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Techniques of High Spatial Density Magnetic Profiling and Mapping

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BOULDER, COLO.
DECEMBER 1970

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TABLE OF CONTENTS

TECHNIQUES OF HIGH SPATIAL DENSITY MAGNETIC PROFILING AND MAPPING

W. P. Hasbrouck, C. O. Stearns, and M. R. Saunders

This report describes data acquisition and reduction methods that were used in investigations of large-amplitude, high-wave number, total magnetic field variations over exposed, basic volcanic rocks. The continuous profiling and discrete-station field operations procedures are detailed. A double-orthogonal-array mapping technique which eliminates mapping bias and allows full use of a folded (sin x)/x interpolator is also described. Discussion of the digital computer data reduction procedures includes description of single and multiple function editing plots and the corrections for endpoint and traverse-velocity mismatch, traverse-velocity inequality, and nonalignment of correlation points between initial and replicate traverses. An example using data obtained by the continuous profiling procedure is given to show output from progressive stages in the data reduction sequence.

1. INTRODUCTION

High spatial density profiles and maps are those whose station separations are equal to or less than one half the shortest significant spatial wavelength. Keeping station spacings within one half the shortest wavelength guarantees that the observed data will be free of aliasing. But the maintenance of these intervals, as required by the sampling theorem (Hancock, 1961), is impractical in field operations unless data can be taken and reduced quickly. In some lava covered areas, for example, a spacing between observation points of less than a half meter may be needed in order to generate smooth magnetic profiles and as many as 50,000 values may be needed to map 1 hectare. To avoid aliasing in the observed data, one must either elevate the magnetometer sensor into the lower spatial wave number regions of the observed field and thus allow an increase in the size of the station spacing, or, if the sensor height is fixed, develop field techniques to take data faster. The consequence of the latter choice is the acquisition of large volumes of data which will require computer processing in order to produce maps and sections in a reasonable amount of time.

The definition of high spatial density profiling and mapping contains within it the word 'significant' used as a subjective qualifier. The term is introduced to emphasize that final selection of station spacing is made with the full realization that some noise will be present in the observed data. The task in exploration practice is not to reduce the noise to its absolute minimum, but rather to suppress the noise to such a level that its introduction will not downgrade the interpreted result significantly. In order to make this judgement, one must run purposely oversampled profiles and arrays and then critically review these test results.

This technical report describes field procedures designed to obtain unaliased magnetic profiles and unbiased maps and discusses the computerized reduction of these data. The techniques have been used in studies whose objective was the determination of spatial magnetic field characteristics of exposed basic lavas. Construction of reliable maps for these volcanic rocks provided a severe test of the field procedures and data processing methods. In one area, for example, anomalies as great as 2000 gammas over a distance of 10 m and spatial wave numbers of 5 per meter (20-cm wavelengths) were observed.

2. FIELD PROCEDURES AND EQUIPMENT

Two operational procedures have been field tested: one employs almost-continuous profiling, and as such is functionally similar to a digital airborne technique; the other uses discrete-station traversing. The latter method resembles the common method of data acquisition except that with this newer technique: shorter station spacings are used, productivity reckoned in stations per hour is increased, and diurnal variation effects are almost eliminated. Both methods described in the sections that follow use the same apparatus, both techniques are pointed toward acquisition of data for digital-computer reduction, and both field procedures can be applied in a double-orthogonal-array system of mapping.

2.1 Field Equipment

The required field equipment is as follows: a pair of rubidium sensors, couplers, and power supplies; a special nonmagnetic staff to carry the roving sensor and a tripod mount to hold the base sensor; a frequency counter with a fast reset circuit if continuous profiling is to be done; a digital printer and clock; and electronic signal scanning and differencing unit; and a set of connecting coaxial cables. A schematic representation showing the deployment of apparatus is given in figure 1. The carrier for the on-traverse sensor and the scanning, mixing unit were specially constructed; all other components were available commercially. Description of equipment in this report is restricted to those specific units which have been field tested.

Obtainable accuracy at a given fixed location is dependent upon the intrinsic reproducibility of the rubidium magnetometer (Hasbrouck, 1970) and its Larmor frequency, magnetic field functional relation. For mapping a prospect with high spatial density methods, the range of magnetic field values usually is within several thousand gammas, therefore the use of the linear conversion factor of 0.214 gammas per 1-Hz change in the rubidium 85 Larmor frequency is acceptable. Nonlinear portions of the intrinsic reproducibility differences are less than several gammas. The rubidium magnetometer is capable of producing a continuous analog output. However, when a digital recording system is used, the output becomes quasi-piecewise continuous, the time separation between stepped functional values being equal to the reset time of the frequency counter and the length of the step being equal to the counter's gate setting.

Sensor power was supplied in two ways: along the total length of cable (300 m) from a direct current (dc) power source at the recorder, in which case the input voltage had to be high enough to overcome ohmic loss; or along shorter cable lengths (30 m) from a storage-battery power source. With the latter system, the coaxial cables connecting the sensor and recorder carried only signal; thus, by imposing a simple decade amplifier between added cable lengths, the distance between the recorder and sensor positions could have been extended. The maximum length of a traverse segment with the battery-powered, 30-m system was 60 m; with the dc power source it was 500 m (fig. 1). Beyond a 300-m sensor distance, the Larmor frequency signal (about 250 KHz) required more amplification than was supplied with the commercially available system.

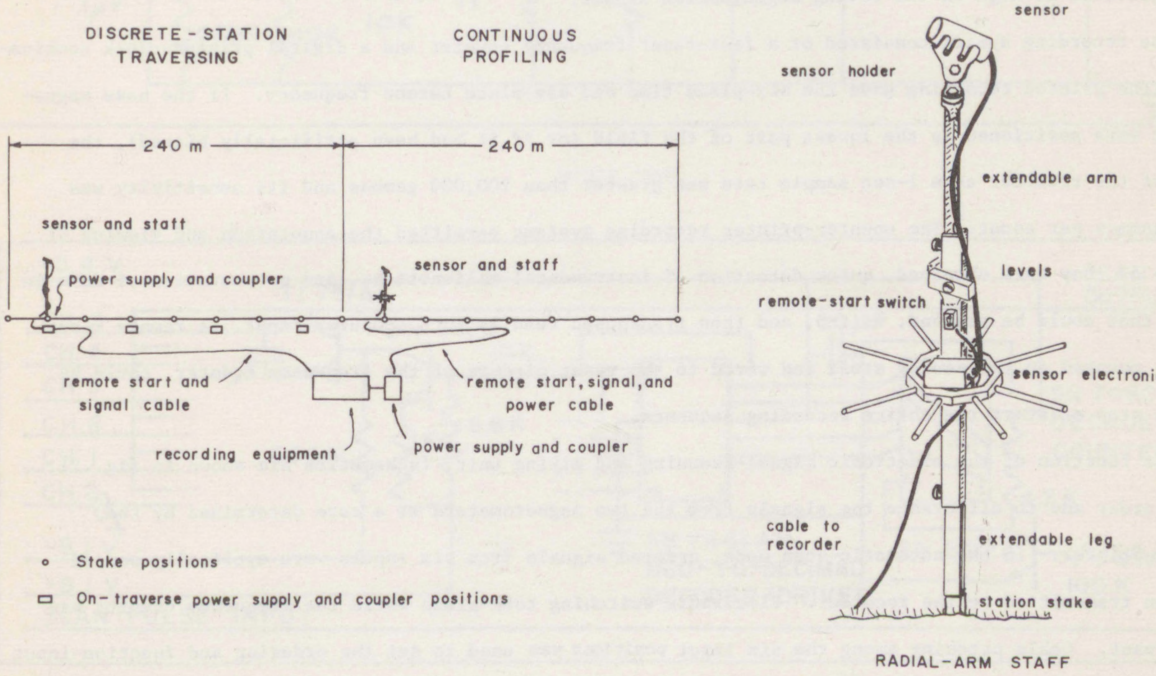


Figure 1. Deployment of field equipment for high spatial density magnetic profiling.

No redesign of the sensor, sensor coupler system was needed to test the effectiveness of the hand-held sensor field techniques. However, if mobile application is contemplated, the use of a dual-cell self-oscillator should be considered. The analog recording components of a commercial magnetic gradiometer were not used; their cost would more than equal that required to purchase the digital system.

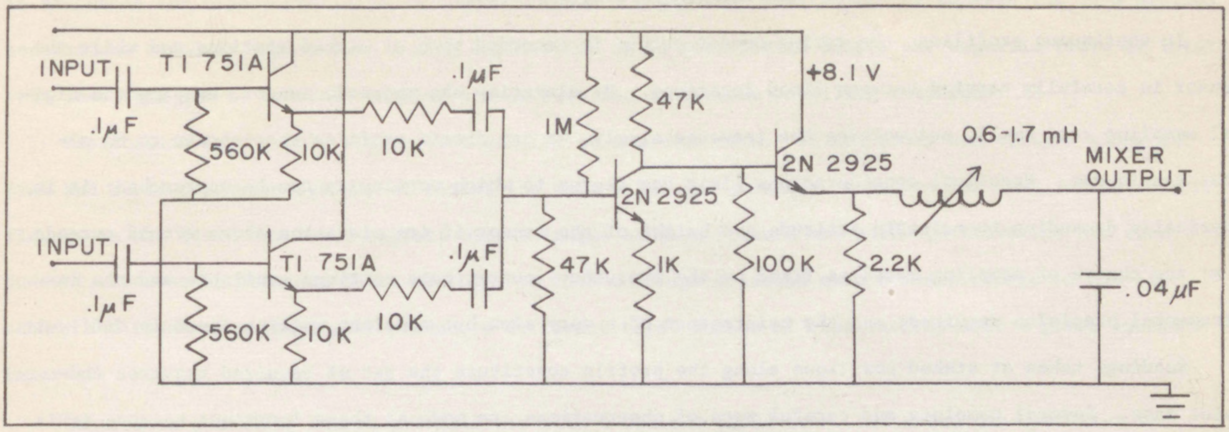
The functions of the aluminum staff were to transport the roving sensor at a constant, high height (3 m for continuous profiling and up to 5 m for discrete-station traversing) while maintaining its attitude and orientation. Attitude control was necessary with a single-cell sensor in order to obtain maximum signal output; constancy in orientation was need to minimize heading error. The staff (a sketch of which is shown in fig. 1) contained eight coplanar radial rods at waist height. A pair of these rods when held at the observer's waist, made maintenance of orientation and sensor height easier. In addition the staff contained two orthogonal level bubbles that were monitored to maintain plumb of the staff as the traverse was walked. The sensor was held atop the staff in a holder that could be rotated, tipped, and then locked into a set attitude. A guided leg on the bottom of the staff was extended so that the staff could be positioned on a wooden stake without altering sensor height; this leg was retracted when traversing between fixed stations of the profile.

