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SIMPLIFIED RADIAL SURVEY OF THE CEA MAGNET RING

K. W. Robinson

W. A. Shurcliff

August 10, 1970

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
and HARVARD UNIVERSITY

CAMBRIDGE ELECTRON ACCELERATOR

CAMBRIDGE 38, MASSACHUSETTS

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TABLE OF CONTENTS

	Summary	1
Part I	Introduction	4
Part II	General Description of New Method	6
Part III	Equipment	9
Part IV	Procedure in Ring	12
Part V	Preliminary Processing of Surveyor's Data . . .	14
Part VI	Errors Made by Surveyor	17
Part VII	Rationale of Magnet-Position Computer Program .	20
Part VIII	Rationale of Orbit-Distortion Computer Program	23
Part IX	Computer Program	24
Part X	April 1970 Survey: Execution and Results . . .	26
Part XI	July 1970 Surveys: Execution and Results . . .	28
Part XII	Discussion	31
	Acknowledgment	31

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SIMPLIFIED RADIAL SURVEY OF THE CEA MAGNET RING

SUMMARY

The new radial-survey method entails use of two of the 48 magnets at a time, rather than four as in the earlier surveys. The line-of-sight is along the upper radially inner portions of the magnets and thus avoids interferences (by external beamruns and the bypass) that since 1966 have made the earlier method useless. The longest line-of-sight is 26 ft, compared to 47 ft in the earlier surveys.

The telescope-and-holder system is mounted on the given magnet in pre-leveled and pre-aimed manner, and the same applies to the optical-target-and-holder system. The systems are held in place by gravity; no clamps are used. No fixture plates are required and no leveling or aiming operations. The surveyor's rms error in making telescope readings of relative radial position is 0.001 inch.

Azimuthal spacing of the magnets is measured with an extension mechanical micrometer. An accuracy of 0.005 inch is adequate.

Two men can complete a survey in 5 hours, compared to 20 hours using the earlier method.

The (Fortran IV) computer program for calculating the positions of the 48 magnets involves calculating the appropriate Green's function, inverting several 6×6 matrices, and making a harmonic analysis in which the 0'th, 1'st, and 24'th harmonic are ignored. The output shows the radial error of each end of each magnet and the downstream error of each magnet as a whole - aside from errors associated with the ignored harmonics.

An auxiliary computer program computes orbit distortion, i.e., the extent to which the equilibrium orbit (at each straight section) deviates radially from the nominal location relative to the two magnet-ends that flank the straight section.

Executing the program on the IBM 360/65 computer takes one minute and costs \$3.

Three actual surveys were made: one in April 1970 and two in July 1970. Tables 1, 2 and 3 show the input and output data in numerical form and Fig. 6 shows the orbit-distortion data in graphical form. The three surveys implied orbit distortions that are in agreement within 10% at the peaks of small distortions and within 5% at the peaks

of the large distortions. The deliberately arranged $\frac{1}{2}$ -inch orbit distortions at Straight Sections 10 and 19 are revealed clearly (with magnitudes of 0.522 inch and 0.470 inch) and several 0.1 to 0.2 inch distortions that were not intended are revealed also.

PART I. INTRODUCTION

The original radial survey of the CEA ring (January 1961) was carried out by intercomparing the positions of the magnets in groups of four, e.g., Magnets 1, 2, 3, 4, then Magnets, 2, 3, 4, 5, etc., as described in CEAL-1000, CEAL-1034, and W. A. Shurcliff's 14-page memorandum of 5/24/61. Telescope and optical target were mounted on carefully leveled fixture-plates attached to the radially outer guide-rails of the magnet structures and the line-of-sight was $1\frac{1}{2}$ to 3 ft radially outward from the series of magnets. See Fig. 1. The resulting 48 sets of data were inserted in a computer program due to K. W. Robinson and the output showed the surveyor the required radial and azimuthal adjustments of each end of each of the 48 magnets. Subsequent radial surveys (through December 1966) were made in the same manner.

With the installation of the CEA Bypass, extending from Straight Section 10 to Straight Section 19 (see Fig. 2), such surveys could no longer be made: the massive components of the bypass blocked the lines-of-sight and also left no room for the fixture plates or for the surveyor himself. Difficulties in assembling and aligning the bypass equipment were formidable and the Bypass Group was reluctant to move the equipment aside to permit a new radial survey to be made. The old survey route was further encumbered

Fig. 1. Original (1961) method of surveying the magnets in groups of four, with fixture plates mounted radially outward from the magnets. Each plate contains four stations for targets; for each telescope set-up, the target is moved successively to seven different stations.

