

[72] Inventors Philip L. Lawrence
Riverside, Conn.;
Gilbert W. Ehlert, Dallas, Tex.; John A.
Lester, Dallas, Tex.; Albert W. Musgrave,
Dallas, Tex.
[21] Appl. No. 860,117
[22] Filed Sept. 22, 1969
[45] Patented Aug. 10, 1971
[73] Assignee Mobil Oil Corporation
Continuation of application Ser. No.
330,413, Dec. 13, 1963, now abandoned.

[50] Field of Search..... 235/181,
182, 184, 153, 164, 61.6; 340/172.5; 324/10

References Cited			
UNITED STATES PATENTS			
2,801,794	8/1957	Garvin et al.	235/61.6
2,959,351	11/1960	Hamilton et al.	235/153
3,112,397	11/1963	Crook	235/181
3,256,480	6/1966	Runge et al.	324/10
3,284,763	11/1966	Burg et al.	235/181 X
3,319,226	5/1967	Mott et al.	235/164 X

Primary Examiner—Malcolm A. Morrison
Assistant Examiner—Felix D. Gruber

[54] METHOD OF AND APPARATUS FOR
DETERMINING AREA GRAVITY
14 Claims, 12 Drawing Figs.

[52] U.S. CL..... 235/181,
235/61.6, 235/164
[51] Int. CL..... G01v 7/06,
G06f 15/34, G06g 7/18

ABSTRACT: Gravity profiles are smoothed by differencing smoothing intervals. Several of the smoothed profiles are then combined, or averaged, to form an averaged area gravity value. The averaged area gravity values are subtracted one from another to generate a plurality of difference area gravity values. Each of these difference area gravity values accentuates an anomaly in a different depth range.

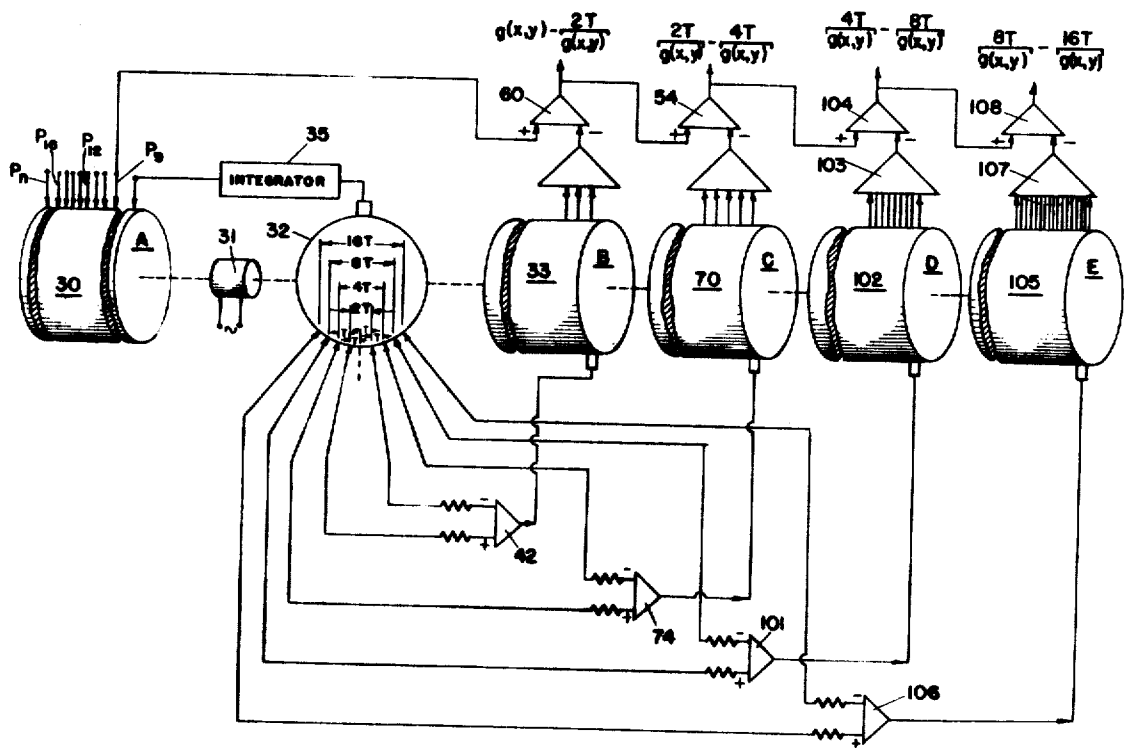
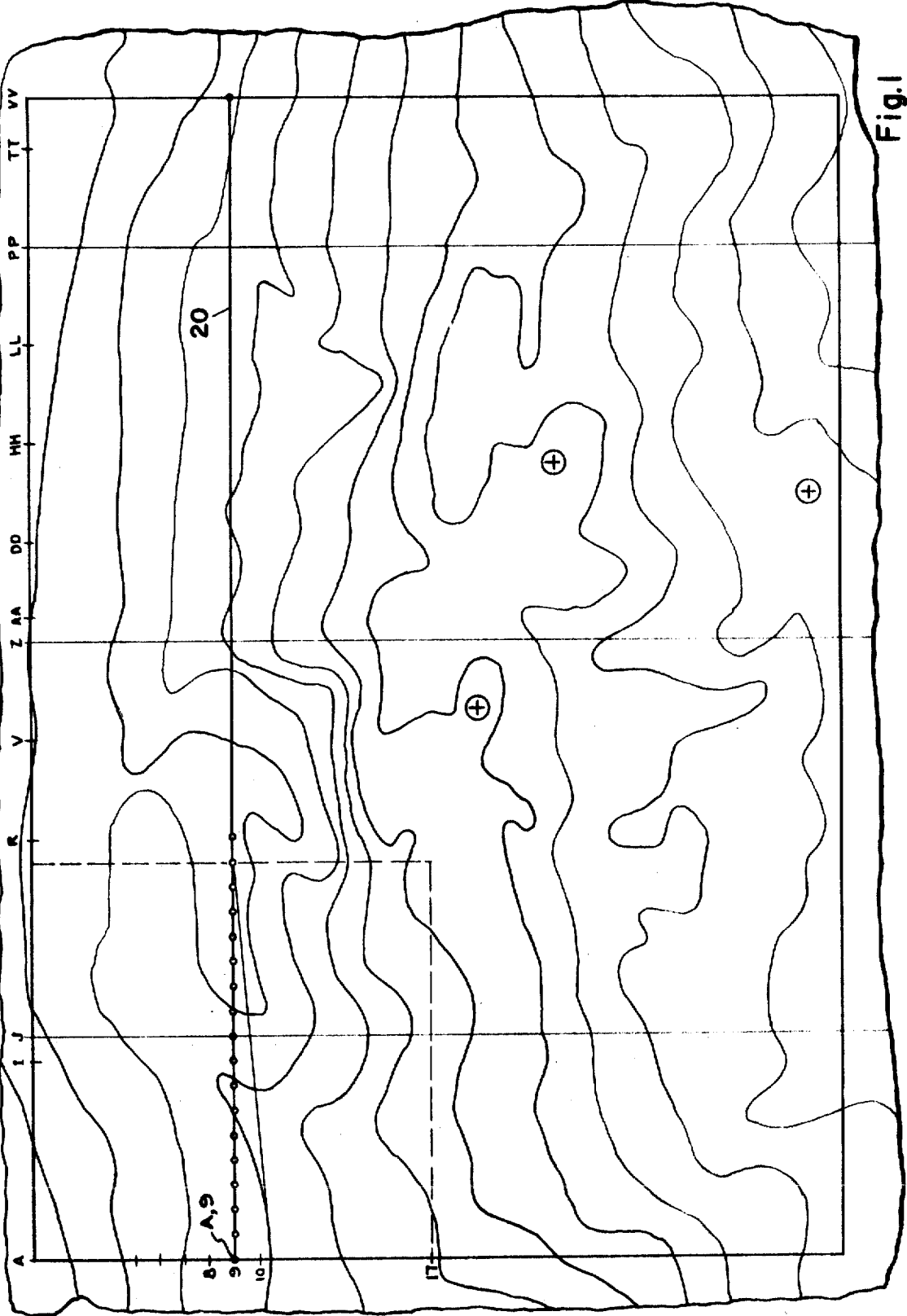


