in the development of more complex representations. The second type of representation is that of the three dimensional charge distribution. These modes illustrate the flexibility of the analysis package.

3.2.1 TWO DIMENSIONAL CONTOUR. The formalism for this depiction was developed by this investigator last summer and was incorporated into the present packages. That development include the generation of a map of the geographic area. The map shows major land features and the location of the field mills in the grid. The time required to produce the analysis was greatly reduced by a modification introduced to Model_A by Mr. Richard Neely of EG&G of Florida, DPS.

3.2.2 THREE DIMENSIONAL CHARGE DISTRIBUTION. This representation gives a picture of the relative scale and scope of the system being observed. It also depicts the relative local and strength of various components of that system as interpreted by the model used.

3.2.2.1 <u>Depiction of the Local</u> The map used in the contour illustration is again used for the three dimensional display. It is placed on the x-y plane of a right handed system. The map is given the usual orientation for quick referencing by the observer.

3.2.2.2 <u>Depiction of Charge Location</u>. The representative charges are shown as closed circles positioned in the x-y-z grid. The scaling of the altitude, z-axis, is the same as the scaling used in the geographic representation. In order to aid the observer in gaining an impression of the horizontal coordinates of each charge, a line is presented which runs from the charge position to its ground level x-y coordinates. The observer is aided in gaining an impression of that height by making that connecting line dashed. A knowledge of h e scaling of the dashes gives a quick indication of the charge's altitude.

3.2.2.3 <u>Depiction of Charge Size and Polarity</u>. The polarity of a representative charge is indicated by color. Currently red is used to label negative charges and white is used to label positive charges. The magnitude of the charge is indicated by the size of the circular marker used to label its position. The scaling currently chosen gives the size of the circle as proportional to the cube root of the charge magnitude. The circle markers give the impression of spheres in the display. With this relation those spheres represent the scaled volume occupied by that charge assuming uniform charge distribution throughout.

3.3 GRAPHICS SOFTWARE EMPLOYED

The software which met all the needs of the current investigation and development was IMSL ™ *exponent* Graphics ™. The versatility and availability of this software made it the only immediate practical choice for the current packages. It is imagined that improvements in this software will be introduced and that other commercial support for graphics imaging will be introduced. Contouring capabilities and 3D plotting are becoming common additions to plotting and spreadsheet software.

3.3.1 SOFTWARE ATTRIBUTES. The version of the software used has the VAX/VMS system as its platform and is easily incorporated into complex programs. It is also compatible with FORTRAN code. These features permitted easy integration of graphics into the package developed.

3.3.1.1 Data Input Versatility. Since this software package can be linked to FORTRAN programs directly there is no need to establish special data files for graphical purposes.

3.3.1.2 Data Output Versatility. The graphics generated by this software can be viewed through several options. The interactive portion of the graphics software directs the image to an appropriate terminal, such as X-Window or Regis. The image can also be filed in a PostScript™ format to be used for producing hard copies in monotone or color..

3.3.2 SOFTWARE LIMITATIONS. This graphics package is versatile but it is not 'friendly' when accepting 3D 'scatter' data. Though this future versions of this software may correct this limitation, the current version is primarily designed to display continuous functions. As a consequence, great care had to be exercised in introducing data and some awkward coding had to be employed. The chief limitation is the software's failure to provide for animation. Time sequenced displays can be achieved through repetitive applications of the software but an unbroken, continuous display of updated results is not a feature of this software.

APPLICATION TO SAMPLE DATA SETS

4.1 EXPERIMENTAL DATA SETS: STORM_A

Data sets obtained from field mill produced by a storm system passing over the field mill grid were chosen to illustrate the packages application to a representative system. A preliminary analysis was carried out and some of the resulting data and graphics are offered as an example of the type of presentations offered by the program and the variety of approaches available for operational or research purpose.

4.1.1 FEATURES OF STORM _A. A storm passing over the KSC/CCAFS region on September 9, 1986 was monitored for an hour and a half. Data from twenty-five electric field mills averaged over one minute intervals was recorded as where readings resulting from several lightning strikes. This record runs from GMT_2126 to GMT_2255 producing a library of eighty-eight data sets of storm activity. Also recorded where the electric field mill readings associated with ten lightning strikes. Readings from these events are stored in a library of data sets prefixed by LIT and carrying the time of occurrence.

4.1.2 ANALYTIC ANALYSIS OF STORM_A. Analysis of all the data sets in both the storm and lightning libraries was carried out using both analytical models, ANALYTIC_D and ANALYTIC_E. All data sets were processed successfully. It is significant that these model packages can deal with charge distributions which cover the region and source charges near but outside the grid boundaries. Analysis results consist of charge distributions, and a calculation of variation C. These results were filed in libraries labeled STORM and STRIKE. This data can be accessed by the graphical portion of the package and is suitable for use in other applications.