Figure 2. Location of the 120-ft bypass train which joins the synchrotron ring at Straight Sections 10 and 19. Massive components along the bypass would obstruct any radial survey that proceeded outside the ring.

by the seven tangential beam-runs from ring to Experimental Hall. For three years (December 1966 through March 1970) no radial survey was made.

The present report describes a new survey method devised in recent months and explains several "dividends" afforded by this method. The project included, as an extra but valuable feature, the calculation of the orbit distortions consequent on the imperfect radial and azimuthal alignments of the magnets.

PART II. GENERAL DESCRIPTION OF NEW METHOD

In September 1969 we started a search for a new survey path. We soon found (following a suggestion by J. M. Paterson) that a path above the upper, radially inner, portions of the magnets was available provided that the path was short, extending along only two magnets, rather than four. See Fig. 3. Only one interference threatened: interference by a vacuum foreline above Straight Section 26. Permission was received to remove this foreline for one hour as the survey progressed through this location.

It was immediately clear that, with a line-of-sight only a few inches above the upper shoulders of the magnets, telescope and target could be set directly on the magnet. No special fixture was required, and no leveling operation was required (because the magnets themselves were already level within 0.005 inch in the 11-ft magnet length).

Also it was clear that the telescope could be "pre-aimed" in the horizontal plane by having it bear suitably against the magnet shoulder. Thus setting the telescope on the magnet with proper radial position, levelness, and aim would take only a few seconds, and the same would be true of the target. (The invariable relationship between magnet top and the magnet poles was assured by the original die-cutting method of fabricating the metal laminations comprising the magnet: the laminations were cut alike dimensionally

- (a) Plan view of two adjacent magnets, with line-of-sight indicated. Telescope is at Position P_0 . Target is placed successively at P_1 , P_2 , and P_3 .

- (b) Vertical section showing distance of line-of-sight above magnet top.

Figure 3. General scheme of simplified radial survey:
 (a) plan view of a pair of magnets, (b) end elevation of a single magnet and its supporting girder.

to 0.001 inch and are held in proper relationship to one another by guide rails straight to similar tolerance.

It was also a simple matter to define the azimuthal position of the telescope with respect to the magnet end, - specifically, the outer face of the magnet end-plate. Special measurements showed that the overall lengths of the individual magnets (distance between the outer faces of the two end-plates) were the same within an rms deviation of 0.02 inch. Such an error in the azimuthal positioning of the telescope or target is acceptable inasmuch as only two magnets are involved in any one group of measurements and they depart from colinearity by only $7\frac{1}{2}$ degrees.

The procedure adopted was to place the telescope on the radially inner portion of the top of the upstream end of the selected magnet, then take readings on the target placed successively at downstream end of this same magnet and then at upstream and downstream ends of the succeeding magnet. A 4-ft mechanical inside micrometer was used to measure the endplate-to-endplate separation between these two magnets with an accuracy of better than 0.005 inch. In summary the surveyor obtained, for each pair of magnets, three readings of radial position and one reading of azimuthal separation. Clearly these four quantities fully determine the plan-view position of the second magnet relative to the first. (Actually the first of the radial-

position measurements is not necessary, in principle; but it was used, as explained in Part VII, to permit the surveyor to correct for slight imperfection in telescope pre-set aim.)

The forty-eight sets of such data (raw data) implicitly determine the relative positions of all 48 magnets. To obtain the positions in explicit form, the surveyor inserts the raw data in an appropriate computer program (see Part IX) and executes this program.

A striking feature of the new method was that the lines-of-sight were so short: the longest of them was only 26 ft. Short lines-of-sight tend to make for large amplitude error of low harmonics of computed positions of the magnets.

However, we found (from a preliminary analysis) that lines-of-sight as short as this would be acceptable provided the surveyor's random errors did not exceed ~ 0.004 inch rms. Preliminary tests indicated that the random error would be considerably less than this, and accordingly the proposed method was judged acceptable.

PART III. EQUIPMENT

In carrying out a radial survey by the new method, we use the 60-power Farrand alignment telescope Type 95360, which has a built-in optical micrometer for reading lateral displacements up to 0.112 inch with 0.0002 inch precision and an accuracy limited only by the homogeneity of the air ($\sim$ 0.001 inch, typically, for a 26-ft-distant target).