Fig. 1



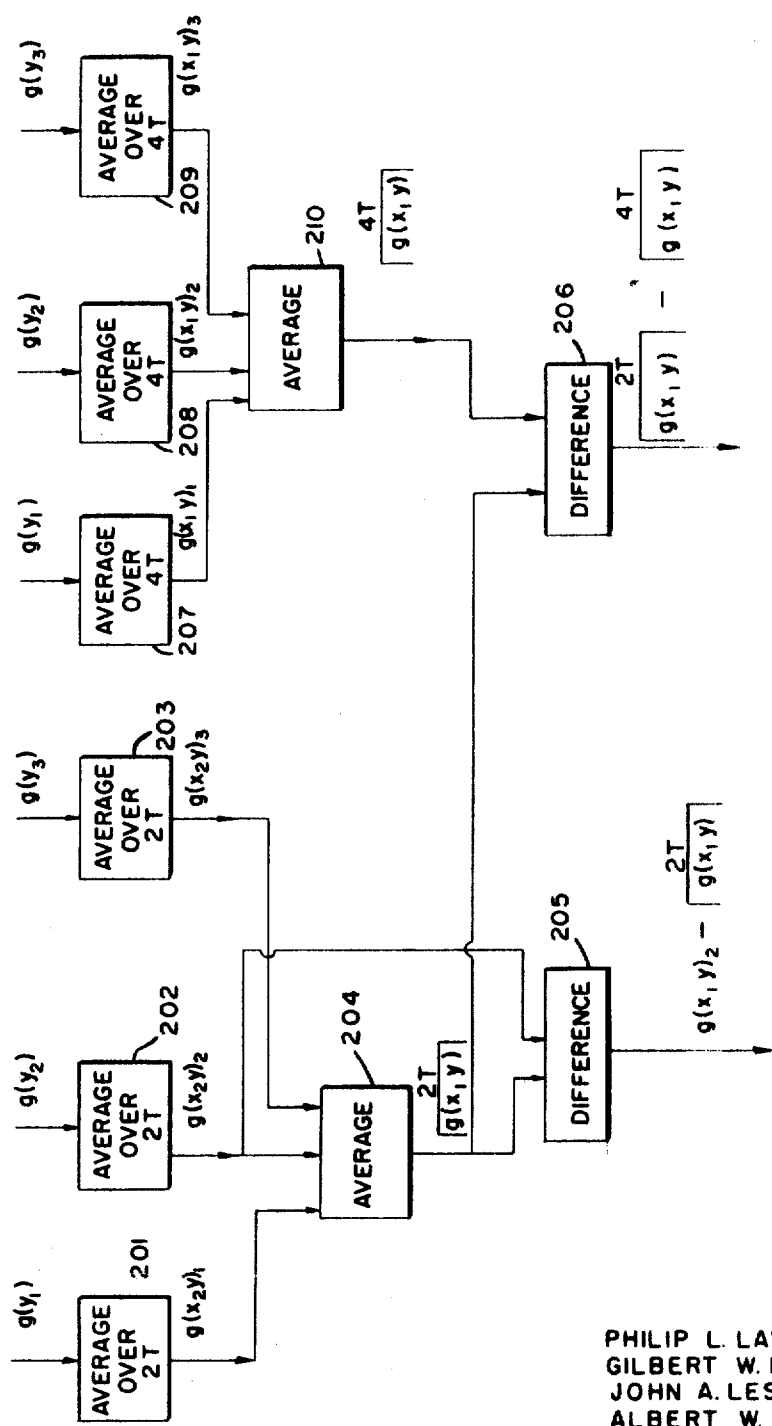


FIG. 1a

INVENTORS
PHILIP L. LAWRENCE
GILBERT W. EHLERT
JOHN A. LESTER
ALBERT W. MUSGRAVE

Fig. 2

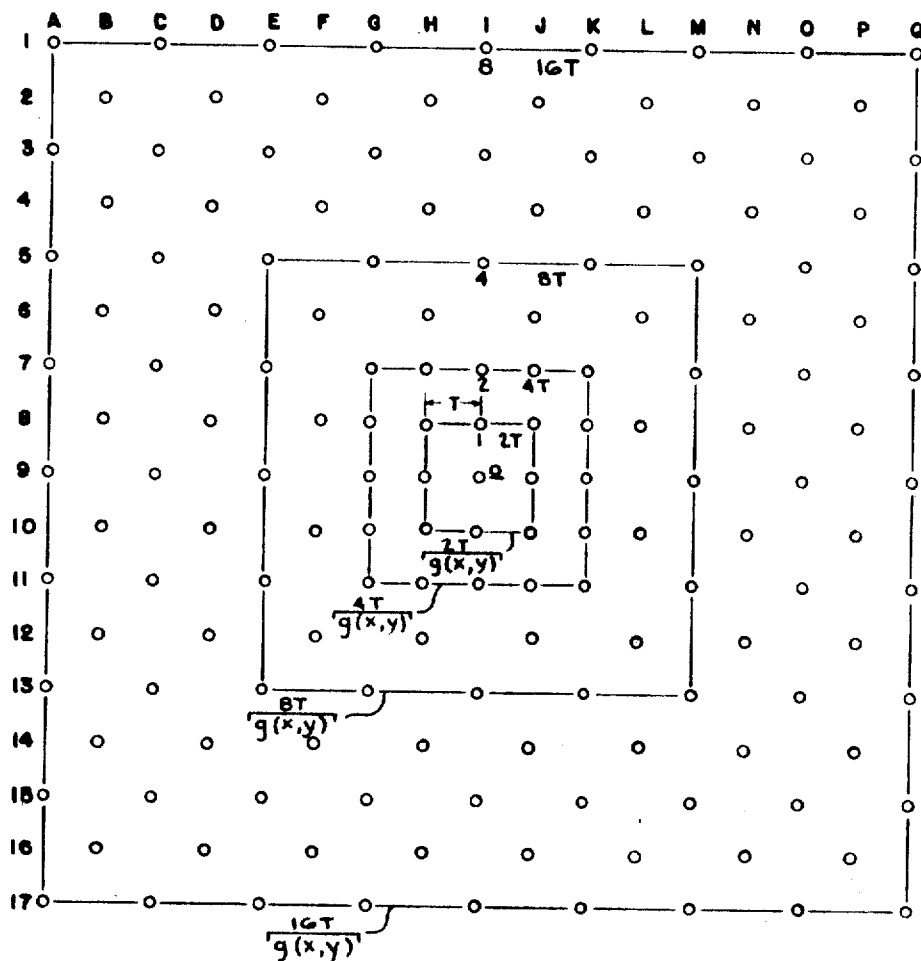


Fig. 4

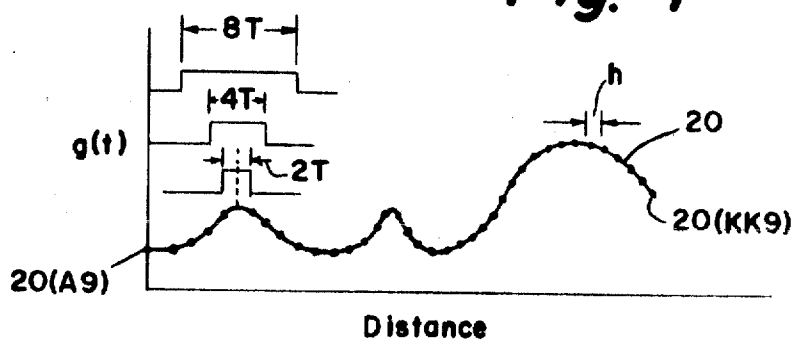
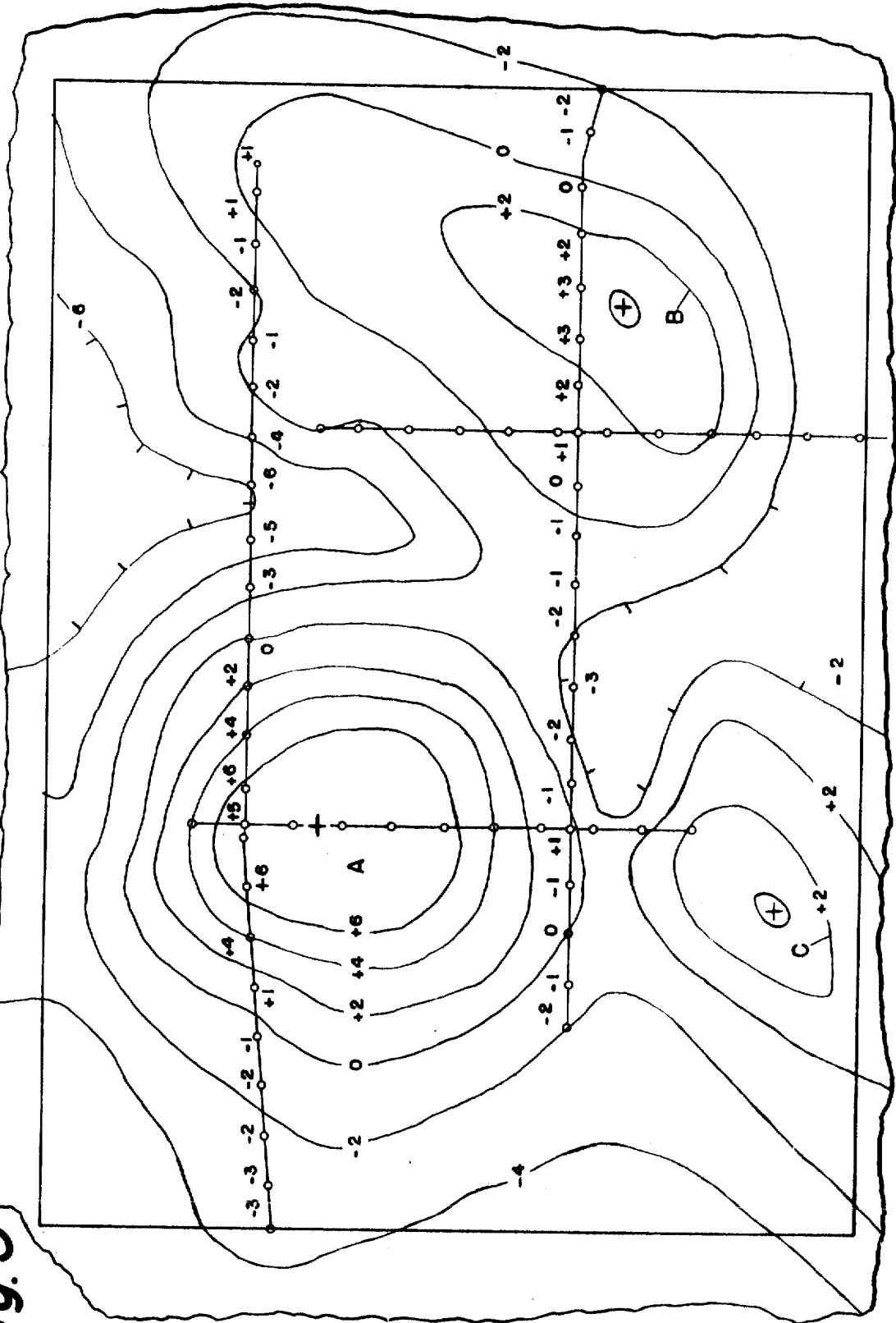
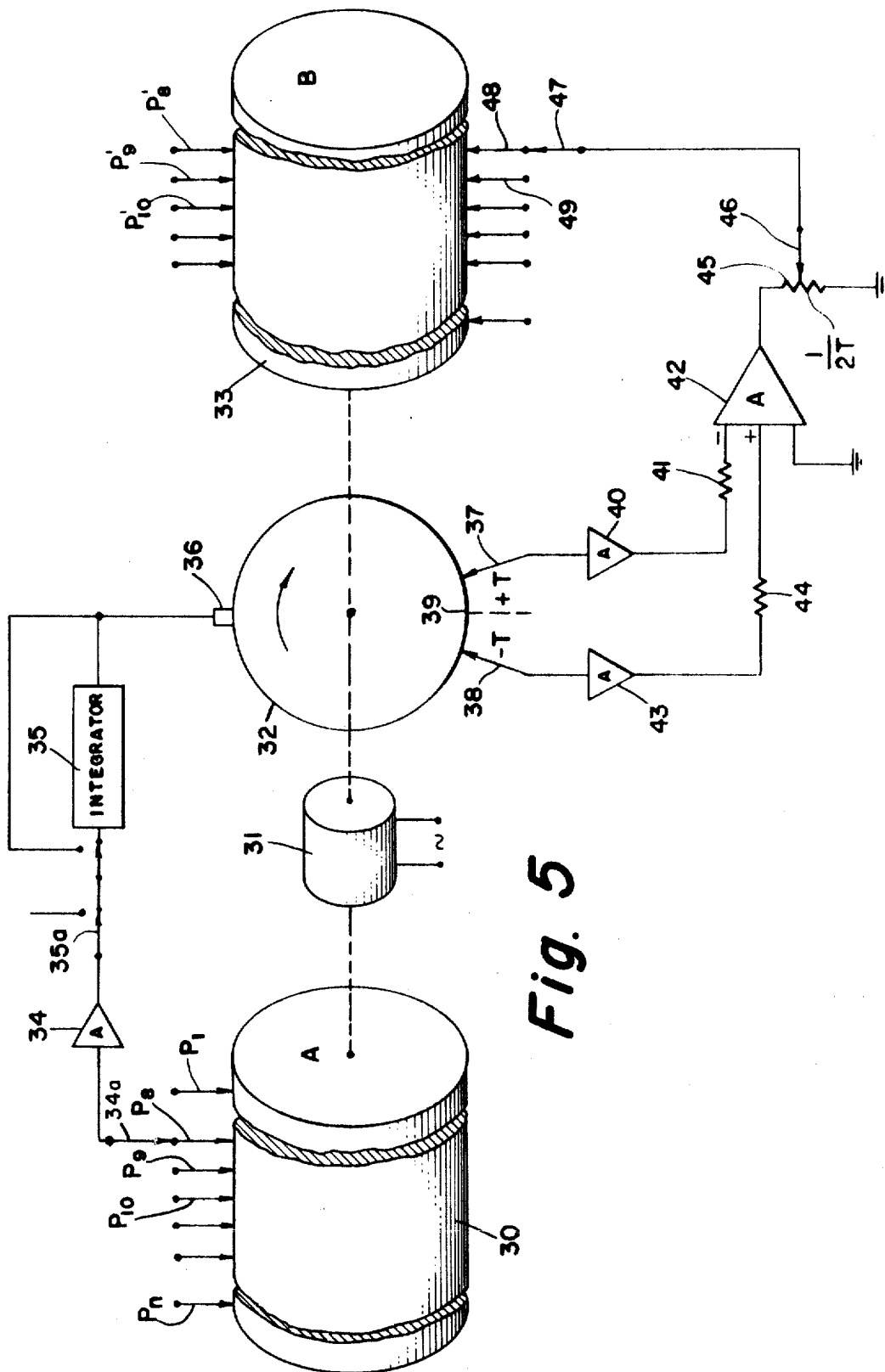