4.1.2.1 Variation C. The field generated by the determined charges for each of these data sets was determine as part of the processing. In particular the field at each field mill sight was compared to the actual field mill reading. The operational error for mill readings is taken to be ± 10% of the input value with a minimum of 300 volts/meter. The average value of the variation is labeled as C. Variation C is defined by:

$$C^2 = (N-1)^{-2} \Sigma^N{}_{i=1} \; ((E_i' - E_i) / s_i)^2,$$

E_i is the reading of the i^{th} field mill,

E_I' is the value of the field at the i^{th} location as calculated by the model,
N is the number of operational field mills, and

s_i is the operational error associated with the i^{th} mill.

Results for the storm and lightning data sets is as shown below:

STORM_A and STRIKE_A VARIATION C

Data Library	Library Size (data sets)	C Value
STORM_AD	88	3.38 ± 2,77
STORM_AE	88	4.86 ± 2.02
STRIKE_AD	10	0.60 ± 0.25
STRIKE_AE	10	0.93 ± 0.72

4.1.2.2 STORM A Energy. The various charge distribution sets, both for the storm and lightning strikes, used in a calculation of the electrical energy associated with the system. This energy is that of the entire system and includes charges at altitude and ground charges. The energy, Q, is given by the expression:

$$Q = \sum^{20}_{i=2} \sum_{j<i} k\, q_j\, q_i / 2\left((x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2\right)^{0.5},$$

where, $k = 9.0 \times 10^9$ N m^2 / $coulomb^2$, and the sum is carried out over all charges, q, including 'mirror' charges. This analysis was carried out as an illustration of the type of information that can be gained from knowledge of the charge distribution and the time development shown in figure seven at the end of this section.

4.1.3 GRAPHIC ANALYSIS OF STORM_A. Samples of the graphical files generated by this component are presented in figures 1 and 2. In those figures, all distances are in kilometers. Charge height is indicated by dashed lines. The scaling is such that the distance from dash to dash represents a distance of 1.35 km. A total of 392 different displays are available using data from these four libraries. Samples are given in figures one, two and three of this section.

4.2 CONTROL DATA SETS: STNDRD

The package programs were surveyed using control data sets of charge distributions. This library of control sets was filed in a library labeled STNDRD. The control data sets of charge distributions were transformed into corresponding sets of field mill readings. This was accomplished using the program ELF_MOLD. Thirty-eight sets