The telescope is mounted in a holder consisting of a flat plate, three short legs, two vertical "locator rods", and a pair of yokes for securing the telescope. See Fig. 4. The locator rods, 7.250 inches apart on centers, project below the plate and also above it; the lower projections bear against the magnet shoulder to provide plan-view pre-aim of holder relative to magnet shoulder and the upper projections serve as references in determining the plan-view positions of the two ends of the telescope's precision cylindrical barrel (2.875 inches in diameter and 6 inches long).

Thus the absolute relationship of telescope and magnet shoulder can be verified easily at any time. (Even a change of 0.002 inch in this relationship during the survey would be harmful.) The position of the holder along the magnet is determined by a 2.437-inch-long feeler block extending from upstream locator rod to upstream face of upstream end-plate of magnet. The length of this block was chosen so

Figure 4. Telescope holder, with locator rods (LR) for providing plan-view pre-aim with respect to shoulder of magnet.

that both locator rods bear against the shoulder of the same core-block - and at a comfortable distance from the coreblock ends.

Weighing only 20 lbs., the combination of telescope and holder can be lifted into position easily by one man. No clamp is necessary: gravity holds the assembly in place.

Drawing D-35M76 on file shows the detailed design of the telescope holder.

The holder was easy to design and build as it includes no high-precision components: all of the high-precision components needed are in the telescope itself (purchased over 11 years ago and still in perfect condition).

Notice that the holder is very rugged, very rigid, contains no moving parts, and has no backlash. Wear is no problem because the critical members (locator rods, which slide along the magnet shoulder when the assembly is being positioned on a magnet) are of large (5/8 inch) diameter. Because the three legs of the assembly are short and far apart and the telescope is mounted close above the base plate, tilt of the assembly (and consequent radial displacement of the telescope axis) is negligible.

The line-of-sight is barely high enough to clear the plastic covers for the massive power cables serving the magnet coils and barely low enough to pass beneath cable trays, rf waveguide support brackets, etc.

The optical target, shown in Fig. 5, consists of a 10-inch-long Keuffel and Esser "Wyteface" scale the 0.1-inch markings of which are accurate to better than 0.0005 inch. This scale too is mounted on a holder that has three short legs and two locator rods, and the basic geometry of this holder is identical to that of the telescope holder (and, when seated on the upstream end of a magnet, seats against the shoulder at the identical place where the telescope holder would seat). The scale is mounted radially and is long enough (10 inches) so that some portion of the scale will be within the field-of-view of the pre-aimed telescope whether the scale is mounted on the downstream end of the same magnet that supports the telescope or is mounted on the upstream or downstream end of the succeeding magnet. The two used portions of the scale are about 8 inches apart. For further details as to the target and target holder, see Drawing D-35M77 on file.

The ~ 47-inch space between magnets was measured by means of a Starrett extension inside micrometer. Measurements were made from the outer surface of the magnet endplate at a location 1/2 inch below the magnet "step" (1 inch below extreme top of magnet and 2 1/2 inches radially outward from radially inner face of magnet). A measurement accuracy of 0.005 inch was considered ample.

Figure 5. Optical target consisting of scale and scale-holder. The scale is oriented with its high (10-inch) mark toward the accelerator centerpoint.

PART IV. PROCEDURE IN RING

When starting his survey work in the Circular Tunnel, the surveyor places the telescope (firmly clamped in its holder) on the upstream end of Magnet 1, presses the holder firmly against the magnet shoulder, and slides the holder along the shoulder until the feeler block shows the distance from the magnet end-plate to be correct within ~ 0.002 inch. He then confirms that the holder is snug against the magnet shoulder. The telescope position is called P_0 .

He places the target correspondingly at the downstream end of that same magnet (Position P_1). An identical feeler block is used in setting the azimuthal position.

He takes a reading with the optical micrometer of the telescope, being sure to sight on that target line that gives a positive reading of the telescope micrometer. The reading is called Ep_1 .

He moves the target to the upstream end of the succeeding magnet (Position P_2) and takes a reading Ep_2 , then moves the target to the downstream end of that magnet (Position P_3) and takes a reading Ep_3 . (The letter p stands for the serial number of the magnet on which the telescope rests.)