Fig. 3





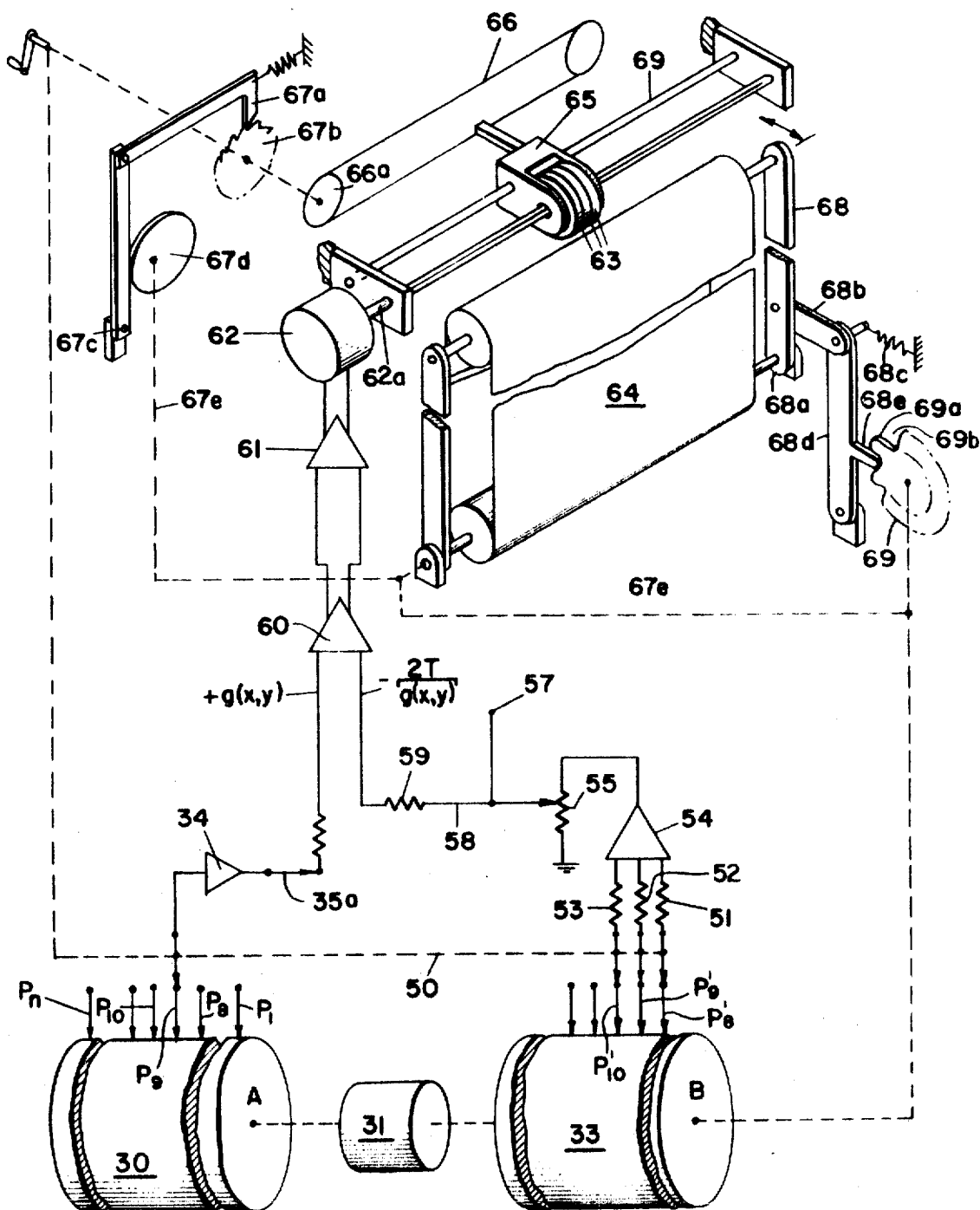
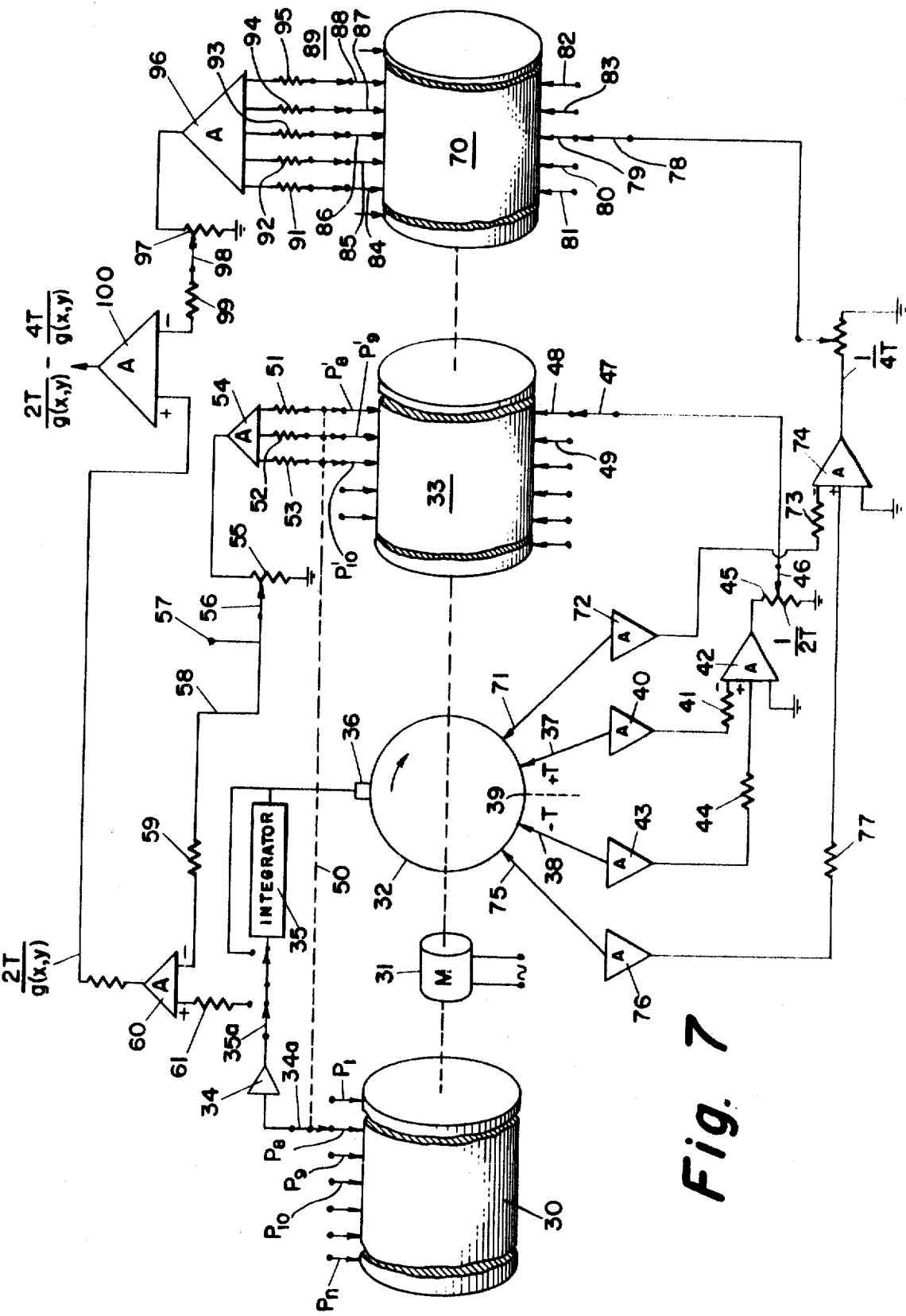


Fig. 6



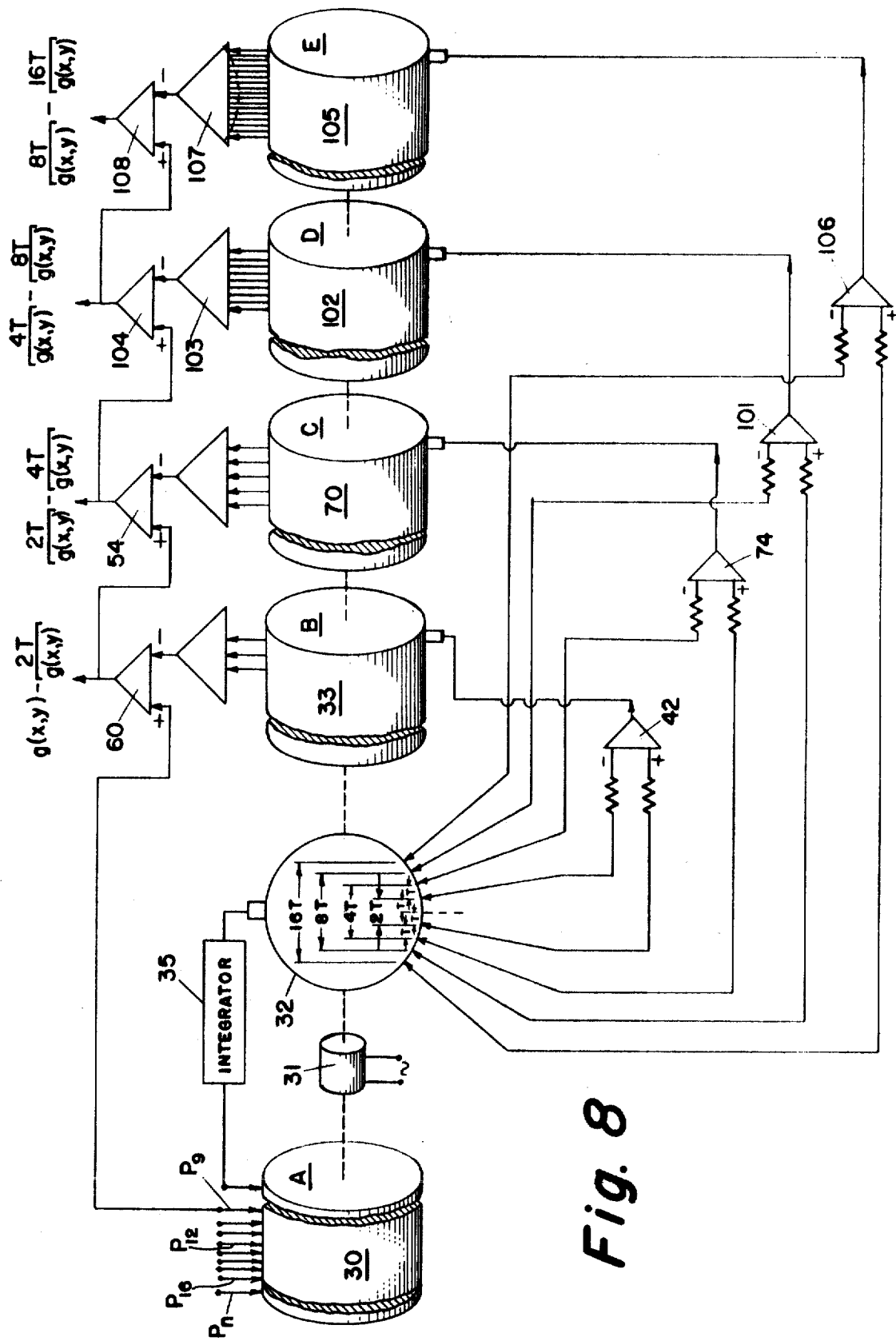


Fig. 8

Fig. 9

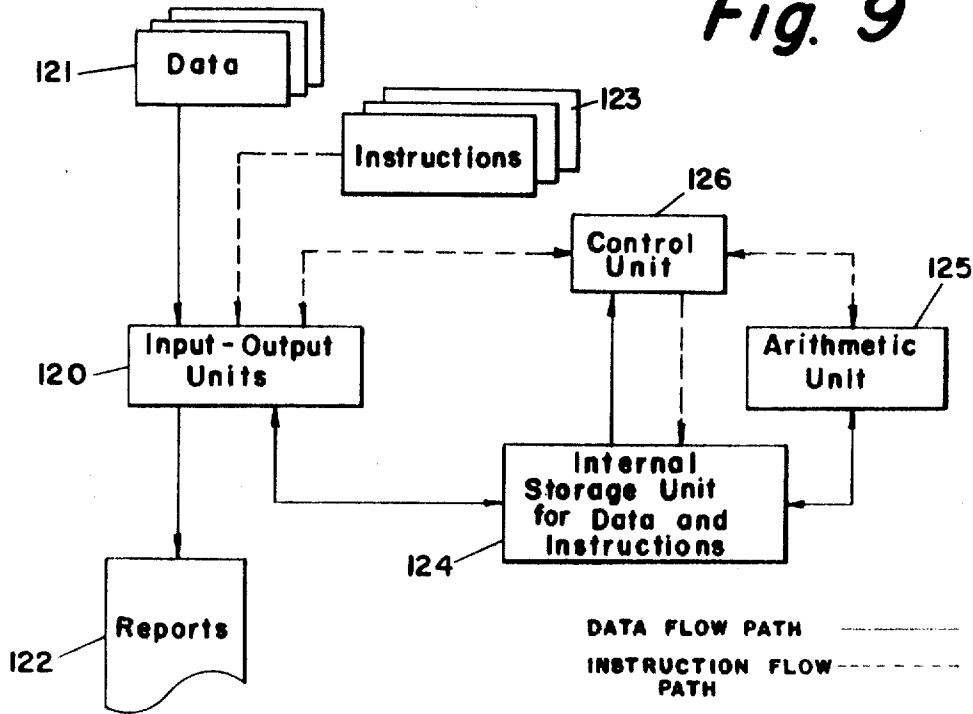


Fig. 10

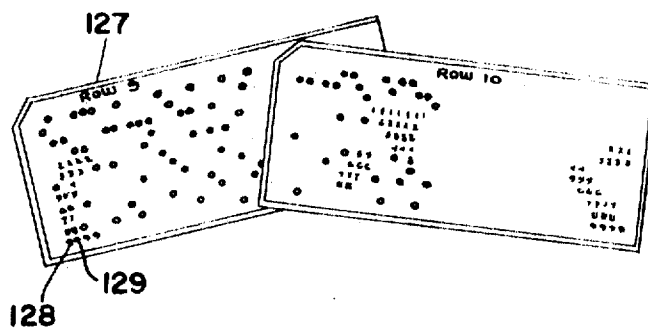
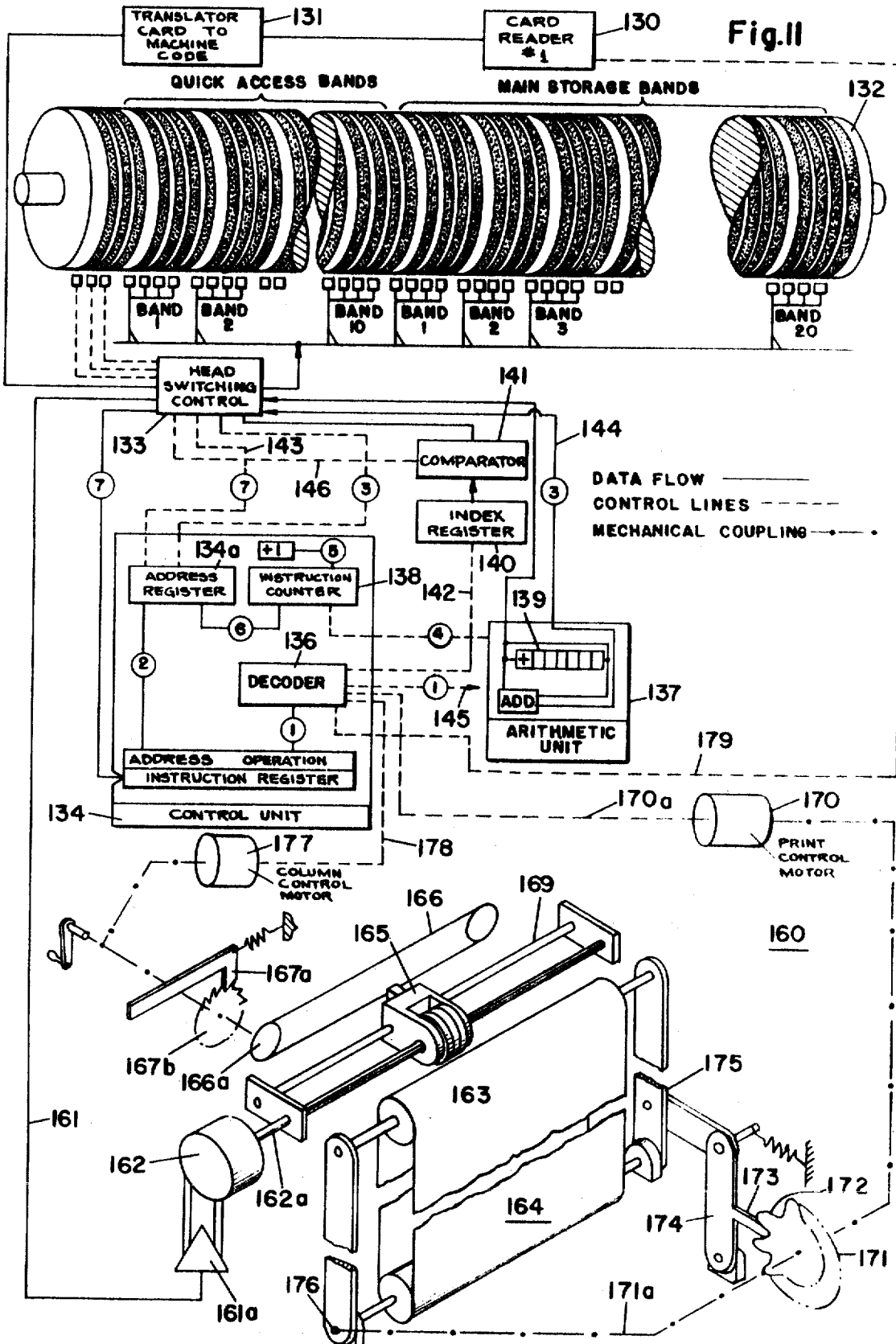