The base sensor was placed in a holder that in turn was fastened to the head of a plane-table tripod. The function of the base sensor was either to provide a reference signal to be mixed with the signal from the roving sensor or to monitor the time-variant behavior of the magnetic field. It did not need to be elevated as high as the roving-magnetometer sensor.

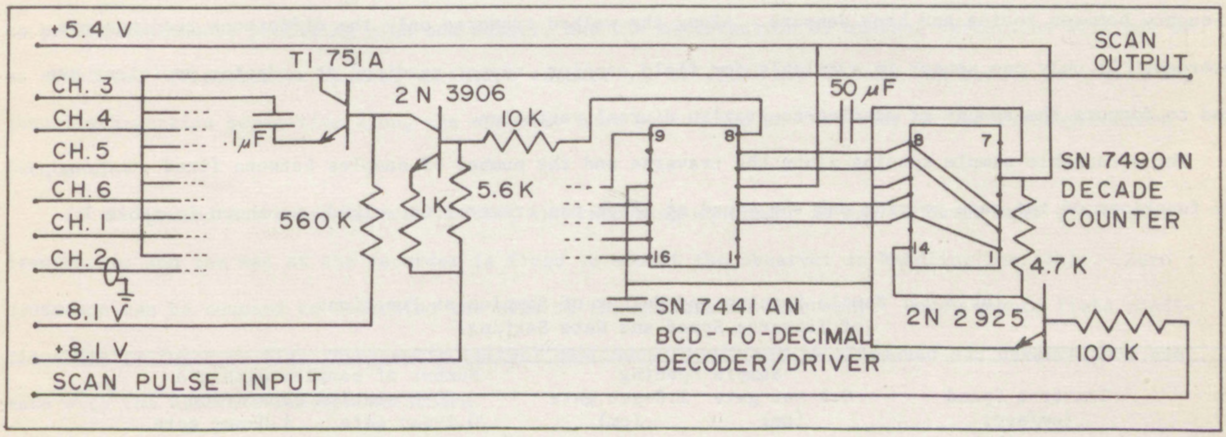
The recording system consisted of a fast-reset frequency counter and a digital printer-clock combination. The printed recording gave the six-place time and six-place Larmor frequency. If the base magnetometer were positioned in the lowest part of the field (or if it had been artificially biased), the range of the recorder at a 1-sec sample rate was greater than 200,000 gammas and its sensitivity was 0.214 gammas per count. The counter-printer recording systems permitted the annotation and viewing of results as they were obtained, quick detection of instrumental malfunctions, and presentation of data in a form that could be scanned, edited, and then transposed readily into computer input. A remote reset switch, mounted on the sensor staff and wired to the reset circuit of the frequency counter, could be used to stop or start the entire recording sequence.

The function of the electronic signal-scanning and mixing unit, (schematics are shown in fig. 2), was to order and to difference the signals from the two magnetometers at a rate determined by the counter-printer. In the automatic-scan mode, ordered signals from six inputs were cyclically sensed and then transmitted to the recorder. Electronic switching took place while the frequency counter was being reset. Cable patching among the six input positions was used to set the ordering and function-input pattern. The following sequence of signals was recorded in discrete-station traversing: roving sensor, base sensor, and then roving minus base for four times. Thus, with a 0.002-sec reset time and with a counter-printer rate of one print per sec, the reading from the base magnetometer was recorded every 6.012 sec. The mixing unit took the signals from the roving and base sensors, mixed them, and then produced an amplified frequency difference. With a difference frequency of only 0.1 Hz, the mixer output was of sufficient amplitude that it could be recorded by a counter whose threshold voltage was 0.1 V.

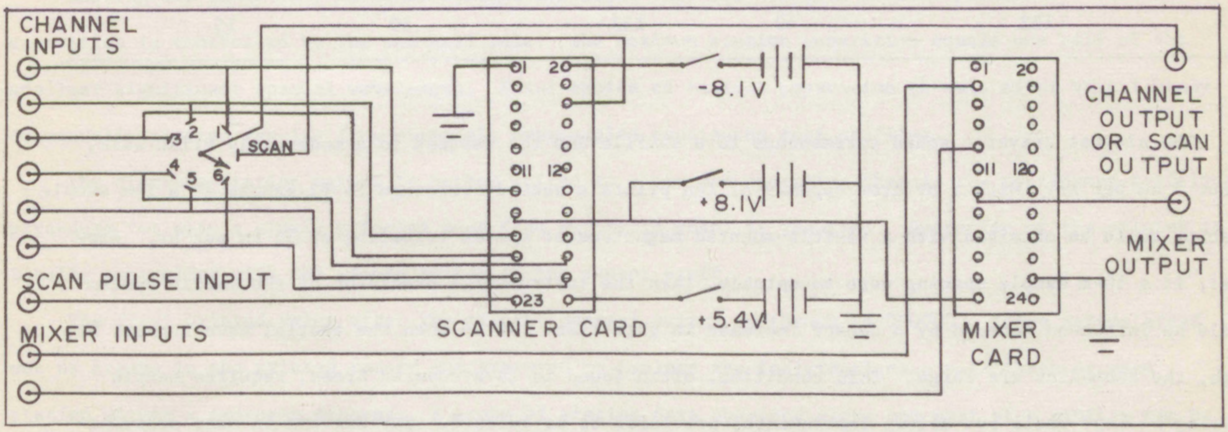
A one-wheeled aluminum cart was used to transport all required apparatus when the traverse positions could not be reached by truck. The recording equipment, including its power supplies, was lashed to this cart so that upon arriving at a traverse-segment midpoint one needed only to rotate the carrying poles of the cart downward, thus transforming it into an instrument table, and the equipment was ready to operate. With use of the cart, two men were able to traverse pahoehoe, loose-cinder, and aa surfaces.



MIXER CARD



SCANNER CARD



SCANNER-MIXER CHASSIS

Figure 2. Schematic diagrams of electronic signal-scanning and mixing unit.

2.2 Continuous Profiling Procedure

In continuous profiling, the roving-sensor output is recorded both at staked stations and while the sensor is carefully carried between fixed locations. By elevating the magnetic sensor, keeping the digital sampling rate small, and walking the traverse slowly, we can obtain profiles that appear to be almost continuous. Practical considerations limit the degree to which continuity can be approached: it is physically demanding to maintain attitude and height of the sensor if its elevation above ground exceeds 3 m; the choice of sampling rates is fixed by the frequency-counter gate settings available and the instrumental precision required; and the maintenance of a very slow but constant walking speed is difficult.

Readings taken at staked positions along the profile constitute the set of required traverse endpoint data. Several complete and careful sets of observations are made at these locations because it is to them that all traverse data are tied. At the fixed stations the usual recording sequence (scanner-mixer box to automatic scan position) is: roving sensor, base sensor, then four readings of difference frequency between roving and base sensors. Along the walked traverse only the difference readings are recorded. If only one sensor is available for field mapping, repeat readings at endpoint positions are used to compute the amount of station-to-station diurnal variation.

The obtainable sample spacing along the traverse and the number of samples between fixed stations are functions of the gate setting and the speed at which the traverse is walked, as shown in table 1.

Table 1. Sample Spacing and Number of Samples as Functions of Traverse Speed and Gate Setting.

Traverse Speed (cm/sec)	Sample Spacing 0.1-sec gate (cm)	Sample Spacing 1.0-sec gate (cm)	Number of samples within a 20-m station separation 0.1-sec gate	Number of samples within a 20-m station separation 1.0-sec gate
33	10	33	200	60
67	20	67	100	30
133	40	133	50	15

The slowest traverse speed corresponds to a shuffle and the fastest to a moderately brisk walk, about 5 km per hr. With a printer capable of ten prints a second, readings to ±2 gammas at a 1-m sample spacing could be obtained with a vehicle-mounted magnetometer system traveling at 36 km per hr. However, if a 10-m sample spacing were acceptable, then the instrumental precision of the mobile system could be increased tenfold by a decade increase in gate time. Often when the spatial wave numbers are high, the anomalies are large. This condition, often found in lava-covered areas, requires sample spacing be kept small but allows instrumental precision to be relaxed. For surveys in many sediment-covered areas, the near-surface lateral magnetic variations are small and the anomaly sources are deep resulting in long spatial wavelengths and small magnitude target anomalies; thus, larger sample spacing is allowable but higher precision is needed. Table 1 shows that for traversing between the 20-m station separations commonly employed in mining exploration it is possible to sample the magnetic field at intervals less than 1 m at moderate walking speeds with the continuous profiling technique.

Replication is the only way to test quality of traverse data. If the peaks and troughs along initial and replicate traverses map at almost the same value and location, then one can have increased confidence in his field results. Perfect mirror images between forward and backward traverses are rare, however, because at printing rates of three to four readings a second even a small change in the constancy and speed of walking will produce a different total number of observations over a given distance interval.

Continuous profiling can be accomplished with a one-man field crew, but a two-man operation is safer and more efficient. If traverses are to be run over rough terrain, then a two-man crew is needed because the equipment cart would be too unwieldy. The basic two-sensor field procedure can be modified to permit continuous profiling with one sensor, but the minimization of diurnal variations will not be as complete. If nonlinear diurnal variation effects are critical and if only one sensor is available, then fixed-station separation along the traverse must be reduced so that they may be reoccupied more frequently.

If the ground traversed is treacherous, the recording equipment is set to print only difference frequencies and the man at the recorder is freed to assist the observer in handling the cable. Zero crossings can be counted to determine the sign of the difference frequency. Under severe field conditions (thick forests, high topographic relief) continuous profiling is abandoned and observations are made with the discrete-station procedure.