He moves the equipment along to the next pair of magnets: Magnets 2 and 3, and repeats the process. And so on for forty-eight pairs: 1,2; 2,3; 3,4; etc.

Finally he measures the separation between magnets as indicated in Part III.

The program writer needs to know the approximate (nominal) distance from telescope to each of the target locations, i.e., from P_0 to P_1 , P_2 , P_3 . For this purpose the telescope position may be defined as a vertical line midway between the axes of the two locator rods. Position P_1 is defined as the location of the target mark viewed by the surveyor when the target is in place at the downstream end of the same magnet that is supporting the telescope. Positions P_2 and P_3 are the positions of the corresponding target marks when the target is on the upstream and downstream ends of the succeeding magnet.

By actual measurement with a simple tape measure the distances were found (with an accuracy of ~ 0.2 inch) to be:

P_0 to P_1 : 123.9 inches

P_0 to P_2 : 183.8 inches

P_0 to P_3 : 308.0 inches

Nearly any intelligent, careful person or persons can make the survey. A beginner can be taught the procedure in 20 minutes.

The survey can be made even when much maintenance and repair activity is underway in the Circular Tunnel.

PART V. PRELIMINARY PROCESSING OF SURVEYOR'S DATA

The surveyor computes the average of the 48 values of spaces between magnets (~ 47.35 inches) and for each space he then computes the excess (Ep_q) with respect to the average. The letter p here designates the serial number of the magnet just upstream from the straight section in question; thus if q is the serial number of the straight section, $p = q - 1$.

No preliminary processing of the telescope readings is required. One might at first suppose that preliminary adjustment is needed because all closed magnets are nominally 0.310 inch farther from the accelerator centerpoint than the open magnets are. But the design of the computer program is such that the 24th harmonic in magnet radial position is ignored; thus this 0.310 inch bias between closed and open magnets causes no difficulty and advance adjustment is not necessary. (To demonstrate this we ran computer programs using data that had and had not been adjusted, and the results did not differ significantly. The orbit distortion values were the same to two significant figures.)

Typical samples of surveyor measurement data are as follows:

	Serial Number	Measurement (mil)			
		<u>Ep₁</u>	<u>Ep₂</u>	<u>Ep₃</u>	<u>Ep₄</u>
April 1 - 8, 1970, survey:	1	9369	9038	832	72
	2	9411	9748	1558	-68
	(etc.; 48 sets in all)				
July 15 - 16, 1970 survey:	1	9378	9048	849	80
	2	9407	9744	1553	-74
	(etc.)				
July 16 - 17, 1970 survey:	1	9376	9046	847	80*
	2	9401	9734	1536	-74*
	(etc.)				

*In July 1970 the azimuthal values Ep_4 were measured only once, and the values were used for both of the July 1970 surveys.

Note that the discrepancies between the first two sets of data having Serial Number 1 correspond to errors in telescope aim. The discrepancies are $(9369 - 9378) = -9$, $(9038 - 9048) = -10$, and $(832 - 849) = -17$. These three numbers, -9, -10, and -17, are in approximately the same ratio as the $P_0 - P_1$, $P_0 - P_2$, $P_0 - P_3$ distances, namely 123.9,

183.8, and 308.0 inches respectively (approximately in the ratio 2:3:5, so that, by coincidence the sum of the first two discrepancies almost exactly equals the third discrepancy).

The same applies to the other corresponding sets: the discrepancies are mainly the result of differences in telescope aim. Typical differences in aim correspond to a radial motion of 0.0005 inch (1/2 mil) of one of the telescope-holder locator rods. Such differences in aim are expected, are hard to eliminate, and are harmless.

PART VI. ERRORS MADE BY SURVEYOR

The rms deviation among the surveyor's readings on a target at position P_1 , 10 ft from the telescope, is 0.0002 inch, provided the readings are made within a few minutes and without moving the telescope or the target. When the target is at the farthest position (P_3 , 26 ft from the telescope), the rms deviation in reading is 0.0005 to 0.001 inch.

If the target assembly at P_1 is removed and then re-installed, the rms change in reading is < 0.0005 inch.

If the telescope assembly is removed, then reinstalled, the reading changes by several mils, ordinarily. When the target is at P_1 the rms difference in reading is ~ 0.005 inch. When the target is at P_2 and P_3 the rms difference in reading associated with reinstalling the telescope assembly is ~ 0.008 and ~ 0.013 inch respectively. The variations in reading are such as can be ascribed virtually in toto to change in aim of telescope. (The change in radial position of the telescope is necessarily the same as that of the target, since the bases of target holder and telescope holder are identical.) Such changes in aim are not significant: it is the relationship between the three telescope readings, not the absolute readings, that is important.