Fig. II



METHOD OF AND APPARATUS FOR DETERMINING AREA GRAVITY

This case is a continuation of application Ser. No. 330,413 filed Dec. 13, 1963, now abandoned.

This invention relates to a method of and means for transforming gravitational potentials obtained over selected areas into forms which accentuate anomalies and provide information as to the depths of the structures giving rise to them.

In accordance with application Ser. No. 669,314 filed Sept. 20, 1967 which is a continuation of Ser. No. 214,973 filed Aug. 6, 1962 and now abandoned, for "Method and Means for Treating Gravity Profiles," filed by one of the joint inventors of this application, gravity profiles are treated with a plurality of selected averaging operators and difference profiles generated by subtracting one from the other in a predetermined manner. While the treatment of gravity profiles as disclosed in said application has proved advantageous in revealing the nature and depth of masses giving rise to gravity anomalies, something has been left to be desired. More particularly, these anomalies are generally not isolated symmetric masses, but rather are elongated and of changing width. Therefore, the area, extent and trends of these anomalies are not immediately evident by comparison of profiles, whereas a study on an area basis does disclose these features.

Accordingly, by utilizing the gravity values at all observation stations on a gravitational map and including interpolated values when needed for developing a plurality of additional gravitational maps each having gravity values averaged over a different selected area, maps of difference values may then be developed which will better display anomalies due to the masses of the character above mentioned.

In accordance with the present invention, the information from which the gravity map has been drawn is treated in a manner greatly to enhance the identification of the anomalies, not only to make them more readily apparent, but also to yield additional and more definitive information from them.

The foregoing and other objects, features and advantages of the present invention will be better understood from the following more detailed description in conjunction with the drawings in which:

- FIG. 1 shows an untreated gravity map;
- FIG. 1a shows a flow sheet of the process of the invention;
- FIG. 2 shows a set of averaging operators;
- FIG. 3 shows a gravity map which has been treated in accordance with this invention;
- FIG. 4 shows a gravity profile;
- FIG. 5 shows a portion of the analog equipment used in practicing this invention;
- FIG. 6 shows another portion of the analog equipment used in practicing this invention;
- FIG. 7 shows still another portion of the analog equipment used in practicing this invention;
- FIG. 8 represents all of the analog equipment used in practicing the present invention;
- FIG. 9 is a schematic showing of digital data processing used in practicing the present invention;
- FIG. 10 shows punched cards on which gravitational data is punched;
- FIG. 11 shows in more detail the digital data processing used in practicing the present invention.

Referring now to the drawings, there has been illustrated in FIG. 1 a gravity map typical of those made in the field for the determination of gravity anomalies from which information can be gained as to the nature and character of subsurface masses giving rise to them.

In the following description, reference will be made to gravity values appearing on the map of FIG. 1 and on other selected portions thereof later illustrated, it being understood, of course, that the gravity values themselves are of prime importance. The gravity values also may be utilized directly in accordance with the following explanation for their modification and treatment in digital form.

There has been illustrated in FIG. 2 a set of averaging operators, each definitive of a selected and different area, and each symmetrical about a common point. Thus, each averaging operator, taking into account a selected area of the surface, will provide better information as to the nature and character of the masses giving rise to gravitational anomalies.

The first operator is designated

$$\frac{2T}{g(x,y)}$$

(which is to be read as the average value at a point x,y of the gravity g measured over a square $2T$ on each side and centered about the point x,y). Similarly, the remaining operators

$$\frac{4T}{g(x,y)}, \frac{8T}{g(x,y)}$$

and

$$\frac{16T}{g(x,y)}$$

represent average values of gravity at the same point x,y but in respect to larger squares the respective sides of which correspond to $4T$, $8T$ and $16T$. For each operator, T is taken as the separation distance between rows and columns of equally spaced observation points of the gravity potential along the periphery of the averaging area which, in each case, is shown as a square in FIG. 2.

A derivation of these operators will be described in substantial detail subsequently. At this point, one need only appreciate that the operators may be obtained by first individually integrating with respect to distance all gravity profiles for the particular operator square. The integrated values for the profiles are then divided by the distance of the square side.

The small circles of FIG. 2 identify the gravity values and in some cases, these may correspond with observation points, though in FIG. 1 these points have been omitted. In most cases, the map of FIG. 1 will have provided a grid on which the points will be spaced as shown in FIG. 2 and in respect to which there will be provided gravity values, though interpolated from the actually observed gravity potentials, if necessary.

It will be observed that the gravity values represented by the small circles on the averaging operators of FIG. 2 may be identified by the several rows numbered on the y -axis respectively 1-17 and the columns along the x -axis identified respectively as A-Q.

As already explained, the operator

$$\frac{2T}{g(I,9)}$$

means that the values of gravity lying on the periphery of and within a square whose sides are $2T$ long and including the symmetrical point I,9 will be averaged together to provide a single value of gravity potential. The operator

$$\frac{2T}{g(x,y)}$$

is then moved (to the right) across the transverse of the map by the distance T , i.e., to the next station J,9, and another average taken. Referred to in FIG. 1, this operation is continued in discrete steps from the position of operator

$$\frac{2T}{g(x,y)}$$

to the right until the outer boundary of the averaging operator

$$\frac{16T}{g(x,y)}$$

coincides with the right-hand limit of the gravity map. The operator

$$\frac{2T}{g(x,y)}$$

is then shifted in discrete steps downwardly from its first location at 1,9 to a new location at 1,10, and the foregoing operations repeated until the whole map has been covered, i.e., until the lower boundary of the averaging operator

$$\overline{g(x,y)}^{16T}$$

coincides with the bottom edge of the map.

In FIG. 1 the boundary lines have been provided for convenient reference, it being understood that the map itself will be considerably larger and that only a significant portion has been illustrated in relation to FIG. 3 later to be described.

It is to be understood that upon completion of the scanning of the map with the averaging operator

$$\overline{g(x,y)}^{2T}$$

as just described, there will be obtained new values of the gravity potential from which a new map may be drawn.

The foregoing operations are then repeated in succession for the operators

$$\overline{g(x,y)}^{4T}, \overline{g(x,y)}^{8T} \text{ and } \overline{g(x,y)}^{16T}$$

new gravity maps then being established for each of the additional operators.

As will be later explained, there will then be subtracted from the gravity value as obtained by the operator

$$\overline{g(x,y)}^{2T}$$

the gravity value obtained by the operator

$$\overline{g(x,y)}^{4T}$$

The subtraction will be point by point and a new map developed therefrom.

The striking results of the technique thus far explained will be apparent by reference to the fractional map of FIG. 3 where the gravity contour lines for the corresponding area of FIG. 1 have significantly different values, and more importantly, where the gravity anomalies are prominently displayed. Thus, for example, three positive gravity anomalies A, B and C appear. For anomaly A, the inner contour line has a gravity potential of +6, with successive contour lines decreasing to zero, and outwardly therefrom additional contour lines have negative values. Such contour lines do not appear on the map of FIG. 1 for the reason that the gravity potentials represented by the contour lines on FIG. 3 have, in the map of FIG. 1, been obscured by shallow and stronger gravity anomalies.

As will be later explained, the masses giving rise to the anomalies A, B and C, FIG. 3, are known to occur at depths between 12,000 feet and 24,000 feet. Since the map of FIG. 3 resulted from the subtraction of the data from the averaging operator

$$\overline{g(x,y)}^{16T}$$

from the data obtained utilizing the averaging operator

$$\overline{g(x,y)}^{8T}$$

For convenience, the depths which will give rise to corresponding anomalies on other maps resulting from the four operations with the four operators of FIG. 2 are as follows:

$$\begin{array}{l} 0 \text{ to } 3,000' \quad \overline{g(x,y)}^{2T} - \overline{g(x,y)}^{16T} \\ 3,000 \text{ to } 6,000' \quad \overline{g(x,y)}^{2T} - \overline{g(x,y)}^{4T} \\ 6,000 \text{ to } 12,000' \quad \overline{g(x,y)}^{4T} - \overline{g(x,y)}^{8T} \\ 12,000 \text{ to } 24,000' \quad \overline{g(x,y)}^{8T} - \overline{g(x,y)}^{16T} \end{array}$$

In explaining the manner in which the foregoing operations are accomplished in analog computing equipment, several Figures will be utilized, each in part duplicating equipment of an earlier Figure. There will then be presented a block diagram illustrating the manner in which the number of components in the analog equipment may be decreased. The switching functions unduly complicate an understanding of the operations which may be more simply explained by using separate Figures of the kind just described. Finally, there will be presented techniques for a digital execution of the present invention.

Referring again to FIG. 1, it will be observed that there has been marked thereon a line 20 representative of a traverse across the gravity map. On this line the small circles indicate gravity stations separated by the distances T at which values of gravity have been measured or established as by interpolation as explained above. If, now, the gravity potentials at each of the stations on the line 20 be plotted, a curve, such as that illustrated in FIG. 4 will be obtained, where the first gravity value will correspond with the station A,9 and the final value on the traverse line at KK,9.

As explained in the aforesaid application Ser. No. 214,973 to Lawrence the interval T between stations is chosen to be less than one-half the length of the shortest fluctuation in the observed gravity potential, i.e., the distance between the beginning and end of the shortest anomaly as measured along the abscissa. In one embodiment of the invention the distance T was selected as 3,000 feet. Though the averaging operators in accordance with the present invention are in terms of area, it is convenient to show these operators for the line or gravity profile 20 and they have been illustrated as 2T, 4T and 8T for profile 20. It is to be understood that there will be a plurality of profiles extending across the map of FIG. 1, each spaced vertically from the other preferably by distances equal to the spacing between the stations of profile 20, i.e., about 3,000 feet. To minimize the number of reference characters on FIG. 1, only a few identifying characters have been utilized. Thus, for example, the first column A has thereon the row 9 identified. Thus, the first observing station for profile 20 is identified at the point A,9. Similarly, the station located at the center of the averaging areas may be identified as 1,9. Finally, it will be noticed that the illustrated part of the map terminates at approximately the row VV. If all of the rows of the columns were to be labeled, they would appear in the same way as the rows and columns have been identified on the averaging operators of FIG. 2 except that they would be extended to cover the gravity map of FIG. 1. Accordingly, for every profile corresponding with the horizontal line through the rows 1, 2, 3, etc., there may be provided a gravity profile corresponding with the one illustrated in FIG. 4. These gravity profiles in turn may be represented by amplitude signals on a magnetic tape or alternatively by amplitude signals on any reproducible medium as, for example, variable area film, and by stored values in a digital system. The manner in which a record may be developed on magnetic tape is well understood by those skilled in the art, an optical arrangement for this purpose having been described in the aforesaid Lawrence application.

Thus, referring to FIG. 5, it will be assumed that on a magnetic drum 30 there will have been recorded the gravity profiles beginning with the first profile taken along the first row 1 of FIG. 1. There will be a pickup head P₁ associated with this record. Similarly, there will be additional pickup heads associated with each of the additional profiles, the pickup heads P₈, P₉ and P₁₀ being shown for the profiles respectively above and below row 9 identified on FIG. 1. A motor 31 drives the drum 30 together with a tape drum 32 a third drum 33 as well as additional drums later to be described. These drums are preferably of like diameter and in each case the length of tape on the drum will be proportional to the distance on the map of FIG. 1 from initial boundary A to final boundary VV.

In order to develop each area averaging operator of FIG. 2 there will first be developed individual averages for each profile. The profiles will then be averaged together. Finally,

differences will be taken to provide the information for the new difference maps which can then be plotted on an area-averaged basis.