2.3 Discrete Station Procedure

Readings are taken only at fixed station locations with the discrete-station procedure. Station separation is controlled by the one-half rule: the maximum station separation equals one half of the smallest significant spatial wavelength. Final choice of station separation is made after visual study of manually plotted results from purposely oversampled continuous test profiles.

The discrete-station method is better suited to a one-man operation than is the continuous-profiling procedure, for only a single printing mode (the automatic scan) is required. Operation of the printer is totally controlled with the remote switch on the sensor staff.

The first printed value after the printer control switch is thrown is 000000. These zeroes stand out as breaks in the printed record and are used to isolate the individual data sets taken at each station within a traverse segment. A group of station data obtained along one part of a profile can be separated from another group by use of the interval times. Within one group, interval times are small; between groups they are large. Using time intervals, printed zeroes, and the known recording sequence, the printed data can be grouped, identified, and labeled.

Intermediate stations are established by laying a marked rope between 30-m staked locations. The observer walks along a path guided by this rope and when he sees the appropriate distance marker he raises the staff. A 5-m folding aluminum stadia rod with clamped on level bubble can be used as a sensor staff by fitting a sensor holder over the end of the rod. In thick brush country it is easier to transport the folding-rod staff than the radial-arm sensor carrier, but maintenance of sensor orientation requires more care.

2.4 Double Orthogonal Array Mapping

Unless profile separations, as well as station intervals, are made small enough to obey the one-half rule, the resulting mapped data when contoured will show magnetic trends normal to the direction of a set of parallel traverses. This effect is called map biasing. The occurrence of these trends, even though it might arouse suspicion, does not by itself call for downgrading a map because the profile directions might indeed be at right angles to the dominant geological framework. In which case, the spatial wave numbers should be higher along the profile directions.

The likelihood of intra-traverse aliasing, and its resulting expression in map biasing, tends to increase when short spacing is called for because of a seeming reluctance to position profiles sufficiently close together. This practice may be a natural outgrowth of a geophysicist's tendency to interpret his results in terms of profile parameters (half width, critical slopes, and so forth) and because he has become accustomed to airborne and marine magnetometry in which almost-continuous data are obtained along in-flight profiles and ship tracks. However, in magnetometric mapping of lava-covered areas there is no guarantee of two dimensionality; therefore, one should make initial observations in these areas with a mapping technique which assures elimination of biasing.

A special mapping array has been developed that eliminates mapping bias and also makes full use of the folded (sin x)/x interpolation method (Bailey, 1966). As shown on figure 3, the array employs a double orthogonal set of traverses. Each element of an array consists of a square and a set of diagonals. The configuration displayed in figure 3 is termed either a two by two (2 x 2) or a four-element array, the former name being preferred because it better indicates the square arrangement of array elements.

Unless the large number of readings accumulated along high-spatial-density traverses are identified systematically, they cannot be entered efficiently into computer storage. Occurrence of information loss due to faulty data bookkeeping is likely unless prior agreement on the data identification scheme is reached between those gathering and those processing the data. The numbering system used to identify lines and stations in double orthogonal mapping is illustrated on figure 3. Stations at the line intersections are labeled with a row-column number. Each line in the array either can be identified by a line number of its end-point-station numbers; for example, line 2 (fig. 3) is the W-E line from station 7,1 to 7,13. Skips in station numbering are made in order to reserve numbers for the interpolation lines. The N-S dashed line (fig. 3) from station 1,3 to 13,3 is an example of one such line. Note that the interpolation line intersects the traverses of the original array at equally spaced intervals; this is a necessary condition for the direct application of the folded (sin x)/x interpolator.

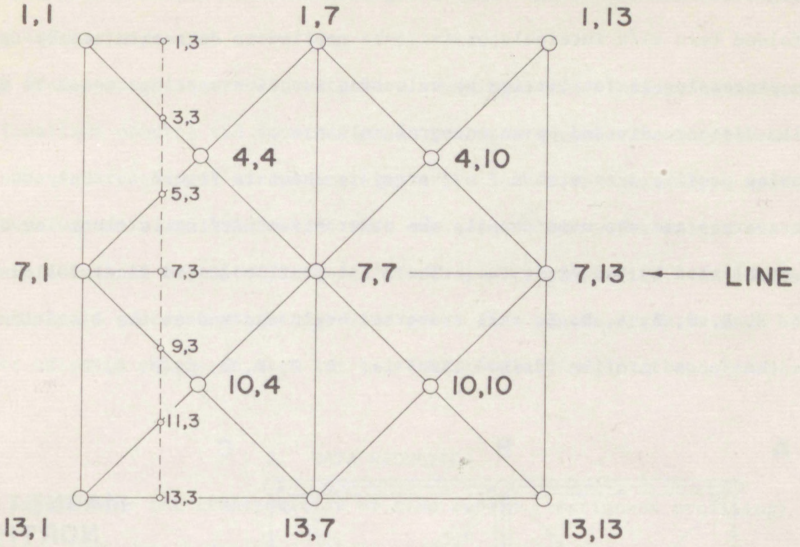


Figure 3. Layout of traverse lines (solid) and station numbering system used with 2 x 2 double orthogonal array. Dashed line from station 1,3 to station 13,3 represents one line along which the folded (sin x)/x interpolator could be applied.

Use of a seven-place indicial system allows every mapped point to be retrieved readily from computer storage. As an example of the notation used, consider the index 1020021, and its expansion:

1------	1 = initial traverse
-020000	02 = line number 2
---0021	0021 = 21st point from west-east along line number 2
1020021	= complete 7-place index

If the above index were used to identify a mapped value from an array with 60-m elements within which a sample interval of 1 m were used for the W-E lines then this index would be assigned to the value observed at station 7,3 (fig. 3) on the initial traverse. The index associated with the value obtained from the same location when crossed by the replicate traverse would be 2020021. Regardless of the direction at which the replicate traverses are run, the last six digits of indicial identification remain the same. This procedure allows results from initial and subsequent replicate traverses to be compared more easily.

The seven-place index is in base 10. Thus it can accommodate 10,000 data points per line and 100 line numbers. For a square assemblage of array elements, the total number of lines equals 6 times the number of elements on a side. Therefore, a 16 x 16 array (96 lines) with 600 readings per line per element (9601 per line) is the largest square-array mapping unit containable within the index range.

Indices cannot be assigned before data are obtained with the continuous profiling method because maintenance of perfectly constant traverse speeds is not possible. However, with the discrete-station procedure, all reading locations can be initially identified with the indicial notation before the data are taken. If the folded (sin x)/x interpolator is to be applied to data obtained by the discrete-station method, data processing is facilitated by selecting interior spacings equal to the quotient of the station-to-station distance divided by an integral multiple of 6.

The order of taking profile data with a 2 x 2 array is shown in figure 4. Only the first two of the eight required traverses are shown in detail; the other six occurring in clockwise order in the traversing pattern established by the first two. The first profile (solid line) follows the station-occupation sequence: E, B, C, B, A, B, E. All traverses begin and end at the E station. The order of reading stations for the second profile (dashed line) is: E, D, F, D, C, D, B, D, E.

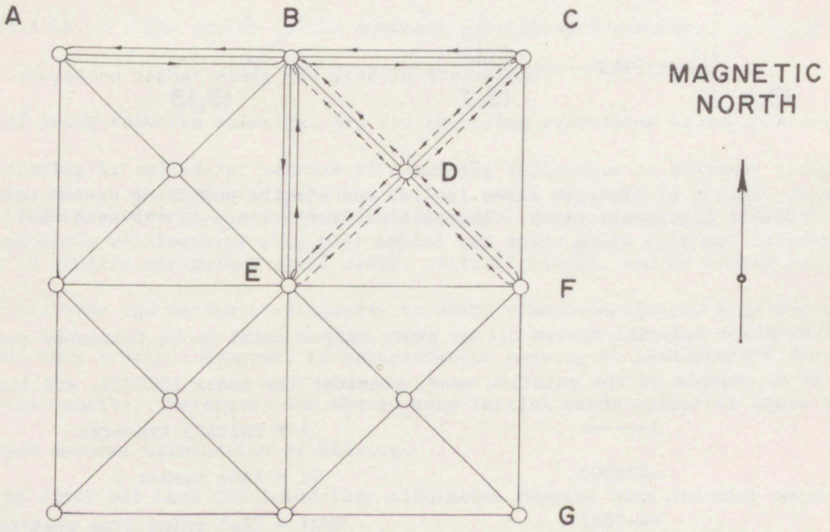


Figure 4. Order of taking profile data with 2 x 2 double-orthogonal-array mapping. First traverses follow solid lines; second set follows dashed lines; next six proceed in clockwise order.

The 2 x 2 array is used primarily to map spatial magnetic-field variations in the neighborhood of a central station (E on fig. 4). Such maps are useful in geopiezomagnetic studies in which relocation errors are minimized by positioning repeat stations in those regions of lowest horizontal gradient. This mapping method also has been used to determine areal spatial characteristics of magnetic fields over exposed lavas.

A different order of operations is employed when the array elements are distributed unsymmetrically or when more than 2 x 2 coverage is required. Traverses for the larger arrays are run in profile sets, each set beginning and ending near the array center. One procedure is to observe along the N-S set of traverses first, then run the W-E sets, and finish with the two sets of diagonals.

Elements are usually added to preexisting arrays in multiples of the 2 x 2. Common traverses between old and new arrays are not rerun. With the large square arrays, greater than 5 x 5, readings along extensions of each of the eight lines radiating from the center position can be doubly (continuous profiling) or singly (discrete-station traversing) replicated.

Arrays built up from sets of square elements have advantages over those constructed of equilateral triangles: In sectionalized country the square-element arrays are easier to locate and survey topographically; stations of the square-element arrays are simpler to number (a matrix-type system can be used); and, because the arrays commonly are laid out so that one set of lines lies within the magnetic meridian and another is aligned normal to it, interpretation of results is simplified. In addition, a (sin x)/x interpolation along a circle centered at the interior point of a square array is made between eight points, but there are only six points in each set if equilateral-triangle array elements are used.