Irregularities in geometry of a given magnet do not produce errors in the determination of other magnets'

positions - provided that the locator rods of the target in position P_2 have the identical position that the telescope will have when it is later mounted on that same end of that same magnet. Because the two devices' locator-rod geometries are alike within 0.002 inch and the means of adjusting the devices' azimuthal positions along the magnet provide identical positioning with 0.002 inch, the radial positions of the two devices are necessarily alike within ~ 0.001 inch, i.e., despite the fact that the magnet is made up of laminations whose exposed edges depart from co-planarity by ~ 0.002 inch. (A projecting lamination affects each of the devices similarly.)

The magnets are presumed to move significantly (of the order of 0.001 to 0.005 inch) as the temperature of the Circular Tunnel changes throughout the day and as the patterns of introduction and circulation of hotter or colder air change. If the survey is made in mid-winter such changes might be important, especially if the survey were to extend over several days.

Even within a period of a few minutes a reading may change as a consequence of change in temperature patterns along the lines-of-sight. Such patterns are affected by intermittent operation of room heaters, presence of bake-out devices just below the line-of-sight, and by operation of the 15 ft x 15 ft door from the Experimental Hall to the truck ramp. (There is no door - only a gate - in the

labyrinth between the Experimental Hall and the Circular Tunnel.) In winter, sudden strong currents of cold air may be felt in the Circular Tunnel when the truck ramp door is opened.

In summary, telescope readings that are made within an hour, with reasonably uniform temperature of the air, are believed to contain an rms relative error of ~ 0.001 inch.

The rms error made in measuring the spaces between magnets was < 0.005 inch. No effort was made to achieve 0.001 inch accuracy because (a) 0.005 inch azimuthal errors produce only negligible errors (< 0.001 inch) in the measurements of radial positions, and (b) the fiducial surfaces themselves (the magnet end-plates) are arbitrary to an extent exceeding 0.005 inch as evidenced by the 0.02-inch rms variability found in magnet length.

PART VII. RATIONALE OF THE MAGNET-POSITION COMPUTER PROGRAM

The computer program as a whole consists of a magnet-position program and an orbit-distortion program. Only the former is considered in this part.

The program is in Fortran IV, for execution on, e.g., the Harvard IBM 360/65 computer.

The purpose of the magnet-position program is to process the surveyor's data and furnish, for each magnet, the following distance data, in mils:

- D_1 The excess of distance from accelerator centerpoint to positioning pin at upstream end of magnet girder.
- D_2 Corresponding excess of downstream end of girder.
- D_3 The excess of downstreamness of the pair of positioning pins.

(The nominal center-to-center distance between the two positioning pins is 127 5/16 in., per Dwg. S-11M-125-D. The pair of pins is azimuthally symmetric with respect to the magnet proper.)

By suitably moving the positioning pins (by means of the radial and azimuthal drive screws incorporated, for this purpose, in the pier-head assemblies) the surveyor can eliminate the indicated excesses, i.e., cause all of the magnets to lie equally spaced on a perfect circle.

The magnet-position-error program was constructed in a similar manner to the program for the old survey method,

described in CEAL-1034. For each of the 48 telescope positions three measurements are obtained. The error measured at the target on the same magnet the telescope is on is used to correct the two measurements on the next magnet for error in telescope aim. Then for each telescope position one obtains two radial error measurements and (using a micrometer) one azimuthal error measurement.

Using these three data (for each of the 48 telescope positions) one calculates the three errors in position of each magnet: the radial error in upstream pierhead (i.e., upstream positioning pin), radial error in downstream pierhead, and azimuthal error common to both pierheads. This is done by a Green's function that is three sets of 3×48 numbers each, which when multiplied by the 3×48 measurements and summed give the three position errors of one magnet. The same Green's function is used to obtain the errors in all magnet positions by appropriately precessing the numbers.

