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ABSTRACT

The continuous demand for large-scale high-precision magnetic field measurements at Lawrence Radiation Laboratory has resulted in the development of streamlined data-handling procedures and data-processing programs. These procedures and computer programs have been developed during the course of processing about 5 000 000 magnetic field measurements in the past four years.

This paper presents techiques which are valid regardless of the data-acquisition system employed. However, examples are drawn from experience with the Lawrence Radiation Laboratory Rapid Mapper Magnet-Measuring system, which has been successful largely because it was designed with these techniques in mind. The Rapid Mapper's standard recording sequences and computer programs for detecting and correcting errors, normalizing the data, comparing sets of data, and producing graphs and contour plots are described.

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INTRODUCTION

There is continuous demand for large-scale high-precision magnetic field measurements in connection with high energy physics experiments. To meet this demand inthe large variety of test situations found at LRL–Berkeley a versatile magnetic-field data-acquisition system has been developed.[1] This paper describes the procedures we use for recording, processing, and representing the magnetic field measurements of dipole magnets made with this system (methods of measuring and processing quadrupole field data are described elsewhere[2]).

Since 1963 the Magnet Test Group at LRL–Berkeley has recorded and processed more than 5 000 000 digital measurements of 75 different beam-transport and momentum-analyzing magnets. In a 2-week period in May 1967 our measuring equipment was used by the Texas A & M Cyclotron Institute to make an additional 3/4 million measurements of their sector-focused cyclotron.[3] Similar measurements at the University of Maryland are scheduled for August 1967.

The system used for making these measurements is the Rapid Mapper, which records magnetic field data and supplementary information onto magnetic tape. The data on this tape are processed with the aid of computer programs to provide the experimenter with printouts and graphs, and also a final set of field values in a convenient format on magnetic tape.

Because of the versatile nature of the Rapid Mapper we have been able to meet most of the test requirements of LRL experimenters without changing the system's basic measuring sequences of data format. Therefore we can use standardized programs to process the data.

MEASURING SYSTEM AND DATA FORMAT

In order to describe the processing procedures and computer programs it is necessary to first describe the Rapid Mapper and the format in which the measurements are collected.

Rapid Mapper

The Rapid Mapper is a magnetic-field data-acquisition system which automatically measures and records magnetic induction as a function of position, and provides identification and calibration data needed by the computer programs that process the data. Magnetic induction is measured by moving a search coil by increments along a straight line and integrating the output voltage of the search coil. At each point the integrated search-coil voltage is read by a digital voltmeter and recorded on magnetic tape by an incremental tape recorder.

Definition of Map

Data are collected in planes--subsets of a four-dimensional space composed of three orthogonal space variables and magnet current (X, Y, Z, and I or R, θ, Z, and I). A set of data on one plane is called a map. A map is a self-contained data-processing unit which consists of three types of records--map-identification records, calibration records, and run records. The map-identification record identifies the magnet, the type of measurement, the coordinate system, and other map parameters, and provides data-processing programs with information needed to carry out the required operations. The calibration record provides the data-processing programs with data necessary for automatic "leveling" of the run record. A run is the basic measuring sequence. A run record consists of eight identifying words and a series of field measurements along a straight line. Each point is measured twice, once as the search coil moves away from the starting point and once as it returns.

Types of Runs

For the purpose of describing the types of runs we define the Cartesian coordinate system in which most of our data are collected and from which our run sequences are named. The Z axis is perpendicular to the magnet's lower pole tip. The Y axis is parallel to the lower pole tip and directed through the aperture of the magnet. The X axis is parallel to the lower pole tip and directed across the aperture.

Runs are named for the direction of search-coil motion. A Y run is made when the search coil travels the length of an aluminum "guide tube" placed in the magnet gap. The search coil is usually started from a zero-field region inside a Mu-metal enclosure located at Y = 0. Measurements are made at 1-in. intervals with a frequency of five measurements per second. An X run is a sequence of measurements on a given YZ line in which the guide tube is automatically translated in the X direction at the rate of 1 in. per second. A Z run is a set of measurements on an XY line in which the guide tube is raised and lowered with hand cranks.