3. DATA REDUCTION

Data reduction begins with the transposition of time series (continuous profiling) or distance series (discrete-station traversing) data from a printed paper strip to computer punchcards. It ends with the generation of an ordered and indicially identified set of magnetic field values on either punchcards or magnetic tape.

3.1 Data Reduction Sequences

Data taken by the discrete-station procedure are the simplest to reduce. After field results are transposed to cards and subjected to an initial editing procedure, they are corrected for linear instrumental drift and diurnal variation. These results are adjusted to put the traverse endpoint values into agreement then the reduced data are ordered, indexed, and stored.

Data reduction of continuous profiling results is more complicated because readings taken at equal intervals of time have to be converted to values at the desired equally spaced distances through use of a traverse velocity correction. For those field operations in which a separate recording system is maintained at one location, its output being used for removal of time-varying effects, the difference field is computed before the traverse-velocity correction is made. If continuous profiling is done with only one instrument, then time effects are handled through linear proration of differences observed at repeat stations. In high-quality continuous profiling studies all lines are replicated. But, because of probable differences in constancy of traverse velocity along and between the forward and backward profiles, the magnetic lateral variations of magnetic field observed on initial and replicate traverses usually are not congruent.

Diurnal-variation effects are almost eliminated when the electronically linked roving and base sensors are sufficiently closely spaced to assure high coherence of the inducing magnetic field. The only remaining time-dependent effects are those caused by intrinsic nonreproducibility of the rubidium sensor pair (Hasbrouck, 1970). Because these instrumental effects are by themselves no more than several gammas, and because they are partially removed during the application of endpoint corrections and traverse-intersection adjustments, the intrinsic-reproducibility effects generally are ignored.

The choice of data reduction method for continuous profile observations obtained with physically unlinked roving and base sensors is dependent upon the degree of nonlinearity in the time-dependent magnetic field changes that occur during the time between traverse endpoint occupancies. If the segmented slope of the diurnal variation curve is sufficiently linear, then a simpler data reduction scheme can be used, figure 5. When the time variations of the inducing field are significantly nonlinear, then the data reduction sequence as shown in figure 6 is followed.

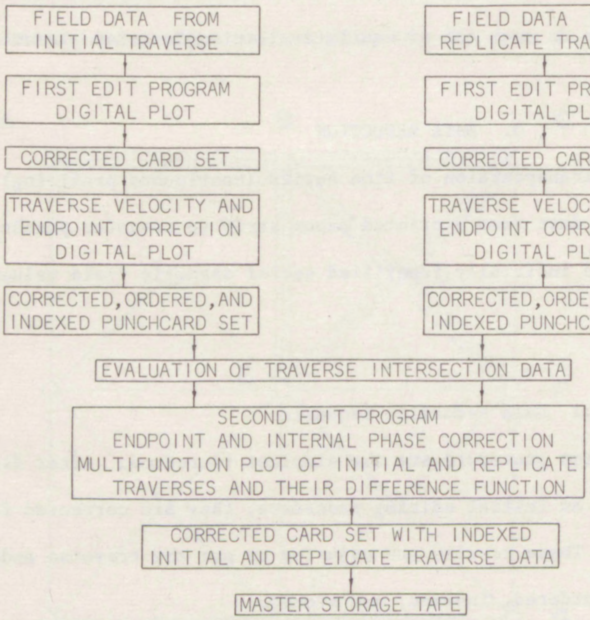


Figure 5. Data reduction sequence used when segments of the diurnal variation curve are sufficiently linear.

Amount of nonlinearity is determined from inspection of the diurnal variation curve produced by the base-station magnetometer. Straight line segments are drawn on this curve between times when the roving sensor was at fixed stations along the profile. The set of differences between the observed and chord values is the measure of the amount of nonlinearity. Significance of these magnitudes is dependent upon the size of the magnetic anomalies measured. For example, an arc-chord deviation of 10 gammas when 2000-gamma lateral variations are encountered is of little significance and thus an assumption of linearity (first reduction procedure, fig. 5) is justified. But if the anomalies sought were only 10 gammas themselves, then the second data reduction sequence (fig. 6) would be required.

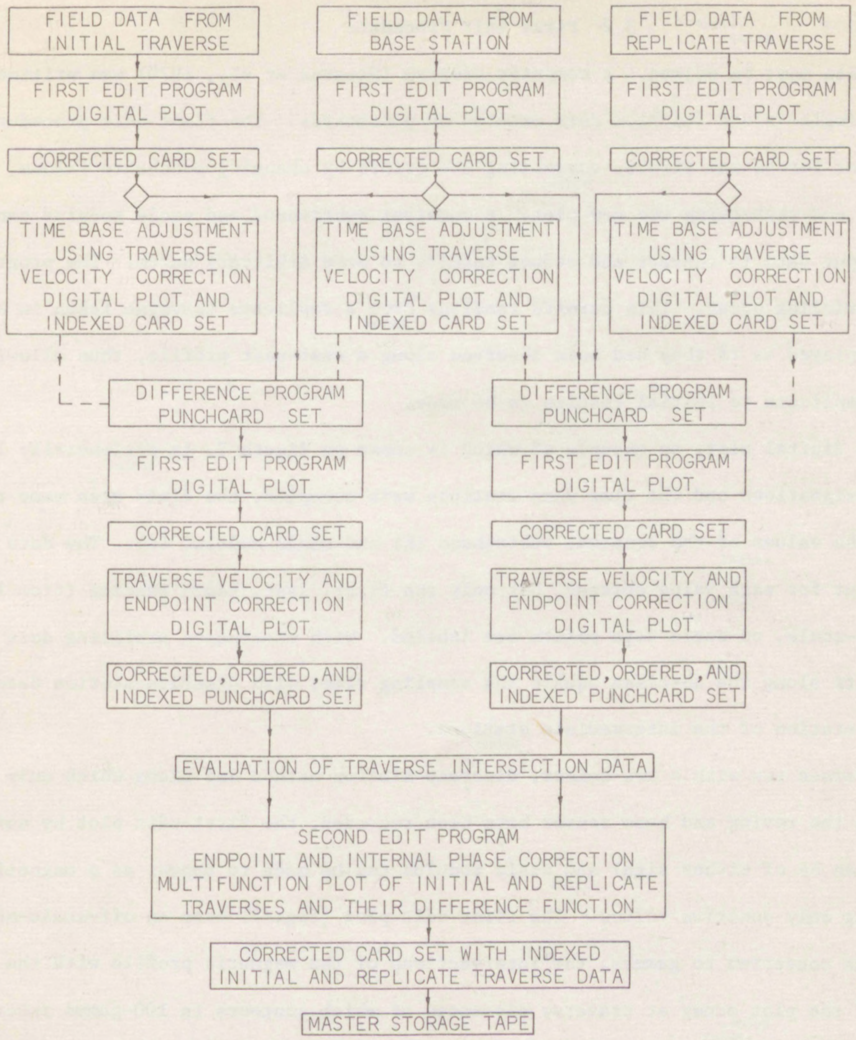


Figure 6. Data reduction sequence used when segments of the diurnal variation curve are not sufficiently linear.

If only one magnetometer is available for continuous profiling, an approximation to the diurnal variation curve can be reconstructed by application of an interpolator to a set of repeat-station readings. The results so generated are then entered as fixed-station field data in the data reduction scheme of figure 6. A magnetogram from a nearby observatory can be scanned for indications of the behavior of the magnetic-field variations, but it cannot serve as an adequate substitute for a base-station set of readings if small anomalies, say 10 gammas, are important. Two synoptically recording rubidium magnetometers separated by 50 km, for example, may show an 8-gamma difference in reading during the occurrence of a 6-hr, 70-gamma magnetic bay.

3.2 First Edit Procedure

All observed data must be edited. A computer program (Stearns et al., 1970) was written to produce a digital plot of single-valued function data entered on punchcards. The first edit procedure consists of scanning this plot for patent errors, correcting the errors by changing punchcard values, resubmitting the corrected deck, and rechecking the new plot. A constant subtrahend and scale modulus can be applied to each block of input data to convert and reduce results to some arbitrary datum. The program also provides a choice of printing order. This permits readings from a replicate traverse taken in an east-west direction to be displayed as if they had been observed along a west-east profile, thus allowing overlay comparison of the replicate to initial results to be made.

The first edit digital plot, an example of which is shown on figure 7, is peripherally labeled to show the station designations and the time when stations were occupied, the field area name and date it was surveyed, and the values of the constant subtrahend (K) and scale modulus (S). The data field contains a plotted point for each value entered, but only the first, last, tenth reading (from left to right), and the off-scale, on-scale data points are labeled. With continuous profiling data the interval between points along the abscissa equals the sampling time; with discrete-station data it corresponds to the separation of the intermediate stations.

For those traverses run with a two-sensor, discrete-station method and along which only frequency differences between the roving and base sensor have been recorded, the first-edit plot by suitable choice of subtrahend (it can be of either sign) and scale modulus can be made to appear as a magnetic profile in gammas containing only positive values. The first-edit plot (fig. 7) uses an off-scale-shift display. Therefore, with data converted to gammas, the intersections of the magnetic profile with the upper and lower boundaries of the plot occur at traverse distances at which contours in 100-gamma intervals would cross the traverse line. Using these contour-intersection points and the locations and values of magnetic highs and lows as observed along the profiles, a reconnaissance map can be constructed quickly without the need for additional computer processing.

3.3 Endpoint and Traverse-Velocity Corrections

The map value at the terminus of one traverse section and the origin of the contiguous segment must be equal because the magnetic field is single valued. If the observed data do not show this equality, they are forced to do so by use of an endpoint correction.