The Green's function was calculated by means of harmonic analysis. Each of the three types of measurements and each of the three errors in magnet position can be expressed as a sum of Fourier harmonics. The harmonic numbers used are zero to 24 as there are 48 magnets. There are no relations between different harmonics: a particular harmonic of magnet position error produces only the same harmonic of measurements. Then for each harmonic there will be six components

of magnet position error because there are three types of magnet position error and each has two phase components. Similarly there will be six components of measurements for each harmonic. A 6×6 matrix which relates the magnet position errors to the measurements is calculated for each harmonic from geometrical considerations. The Green's function elements are then obtained by inverting the matrices for each harmonic and appropriately summing them. The harmonics 0, 1, and 24 would have to be treated in special ways, and they are not included in the calculation as they have very little effect on the orbit distortion.

PART VIII. RATIONALE OF ORBIT-DISTORTION COMPUTER PROGRAM

The purpose of this program is to show the orbit distortions that currently exist, i.e., the extent to which the equilibrium orbit is displaced radially with respect to the straight sections as a consequence of the current imperfect positions of the magnets. The orbit distortions are usually several times greater than the typical errors in radial positions of the magnets, and it is usually impossible - merely by inspection of the magnet position data - to obtain an adequate estimate of the locations and magnitudes of the orbit distortions. (The graphs of CEAL-1034 demonstrate this fact dramatically.)

The program for calculating orbit distortion is similar to that used with the old radial survey discussed in CEAL-1034. In the present case we calculate the orbit distortion due only to the average radial position error calculated from the average of the pierhead errors. (Here average means: average of the two radial values for the individual magnet.) We neglect the effect of errors in the angular position of the magnet and the azimuthal error, as the effect of these errors is very small compared with the effect of the radial errors.

The errors are calculated relative to the straight section position as determined by the average of the adjacent pierhead radial positions. The actual program for calculating the orbit distortion (DP) may be seen in the Fortran program from Statements 56 to 70.

PART IX. COMPUTER PROGRAM

The combined computer program, in Fortran IV, for calculating errors in magnet position and also orbit distortion is presented below.

```

FORTRAN IV C LEVEL 18          MAIN          DATE = 70176    16/03/52

C      SYNCHROTRON MAGNET SURVEY PROGRAM
C      WRITTEN IN FORTRAN IV
C      SEE CEAL-1052 FOR DETAILS
C      JUNE, 1970  J.KOCH
C
0001      INTEGER P,R,H
0002      REAL M(6,6,24),A(3,3,3),G(3,48,3),E(5,48),D(48,3)
0003      DIMENSION I(16),I2(16)
0004      NAMELIST /DATA/E
0005      DATA A/-.579,-.399,0.,.982,-.0044,.0681,.0264,-.0264,-1.0,
1-.0044,.982,.0681,-.399,-.579,0.,.0264,-.0264,1.0/
C
0006      C1=0.403
0007      C2=0.597
0008      P1=3.1416
C
0009      DO 100 R=2,23
0010      DO 100 J=1,3
0011      DO 100 H=1,3
0012      M(H,J,R)=A(J,H,1)+A(J,H,2)*COS(R*PI/24.)
0013      M(H,J+3,R)=-A(J,H,2)*SIN(R*PI/24.)
0014      M(H+3,J,R)=A(J,H,2)*SIN(R*PI/24.)
0015      M(H+3,J+3,R)=A(J,H,1)+A(J,H,2)*COS(R*PI/24.)
C
0016      DO 101 I=2,23
0017      CALL MINV(M(1,1,1),6,DET,I1,I2)
0018      CONTINUE
C
0019      DO 103 P=1,48
0020      DO 103 K=1,3
0021      DO 103 L=1,3
0022      G(L,P,K)=0.
0023      DO 103 R=2,23
0024      103      G(L,P,K)=G(L,P,K)+(1./24.)*(M(K,L,R)*COS(P*R*PI/24.)
1+M(K+3,L,R)*SIN(P*R*PI/24.))*COS(R*PI/24.)+(1./24.)*(M(K,L+3,R)
2+COS(P*R*PI/24.))+M(K+3,L+3,R)*SIN(P*R*PI/24.))*SIN(R*PI/24.)
0025      GO TO 104
0026      104      CONTINUE
C
0027      READ(5,DATA)
C
0028      WRITE(6,9)
0029      WRITE(6,10)
0030      WRITE(6,11)((I,(E(J,I),J=1,4),I=1,48)
0031      9      FORMAT('IRING SURVEY DATA IN MILS'//
1' SEE CEAL-1052 FOR DETAILS'//)
0032      10      FORMAT(' P      E(1,P)      E(2,P)      E(3,P)      E(4,P)'//)
0033      11      FORMAT(1H ,12,3X,4F10.0)
C