X, Y Maps

For maximum efficiency the bulk of our data is collected in the form of XY maps--a set of Y runs at equally spaced X positions at one elevation and magnet current. An XY map is made completely automatically in that at the end of each Y run the guide tube is automatically moved to the next X position and the next run is begun. One XY map is made for each current level and elevation required.

XI Magnetization Maps

In tests in which the measuring accuracy requires precision within less than 0.1% of the central field value we augment the XY maps with a YI Magnetization map and an XZ tie-in map. A YI map is a set of Y runs at equally spaced magnet current settings and along a specific XZ line (usually on a line passing through the center of the magnet aperture). Because the YI map is a base for a leveling process which increases the accuracy of the XY maps, special care is taken in setting and monitoring magnet current.

XZ Tie-In Maps

XZ maps tie the XY maps together and to the YI map to produce a consistant set of measurements in four variables (X, Y, Z, I). XZ tie-in maps are composed of a family of X runs (one run for each elevation) and a Z run (one measurement for each elevation) for each measured current level.

DATA PROCESSING

Despite all our precautions in recording magnetic measurements, errors and malfunctions do occur. Initial checks of data quality are made by the Rapid Mapper Operator, but the majority of the processing is done with the aid of four computer programs, CERTFY, FILMER, OMNIBUS, AND PLOTOR. (These programs are primarily Fortran IV coded programs with some machine language subroutines. They were written for the IBM 7090 computer and modified for the CDC 6600 computer.

The steps necessary to process a given group of maps depend on the quality of the raw data and the requirement of the customer. Figure 1 shows the order in which the data are normally processed. At each step the operator examines the printed information, decides on the next processing step, and prepares control cards for input to the appropriate program.

Processing during Data Acquisition

Processing is begun while the measurements are in progress. The Rapid Mapper operator spot checks the recorded measurements as they are sampled by a printer in parallel with the tape recorder. By comparing equivalent measurements in the two halves of a run the operator can detect--and often determine the cause of--malfunctions. Other conditions known to adversely affect the quality of the data are called to the operator's attention by an audible alarm system incorporated in the Rapid Mapper. Experience has shown that it is invariably more efficient to correct problems and repeat measurements than to struggle in an attempt to process substandard data. There is no substitute for good data!

The operator also maintains a map log and fills out a processing form for each map, to identify the measurements and note unusual events. When a reasonable number of maps has been completed the operator identifies the data tape and sends it to the computer center for processing on the CDC 6600 computer.

CERTFY

The initial processing is done with the program CERTFY. This program reads the data tape, sorts the records, corrects discrepancies in the two halves of each run, lists the run corrections, and provides four matrix-formatted printouts for each map. The first printout lists the differences between corresponding measurements in the out and back halves of each run. These differences are calculated before corrections are made, so this printout indicates the quality of the raw data. The second printout lists the average of the out and back field values after all necessary adjustments have been made. The two remaining printouts are tests of smoothness in the X and Y directions respectively as determined by polynomial approximations to the data in localized regions throughout the map.

Because we record two measurements at each point, a simple algorithm can detect and correct most random errors above the noise level of the data. Without this redundant information it would be necessary to approximate the data with a function expressed numerically and to compare the data with the function at each point. The problem here is finding a simple function, even in localized regions, which accurately represents the field shape. We circumvent this problem by operating on the differences of the field values in the two halves of a run. A significant random error probably will occur in only one of the two measurements at a point, and even very small errors can be detected by scanning these differences. CERTFY detects random errors by an algorithm which calculates what the difference at each point should be (according to a polynomial fitted to neighboring differences) and compares it with the real difference between the two measured values. The algorithm systematically finds the largest error, checks the error pattern to determine the magnitude of the correction to be made, determines if the error is in the out or back half of the run, and corrects the appropriate field value.

Any remaining random errors and the inevitable small systematic errors (due to integrator drift, dielectric adsorption in the integrating capacitor, and probe position backlash in high gradient fields) are reduced by averaging the corrected out and back field values and adding a single leveling constant to the results.

When all the runs in a map have been adjusted and the results printed, CERTFY produces an output tape referred to as an "Auxiliary Tape" to be used for subsequent processing.