Assuming now that the motor 31 has been energized to initiate rotation of the drums 30, 32 and 33 at the beginning of the record, it will be observed that pickup head P_s will apply to an amplifier 34 signals representative of the gravity profile spaced just above the profile 20 on the map of FIG. 1. The output from the amplifier 34 is applied to an integrator 35 and, through a recording head 36, is recorded on the drum 32. This drum 32 has associated with it two pickup heads 37 and 38 spaced apart from a reference point 39 by distances equal to T corresponding with the separation distances between each of the stations illustrated in FIG. 1 and also in FIG. 2. The pickup head 37 has been indicated as being spaced from the reference point 39 by the value $+T$ while the pickup head 38 is spaced from the reference point by the amount $-T$, this being the correct notation with drum rotation as indicated by the arrow. The signal on drum 32 corresponding with $\int g(t)dt$ will be first applied to an amplifier 40 and thence through a resistor 41 to a summing amplifier 42. As the record arrives at the pickup head 38, signals representative of the gravity profile will be applied to an amplifier 43 and thence by way of resistor 44 to the amplifier 42. It will be noted that the polarity of the inputs to amplifier 42 are of opposite sign; that from the amplifier 40 being negative and that from amplifier 43 positive. The opposing polarities are readily obtained by reversing the connections to one amplifier relative to those to the other and as applied to the summing resistors 41 and 44. The signal applies by way of summing resistor 41 may be represented as $\int g(t+T)dt$ and the signal applied by way of summing resistor 44 may be represented as $\int g(t-T)dt$. Inasmuch as it is desired to generate an output signal which is independent of the length of the operator, the output signal from the amplifier 42 is divided by the length of the operator, in the present case, $2T$. Accordingly, the resistor 45 will have its tap or movable connection set at a value representative of $(1/2T)$. In this connection, the distance between the heads 37 and 38 corresponds with the value of $2T$. That distance will, of course, be proportional to twice the spacing of the observing stations appearing on the map on FIG. 1. The output of the amplifier 42 after the division just described is applied by way of a switch 47 to a recording head 48 associated with the drum 33. Thus, there will be recorded on drum 33 the profile detected by the pickup head P_s after averaging by the operator $2T$.

After the completion of the foregoing operations, the drum 30 will have been returned to its initial position. At this time, the switches 34a and 47, preferably ganged together, are moved to the next left-hand positions, i.e., to connect the pickup head P_s to the amplifier 34 and to connect the output from the dividing resistor 45 to the next recording head 49. The second operation will be identical to that just described and as the drum 30 completes another revolution the switches 34a and 47 will again be stepped to the left until there will have been scanned the multiplicity of profiles recorded on the drum 30 and the average values of each over the interval $2T$ recorded on the drum 33.

Assuming now that there have been recorded on the drum 33 the averaged profiles with the averaging operator $2T$, it will be understood at once that the pickup heads P_s' , P_s'' and P_{10}' can reproduce continuously the averaged profiles. If, now, these three averaged profiles are averaged together, then a consideration of area is introduced. More specifically, and referring to FIG. 2, there will have been recorded on the drum 33 the average values for a profile corresponding with the points H8, I8 and J8. Similarly, there will be corresponding averages for points on profiles 9 and 10 at H, I and J. If, now, these profiles be averaged together, there will be obtained the average area-gravity potential

$$\frac{2T}{g(x, y)}$$

across the map for the strip between H and J. The manner in which the average values as reproduced by pickup heads P_s' , P_s'' and P_{10}' are utilized to accomplish the foregoing results will now be described in connection with FIG. 6 where the drums 30 and 33 have again been illustrated but with drum 32 omitted. In this Figure as well as in the arrangement of FIG. 5, the pickup heads associated with drum 33 are located in the same relationship in the record as are the pickup heads associated with drum 30. The reason for this will soon be made apparent. The pickup heads P_s' , P_s'' and P_{10}' are connected by a gang switch 50 respectively to summing resistors 51, 52 and 53 of a summing amplifier 54. Inasmuch as average values are desired, the resistor 55 has its associated contact or tap set at a value to divide the output of the amplifier 54 by three. In some instances, it may be desirable to record the average values obtained in the manner just described and an output terminal 57 connected to output conductor 58 may be provided for connection to a recorder of a kind later to be described, or it may be a recorder of the continuous type as illustrated in FIG. 7 of said Lawrence application.

The average gravity values obtained at the output conductor 58 are applied by way of a summing resistor 59 to a summing amplifier 60. As indicated by the + and - signs, the polarities to this summing amplifier are reversed, the signal from summing resistor 59 being negative. The other input to summing amplifier 60 is obtained from pickup head P_s of drum 30. After amplification by amplifier 34 the signal is applied through the summing resistor to the amplifier 60. Thus, there has been illustrated the manner in which there is obtained the operation

$$g(x, y) - \frac{2T}{g(x, y)}$$

Inasmuch as there has already been described the manner in which the area averaging operator

$$\frac{2T}{g(x, y)}$$

moves across the traverse of the map in discrete steps, there will now be explained how the system of FIG. 6 achieves readout of the desired information.

The output of amplifier 60 is applied to the input of amplifier 61 forming a part of a self-balancing measuring system and including a motor 62 operable in one direction or another proportional to the magnitude or phase of the output from amplifier 60. Such an arrangement of amplifier and motor is well understood by those skilled in the art and has been discussed in U.S. Pat. No. 2,113,164 to Williams. The motor 62, through its shaft 62a, drives a plurality of print wheels 63 printing digits 0-9 and together forming a printer mechanism for applying to a chart 64 digits relative to the magnitude of the output of amplifier 60 and proportional to the quantity

$$g(x, y) - \frac{2T}{g(x, y)}$$

Counting mechanisms including print wheels are well known to those skilled in the art. The print wheels 63 are driven in succession one after the other by the shaft 62a and are suspended on a carriage 65 positioned along the chart by means of a violin string 66 suspended on pulleys, one of which is driven by a driving pulley 66a. The drive for pulley 66a comprises a pawl 67a and a ratchet wheel 67b. The pawl pivoted about the support 67c is operated by cam 67d driven through mechanical connection 67e and by motor 31. The cam 67d rotates the ratchet wheel 67b one notch for each revolution of the drums 30 and 33. Thus, the ratchet wheel 67b moves the stepping switch 50 to the left through one position and at the same time moves the carriage 65 along the chart 64 by a distance proportional to the distance T .

It is to be observed that the print wheels 63 are illustrated in spaced relation with the chart 64. The chart 64 is held in this spaced relation by a mechanical linkage including the arm 68

which is pivoted at 68a. Arm 68 moves the chart into and out of engagement with the print wheels 63 in response to movement of arm 68b which is biased outwardly by spring 68c. Arm 68b is pivoted hitting arm 68d which carried a cam follower 68e. The printing operation is directly controlled by a notched wheel 69 carrying a plurality of succeeding teeth and troughs, the tooth 69a and the trough 69b pulled as the motor 31 rotates drums 30 and 33 through a distance corresponding with the distance T, the wheel 69 is moved to bring the tooth 69a beneath the cam follower 68e. The mechanical linkages 68, 68b and 68d position the chart into engagement with the print wheels 63. When the wheel 69 rotates further so that the trough 69b is behind cam follower 68b, the chart is moved out of engagement with the print wheels. The chart 64 is likewise driven by way of the mechanical connection 67e. The chart 64 has been shown as endless and its length will be proportional, preferably equal, to the length of the gravity information stored on circumferential track of the drums 30 and 33.

For details of the print operating mechanism, only diagrammatically illustrated in FIG. 6, reference may be had to U.S. Pat. No. 2,080,065 to Ross et al. wherein instead of a print wheel, the carriage support and operating mechanism therefore have been illustrated as applied to a chart marker in the form of a pen. With the above understanding of the areas of the readout mechanism, a brief resume of the operation may be helpful. With the gravity records on drums 30 and 33 in their initial or zero positions in respect to the pickup heads it will be remembered that the chart 64 will likewise be in its initial position and the carriage 65 in its left-hand position. Accordingly, the print wheels 63 will print in succession with spacings therebetween equal to T the gravity values as determined at the output of amplifier 60 and as referred to in FIG. 1 across the first and uppermost row. The operation, of course, is continuous until there will have been recorded gravity values which may be held positive or negative as shown in FIG. 3 and of the same or differing magnitude. After a single revolution of drums 30 and 33 and of chart 64, the gang switch 50 is operated and the carriage 65 is stepped to row 02 of FIG. 1 and the operations are repeated, and it is in this manner that there is produced on the chart 64 the gravity values for each station. By merely interconnecting points of equal value the equal gravity lines may be drawn to delineate the gravity patterns as illustrated in FIG. 3.

It will now be seen that there has been provided an arrangement in which the operator

$$\frac{2T}{g(x,y)}$$

has been moved from the left-hand side of the map, FIG. 1, to the right-hand side thereof and the manner in which the average values of gravity taken over the area represented by that operator have been read out and recorded as discrete values of gravity potential.

It will be understood that the foregoing operations are again carried out with a change in position of the operator by one unit T as from A,9 to A,10 on the map of FIG. 1. This is done by shifting the gang switch 50 one space to the left. By successive cycles of operation, corresponding with the multiplicity of traverses across the map, there will be generated a new set of gravity values by means of which there may be plotted a map corresponding to the foregoing function

$$g(x,y) - \frac{2T}{g(x,y)}$$

If gravity anomalies appear on the map, for example, the kind already described in connection with FIG. 3, it will be known that the masses giving rise to them will be at relatively shallow depth as, for example, from 0 to 3,000 feet. It will be understood, of course, that this range of depth and those earlier discussed are applicable to the examples utilized for explaining the invention. Different ranges will be associated with different intervals of T.

What has been described thus far has been the steps involved in generating the function

$$g(x,y) - \frac{2T}{g(x,y)}$$

As already stated, a map of this function provides useful information regarding anomalies falling in the depth range of 0 to 3,000 feet.

There will now be described the manner in which the function

$$\frac{2T}{g(x,y)} - \frac{4T}{g(x,y)}$$

is generated. By plotting values of this function on a map, useful information regarding anomalies falling in the depth range of 3,000 to 6,000 feet may be obtained. Referring to FIG. 7, the drums 30, 32 and 33 are again shown. It will be remembered that drum 33 has recorded thereon, in successive tracks, the gravity profiles along the rows 1—17, FIG. 1, averaged over the interval 2T. More particularly, the drum 33 has recorded on the track under the pickup head P₈' the gravity profile along the row 8, FIG. 1, averaged over the interval 2T; under the pickup head P₉' the gravity profile along the row 9 averaged over the interval 2T; and under the pickup head P₁₀' the gravity profile along the row 10 averaged over the interval 2T.

Also shown in FIG. 7 is the drum 70 which has recorded thereon, on successive tracks, gravity profiles recorded along the rows 1—17, FIG. 1, and averaged over the interval 4T. The manner in which the gravity profiles have been averaged over 4T is as follows.

The gravity profile along the row 8 has been recorded on drum 30 under the pickup head P₈. This gravity profile signal is sensed by pickup head P₈, amplified at 34, integrated at 35 and recorded on drum 32. This integrated gravity profile is picked up on drum 32 at the pickup head 71. The signal from pickup head 71 is amplified by amplifier 72 and connected through summing resistor 73 to an amplifier 74. The profile recorded on the drum 32 is also picked up by a pickup head 75 spaced by an interval 2T on the other side of the reference mark 39. It will be noted that the pickup heads 71 and 75 are spaced from one another by an interval 4T. The profile from pickup head 75 is amplified by amplifier 76 and applied through summing resistor 77 to the amplifier 74. The signal from amplifier 76 is of opposite polarity to the signal from amplifier 72. As explained above, the output of amplifier 74 after division by four by the voltage divider 45 a will be proportional to the gravity profile along the row 8 averaged over the interval 4T. The output of amplifier 74 is connected through stepping switch 78 to the pickup head 79 which records the averaged gravity profile for the row 8, FIG. 1, on a track of the drum 70. The gravity profile along the row 9 is next averaged over the interval 4T and recorded on the drum 70 as shown, the stepping switch 34a having been moved to the left to pick up the signal from pickup head P₉. This signal is averaged over the interval 4T by means of the drum 32, summing amplifier 74 and voltage divider 45a, as described above. The stepping switch 78 is moved to the left one position so that the profile along the row 9 is recorded at the pickup head 80 on the drum 70. In a similar manner, the profile along the row 10 averaged over the interval 4T is recorded by the recording head 81; the gravity profile along row 6 averaged over the interval 4T is recorded by recording head 82 and the profile along the row 7 averaged over the interval 4T is recorded by recording head 83.