```

```

0034      DO 200 P=1,48
0035      E(1,P)=E(1,P)-C1*E(3,P)
0036      E(2,P)=E(2,P)-C2*E(3,P)
0037      200 E(3,P)=E(4,P)
          C
0038      DO 201 L=1,3
0039      DO 201 N=1,48
0040      D(N,L)=0.
0041      DO 201 K=1,3
0042      DO 201 P=1,48
0043      J=P+N-1
0044      IF(J.GT.48) J=P+N-49
0045      201 D(N,L)=D(N,L)+G(L,P,K)*E(K,J)
          C
0046      WRITE(6,8)
0047      WRITE(6,12)
0048      WRITE(6,13)(I,(D(I,J),J=1,3),I=1,48)
0049      8   FORMAT('1N=MAGNET NUMBER'//
1' D(N,1)=RADIAL ERROR AT UPSTREAM END OF MAGNET (+ IS OUT,IN MILS)
2'//° D(N,2)=RADIAL ERROR AT DOWNSTREAM END OF MAGNET (+ IS OUT,IN
3MILS)'//° D(N,3)=AZIMUTHAL ERROR (+ IS DOWNSTREAM,IN MILS)'//)
0050      12  FORMAT('  N      D(N,1)      D(N,2)      D(N,3)'//)
0051      13  FORMAT(1H ,12,3X,3F10.0)
          C
          C   NEW RADIAL SURVEY CALCULATION
          C   CALCULATION OF DP
          C
0052      WRITE(6,7)
0053      WRITE(6,14)
0054      7   FORMAT('1P=STRAIGHT SECTION UPSTREAM OF MAGNET P'//
1' DP=RADIAL ORBIT DISTORTION AT CENTER OF SS (+ IS OUT,IN MILS)'
2//)
0055      14  FORMAT('  P      DP'//)
          C
0056      DO 301 P=1,48
0057      DP=0.
0058      DO 300 N=1,24
0059      I=P+2*(N-1)
0060      IF(I.GE.49) I=I-48
0061      J=P+2*(N-1)+1
0062      IF(J.GE.49) J=J-48
0063      IF(MOD(P,2).EQ.1) GO TO 400
          C
0064      DP=DP+2.37*(D(J,1)/2.+D(J,2)/2.)*COS(((N-1)*96+12)*PI/180.)
1-1.17*(D(I,1)/2.+D(I,2)/2.)*COS(((N-1)*96-36)*PI/180.)
0065      GO TO 300
          C
0066      400  DP=DP+2.37*(D(I,1)/2.+D(I,2)/2.)*COS(((N-1)*96-60)*PI/180.)
1-1.17*(D(J,1)/2.+D(J,2)/2.)*COS(((N-1)*96-12)*PI/180.)
          C
0067      300  CONTINUE
0068      K=P-1
0069      IF(P.EQ.1) K=48
0070      DP=DP-(D(P,1)+D(K,2))/2.
          C
0071      WRITE(6,15)P,DP
0072      15  FORMAT(1H ,12,3X,F10.0)
          C
0073      301  CONTINUE
0074      RETURN
0075      END

```

PART X. APRIL 1970 SURVEY: EXECUTION AND RESULTS

A. Execution

The new survey method was tried out first by one of us (W.A.S.) in the period April 1 - 8, 1970.

Surveying near Straight Section 26 was postponed a few days until an interfering vacuum foreline was temporarily removed by the Vacuum Group.

The survey (which included a large amount of double-checking, and making studies of reproducibility) took 15 hours. Obviously, it would have been completed much more quickly if the survey party had included two men, rather than just one.

B. Results

Table 1 shows the surveyor's data (input to computer) and the results (output from computer). The significance of the column headings (except the last) is explained in earlier parts of this report. The last column (DP) shows the orbit distortion. Specifically, it shows the radial displacement (in mils) of equilibrium orbit (at center of straight section downstream from indicated magnet, relative to the magnet ends flanking that straight section) resulting from the currently existing errors in magnet positions. Notice the non-correspondence of magnet serial number and straight-section serial number. The first row of data, for example, applies to Magnet 1 (and the magnet downstream therefrom) and (in the last column) Straight Section 2.

Figure 6 shows the orbit-distortion output data graphically.