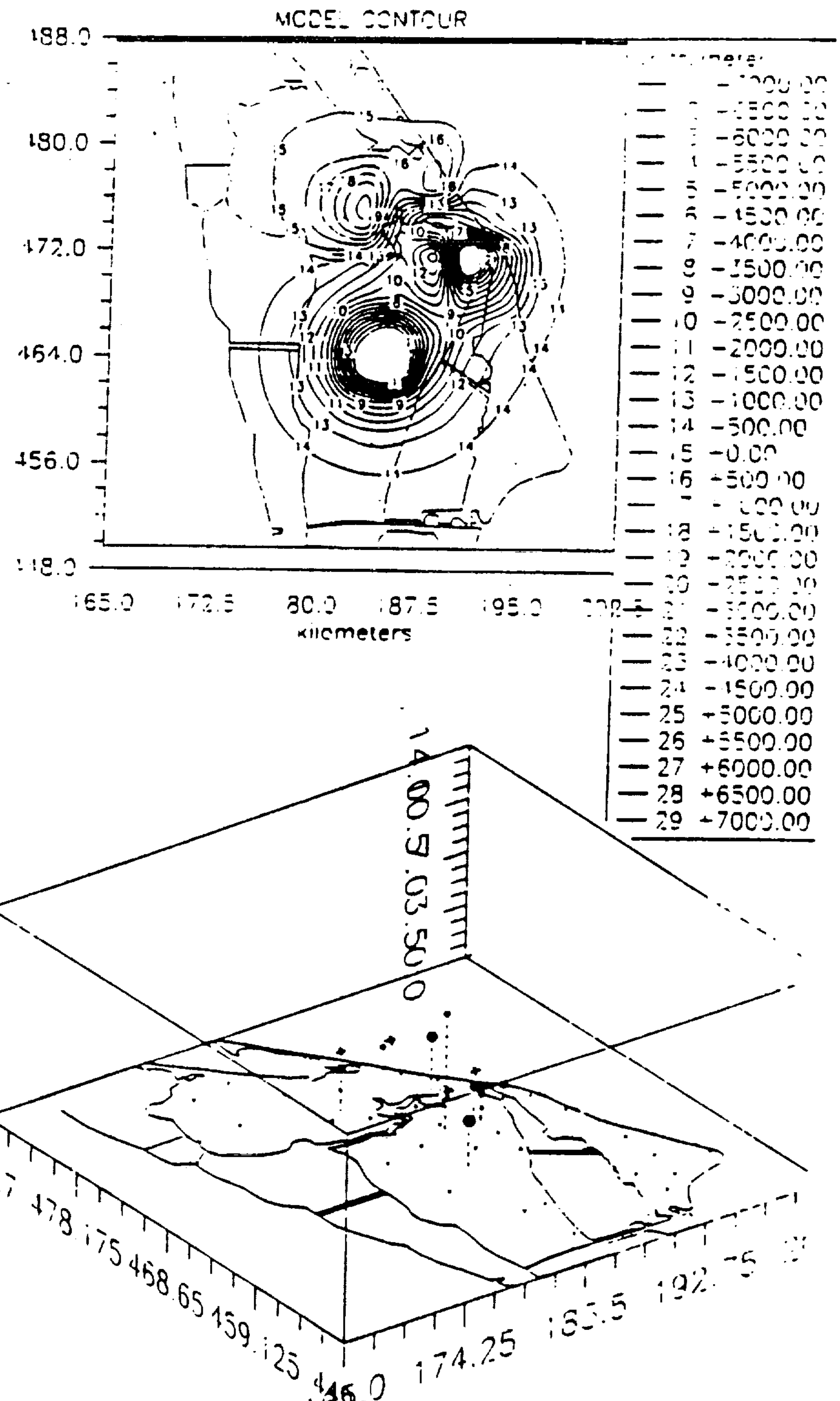

Figure 1. MODEL_D's GMT_2131

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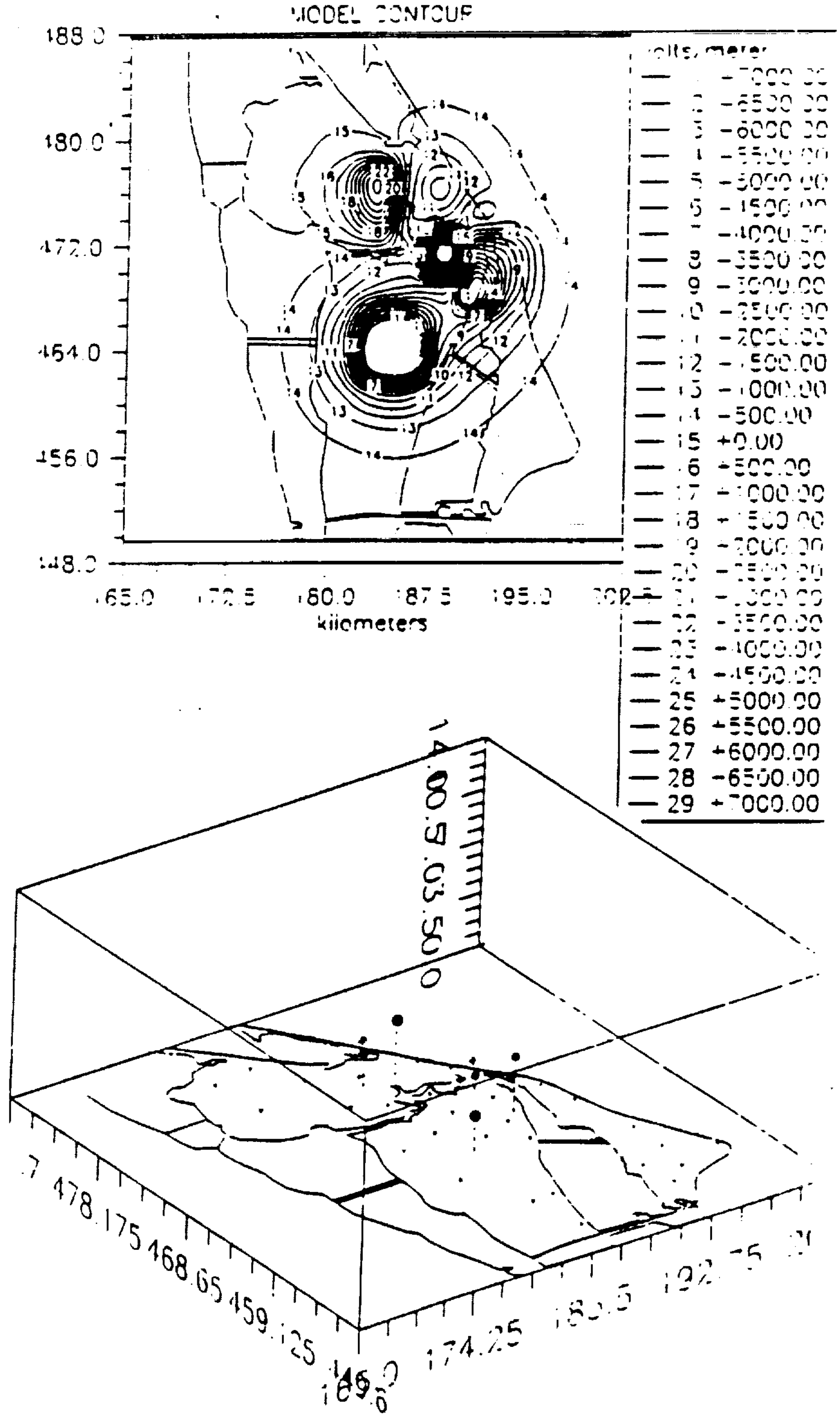