The five recorded tracks referred to above are picked up by the recording heads 84—88. The five picked-up signals are connected through the stepping switch 89 and the summing resistors 91—95 to the input to summing amplifier 96. The output of summing amplifier 96 is connected to the voltage divider 97 which divides the output of amplifier 96 by a factor of 5. The signals appearing at the tap 98 are equal to the averaged values of the five gravity profiles recorded on the drum 70. The signal appearing at the tap 98 is the function

9

$$\frac{4T}{g(x,y)}$$

This signal is applied through resistor 99 to one input of a summing amplifier 100. The signal proportional to

$$\frac{2T}{g(x,y)}$$

taken from amplifier 60 is applied with reverse polarity to the other input to amplifier 100. The output of amplifier 100 is proportional to

$$\frac{2T}{g(x,y)} - \frac{4T}{g(x,y)}$$

By moving stepping switches 34a, and 89 to successively different left-hand positions, the functions

$$\frac{2T}{g(x,y)} - \frac{4T}{g(x,y)}$$

will be generated in succession for each gravity profile. These functions can be plotted in a manner similar to that shown in FIG. 3 to produce a map which accentuates the anomalies falling in the depth range of 3,000 to 6,000 feet.

There has now been described in detail the manner in which the functions

$$g(x,y) - \frac{2T}{g(x,y)} \text{ and } \frac{2T}{g(x,y)} - \frac{4T}{g(x,y)}$$

are generated. There will now be described the manner in which the functions

$$\frac{4T}{g(x,y)} - \frac{8T}{g(x,y)} \text{ and } \frac{8T}{g(x,y)} - \frac{16T}{g(x,y)}$$

are generated. FIG. 8 shows a complete analog computing system of the type required to generate all of the desired functions. To simplify the description, FIG. 8 is somewhat diagrammatic in that many of the amplifiers, stepping switches and averaging voltage dividers have been omitted. However, the inclusion and connection of these circuit components can readily be ascertained by comparing FIG. 7, showing all of these circuit components in detail, with that portion of FIG. 8 which repeats the showing of drums 30, 32, 33 and 70 but omits the detailed circuit components.

Gravity profiles averaged over the interval 8T are produced at the output of summing amplifier 101 and recorded on drum 102. Nine of these profiles are averaged in amplifier 103, the output of which is proportional to the function

$$\frac{8T}{g(x,y)}$$

As before described, the function

$$\frac{8T}{g(x,y)}$$

can be generated for all gravity profiles on the map shown in FIG. 1. This value is subtracted from the function

$$\frac{4T}{g(x,y)}$$

in the amplifier 104 to produce the function

$$\frac{4T}{g(x,y)} - \frac{8T}{g(x,y)}$$

This function can be plotted to form a map which accentuates anomalies falling in the depth range of 6,000 to 12,000 feet.

In order to generate the function

$$\frac{8T}{g(x,y)} - \frac{16T}{g(x,y)}$$

the drum 105 is provided. The signals proportional to gravity profiles averaged over the interval 16T are obtained from summing amplifier 106. These gravity profiles are recorded on the drum 105. Seventeen of the profiles recorded on drum 105

10

are picked up simultaneously and averaged in the amplifier 107. The output of this amplifier, proportional to

$$\frac{16T}{g(x,y)}$$

is applied to amplifier 108. The function

$$\frac{16T}{g(x,y)}$$

is subtracted from the function

$$\frac{8T}{g(x,y)}$$

by the amplifier 108. The function

$$\frac{8T}{g(x,y)} - \frac{16T}{g(x,y)}$$

can be obtained for all of the gravity profiles on the map shown in FIG. 1. The functions

$$\frac{8T}{g(x,y)} - \frac{16T}{g(x,y)}$$

for the map of FIG. 1 are plotted in FIG. 3. The map of FIG. 3 accentuates the anomalies falling in the depth range of 12,000 to 24,000 feet.

There has been described the manner in which a gravity map of the type shown in FIG. 1 has been transformed to a map of the type shown in FIG. 3 by analog techniques.

There will now be described the manner in which the gravitational data is treated digitally on an area basis to produce a map such as shown in FIG. 3. In FIG. 9 there is shown a diagrammatic representation of a data processing system. This is a representation of most commonly available digital data processing systems which include an input-output units 120 for accepting input data 121 and for producing as an output reports indicated at 122. The digital data processing system operates under control of instructions 123 which are fed into the computer through input-output units 120. External data 121 and instructions 123 are stored in the computer internal storage unit 124. These data and instructions are processed by arithmetic unit 125 under control of the control unit 126 which operates in accordance with instructions 123.

There will now be described a particular digital computer which can be used in digitally processing the gravitational data. However, it will be understood that the input-output units 120, internal storage unit 124, arithmetic unit 125 and control unit 126 can take many forms apart from those to be subsequently described.

In the computing system to be presently described, data 121 and instructions 123 are punched onto cards such as those shown in FIG. 10. These cards are prepared by an operator at a card punch. The operator prepares a card similar to the ones shown in FIG. 10 for each of the gravitational profiles on the map of FIG. 1. As an example, the card 127 will be punched to represent the gravitational values along row 9 of FIG. 1. Each of the vertical columns on the card is a digital code representing the gravitational potential at a particular station along row 9. For example, the vertical column 128 contains a punched digital code representing the observed gravity at the station A, 9, FIG. 1. Vertical column 129 contains a punched digital code representing the observed gravity at the station B, 9 and so on. The observed gravity values for each of the rows 1—17 are punched onto cards similar to those shown in FIG. 10. Cards containing the gravitational information are stacked in the card reader 130, FIG. 11. Any commercial available card readers may be used for this purpose, the card reader commercially available as IBM Model No. 522 is one of many suitable for this purpose. As the cards are read, the codes are translated in the translator 131 to a code which is usable by the computer. Translator 131 converts each card code to a code which is usable in the magnetic drum computing system shown in FIG. 11. The commercially available IBM 650 Magnetic Drum Computer is suitable for use as the computer illustrated in FIG. 11.

Before describing the manner in which the computing system shown in FIG. 11 operates on the gravitational data to produce a map such as shown in FIG. 3, there will be described several operational features of the computing system. An understanding of the operation of the computer in executing the following stored instructions is necessary to understand the techniques used to process the gravitational data:

1. The instruction RC1 000 used to transfer data from the card reader to the storage locations, or addresses in internal storage of the computer;
2. The instruction ADD 000 and similar instructions used to perform arithmetical operations on data stored in internal storage;
3. The instructions SIS 000, CIS 008, JMP 061 and other instructions used in performing an indexing cycle;
4. The instructions PNI 000 and CSP 001 used in printing out the computed gravitational values.

The performance of the foregoing instructions is described in conjunction with the following short description of the data processing system shown in FIG. 11.

The codes from translator 131 are stored in one of the storage locations on magnetic drum 132 in response to, for example, the instruction RC1 001. This instruction has an operation code portion (Op. Code) RC1 specifying that the next card in card reader 130 is to be read, and an address portion, 001, specifying that codes from the card are to be stored in consecutive storage locations on magnetic drum 132 beginning at storage location 001.

Magnetic drum 132 includes a plurality of quick access bands, the quick access bands 1, 2 ... 10 being shown and a plurality of main storage bands, the main storage bands 1, 2, 3 ... 20 being shown. The input codes are stored in particular storage locations on the magnetic drum 132 under control of the head switching control circuit 133. Head switching circuit 133 is, in turn, responsive to the address portion of the instruction stored in address register 134a.

Each band on magnetic drum 132 is divided into many unit areas per inch, each of which stores a bit. A magnetized area represents a 1; an unmagnetized area represents a 0. Each code from translator 131 can be put into one bit position on a band. We will assume that all of the codes on a card can be recorded on one band. Each band on magnetic drum 132 will be assumed to contain 80 storage locations. Therefore, main storage band 1 contains the storage locations 1—80, main storage band 2 contains the storage locations 81—160, main storage band 3 contains the storage locations 161—240, and so on.

The codes are transferred to and from storage locations on magnetic drum 132 under control of the control unit 134. The control unit 134 includes an instruction register 135 which stores an instruction to be executed. Each instruction to be executed includes an address portion and an operation portion. The address portion of the instruction is set into the address register 134a as previously mentioned. This address register 134a controls the storage location on magnetic drum 132 from which the code to be operated on is transferred.

The operation portion of the instruction register 135 is decoded by decoder 136 which controls many functions including the operation to be performed by arithmetic unit 137. When the operation has been performed by arithmetic unit 137, the arithmetic unit 137 advances the instruction counter 138 by one count to indicate the present instruction has been performed and that the next instruction can be called up from memory to be performed.

The operation of the control unit 134 and the arithmetic unit 137 is best illustrated by describing the operation in conjunction with the performance of a simple instruction. As an example, the instruction ADD 268 that is stored in storage location 062 will be performed. This instruction means that the contents of storage location 268 are to be added to the contents of the accumulator 139 in the arithmetic unit. The operating cycle can best be described as consisting of seven steps. The seven steps are listed below and the associated numbers are indicated on the drawing as circled numbers on

the data flow and control lines which perform the step. The steps in the performance of the instruction ADD 268 are as follows:

1. Transfer the operation part of the instruction, ADD, from the instruction register 135 to the decoder 136.
2. Transfer the address part of the instruction, 268, from the instruction register 135 to the address register 134a.
3. Copy into the arithmetic unit 137 the operand (which may be either data or an instruction) located at address 268.
4. Execute the required operation, ADD, in the arithmetic unit. Notify the control unit when the operation is executed.
5. Increase the number 062 in the instruction counter 138 by 1, to 063, to indicate the address of the next instruction.
6. Transfer the number 063 from the instruction counter 138 to the address register 134a.
7. Get the instruction, "SUB 495," located at address 063 and put it into the instruction register.

In order to make the most efficient use of programming time and the use of storage for instructions, and indexing cycle is provided for in the digital computing system. An index register 140 together with comparator 141 are used to change a single instruction so that it can be used over and over again to carry out a program of instructions. The operation of the index register 140 and comparator 141 in performing an indexing cycle is best illustrated by the following example. Assume that it is desired to add together the contents of three storage locations 068, 069 and 070 and to store the result in storage location 071. The easy way to perform this operation would be to insert the following instructions in sequence in the program assuming that the program is starting with the instruction stored in location 0.60:

Instructions		
Address	Op. Code	Address
060	ADD	068
061	ADD	069
062	ADD	070
063	STA	071

In carrying out this simple program, the computer would remove the instruction ADD 068 from storage location 060 and insert it in instruction register 135. The instruction would be performed by adding the contents of storage location 068 to the accumulator 139. After performance of this instruction the instruction stored in storage location 061 would be put into instruction register 135 and this instruction would be performed by adding the contents of 069 to accumulator 139. After performance of this instruction, the instruction stored in location 062 would be transferred to instruction register 135 and this instruction executed by adding the contents of storage location 070 to the accumulator 139. Next, the instruction stored in storage location 063 is transferred to instruction register 135 and this instruction is performed by transferring the contents of the accumulator to the storage location 071.

While the above routine is quite straightforward when only the contents of three storage locations are to be added together, this approach becomes quite cumbersome when a great number of storage locations are to be added together. In order to perform this operation more simply an indexing cycle is programmed. The above problem would be programmed with an indexing cycle as follows:

Storage Location

Assuming that we begin the program with the instruction stored at storage location 060, the instruction SIS 000 is performed by the decoder 136 acting over control line 142 to set the index register 140 to zero. The next instruction, ADD 068 is performed by address register 134a acting over the control line 143 to gate the contents of storage location 068 over the data flow line 144 to the arithmetic unit. The decoder 136 acts through control line 145 to cause the number in storage location 068 to be added to the contents of accumulator 139.

Storage location	Instructions	
	Op. code	Address
008...	000	003
060...	SIS	000
061	ADD	008
062	INC	001
063...	CIS	006
064	JMP	061
065	STA	071

Set index register to 0.
Add to accumulator the number stored at the address 068 plus contents of the index register.
Increment index register by 1.
Compare contents of index register with the contents of storage location 008 which contains the number 3. If contents are unequal, take the next instruction in sequence 064; if equal, skip one instruction to the storage location 065.
Jump to the instruction at storage location 061.
Store contents of accumulator in storage location 071.

The next instruction INC 001 is performed by the decoder 136 acting over control line 142 to increment index register 140 by 1.

The next instruction CIS 008 is performed by the comparator 141 which compares the contents of index register 140, the contents now being 001, with the contents of storage location 008. The storage location 008 contains the number 3. Since the comparator 141 indicates that the two numbers are unequal, it acts over control line 146 to gate the next instruction stored in storage location 064 to the instruction register.

The instruction stored in storage location 064 is a jump instruction JMP 061. The instruction JMP 061 acts through control line 143 to cause the head-switching control circuitry 133 to transfer the instruction stored at storage location 061 to the instruction register. This differs from the normal sequence of operation in which the instruction at address 065 would next be transferred to instruction register 135.

The instruction stored at storage locations 061 is ADD 068. The contents of the index register 140 are added to the address portion 068. The index register 140 now contains a 1 and when this is added to the address 068, the address is modified to 069. The contents of storage location 069 are added to the contents of accumulator 139 to complete this instruction.

The instructions INC 001 and CIS 008 are performed as before. Since the contents of index register 140 is incremented to 2 and since this still produces no comparison with the contents of storage location 008, a 3, the next instruction JMP 061 is performed. This causes a jump back into the instruction stored at address 061 and another cycle is performed. In this cycle the contents of storage location 070 are added to the accumulator. In this cycle, when the instruction CIS 008 is performed, the comparator 141 indicates a comparison. The comparator 141 then acts over control line 146 to skip an instruction and to gate the instruction stored at storage location 065 to the instruction register 135. The instruction stored at address 065 is STA 071. This instruction is performed by storing the contents of the accumulator in storage location 071.