FILMER

Certain kinds of format errors caused by an operator's mistake or equipment failure interfere with the operation of CERTFY. These can often be corrected by a tape-editing program called FILMER. FILMER transfers data selected from data cards and one or more input tapes onto an output tape while replacing, adding, or omitting blocks of data. These data blocks can be entire files, records, words, or individual characters. Control cards define the operations to be performed and provide the details necessary to accomplish the operation. After a data tape is edited it is again processed by CERTFY.

Although the primary use of FILMER is in editing data tape, it is a general-purpose program and can be used to edit and combine any binary-formatted input tapes.

OMNIBUS

After a group of maps has been processed by CERTFY all additional adjustments are made by OMNIBUS. As the name implies, OMNIBUS accomplishes a number of varied tasks within the execution of one program. Input to the program is an auxiliary tape and a set of control cards which specify the operations required on each map. There are three classes of operations--input, computational, and output. (i) Input operations interpret control cards and transfer the required data from the input tape to the appropriate locations in the computer. (ii) Computational operations include correcting field values, generating XZ reference maps, normalizing XY maps using the XZ reference maps, combining maps, and testing the smoothness of maps. (iii) Output operations include producing matrix-formatted printouts, drawing graphs on the Cal-Comp plotter, and producing output tapes. These operations can be carried out in any reasonable order and repeated as often as necessary to accomplish the desired results. Most of these operations and their purpose are described below.

Correcting data. Adjustments may be necessary to correct errors that CERTFY is unable to handle. (A run may be missing entirely, an entire map or several runs in a map may be in error due to an erroneous calibration record, or interfering adjacent errors may have prevented CERTFY from making the proper corrections.) OMNIBUS makes corrections, specified by a control card, to a single point, a single run, or a group of adjacent runs. Corrections may be made by replacement, addition, multiplication, or interpolation.

Normalizing XY maps. The purpose of producing a YI magnetization map and a set of XZ tie-in maps is to provide a means whereby all the XY map data at one current are normalized to the magnetization map data at that current. Some minor adjustments may be necessary to correct for slightly misset currents or minor current drift. To determine the necessary adjustment, OMNIBUS first combines the YI map with the XZ tie-in maps to generate a set of XZ reference maps. The reference maps have one point in common with each run of the XY maps. By comparing the appropriate field value in a run with the corresponding value in the reference maps, OMNIBUS determines the proper adjustment factor and adjusts the run.

Combining maps. OMNIBUS combines maps either to compare two sets of data or to artificially produce an intermediate set of data. A point-by-point difference between two maps can be used to study reproducibility, symmetry, or the change of field shape with magnet current. Two maps can be normalized and added together to artificially produce a new map at an intermediate current level.

Testing smoothness. OMNIBUS tests the smoothness in the X and Y directions, as is done in CERTFY. It also compares each field value with the weighted average of 34 surrounding field values in a 5×7 mesh.

Printouts. The tests of smoothness are printed in a matrix-formatted printout for the user's inspection. OMNIBUS also prints out the final array of field values along with the field integral $\int B_z dy$ at each X position.

Graphs. The graphs which OMNIBUS produces are for showing magnetic induction or a field integral as a function of one of the map variables. For the YI magnetization we normally plot B vs I, B/I vs I, $\int B_z dy$ vs I, $\int B_z dy/I$ vs I, and $\int B_z dy/B$ (effective length), where B is the induction at the magnet center and $\int B_z dy$ is the integral of field along the aperture center line. For the XY maps we normally plot the variation of the field integral with X position ($\int B_z dy$ vs X).

Output tapes. OMNIBUS also produce two output tapes. One is an updated version of the auxiliary tape used as input. The other, designated a field tape, contains the final set of field values in an easily read format. The field tape is used as input to a contour-plotting program and eventually is turned over to the experimenter for input to his program.

PLOTOR

PLOTOR produces contours of constant B which are plotted on a Cal-Comp plotter. As many as twenty different levels of magnetic induction are plotted with up to nine different symbols. PLOTOR can also be programmed to superimpose an outline, such as a magnet pole tip, on the contour plots.

Input to PLOTOR is a field tape and a set of control cards which provide the setup and plotting parameters. Output is a set of coordinate pairs (points in the XY plain where the field is of a specific magnitude). The coordinate pairs are listed by a printer and the points are plotted by the Cal-Comp plotter.