The endpoint correction consists of a set of values distributed along a straight line whose slope equals the difference in station values at the end of the traverse segment divided by the time required to run that segment. Magnitude and sign of the correction are determined through joint study of repeat values at the traverse endpoints and the magnetic field variations recorded by the base-station magnetometer. When profile data are obtained from the set of electronically differenced readings between the roving and base sensors, the endpoint correction is small. That amount of station-value inequality

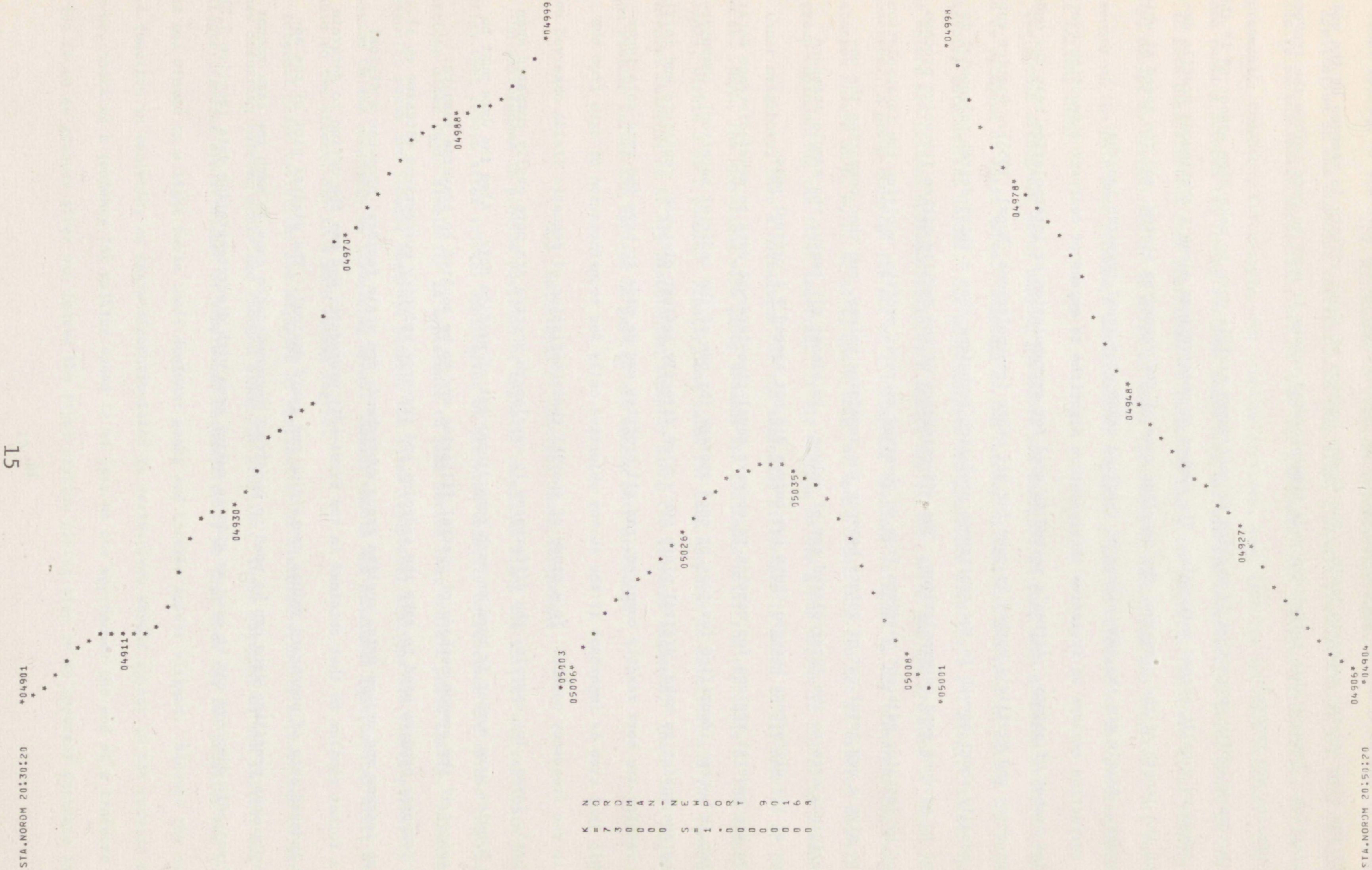


Figure 7. Sample of first edit display.

which remains is due to intrinsic nonreproducibility of the rubidium-sensor pair and to spatial incoherence of the time-varying magnetic field. The linear portion of these effects is removed by the endpoint correction. Because this correction uses time-prorated values it must be made before the traverse-velocity effects are removed.

A traverse-velocity correction is applied to continuous profile data to make them appear as if they had been taken at equally spaced intervals. The number of observations along a continuous profile depends upon the length of the traverse, the sampling rate of the recording system, and the speed at which one traverses. Rarely are the same number of readings taken over equal traverse lengths.

The correction employs an iterative interpolation algorithm to expand or contract a function over a specified number of points. Aitken's method is used for extrapolation or interpolation near the ends of a given array and Neville's method is used for all other interpolations (Kopal, 1955). Station spacings are usually short enough in the continuous profiling technique that a third-degree polynomial is sufficient to produce good interpolations. The effectiveness of the Neville-Aitken iterative process was tested by incising adjacent readings from an observed magnetic profile, applying the interpolation program to give a new total set of points between the remaining values, and then comparing the unaltered original data to the interpolated set of values. In almost all tests, the sample standard deviations of the difference between these two curves did not exceed ± 1 ordinal unit.

There are several reasons for wanting to convert equal-time-interval data to equal-distance data: information is better identified for tape or card storage (by use of the indicial notation), computer-drawn maps are easier to make, digital plots are scaled directly against distance, replicate and initial traverse results are more readily compared, and all profiles can be made to have the same data intervals. This last step is important if the survey objective calls for transformation of data from the spatial to the frequency domain. In a study of spatial characteristics of magnetic fields observed over exposed basic lavas, for example, the differences in wavelength spectra are more easily compared when the same Nyquist wave number is used on each constituent set of profile data. Also the data must be equally spaced if the common methods of spatial filtering are to be applied to traverse results.

The computer program used to make the endpoint and traverse velocity corrections (Stearns et al., 1970) also indexes and orders data, applies group subtrahends and scale factors, produces a digital plot in a format similar to that obtained in the first-edit procedure, and has the option to generate serially indexed sets of punchcard values containing one guard decimal. The digital plot of the adjusted continuous profiling data can be used to construct reconnaissance maps in much the same manner as the first-edit displays can be used as aids in making maps with discrete-station data (section 3.2).

3.4 Adjustment of Traverse Intersection Values

Application of the endpoint correction to data along a single traverse forces the data on that one profile to be internally consistent, but it does not guarantee that traverse-intersection values will be in agreement. Consider, for example, two crossing profiles, each with its own base station. The difference reading between the roving and base sensors at the profile-intersection point would be the same only if both base stations were positioned at locations where the magnetic field was equal (highly unlikely, except by design) and if no drift or other instrumental variations had occurred. If, for example, one sensor of the pair were retuned, a difference of 6 gammas might be observed at the profile-intersection point (Allen, 1968).

The double orthogonal array mapping procedure was designed so that each numbered station (fig. 3) would be occupied at least twice. Readings at the reoccupied stations are used in making the adjustment of traverse intersection values. Let us illustrate the procedure with the 2 x 2 array. First, the endpoint values are written systematically on a sketch map of the array and the grouping of these values is observed. A group contains the set of all endpoint readings obtained on one traverse; for example, the station values at E, B, D, B, A, B, and E (fig. 4) would constitute the set of ordered members of the group representing the first traverse. If all members of one group appear to differ by a constant from their neighbors, then a correction for the indicated difference is added to all members of that traverse. Next, the operations with group addends are continued until the residuals at the endpoints are small, within 1 or 2 counts. Finally, one value for each endpoint is selected, and the remaining differences relative to it are distributed linearly along the traverse segments. These last adjustments to the station values are applied as part of the second edit procedure.

3.5 Adjustment of Internal Phase Variations

The differences in plotted position of magnetic anomalies along the initial and replicate continuous profiles that remain after initial application of traverse-velocity corrections are termed internal phase variations after their similarity in appearance to time series that exhibit phase shifts. Misalignments of magnetic peaks and troughs observed between the fixed (endpoint) stations are caused primarily by variation in the constancy of traversing speed. Sensor wobble and nonlinear instrumental drift also contribute to the effect, but to a much lesser degree.

Internal phase variations are adjusted by application of traverse-velocity corrections to sets of values occurring between peaks and troughs along the profiles. These portions of the initial and replicate traverse are stretched or compressed mathematically so that when the two profiles are superposed and viewed on a light table their dominant peaks and troughs appear aligned. Because the magnetic-field function is analytic, no sharp discontinuities in derivatives should appear in the reduced profiles. However, there is a tendency for walking speed to be less as one approaches the end of a traverse segment and for it to be greater after one leaves the fixed station giving rise to an apparent decrease and increase respectively in observed profile slopes. The break in the first derivative of the magnetic profile caused by this difference in walking speed is removed by establishing equal-function-value correlation points back from the fixed-station position and compressing and expanding the profile function between these positions and their respective traverse endpoints.

3.6 Second Edit Procedure

The computer output from the second edit procedure is a three-function digital plot showing the initial traverse, the replicate traverse, and the differences between them. The ordinate is in either Larmor frequency or gammas. The difference function represents the residual traverse noise, and as such it can be used to judge the quality of the field operation and the effectiveness of the data reduction procedure.

The second edit computer program (Stearns et al., 1970) produces the multifunction plot, an ordered and indexed listing of functional values with their first and second differences and a punchcard set. Scanning of the plotted and listed values will reveal any errors that might have escaped detection in the first edit procedure. Punchcards generated by the second edit program contain sets of reduced readings for both the initial and the replicate traverses. Each magnetic-field value is paired with a seven-place index that includes: function identification number, line number (two digits), and a sequence number (four digits). Two label cards for each data group also are produced: the first identifies the area in which data were taken and gives the dates and inclusive time of the data set; the second names the terminal stations of the traverse segment and gives the locations of the endpoints relative to an arbitrary reference station. These punchcard data can be used directly for data storage, or their contents can be read onto a magnetic storage tape. The computer program needed for the card-to-tape transfer is given in the Technical Memorandum by Stearns et al. (1970).

3.7 Example of Reduction of Traverse Data

Data for the following example were taken from a set of initial and replicate magnetic traverses run between stations 12 and 14 of a 25-station line. The area name is Tickner Cave. In the continuous profiling method used, base and roving sensor outputs were recorded sequentially. Sensor height was 3 m. The profile was run across exposed basaltic lavas with pahoehoe flow characteristics.

Reduced data are shown as they appeared at progressive stages of data processing. Before photographic reduction for inclusion in this report, the ordinal distance of each profile was 13.2 in. and the incremental separation of data values was 0.1 in.; data field was therefore 10 in.