Figure 2. MODEL_E's GMT_2131

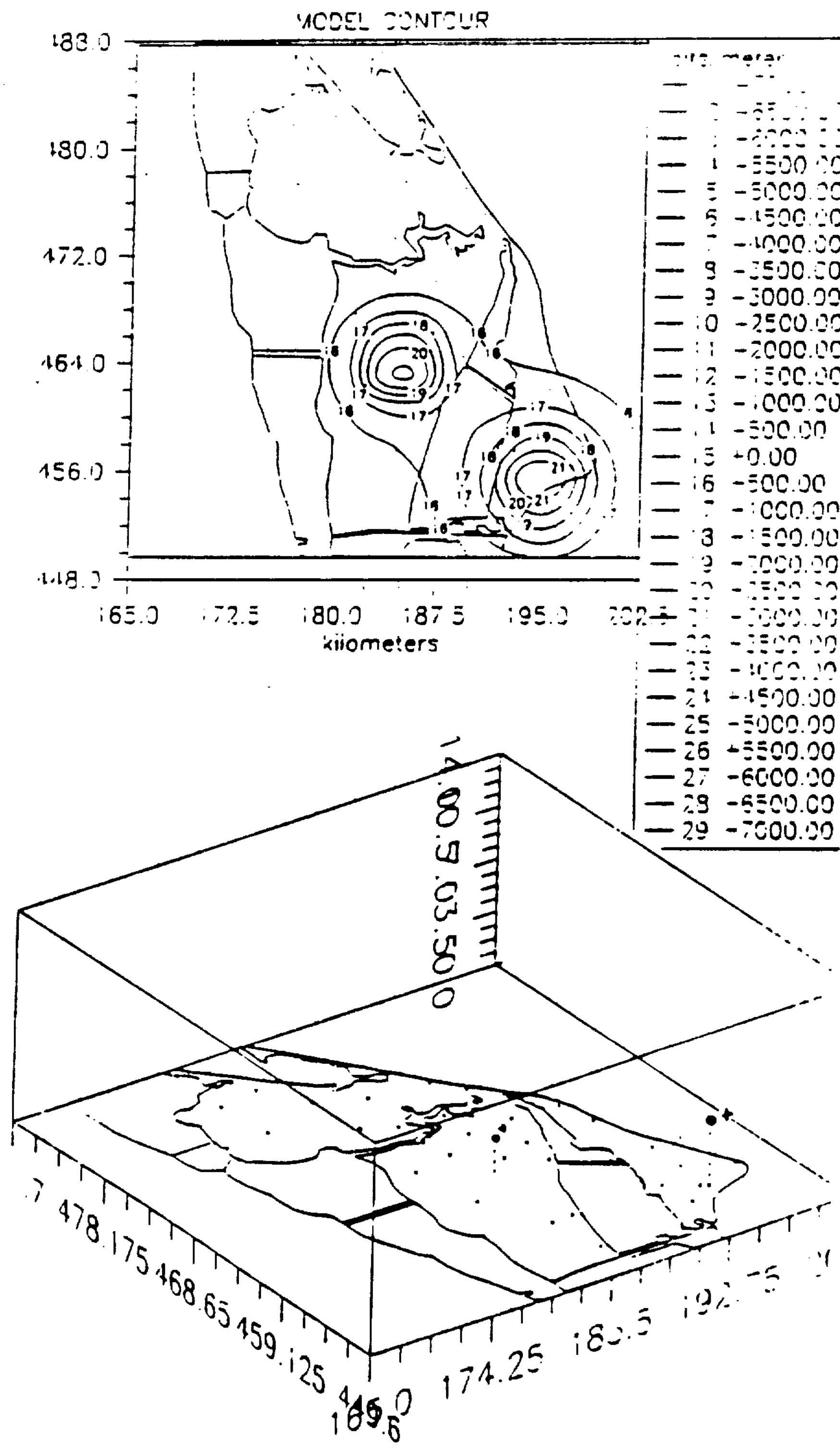


Figure 3. MODEL_D's LIT_2150

of field mill readings carry the prefix TMT. It was these field mill values which were analyzed using the application portion of the package. The results were filed in libraries labeled STNDRD_D and STNDRD_E. These results were compared directly to the control data sets.