Automatic Bookkeeping

Test programs typically come in spurts, and keeping track of magnetic tapes and printouts is not a trivial problem. We have recently incorporated an automatic bookkeeping routine in each of our programs which keeps track of all the programs used previously for processing a given set of data. A table designating the input and output tape used and the date on which each program was executed is stored on the output tape and listed on the printouts. This table provides positive identification of the tape to be used as input for the next processing step, and enables us to retrace our steps when anomalies occur. It also enables us to systematically remove intermediate tapes when a job is complete.

COST ANALYSIS

The major cost of a test program is divided between measurements and processing. These costs depend both on the quality of the raw data and on the use to which the information will be put. When the measurements are well planned, the Rapid Mapper is functioning properly, and the operator pays close attention to the details of measurement, the total cost can be as low as \$0.02 per measurement.

The measurements of the Texas A & M cyclotron provide an outstanding example of the efficiency of the Rapid Mapper. The cost of recording these measurements was about \$0.005 per measurement (based on two operators at \$9 per hour and 3600 measurements per hour). The cost of processing the Texas measurements has not been reported and is not directly applicable to the processing procedures reported here.

A cost analysis of the data most recently processed with CERTFY, OMNIBUS, and PLOTOR showed computer time charges as follows:

Program	Date	Total Points	Computer charge	Cost per point
CERTFY	5-1-67	6 000	$12	$0.002
OMNIBUS	6-19-67	17 000	$12	0.001
PLOTOR	3-15-67	6 300	$ 5	0.001
			Total	$0.004

The cost of preparing control cards, examining the printouts, and communicating with the customer can be as low as $0.01 per point, bringing the total cost for measuring and processing to about $0.02 per point.

CONCLUSION

Although the cost of developing the Rapid Mapper and its data-analysis programs was substantial,[4] we believe it has proved its worth. The success of many momentum-analysis experiments requires detailed and accurate magnetic field measurements in a format which this system provides directly. Using this sytem and our standard processing programs reduces the cost of the experiment and the time between the definition of a test program and the delivery of the final data.

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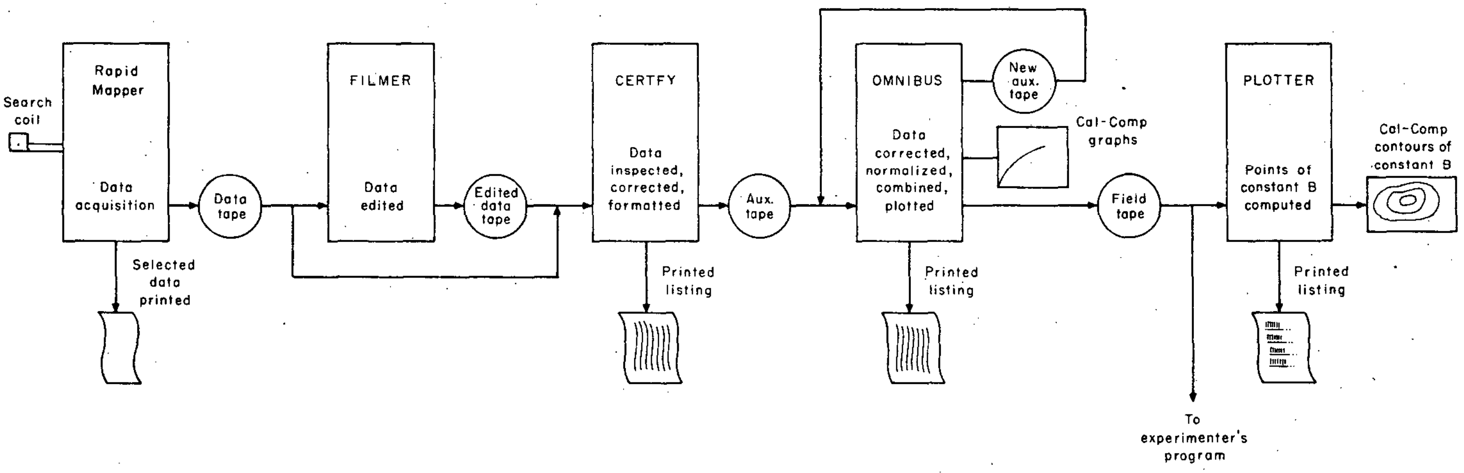

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Fig. 1. Data processing flow diagram.