Figure 8 shows both the initial-and replicate-profile data displayed in first-edit format. The jump at station 13 on the initial traverse (upper plot) probably is not a reflection of a true lateral magnetic field change for the steep rise does not appear on the replicate traverse (lower plot) nor do jumps of this magnitude occur anywhere else along the recorded profiles. Because fixed data were taken with

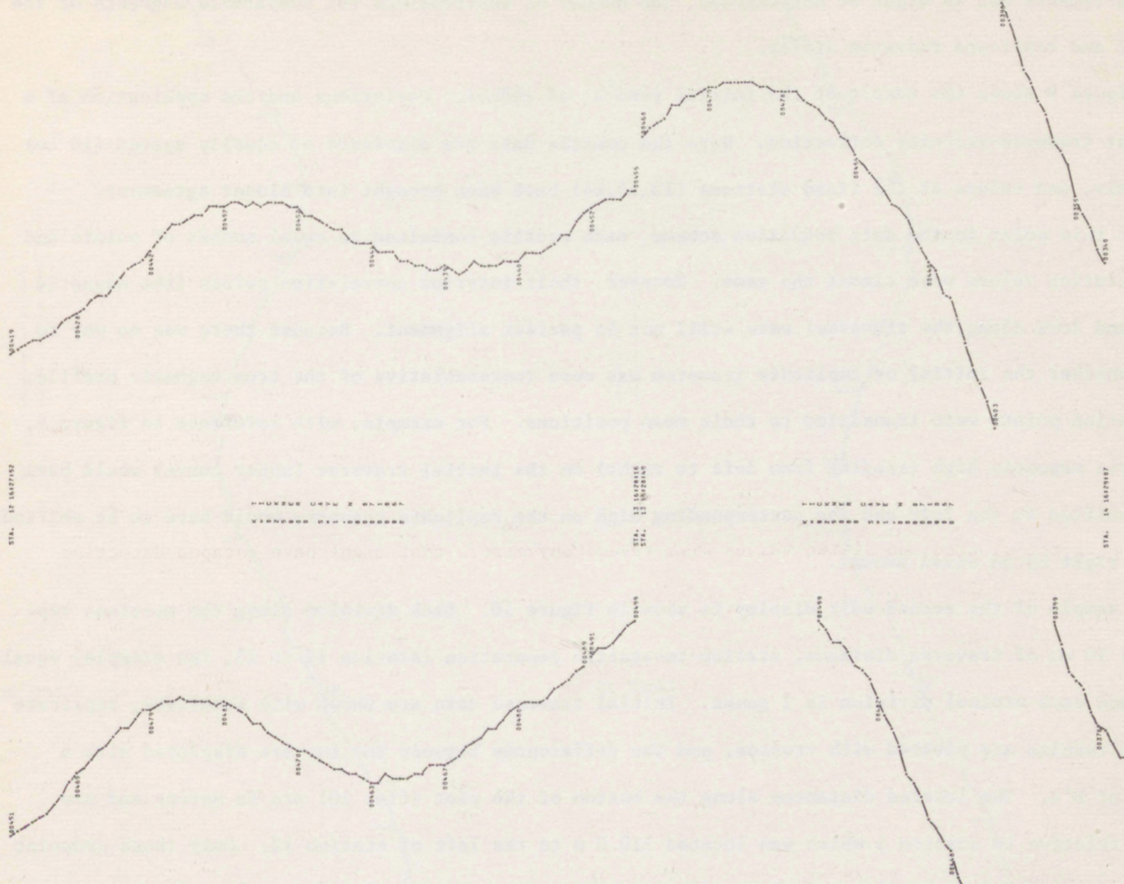


Figure 8. First edit display of initial (upper curve) and replicate (lower curve) continuous profiling traverse data.

a continuous profiling method, the plotted profile is a time series with readings displayed at equal time increments and as might be anticipated, the number of observations for comparable segments of the initial and replicate traverse differ.

Figure 9 shows the result of the initial removal of endpoint variations and the application of a constant traverse-velocity correction. Here the profile data are displayed at equally spaced (10 cm) intervals, and values at the fixed stations (12,13,14) have been brought into closer agreement.

To this point in the data reduction scheme, each profile contained an equal number of points and their station values were almost the same. However, their interior correlation points (the magnetic highs and lows along the traverse) were still not in perfect alignment. Because there was no way to judge whether the initial or replicate traverse was more representative of the true magnetic profile, correlation points were translated to their mean positions. For example, with reference to figure 9, the first magnetic high (reading from left to right) on the initial traverse (upper curve) would have to be shifted to the left and the corresponding high on the replicate traverse would have to be shifted to the right by an equal amount.

A sample of the second edit display is show in figure 10. Each division along the abscissa represents 10 cm of traverse distance, station-to-station separation (station 12 to 13, for example) equals 10 m, and each ordinal division is 1 gamma. Initial traverse data are shown with asterisks, replicate profile results are plotted with crosses, and the differences between the two are displayed with a series of D's. The labeled distances along the bottom of the plot (fig. 10) are in meters and are stated relative to station 1 which was located 110.0 m to the left of station 12. Only those endpoint values of the terminal stations of the particular traverse segment displayed are shown (119 gammas at station 12, 16 gammas at station 14).

Figure 11 is an illustration of a multifunction listing of results. In this example only the first forty-one sets of values plotted in figure 10 are given. Note that the seven-place index is one unit greater than the distance value expressed in tenths of a meter; for example, at station 12 the distance is 110.0 m, but the last 4 numbers of the index are 1101. This procedure is necessary because many computers do not accept a zero index. The first point in the initial traverse (traverse line number 61) would carry the index, 1610001; for the replicate traverse it would be 2610001. The function listings contain 1 guard decimal; thus, in the example, 1190.0 at station 12 equals 119 gammas. If one value of a special set of data were very much different than its neighbors (a so-called data spike) then its presence would be detected easily in a first-difference listing such as shown in figure 11.

An illustration of the printout of data as retrieved from the master storage tape is shown in figure 12. In this example, Tickner Cave data from initial and replicate traverses run between stations 12 and 14 (at distances of 110.0 m and 130.0 m respectively from the reference position) are shown. Time at the beginning and end of each run (for example, 16:27:52 to 16:29:08 on the initial traverse) and the date at which data were taken (July 10, 1967) are also included. The listing displayed in

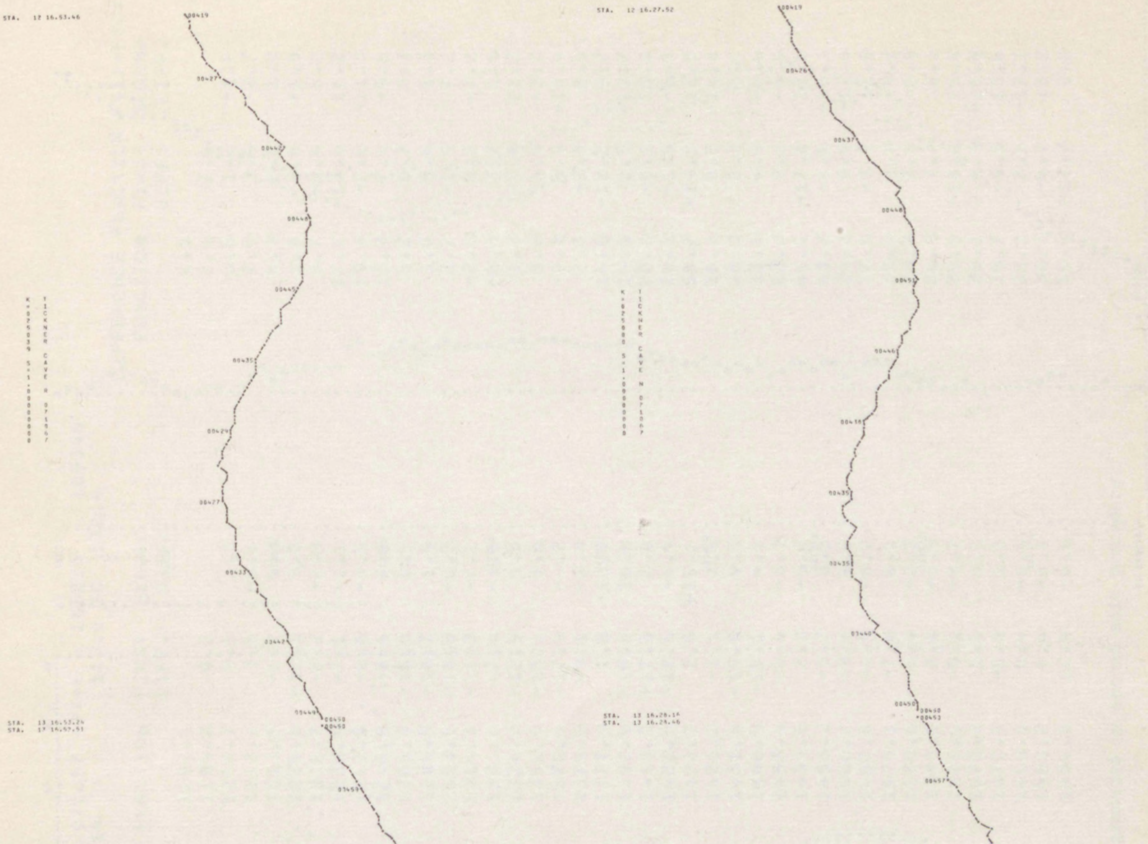


Figure 9. Initial and replicate traverse data after endpoint and traverse-velocity corrections have been applied.