4.2.1 ANALYTICAL ANALYSIS OF STNDRD. A variety of situations were considered to give an indication of the ability of the models to reconstruct the input charge distributions. Variations include the number, size and location of charges. A basic test of the models is their capacity to deal with situations where physical system is comprised of fewer than ten charges. Both models are designed not to over-determine the situation and responded favorably to those control situations. Where there is agreement between the number of charges in the control and result sets a statistical comparison is made. In those situations where the models generate a number of charges greater than that in the control set, a comparison of the graphical results is informative.

STNDRD VARIATION C

Data Library	Library Size (data sets)	C Value
STNDRD_D	38	0.52 ± 1.00
STNDRD_E	38	0.54 ± 0.60

4.2.1.1 Monopole Variation in Altitude. As a first test in the ability of the models to determine the altitude of a point charge. A sample charge of fifty coulombs is positioned at fixed central x-y coordinates and a variable z coordinate. Five sets, TMT_1001 through TMT_1005, were generated with altitudes ranging for four kilometers to sixteen kilometers. The results are shown below. Both models show a good ability to follow such variations.

AVERAGE ERRORS ASSOCIATE WITH VARIATIONS IN ALTITUDE

	Charge (coulombs)	Altitude (meters)	X-coordinate (meters)	Y-coordinate (meters)
Model_D	0.098 ± 0.076	9.98 ± 5.10	2.72 ± 3.11	1.78 ± 0.80
Model_E	0.098 ± 0.076	9.98 ± 5.10	2.72 ± 3.11	1.78 ± 0.80

4.2.1.2 Monopole Variation in Magnitude. Five sets of values of field mill readings, TMT_2001 through TMT_2005, were generated to represent the field environment of a point charge which varies in magnitude from ten to ninety coulombs at an altitude of ten kilometers and fixed central x-y coordinates. The results are shown in the table below. Both model were able to locate and determine the size of the charge.

AVERAGE ERRORS ASSOCIATED WITH VARIATIONS IN MAGNITUDE

	Charge (coulombs)	Altitude (meters)	X-coordinate (meters)	Y-coordinate (meters)
Model_D	0.153 ± 0.172	17.3 ± 11.3	4.31 ± 2.89	2.64 ± 1.65
Model_E	0.149 ± 0.173	17.1 ± 11.5	4.36 ± 2.83	2.66 ± 1.61

4.2.1.3 Twin Pole and Dipole Variation in Separation. Ten sets of values of field mill readings, TMT_3001 through TMT_3010, were generated to represent two charges, each with a magnitude of fifty coulombs, at fixed altitudes of ten kilometers and identical x coordinates. The first group of five sets follows twin positive charges as the y coordinate is increased from four kilometers to twenty kilometers. The second group illustrates identical movement of a charge dipole. These variation gives indication of the resolving power of the detection system, the grid of field mills. The results indicate that, along the y axis, the field mill grid can distinguish two charges separated by more than eighteen kilometers. This is illustrated in figure four and the analytic results included in table below.

AVERAGE ERRORS ASSOCIATED WITH CHARGE SEPARATION

	Charge (coulombs)	Altitude (meters)	X-coordinate (meters)	Y-coordinate (meters)
Model_D	0.033 ± 0.022	3.34 ± 2.19	1.62 ± 1.11	3.85 ± 2.48
Model_E	0.042 ± 0.046	4.97 ± 4.19	1.02 ± 0.60	1.675 ± 1.38

4.2.1.4 Crossed Pairs of Charges with Variation in Separation. Ten sets of values of field mill readings, TMT_4001 through TMT_4010, were generated to represent two pairs of crossed pairs of fifty coulomb charges. One pair is orientated along the x axis and the other along the y axis. In the first group of five data sets, all the charges are positive. The separation between the elements of each pair are