In this manner, the contents of storage locations 068, 069 and 070 have been added together and the results stored at location 071. This sequence has been performed by using indexing cycles.

The remaining component in the digital computer of FIG. 11 to be described is the output printer indicated generally at 160. Digital codes from storage are connected through head switching control 133 over the data line 161 to the amplifier 161a. The digital codes are decoded by positioning mechanism 162 which rotates the shaft 162a to set the print wheels 163 to the proper position corresponding with the digital code to be printed. The manner in which digital codes are translated to rotational movement to position printing wheels is well known to those skilled in the art.

The print wheels 163 are positioned to be brought into engagement with the moving chart 164. The moving chart 164 is brought into engagement with the print wheels 163 by means of the print control motor 170. In response to an instruction PN1 which is decoded in decoder 136, the print control motor 170 will be energized and will rotate an incremental amount. The print control motor 170 rotates the notched wheel 171 to cause the tooth 172 to engage cam follower 173 on mechanical linkage 174. When a tooth of notched wheel 171 engages the cam follower 173, the mechanical linkage is rocked forward causing the arm 175 to push the moving record 164 into engagement with the print wheels 163. Further rotation of the wheel 171 causes cam follower 173 to fall into a trough in the

wheel thereby disengaging the chart 164 from print wheels 163.

Actuation of print motor 170 also rotates the moving chart 164 by means of the mechanical connection at 176. After the printing of the digit has been completed, the chart 164 is incremented to the next position at which the printing is to occur. The operation of the printer is best described in conjunction with the performance of an instruction. Assume the instruction PN1 068 is in the instruction register 135. The address portion, 068, is transferred to address register 134a. Address register 134a acts over control line 143 to set the head switching control 133 so that the contents of storage location 068 are transferred over line 161, through amplifier 161a to the decoder 162. The decoder 162 sets the print wheels 163 to the number specified by the contents of storage location 068. The Op. Code portion PN1 of the instruction is decoded in decoder 136. In response to the instruction PN1 the decoder 136 acts over control line 170a to actuate print control motor 170. Print control motor 170 rotates the notched wheel 171 to cause the record 164 to be moved into engagement with print wheels 163 to print the number recorded in storage location 068. Further rotation of notched wheel 171 causes the record 164 to be moved out of engagement with the print wheels 163. Still further rotation of mechanical linkage 171a causes the moving record to be moved at 176 thereby incrementing the record to the next position which is to be printed. In making the gravitational computations involved in the present invention, the moving record will be incremented a distance corresponding to the distance T on the moving record.

The printer 160 also has provision to move the print wheels 163 to different columns on the moving chart. The print wheels are carried on a carriage 165 which is movable along the shaft 169 by means of the violin string 166 which is moved at one end by the pulley 166a. The pulley 166a is rotated by ratchet wheel 167b which is held in position by the associated pawl 167a. The ratchet wheel 167b is rotated in response to the column control motor 177. Column control motor 177 is actuated in response to an instruction CSP. The instruction CSP is decoded in decoder 136 which acts over control line 178 to actuate column control motor 177.

When a complete column including all of the values across a gravitational profile has been printed out, an instruction CSP will be programmed to increment the print head to the next column so that another gravitational profile can be printed on the moving record 164. In the computations involved in the present invention, the print wheel will be incremented by a columnar distance corresponding to the distance T.

There will now be described the manner in which the digital computing system shown in FIG. 11 operates on the gravitational data in accordance with this invention. There will be described the manner in which the gravitational data along the profiles 8, 9 and 10, FIG. 1, are combined on an area basis to form the function

$$g(x, y) - \frac{2T}{g(x, y)}$$

This expression will be computed for the profile along the row 9, FIG. 1.

As previously mentioned, the gravitational data along rows 8, 9 and 10, FIG. 1, are punched into three cards. It will be assumed that the card containing the gravitational data along the row 8 is the next card in the card reader 130, FIG. 11. It will also be assumed that the printer wheels 163 are now positioned over a column on record 164 which will correspond with row 9 on the final record. The computer will then proceed with the following program beginning with the in-

struction stored in storage location 010. The computer will proceed with the instructions stored in successive storage locations 011, 012 and so on. It should be pointed out that the storage locations 001, 002 and 003 contain parameters which are to be used in the computation and do not contain instructions. The program is as follows:

Instruction			
Storage location	Op. code	Address	
001	000	008	Constant used in computation.
002	000	048	Do.
003			
004			
005			
006			
007			
008			
009			
010	RCI	100	Read the next card in Card Reader #1 and store in 100 consecutive locations beginning at address 100.
011	RCI	200	Read the next card in Card Reader #1 and store in 100 consecutive locations beginning at address 200.
012	RCI	300	Read the next card in Card Reader #1 and store in 100 consecutive locations beginning at address 300.
013	SIS	000	Set Index Register to 0.
014	CAA	100	Clear the accumulator and add to the accumulator the number stored at the address 100 plus the contents of the Index Register.
015	ADD	101	Add to the accumulator the number stored at the address 101 plus the contents of the Index Register.
016	ADD	102	Add to the accumulator the number stored at the address 102 plus the contents of the Index Register.
017	DIA	001	Divide the contents of the accumulator by the number stored at address 001.
018	STA	400	Store the contents of the accumulator at the address 400 plus the contents of the Index Register.
019	INC	001	Increment the Index Register by 1.
020	CIS	002	Compare the contents of the Index Register with the number stored in location 002 which contains the number 48. If the contents are unequal, take the next instruction; if equal, skip 1 instruction.
021	JMP	014	Arrival at this point from the preceding comparison means that the cycle count is not yet complete; therefore, jump to storage location 014 to begin another cycle.
022	SIS	000	Set Index Register to 0.
023	CAA	200	Clear the accumulator and add to the accumulator the number stored at the address 200 plus the contents of the Index Register.
024	ADD	201	Add to the accumulator the number stored at the address 201 plus the contents of the Index Register.
025	ADD	202	Add to the accumulator the number stored at the address 202 plus the contents of the Index Register.
026	DIA	001	Divide the contents of the accumulator by the number stored at address 001.
027	STA	500	Store the contents of the accumulator at the address 500 plus the contents of the Index Register.
028	INC	001	Increment the Index Register by 1.
029	CIS	002	Compare the contents of the Index Register with the number stored in location 002 which contains the number 48. If the contents are unequal, take the next instruction; if equal, skip 1 instruction.
030	JMP	023	Arrival at this point from the preceding comparison means that the cycle count is not yet complete; therefore, jump to storage location 023 to begin another cycle.
031	SIS	000	Set Index Register to 0.
032	CAA	300	Clear the accumulator and add to the accumulator the number stored at the address 300 plus the contents of the Index Register.
033	ADD	301	Add to the accumulator the number stored at the address 301 plus the contents of the Index Register.
034	ADD	302	Add to the accumulator the number stored at the address 302 plus the contents of the Index Register.
035	DIA	001	Divide the contents of the accumulator by the number stored at address 001.
036	STA	600	Store the contents of the accumulator at the address 600 plus the contents of the Index Register.
037	INC	001	Increment the Index Register by 1.
038	CIS	002	Compare the contents of the Index Register with the number stored in location 002 which contains the number 48. If the contents are unequal, take the next instruction; if equal, skip 1 instruction.
039	JMP	032	Arrival at this point from the preceding comparison means that the cycle count is not yet complete; therefore, jump to storage location 032 to begin another cycle.
040	SIS	000	Set Index Register to 0.
041	CAA	400	Clear the accumulator and add to the accumulator the number stored at the address 400 plus the contents of the Index Register.
042	ADD	500	Add to the accumulator the number stored at the address 500 plus the contents of the Index Register.
043	ADD	600	Add to the accumulator the number stored at the address 600 plus the contents of the Index Register.
044	DIA	001	Divide the contents of the accumulator by the number stored at address 001.
045	STA	700	Store the contents of the accumulator at the address 700 plus the contents of the Index Register.
046	INC	001	Increment the Index Register by 1.
047	CIS	002	Compare the contents of the Index Register with the number stored in location 002 which contains the number 48. If the contents are unequal, take the next instruction; if equal, skip 1 instruction.
048	JMP	041	Arrival at this point from the preceding comparison means that the cycle count is not yet complete; therefore, jump to storage location 041 to begin another cycle.
049	SIS	000	Set Index Register to 0.
050	CAA	201	Clear the accumulator and add to the accumulator the number stored at the address 201 plus the contents of the Index Register.
051	SUA	700	Subtract from the accumulator the number stored at the address 700 plus the contents of the Index Register.
052	STA	800	Store the contents of the accumulator at the address 800 plus the contents of the Index Register.
053	INC	001	Increment the Index Register by 1.
054	CIS	002	Compare the contents of the Index Register with the number stored in location 002 which contains the number 48. If the contents are unequal, take the next instruction; if equal, skip 1 instruction.
055	JMP	050	Arrival at this point from the preceding comparison means that the cycle count is not yet complete; therefore, jump to storage location 050 to begin another cycle.
056	SIS	000	Set Index Register to 0.
057	PN1	800	Print on the Printer #1 the number stored at the address 800 plus the contents of the Index Register.
058	INC	001	Increment the Index Register by 1.
059	CIS	002	Compare the contents of the Index Register with the number stored in location 002 which contains the number 48. If the contents are unequal, take the next instruction; if equal, skip 1 instruction.
060	JMP	057	Arrival at this point from the preceding comparison means that the cycle count is not yet complete; therefore, jump to storage location 057 to begin another cycle.
061	CSP	001	Increment the printing head by 1 column.

The operation of the digital computer in performing the above program is as follows. The instruction RCI 100 is decoded in decoder 136 which acts over control line 179 to cause card reader 130 to read out the digital codes representing the gravity values along the profile of row 8, FIG. 1. The address portion of this instruction, decoded in address register 134a, acts over control line 143 to gate the digital codes to consecutive storage locations on magnetic drum 132. The codes will be stored in locations 100 to 149 since there are 49 codes representing the gravitational values at each of the stations A, 8 to VV, 8 on FIG. 1. Similarly, the next two instructions RCI 200 and RCI 300 will cause the digital codes representing gravitational values along the rows 9 and 10, FIG. 1, to be stored in consecutive storage locations beginning at address 200 and address 300 respectively. In order to generate an averaged gravity profile over the smoothing interval $2T$, the instructions at addresses 013 through 021 are executed.

The instruction SIS 000 sets the index register to 0. The instruction CAA 100 clears accumulator 139 and adds to the accumulator the number stored at the address 100 which is the gravitational value at the first station along the row 8. The instructions ADD 101 and ADD 102 completes the sum of all gravitational values in the interval $2T$, i.e., $\int g(t+T)dt - \int g(t-T)$

60 *dt*. The instruction DIA 001 causes the sum stored in the accumulator 139 to be divided by 3 which is the contents of storage location 001. By dividing the contents of the accumulator by 3, the gravitational value averaged over an interval $2T$ is obtained.

65 The instruction STA 400 stores the contents of the accumulator at the address 400.

The index register is incremented by the instruction INC 001; and a comparison is made which indicates the indexing cycle is not complete. Therefore, the cycle is started over beginning at the instruction CAA 100 beginning at address 014. However, during this cycle each of the addresses will be incremented by the contents of the index register which is 1. Therefore, the gravitational values stored at storage locations 101, 102 and 103 will be added and divided by 3 and these will be stored in storage location 401. In the next indexing cycle the contents of storage locations 102, 103 and 104 will be

17

added, divided by 3 and stored in storage locations 402. The indexing cycles will continue until all 49 of the gravitational values along the row 8 of FIG. 1 have been averaged over the interval $2T$. At this time the index register will contain a 49 and an equal comparison will cause the computer to skip to the instruction at address 022 which is SIS 000.

The same cycles described above will be repeated for the gravitational values on the rows 9 and 10. These gravitational values will be averaged over the interval $2T$ as described above. In order to generate area-gravity profiles by combining a plurality of the profiles averaged by the same smoothing interval, the instructions at addresses 040 through 048 are executed.

The block of instructions stored at addresses 040 through 048 causes the three gravity profiles from the rows 8, 9 and 10, which have been averaged over the interval $2T$, to be added together and divided by 3 to produce the average area profile represented as

$$\frac{\frac{2T}{g(x,y)}}{\frac{2T}{g(x,y)}}$$

is stored in consecutive storage locations starting with the address 700.

In order to subtract an area-gravity profile resulting from one smoothing interval from an area-gravity profile resulting from a different interval, the instructions at addresses 049 through 055 are executed. These values of

$$\frac{2T}{g(x,y)}$$

are called up from storage and subtracted from the values $g(x,y)$ which have previously been stored in consecutive storage locations starting at address 200. This subtraction is performed by the instructions at the addresses 049 through 055.

The results of this subtraction, representing the expression

$$g(x,y) - \frac{2T}{g(x,y)}$$

are stored in consecutive storage locations starting at address 800.

The values of

$$g(x,y) - \frac{2T}{g(x,y)}$$

are printed out on a column of the moving chart by the instructions at the addresses 056—060.