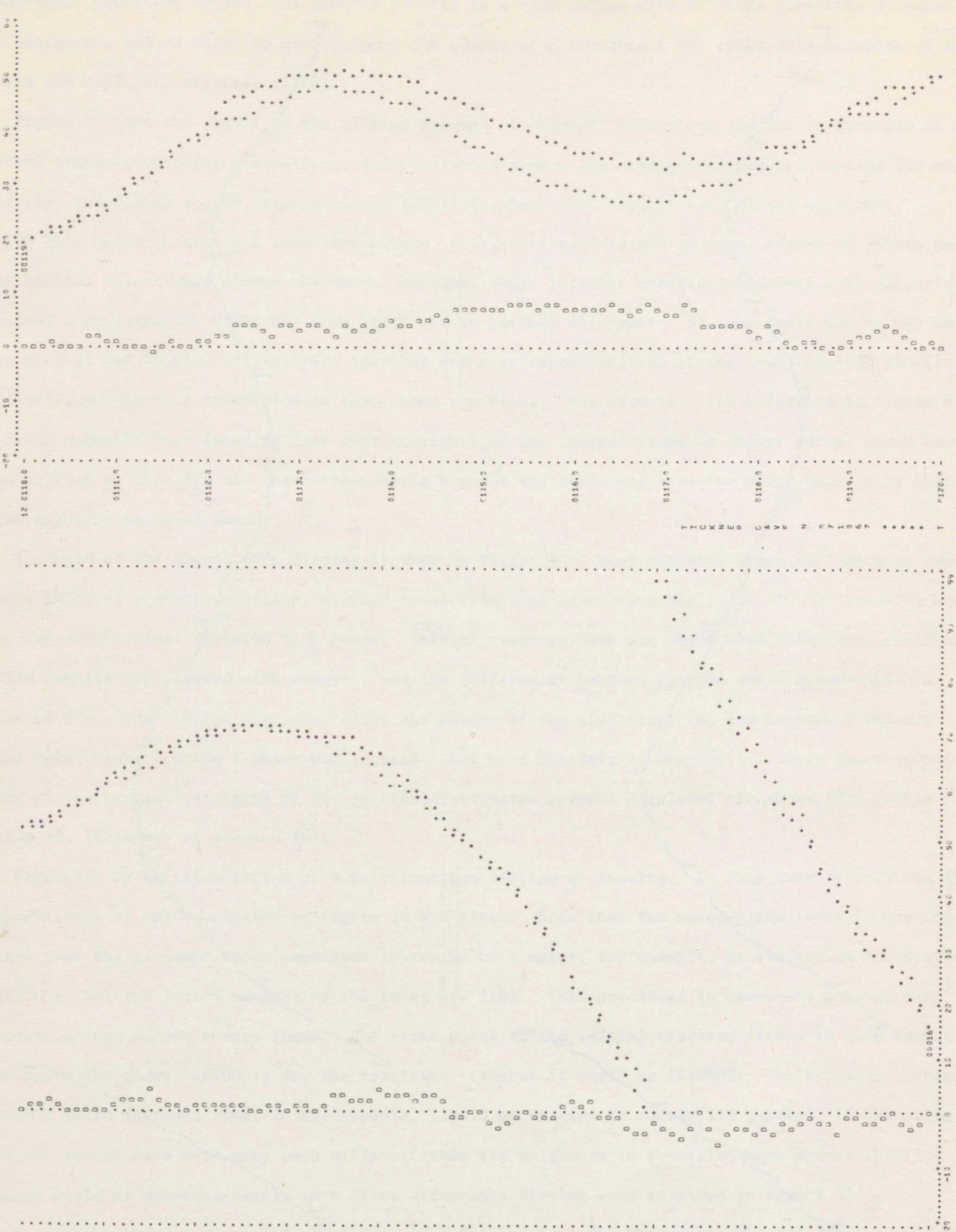
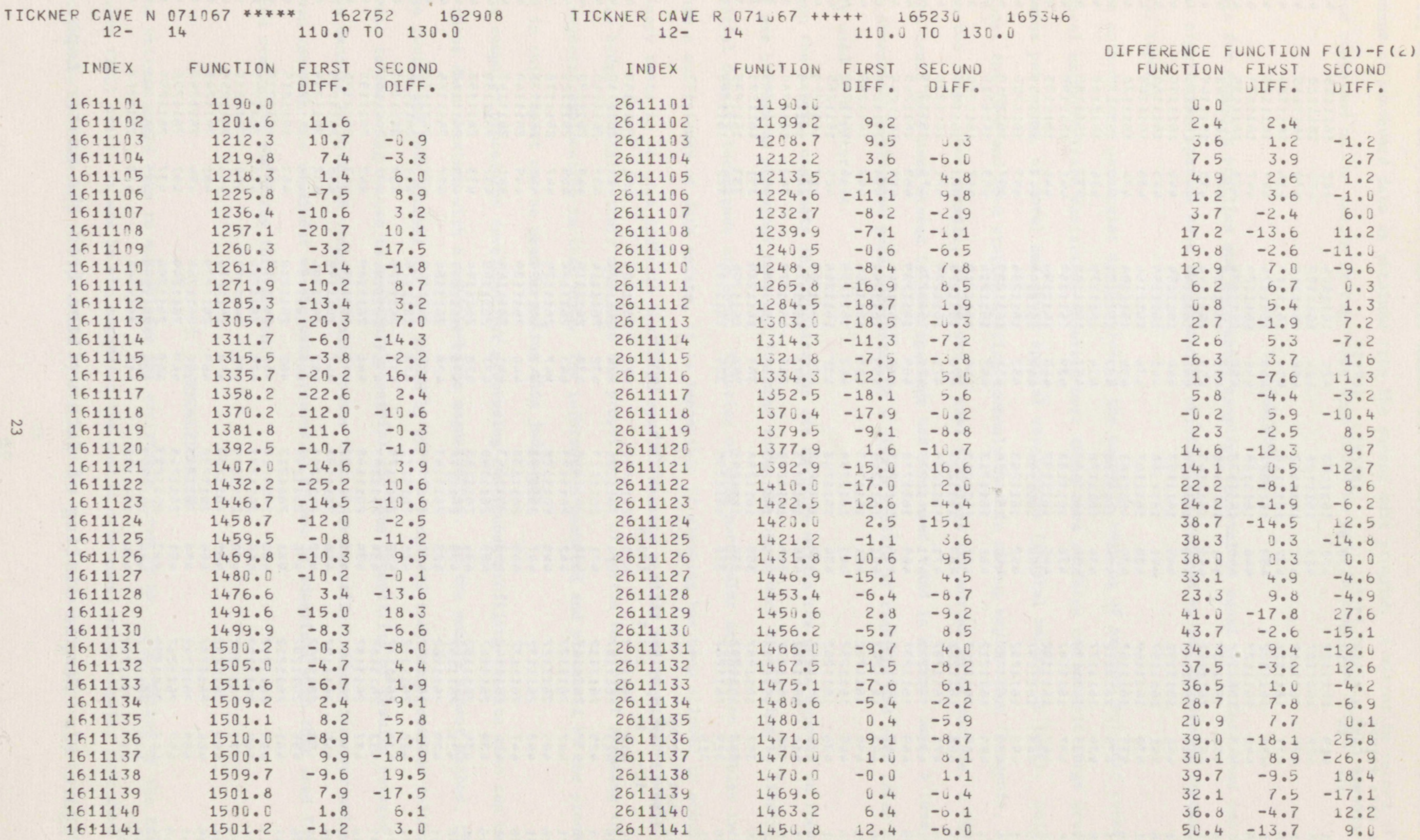


Figure 10. Second edit display of reduced initial (asterisks), replicate (crosses), and difference-function (D's) traverse data after adjustments for internal phase variations have been applied.



```
TICKNER CAVE N 071067 *****   162752   162908     TICKNER CAVE R 071067 +++++   165230   165346
    12-    14         110.0 TO  130.0                 12-    14         110.0 TO  130.0
                                                                         DIFFERENCE FUNCTION F(1)-F(2)
      INDEX   FUNCTION  FIRST SECOND        INDEX   FUNCTION  FIRST SECOND    FUNCTION  FIRST SECOND
                        DIFF.  DIFF.                          DIFF.  DIFF.              DIFF.  DIFF.
    1611101     1190.0                    2611101     1190.0                       0.0
    1611102     1201.6   11.6             2611102     1199.2    9.2                2.4    2.4
    1611103     1212.3   10.7   -0.9      2611103     1208.7    9.5    0.3         3.6    1.2   -1.2
    1611104     1219.8    7.4   -3.3      2611104     1212.2    3.6   -6.0         7.5    3.9    2.7
    1611105     1218.3    1.4    6.0      2611105     1213.5   -1.2    4.8         4.9    2.6    1.2
    1611106     1225.8   -7.5    8.9      2611106     1224.6  -11.1    9.8         1.2    3.6   -1.0
    1611107     1236.4  -10.6    3.2      2611107     1232.7   -8.2   -2.9         3.7   -2.4    6.0
    1611108     1257.1  -20.7   10.1      2611108     1239.9   -7.1   -1.1        17.2  -13.6   11.2
    1611109     1260.3   -3.2  -17.5      2611109     1240.5   -0.6   -6.5        19.8   -2.6  -11.0
    1611110     1261.8   -1.4   -1.8      2611110     1248.9   -8.4    7.8        12.9    7.0   -9.6
    1611111     1271.9  -10.2    8.7      2611111     1265.8  -16.9    8.5         6.2    6.7    0.3
    1611112     1285.3  -13.4    3.2      2611112     1284.5  -18.7    1.9         0.8    5.4    1.3
    1611113     1305.7  -20.3    7.0      2611113     1303.0  -18.5   -0.3         2.7   -1.9    7.2
    1611114     1311.7   -6.0  -14.3      2611114     1314.3  -11.3   -7.2        -2.6    5.3   -7.2
    1611115     1315.5   -3.8   -2.2      2611115     1321.8   -7.5   -3.8        -6.3    3.7    1.6
    1611116     1335.7  -20.2   16.4      2611116     1334.3  -12.5    5.0         1.3   -7.6   11.3
    1611117     1358.2  -22.6    2.4      2611117     1352.5  -18.1    5.6         5.8   -4.4   -3.2
    1611118     1370.2  -12.0  -10.6      2611118     1370.4  -17.9   -0.2        -0.2    5.9  -10.4
    1611119     1381.8  -11.6   -0.3      2611119     1379.5   -9.1   -8.8         2.3   -2.5    8.5
    1611120     1392.5  -10.7   -1.0      2611120     1377.9    1.6  -10.7        14.6  -12.3    9.7
    1611121     1407.0  -14.6    3.9      2611121     1392.9  -15.0   16.6        14.1    0.5  -12.7
    1611122     1432.2  -25.2   10.6      2611122     1410.0  -17.0    2.0        22.2   -8.1    8.6
    1611123     1446.7  -14.5  -10.6      2611123     1422.5  -12.6   -4.4        24.2   -1.9   -6.2
    1611124     1458.7  -12.0   -2.5      2611124     1420.0    2.5  -15.1        38.7  -14.5   12.5
    1611125     1459.5   -0.8  -11.2      2611125     1421.2   -1.1    3.6        38.3    0.3  -14.8
    1611126     1469.8  -10.3    9.5      2611126     1431.8  -10.6    9.5        38.0    0.3    0.0
    1611127     1480.0  -10.2   -0.1      2611127     1446.9  -15.1    4.5        33.1    4.9   -4.6
    1611128     1476.6    3.4  -13.6      2611128     1453.4   -6.4   -8.7        23.3    9.8   -4.9
    1611129     1491.6  -15.0   18.3      2611129     1450.6    2.8   -9.2        41.0  -17.8   27.6
    1611130     1499.9   -8.3   -6.6      2611130     1456.2   -5.7    8.5        43.7   -2.6  -15.1
    1611131     1500.2   -0.3   -8.0      2611131     1466.0   -9.7    4.0        34.3    9.4  -12.0
    1611132     1505.0   -4.7    4.4      2611132     1467.5   -1.5   -8.2        37.5   -3.2   12.6
    1611133     1511.6   -6.7    1.9      2611133     1475.1   -7.6    6.1        36.5    1.0   -4.2
    1611134     1509.2    2.4   -9.1      2611134     1480.6   -5.4   -2.2        28.7    7.8   -6.9
    1611135     1501.1    8.2   -5.8      2611135     1480.1    0.4   -5.9        20.9    7.7    0.1
    1611136     1510.0   -8.9   17.1      2611136     1471.0    9.1   -8.7        39.0  -18.1   25.8
    1611137     1500.1    9.9  -18.9      2611137     1470.0    1.0    8.1        30.1    8.9  -26.9
    1611138     1509.7   -9.6   19.5      2611138     1470.0   -0.0    1.1        39.7   -9.5   18.4
    1611139     1501.8    7.9  -17.5      2611139     1469.6    0.4   -0.4        32.1    7.5  -17.1
    1611140     1500.0    1.8    6.1      2611140     1463.2    6.4   -6.1        36.8   -4.7   12.2
    1611141     1501.2   -1.2    3.0      2611141     1450.8   12.4   -6.0        50.4  -13.7    9.0
```

Figure 11. Sample of listing produced by second edit procedure.

```
FILE   1

     201 DATA POINTS
        TICKNER CAVE N 071067 *****            162752     162908
            12-    14       110.0          130.0
1611101        419   1611102          420   1611103          421   1611104          422   1611105          422
1611106        422   1611107          423   1611108          424   1611109          426   1611110          426
1611111        426   1611112          427   1611113          428   1611114          430   1611115          431
1611116        431   1611117          432   1611118          434   1611119          436   1611120          437
1611121        438   1611122          439   1611123          440   1611124          442   1611125          444
1611126        445   1611127          446   1611128          446   1611129          447   1611130          448
1611131        448   1611132          448   1611133          450   1611134          450   1611135          450
1611136        451   1611137          451   1611138          451   1611139          450   1611140          451
1611141        450   1611142          451   1611143          450   1611144          450   1611145          450
1611146        449   1611147          449   1611148          447   1611149          447   1611150          446
1611151        446   1611152          445   1611153          444   1611154          444   1611155          442
1611156        441   1611157          441   1611158          441   1611159          440   1611160          438
1611161        438   1611162          438   1611163          436   1611164          436   1611165          436
1611166        435   1611167          435   1611168          434   1611169          434   1611170          435
1611171        435   1611172          434   1611173          433   1611174          434   1611175          436
1611176        434   1611177          434   1611178          434   1611179          434   1611180          435
1611181        435   1611182          435   1611183          437   1611184          437   1611185          437
1611186        437   1611187          438   1611188          439   1611189          441   1611190          441
1611191        442   1611192          445   1611193          445   1611194          445   1611195          447
1611196        448   1611197          448   1611198          448   1611199          448   1611200          450
1611201        450   1611202          452   1611203          453   1611204          453   1611205          454
1611206        455   1611207          456   1611208          456   1611209          457   1611210          458
1611211        459   1611212          461   1611213          462   1611214          463   1611215          464
1611216        465   1611217          467   1611218          466   1611219          467   1611220          468
1611221        468   1611222          469   1611223          470   1611224          470   1611225          470
1611226        471   1611227          471   1611228          471   1611229          471   1611230          471
1611231        471   1611232          471   1611233          470   1611234          470   1611235          470
1611236        469   1611237          469   1611238          469   1611239          469   1611240          469
1611241        467   1611242          466   1611243          466   1611244          465   1611245          463
1611246        462   1611247          461   1611248          459   1611249          458   1611250          456
1611251        454   1611252          451   1611253          450   1611254          449   1611255          447
1611256        445   1611257          443   1611258          442   1611259          441   1611260          439
1611261        436   1611262          434   1611263          432   1611264          429   1611265          428
1611266        424   1611267          422   1611268          421   1611269          417   1611270          413
1611271        410   1611272          406   1611273          403   1611274          400   1611275          396
1611276        392   1611277          388   1611278          385   1611279          382   1611280          378
1611281        373   1611282          371   1611283          368   1611284          365   1611285          362
1611286        357   1611287          355   1611288          353   1611289          351   1611290          345
1611291        342   1611292          339   1611293          337   1611294          333   1611295          330
1611296        329   1611297          328   1611298          325   1611299          322   1611300          319
1611301        316

     201 DATA POINTS
        TICKNER CAVE R 071067 +++++            165346     165230
            12-    14       110.0          130.0
2611101        419   2611102          420   2611103          421   2611104          421   2611105          422
2611106        423   2611107          424   2611108          424   2611109          425   2611110          427
2611111        429   2611112          431   2611113          432   2611114          433   2611115          435
2611116        437   2611117          438   2611118          438   2611119          440   2611120          442
2611121        442   2611122          442   2611123          443   2611124          445   2611125          445
2611126        445   2611127          446   2611128          447   2611129          447   2611130          448
2611131        448   2611132          447   2611133          447   2611134          447   2611135          447
2611136        447   2611137          445   2611138          446   2611139          445   2611140          445
2611141        444   2611142          443   2611143          441   2611144          441   2611145          441
2611146        439   2611147          438   2611148          437   2611149          437   2611150          436
2611151        435   2611152          434   2611153          433   2611154          433   2611155          432
2611156        431   2611157          430   2611158          430   2611159          430   2611160          429
2611161        429   2611162          428   2611163          428   2611164          427   2611165          427
2611166        428   2611167          428   2611168          427   2611169          427   2611170          427
2611171        428   2611172          428   2611173          428   2611174          430   2611175          430
2611176        430   2611177          430   2611178          431   2611179          432   2611180          433
2611181        433   2611182          434   2611183          435   2611184          437   2611185          437
2611186        437   2611187          439   2611188          441   2611189          442   2611190          442
2611191        443   2611192          443   2611193          443   2611194          443   2611195          443
2611196        445   2611197          446   2611198          447   2611199          448   2611200          449
2611201        450   2611202          452   2611203          452   2611204          452   2611205          453
2611206        455   2611207          456   2611208          457   2611209          458   2611210          460
2611211        461   2611212          461   2611213          462   2611214          463   2611215          463
2611216        464   2611217          465   2611218          467   2611219          468   2611220          468
2611221        469   2611222          469   2611223          470   2611224          470   2611225          471
2611226        471   2611227          470   2611228          470   2611229          470   2611230          469
2611231        469   2611232          469   2611233          468   2611234          466   2611235          466
2611236        466   2611237          464   2611238          463   2611239          461   2611240          460
2611241        459   2611242          458   2611243          456   2611244          454   2611245          452
2611246        452   2611247          451   2611248          449   2611249          447   2611250          446
2611251        445   2611252          443   2611253          440   2611254          437   2611255          435
2611256        432   2611257          429   2611258          424   2611259          422   2611260          420
2611261        418   2611262          414   2611263          412   2611264          410   2611265          408
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Figure 12. Sample listing of data written from the master tape.

figure 12, with the exception of the file number and the number of data points in each group, shows the arrangement of punchcard data as obtained from the second edit program. A microfilm record of the information contained on the master storage tape also could be made in this same format.

4. CONCLUSIONS

Data for magnetic profiles and maps whose sampling interval is equal to or less than one half the shortest significant spatial wave length can be obtained and reduced by the procedures discussed in this technical report.

The methods have particular application in the magnetic mapping of exposed volcanic rocks. Often the lateral magnetic-field variations observed over these lava surfaces can exhibit large gradients (100 gammas per meter, or more) and short spatial wavelengths (several meters, or less). Under these conditions, the 10-m and 20-m station spacing commonly used in mining exploration (Parasnis, 1966) would be too large. For example, on one set of test traverses run across an aa surface, a 700-gamma variation could have been missed if 10-m spacings had been used. And in another case, a lava tube of average dimensions could have gone undetected on a single profile if readings had been taken at the commonly used 10-m intervals.

When the lateral contrasts in magnetization are as large within the units exposed on the surface as they are between an anomalous body and its host rock, the occurrence of aliasing is likely unless high spatial density techniques are used. Solution of this particular exploration problem is difficult even when a sufficiency of data exists, it is impossible if aliasing has been allowed to occur. When preliminary tests in an area indicate that high spatial density methods are required but when the exploration budget prohibits their use, then the proper course of action in project planning is to abandon ground magnetic exploration in that area. The information gathered and processed by the procedures described in this report can be used in making this judgement.

The computer procedures developed for processing continuous profiling results also can be used to reduce those data obtained with a vehicle-borne magnetometer. In the mobile sensor method, the signals from the roving and base sensors are not linked by wire to a central recording position (although an electronic telemetering system is certainly possible) and thus synopticity of results between the mobile and base sensors is obtained computationally rather than instrumentally. After time-variation effects have been removed, the remainder of the data processing scheme is identical with that used for reduction of linked continuous profiling information.

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GPO 834-141