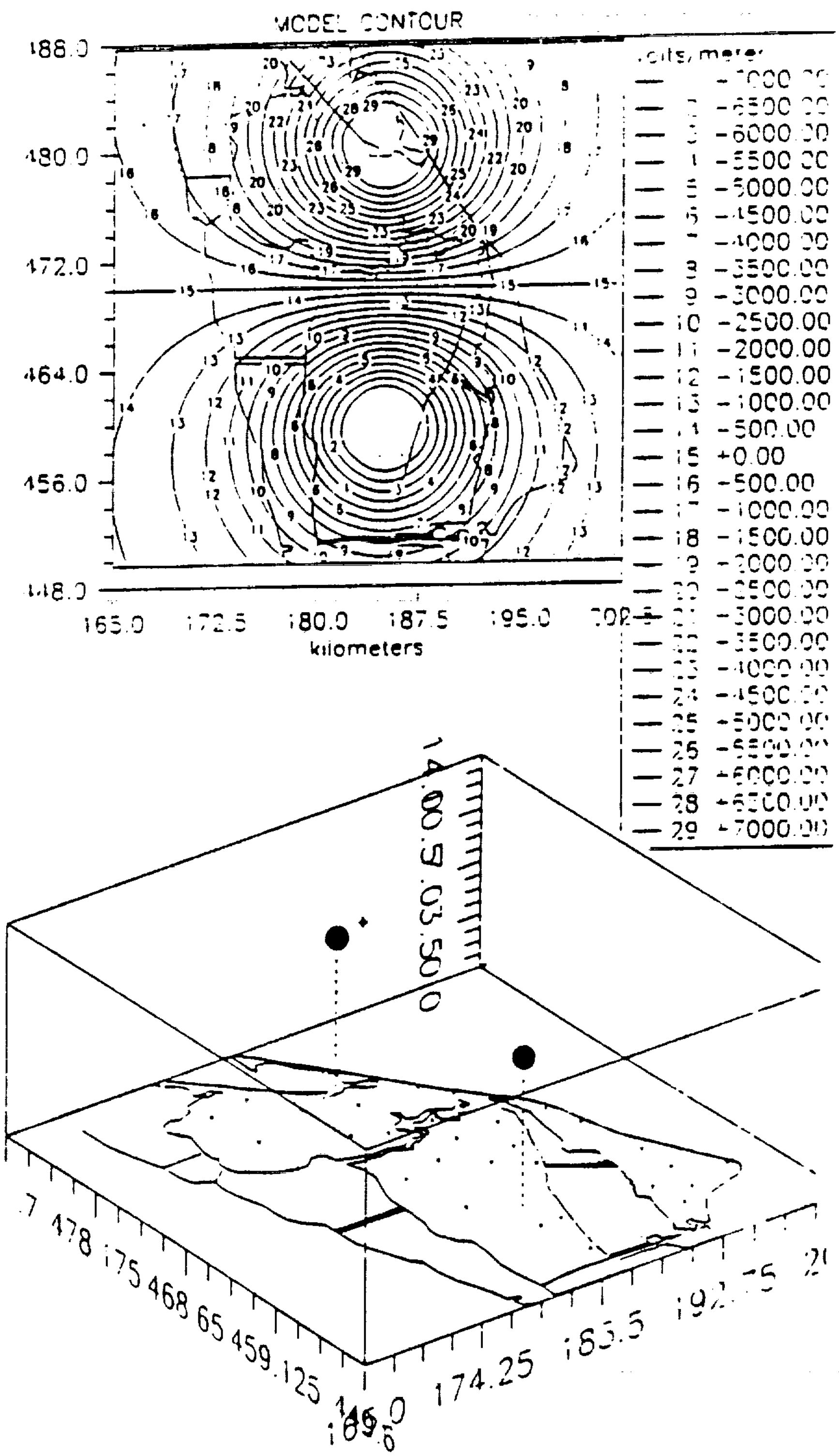


Figure 4. MODEL_D'S TMT_3010

varied from four kilometers to twenty kilometers. The second group of five data sets deals with the same variation applied to two dipoles. The results indicate that the resolution capability of the grid system is less along the x-axis than the y-axis. This is due to the decrease in mill population along the western portion of the region. This is illustrated in figure five.

4.2.1.5 Variation in the Number of Field Mills Used in the Analysis. The data set associated with GMT_2127 was used to generate a group of data sets, TMT_5000 through TMT_5006, in which the number of mills used in the analysis is diminished. The first set of the group represents the full mill complement. In each of the subsequent sets, one mill is removed from the data pool. The mills removed from the data pool gradually spanned the y coordinate of the region. The results of the analysis are presented in figure six.

4.2.2 GRAPHICAL ANALYSIS OF STNDRD. Those variations in charge number, size and position which are described above can be view using the graphic portion of the package. There are over two hundred different graphical displays available using the three control libraries. A full analysis of portion of those libraries is outside space limitation on this presentation. Samples from each library are presented to illustrate the views available. The value of this component of the package is in viewing the development of patterns as charges are separated and noting the relative change in the solutions arrived at by the models. Whereas it is difficult to give a strict analytical comparison between the result and control data sets when the number of charges in each differs, the graphical results show how limitations on the resolving power of the models and the grid are compensated for by the models. In general, this is achieved through the inclusion of small stray charges.

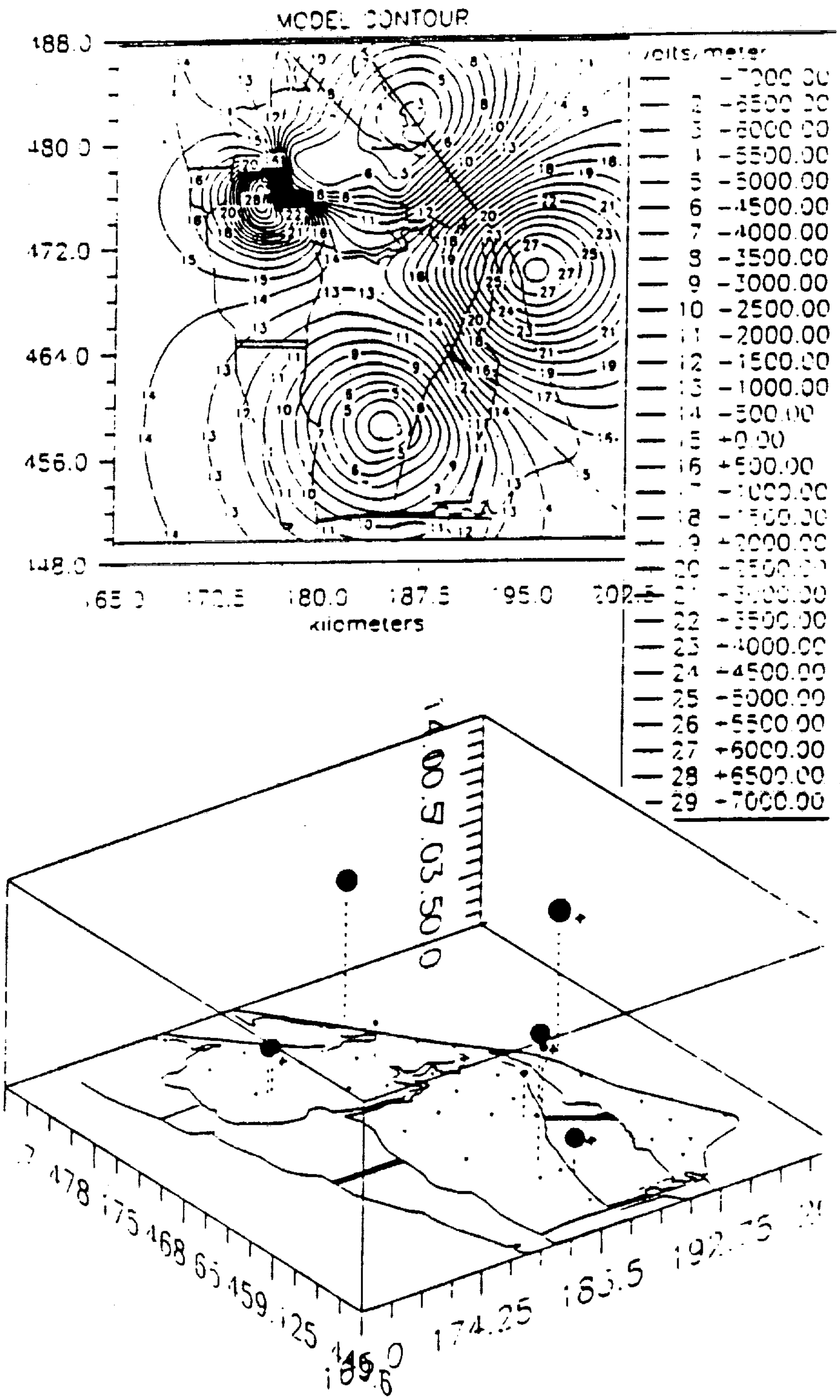


Figure 5. MODEL_D'S TMT_4010

Figure 6. VARIATION C Due to Reduced Mill Population
Data Sets: TMT-5000 through TMT-5006

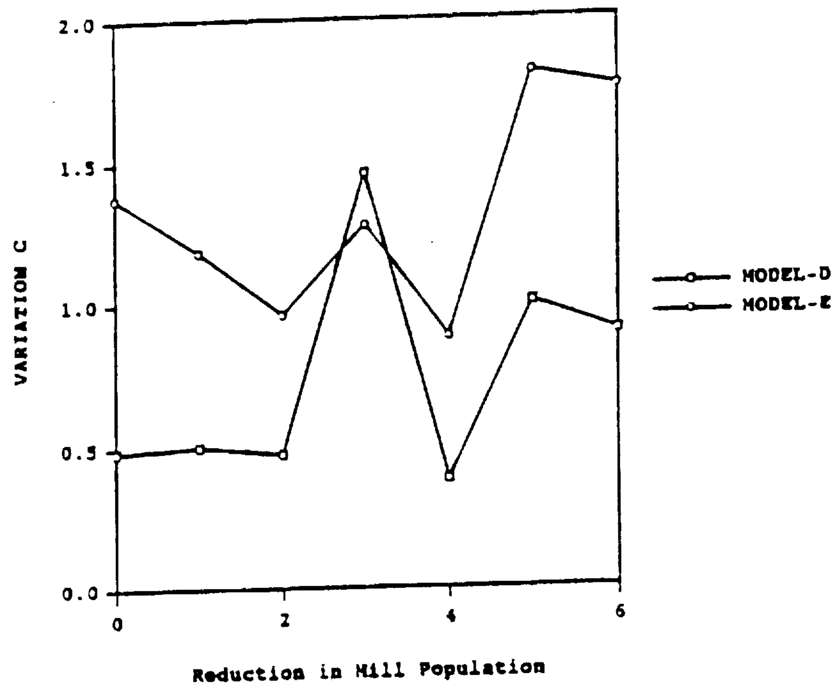
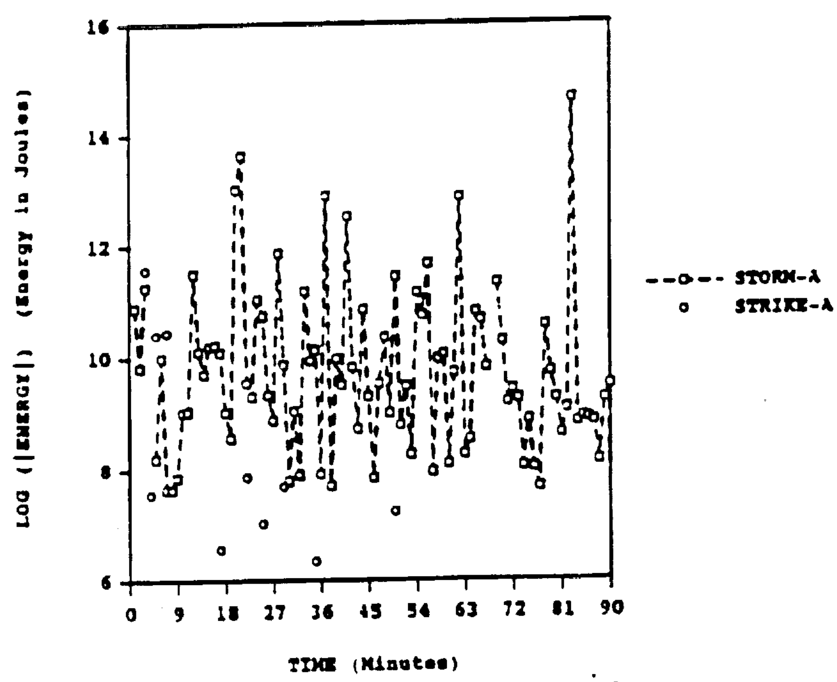


Figure 7. STORM-A and STRIKE-A
MODEL-E ENERGY ANALYSIS



CONCLUDING REMARKS

5.1 ANALYTIC ANALYSIS CAPABILITIES

The analytic portion of the package functions well. Model_D and Model_E are able to establish model sets of charges based on field mill value and limiting constraints. This was accomplished for a wide variety of conditions. The system is able to deal with all calculational anomalies that occur for these conditions. This was verified by its ability to deal with data from a sets sampling actual and controlled situations. Both models demonstrated similar analytic capabilities.

5.1.1 MONOPOLES. The systems showed exceptional accuracy in determining the location and size of monopole charges. This ability was demonstrated repeatedly using controlled input data. This attribute makes the programs extremely valuable in interpreting field change. The system should be able to determining the sign, size, and location of changes in charge density associated with lightning strikes.

5.1.2 RESOLVING POWER. In tests on the ability of the charges to resolve two charges, distinct resolution was not achieved until a dipole separation of about 18 km was reached. Once resolved, the two charges in the control set were characterized with the accuracy demonstrated with monopoles. Until that point the system introduced additional charges. The distinction between the resolving power of the program and that of the field mill grid system was not established.

5.1.3 MODEL FIELD. The model fields generated by the system agreed favorably with input data when weighed against the reliability of that data.

5.2 GRAPHIC ANALYSIS CAPABILITIES

The graphics portion of the package demonstrated its utility as an aid in appraising data set. This was demonstrated when the gradual development of systems was considered as in the gradual resolution of dipoles and the quadrapole control systems. The graphics showed how the analytic portion of the program was sorting out information and the progress being made toward resolution of the poles. It also illustrated the systems dependence on a complete grid system for full information if resolution is to be achieved. As a consequence this portion of the package shows an ability to analyze grid systems.

5.3 RESEARCH AND OPERATIONS APPLICATIONS

The package verified that it is possible to formulate a charge distribution which corresponds to the source charges generating the input data. The strongest limiting factors in achieving a strong correlation between model and source are the

resolving power of the algorithm and that of the monitoring grid.
The programs and the techniques introduced can be used as a mechanism for addressing these limitations. Once accomplished the package can be used in research and operations as projected.

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