Finally, the instruction CSP 001 increments the printing head to the right by 1 column so that during the next cycle of operation the values

$$g(x,y) - \frac{2T}{g(x,y)}$$

will be printed in an adjacent column. When the gravitational data from all of the stations on the map of FIG. 1 have been averaged on an area basis and printed on the record 164, equal values on the chart can be interconnected to form an equigravity map such as that shown in FIG. 3.

Referring now to the flow sheet shown in FIG. 1a the gravity profile $g(y_1)$ which may be, for example, the gravity values along the line 20 in FIG. 1, is averaged over the smoothing interval $2T$ as indicated at 201. Similarly, the gravity profiles $g(y_2)$ and $g(y_3)$, which may be a series of gravity values along lines parallel to and below the line 20 in FIG. 1, are averaged over the same smoothing interval $2T$ as indicated at 202 and 203. The smoothed gravity profiles $g(x,y)_1$, $g(x,y)_2$, and $g(x,y)_3$ are averaged as indicated at 204 to generate the average area value

$$\frac{2T}{g(x,y)}$$

In order to accentuate the appearance of anomalies at a particular depth, the area gravity value

18

$$\frac{2T}{g(x,y)}$$

is subtracted from the value $g(x,y)_2$ as indicated at 205.

To accentuate anomalies at a different depth, the area gravity value

$$\frac{4T}{g(x,y)}$$

is subtracted from the area gravity value

$$\frac{2T}{g(x,y)}$$

as indicated at 206. The area gravity value

$$\frac{4T}{g(x,y)}$$

is generated by averaging gravity profiles over the interval $4T$ as indicated at 207—209 and then averaging the smoothed profiles on an area basis as indicated at 210.

The foregoing demonstrates the principles of the digital computer routine which may be extended to include generating values which accentuate anomalies at differing depths as previously discussed.

Of course, it will be understood that various modifications may be made without departing from the principles of the invention. The appended claims are, therefore, intended to cover any such modifications within the true spirit and scope of the invention.

We claim:

1. The method for processing data representing physical properties of the earth including anomalies in a particular area comprising the following sequential steps executed by an automatic computing apparatus:

generating signals representing smoothing data profiles across lines of said particular area, said smoothed profiles being smoothed by differing smoothing intervals extending along said data profiles,

generating signals representing area-data values comprising the combination of a plurality of the profiles smoothed by the same smoothing intervals, and

generating signals representing subtracting an area-data value formed by combined profiles smoothed by one smoothing interval from an area-data value formed by combined profiles smoothed by a different smoothing interval to enhance the appearance of the anomalies on an area basis.

2. The method of claim 1 in which the step of generating signals representing said smoothed profiles comprises integrating with respect to distance along said data profiles, and

algebraically adding together values from said integrated profile corresponding with $\int g_x(t+nT)dt - \int g_x(t-nT)dt$ where $g_x(t)$ represents data values along the x data profile where

nT represents one-half the smoothing interval, and

t represents distance along said data profile to provide a resultant sum.

3. The method of operating a computing apparatus to treat gravity profiles representing gravitational anomalies comprising the following sequential steps executed by an automatic computing apparatus:

generating a plurality of transducible digital codes representing smoothing gravity profiles $g(x,y)$ over differing smoothing intervals extending along each gravity profile,

generating transducible digital codes representing gravity profiles smoothed by the same smoothing interval and representing a plurality of averaged area-gravity values, and

generating transducible digital codes representing subtracting averaged area values one from the other to generate difference area-gravity values thereby to enhance the appearance of anomalies on the separate several difference area-gravity values.

4. The method of operating a computing apparatus recited in claim 3 in which said step of generating transducible digital codes representing averaged area-gravity values comprises averaging a group of gravity profiles each of which is smoothed by the interval $2T$, averaging a group of profiles each of which is smoothed by the interval $4T$ and by further averaging other groups of smoothed gravity profiles, the profiles in each group each being smoothed by smoothing intervals represented by $2^n T$ where n is an integer and T is one-half the length of the smallest smoothing interval.

5. The method of operating a computing apparatus recited in claim 4 wherein said step of generating transducible digital codes representing averaged area-gravity values comprises averaging 2^{n+1} of said profiles smoothed over the smoothing interval $2^n T$ to form the averaged area-gravity value

$$\frac{2^n T}{g(x, y)}$$

[wherein] and averaging 2^{n+1} of said profiles smoothed over the interval $2^{n+1} T$ to form the averaged area-gravity value

$$\frac{2^{n+1} T}{g(x, y)}$$

and said step of generating transducible digital codes representing subtracting averaged area values comprises subtracting [wherein] the averaged area-gravity value

$$\frac{2^n T}{g(x, y)}$$

[is subtracted] from the averaged area-gravity value

$$\frac{2^{n+1} T}{g(w, y)}$$

to generate a plurality of difference values which enhance the appearance of the anomalies in a given depth range.

6. The method of operating a computing apparatus recited in claim 4 wherein said step of generating transducible digital codes representing area-gravity values comprises averaging three of said profiles smoothed over the smoothing interval $2T$ to form the averaged area value

$$\frac{2T}{g(x, y)}$$

and wherein said step of generating transducible digital codes representing subtracting averaged area values comprises subtracting the averaged area-gravity value

$$\frac{2T}{g(x, y)}$$

from the gravity profile $g(x, y)$ to compute a difference value on an area basis which enhances the appearance of anomalies in one given depth range,

wherein said step of generating transducible digital codes representing averaged area-gravity values comprises averaging five of said profiles smoothed over the smoothing interval $4T$ [are] averaged to form the averaged area-gravity value

$$\frac{4T}{g(x, y)}$$

and wherein said step of generating transducible digital codes representing subtracting averaged area values comprises subtracting the averaged area-gravity value

$$\frac{4T}{g(x, y)}$$

[is subtracted] from the averaged area-gravity value

$$\frac{2T}{g(x, y)}$$

to obtain a difference value on an area basis which enhances the appearance of anomalies in a second given depth range, and

wherein further difference values are obtained to enhance anomalies appearing in other depth ranges by repeating said step of generating transducible digital codes representing averaged area-gravity values combining $2^n + 1$ of said profiles smoothed over the smoothing interval $2^n T$ to form the averaged area-gravity value

$$\frac{2^n T}{g(x, y)}$$

[, by] and combining $2^{n+1} + 1$ of said profiles smoothed over the interval $2^{n+1} T$ to form the averaged area-gravity value

$$\frac{2^{n+1} T}{g(x, y)}$$

and by repeating said step of generating transducible digital codes representing subtracting the averaged area-gravity value

$$\frac{2^n T}{g(x, y)}$$

from the averaged area-gravity value

$$\frac{2^{n+1} T}{g(x, y)}$$

to obtain said difference values which enhance the appearance of the anomalies in given ranges of depth.

7. The machine implemented method for automatically treating data representing a plurality of gravity profiles separated one from the other by a distance T and together coextensive with a mapped area which comprises

generating signals in said machine representing modified gravity profiles in response to signals in said machine representing gravity values from each profile separated by the distance T wherein the generating step includes generating signals representing algebraic addition together of said values in accordance with the expression

$$\int g_x(t+T)dt - \int g_x(t-T)dt$$

where $g_x(t)$ represents gravity values along the x gravity profile,

T represents one-half the distance of the smallest smoothing operator, and

t represents distance along said gravity profile to produce physical representations in said machine representing a resultant sum, modifying said sum by the factor $(1/2T)$ further modified by division by the number of profiles which have been added together,

generating signals in said machine representing subtracting said modified profiles averaged together with one smoothing interval from other modified gravity profiles including a different smoothing interval, and

generating signals in said machine representing said gravity values each separated from the other by the distance t for production of new gravity values in the same locations on the mapped area.

8. The method of operating a programmed computing apparatus to treat gravity information representing gravitational anomalies in a particular area which comprises

generating signals in said computing apparatus representing a plurality of gravity profiles derived from said gravity information each of which represents said gravity information across a different section of said area,

generating signals in said computing apparatus representing smoothing each of said gravity profiles by differing smoothing intervals extending along said gravity profiles,

generating signals in said computing apparatus representing averaging together groups of said smoothed gravity profiles, the gravity profiles in each group having been smoothed by the same smoothing interval, to obtain averaged area-gravity values, and

generating signals in said computing apparatus representing subtracting said averaged area values one from the other to generate difference area-gravity values thereby to enhance the appearance of anomalies on the separate several difference area-gravity values.

9. The method of automatically operating a computing ap-

paratus to treat gravity information to obtain an averaged area-gravity value relative to a particular location x, y so that gravitational anomalies represented by said information are enhanced comprising the steps of,

generating signals within said computing apparatus representing gravity profiles of said gravity information across a particular section, each of said gravity profiles representing gravity information along parallel lines spaced integral multiples of an interval distance T from the location x, y for which the averaged area-gravity value is to be obtained,

generating signals within said computing apparatus representing smoothing each of said gravity profiles to form a plurality of smoothed gravity profiles, smoothed by differing smoothing intervals extending along said profiles,

generating signals within said computing apparatus averaging together a group of smoothed gravity profiles each of which has been smoothed by a smoothing interval which is an even multiple of the distance T to represent a plurality of averaged area-gravity values, an equal number of profiles in each group being spaced on both sides of the location x, y by integral multiples of said distance T with the furthestmost spaced profile in each group being spaced a distance from said location x, y corresponding with one-half the smoothing interval used to smooth said profiles, and

generating signals within said computing apparatus representing subtracting said averaged area values one from the other to represent difference area-gravity values thereby to enhance the appearance of anomalies on the separate several difference area-gravity values.

10. The method recited in claim 9 wherein said step of generating signals within said computing apparatus representing smoothed gravity profiles comprises representing integrating said gravity profiles with respect to distance, and

algebraically obtaining the difference between an integrated gravity profile represented by $\int g_x(t+nT)dt$ and $\int g_x(t-nT)dt$ where $g_x(t)$ represents gravity values along the x gravity profile, t represents distance along said gravity profile and n is an integer.

11. The method recited in claim 9 wherein said step of generating signals within said computing apparatus representing said plurality of averaged gravity profiles comprises averaging together the smoothed gravity profile passing through the location x, y and an equal number of smoothed gravity profiles on both sides of location x, y the total number of smoothed gravity profiles which are averaged being specified by 2^n+1 , and

wherein each of the smoothed gravity profiles has been smoothed by an interval 2^nT where n is an integer.

12. The method recited in claim 11 wherein said step of generating signals within said computing apparatus represents subtracting said area-gravity values comprises subtracting an

area-gravity value formed by averaging gravity profiles smoothed by the integral 2^nT from an area-gravity value formed by averaging gravity profiles smoothed by the interval $2(n-1)T$ to form a difference area-gravity value which accentuates anomalies in a particular depth range.

13. The computer performed method of automatically and sequentially processing data representing physical properties of the earth including anomalies in a particular area which comprises

converting said data to first physical representations within said computer representing data profiles across lines of said area,

generating second physical representations within said computer from said first physical representation representing smoothing each of said profiles by differing smoothing intervals extending along said profiles,

generating third physical representations within said computer from said second physical representation representing adding a plurality of profiles smoothed by the same sampling interval to represent a first sum,

generating fourth physical representations within said computer from said first and second physical representations representing adding a plurality of profiles smoothed by a different smoothing interval to represent a second sum, and

generating fifth physical representations within said computer from said third and fourth physical representations representing subtracting said first sum from said second sum to enhance the appearance of an anomaly representing said physical properties of the earth.

14. Apparatus for processing gravity profile data representing gravitational anomalies of the earth in a particular area which have been converted to physical representations representing gravitational values including circuitry comprising

an averaging means for generating from said gravity profile data first signals representing gravity profiles smoothed by differing smoothing intervals extending along said profiles,

an adder means for generating second signals from said first signals representing adding together a plurality of said gravity profiles smoothed by a first smoothing interval to generate a first sum,

an adder means for generating third signals from said first signals representing adding together a plurality of said gravity profiles smoothed by a second smoothing interval, which is different from said first smoothing interval, to generate a second sum, and

a difference means for generating fourth signals from said second signals and said third signals representing subtracting said first sum from said second sum to enhance the appearance of anomalies in the resultant.

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,598,980

Dated August 10, 1971

Inventor(s) Philip L. Lawrence, Gilbert W. Ehlert,
John A. Lester, and Albert W. Musgrave

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 2, line 60, "transverse" should read --traverse--.
Column 9, lines 50-52, that portion of the function reading
"(x,y)g" should read -- g(x,y) --.
Column 12, line 32, "0.60" should read --060--.
Column 19, line 19, cancel "[wherein]";
same line, " $2^{n+1} + 1$ " should read -- $2^{n-1} + 1$ --;
line 20, " $2^{n+1}T$ " should read -- $2^{n-1}T$ --;
line 27, cancel "[wherein]";
line 31, cancel "[is subtracted]";
lines 33-35, that portion of the value reading
"g(w,y)" should read -- g(x,y) --;
line 59, cancel "[are]"; and
line 71, cancel "[is subtracted]".
Column 20, line 10, cancel "[, by]";
same line, " $2^{n+1} + 1$ " should read -- $2^{n-1} + 1$ --.

Signed and sealed this 25th day of January 1972.

(SEAL)

Attest:

EDWARD M. FLETCHER, JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents