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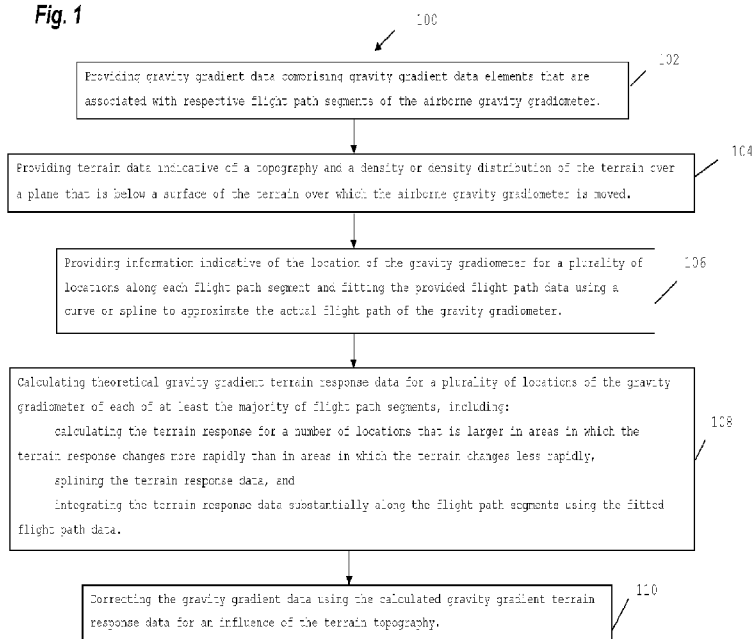
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(54) Title: A METHOD OF PROCESSING GRAVITY GRADIENT DATA

Fig. 1



(57) Abstract: The present disclosure provides a method of processing gravity gradient data indicative of an output generated by an airborne gravity gradiometer that is moving along a flight path over a terrain. The method comprises the step of providing the gravity gradient data. The gravity gradient data comprising gravity gradient data elements that are associated with respective flight path segments of the airborne gravity gradiometer. Further, the method comprises providing terrain data indicative of a topography and a density or a density distribution of the terrain above a datum that is below the surface of the terrain over which the airborne gravity gradiometer is moved. The method also comprises providing information concerning the flight path of the airborne gravity gradiometer in three dimensions. In addition, the method comprises calculating the gravity gradient response of the terrain using the provided terrain data and the provided information concerning the flight path. The gravity gradient terrain response data is calculated for a plurality of locations of the gravity gradiometer along at least some of the flight path segment. In addition, the method comprises correcting the gravity gradient data by forming a difference between the calculated gravity gradient terrain re-

sponse of the terrain topography and the gravity gradient data.

A METHOD OF PROCESSING GRAVITY GRADIENT DATA

Field of the Invention

The present invention relates to a method of processing gravity gradient data indicative of an output generated by an airborne gravity gradiometer that is moving along a flight path over a terrain and relates particularly, though not exclusively, to a method of processing gravity gradient data for locating valuable materials, such as an ore.

10 Background of the Invention

Valuable materials in the ground, such as ores or oil deposits, can be detected directly or indirectly using suitable airborne gravity gradiometers. Such valuable materials usually have a density other than that of surrounding materials, which results in a local variation or "anomaly" in gravity gradient that is detectable by the gravity gradiometer when the gravity gradiometer is flown over a terrain including the valuable material. The gravity gradient anomaly is usually extremely small and its detection requires high precision instrumentation.

20 The valuable material often is below the surface of the terrain and the gravity gradient anomaly is proportional to $1/r^3$ (r : distance from the centre of the valuable material to a detector of the gravity gradiometer).

Topographical changes of the surface of the terrain also cause variations in gravity gradient and these variations may be larger than the gravity gradient anomalies arising from the valuable material, as the surface of the terrain is closer to the airborne gravity gradiometer than the (usually deeper) targets. It is consequently desirable to correct gravity gradiometer measurements for these terrain effects in order to facilitate recognition of anomalies from deeper sources.

US patent application publication number US 2010/0094556
discloses a method of correcting gravity gradient data. The
measured gravity gradient data is integrated in the time domain
5 and then corrected for terrain effects. The present invention
used an alternative approach that provides further improvement.

Summary of the Invention

The present invention provides a method of processing gravity
10 gradient data indicative of an output generated by an airborne
gravity gradiometer that is moving along a flight path over a
terrain, the method comprising the steps of:

providing the gravity gradient data using the airborne
gravity gradiometer, the gravity gradient data comprising
15 gravity gradient data elements that are associated with
respective flight path segments of the airborne gravity
gradiometer;

providing terrain data indicative of a topography and a
density or a density distribution of the terrain above a datum
20 that is below the surface of the terrain over which the airborne
gravity gradiometer is moved;

providing information concerning the flight path of the
airborne gravity gradiometer in three dimensions;

calculating a theoretical gravity gradient response of
25 the terrain using the provided terrain data and the provided
information concerning the flight path, the theoretical gravity
gradient terrain response being calculated for a plurality of
locations along each of at least some of the flight path
segments of the airborne gravity gradiometer; and

correcting the provided gravity gradient data comprising calculating a difference between the calculated theoretical gravity gradient terrain response and the provided gravity gradient data.

- 5 The theoretical gravity gradient response may be calculated for a plurality of locations of the gravity gradiometer along each of at least the majority of the flight path segments.

The gravity gradient may be measured continuously while the gravity gradiometer is moved over the ground plane, but the gravity gradient data elements may be provided in the form of
10 integrals corresponding to respective flight path segments along which the gravity gradiometer is moved. The flight path segments may have any suitable length, such as 30, 40, 50, 60, 70, 80, 90, or 100m and may correspond to periods of flying time ranging
15 from a fraction of a second to one second or more.

The step of calculating the theoretical gravity gradient terrain response may comprise providing theoretical gravity gradient terrain response data corresponding to any number of locations, such as 2, 3, 5 10 or more locations along each of the flight
20 path segments.

Further, the step of calculating the theoretical gravity gradient terrain response may comprise integrating gravity gradient terrain response data along the respective flight path segments to provide integrals of the theoretical gravity
25 gradient terrain response data that correspond to the respective flight path segments along which the gravity gradiometer is moved. The theoretical gravity gradient terrain response data may initially be fitted using a curve or spline and the fitted data may then be integrated.

The step of calculating the difference between the calculated theoretical gravity gradient terrain response and the provided gravity gradient data may comprise calculating a difference between the gravity gradient data elements provided in the form of integrals and the integrals of the theoretical gravity gradient terrain response data.

In one specific embodiment the step of providing flight path information comprises providing flight path data indicative of a plurality of locations along each of at least some (typically at least the majority) of the flight path segments, for example at 2, 5, 10 or more locations along each flight path segment. The step of providing flight path information may further comprise fitting the provided flight path data using a curve or spline to approximate the actual flight path segments of the gravity gradiometer. In this embodiment the step of calculating the theoretical gravity gradient terrain response may comprise integrating the theoretical gravity gradient terrain response data using the curve or spline fitting flight path data.

The step of calculating the theoretical gravity gradient response of the terrain may comprise calculating the terrain response for a number of locations that are closer together in areas in which the terrain response changes more rapidly than in areas in which the terrain changes less rapidly.

The method may also comprise selecting a spacing between locations along the flight path for which the gravity gradient response of the terrain is calculated. Selecting the spacing may be performed as a function of a change in the gravity gradient data along the flight path and/or as a function of a change in the gravity gradient response of the terrain initially calculated for some of the locations.

The step of correcting the gravity gradient data may comprise forming a difference between the calculated theoretical gravity

gradient terrain response of the terrain topography and the provided gravity gradient data in a manner such that the formed difference is only indicative of variations from an assumed density above the datum, and any variations below the datum.

5 The step of providing terrain data may comprise providing a digital terrain model that may be determined independent of gravity gradient measurements that were used to provide the above-mentioned gravity gradient data. Further, the step of providing the terrain data may comprise selecting or estimating
10 a density or density distribution of the terrain between the datum and the surface of the terrain.

The invention will be more fully understood from the following description of specific embodiments of the invention. The description is provided with reference to the accompanying
15 drawings.

Brief Description of the Drawings

Figures 1, 2 (a) and 2(b) illustrate a method of processing gravity gradient data indicative of an output generated by an
20 airborne gravity gradiometer in accordance with a specific embodiment of the present invention;

Figures 3 and 4 illustrate terrain and flight path data; and

Figures 5 illustrates a plot of the difference between terrain correction using a method in accordance with a specific
25 embodiment of the present invention and results of a point determination of terrain effects using a known terrain correction method.

Detailed Description of Specific Embodiments

Referring initially to Figures 1 and 2, a method of processing gravity gradient data indicative of an output generated by an airborne gravity gradiometer is now described.

- 5 The gravity gradiometer is in this embodiment provided in the form of the gravity gradiometer as described in US patent number 7823449 in the name of the present applicant. However, it will be appreciated by a person skilled in the art that the gravity gradiometer may also be provided in other forms.
- 10 The gravity gradiometer may be flown over a terrain 200 and may be used to detect deposits of valuable materials (ores or other deposits) below the surface 202 of the terrain 200.

- The gravity gradiometer is a high precision instrument that is used to detect very small variations in gravity gradients. In
- 15 the present example the gravity gradiometer is flown along a flight path 203 over a topographic surface 202 in an aircraft in a predetermined grid pattern and in this embodiment detects the gravity gradient continuously. In this example the gravity gradient data is integrated to provide gravity gradient data
- 20 elements that correspond to segments of the flight path 203, such as flight path segments along which the gravity gradiometer was moved during 1 second. However, it will be appreciated by a person skilled in the art that alternatively the gravity gradiometer data may be integrated in any other suitable manner.
- 25 Generally, an output of the gravity gradiometer is integrated such that a sequence of data elements is generated and each data element corresponds to a flight path segment along which the gravity gradiometer was flown.

- Consequently, the method 100 comprises the initial step of
- 30 providing gravity gradient data comprising gravity gradient data elements (values) that are associated with respective flight path segments of the airborne gravity gradiometer.

The gravity gradient response is proportional to $1/r^3$ (r: distance from the body causing the gravity gradient response to the gravity gradiometer) and consequently deposits of valuable material that are located well below the surface 202 of the terrain 200 often only cause a very small variation in gravity gradient compared to that arising from topographical changes of a surface 202 of the terrain 200. Consequently, it is often desirable to correct measured gravity gradient data for terrain effects.

Information concerning the topography of the terrain 200 over which the gravity gradiometer is flown is in this example provided using Laser Imaging Detection and Ranging (LIDAR) or other suitable techniques. The method 100 comprises step 104 of providing such terrain data indicative of the topography of the terrain 200. Further, step 104 provides a density distribution of the terrain 200 over a datum that is below the surface 202 of the terrain 200. The density is usually, but not necessarily, assumed to be uniform between the datum and the surface 202 of the terrain 200. The datum typically is a flat plane, but in very large surveys, this datum may also be a curved surface e.g. the Geoid or mean sea level.

As mentioned above, the gravity gradient is detected continuously, but integrated over finite intervals. In this example, the intervals correspond to flight path segments along which the gravity gradiometer is moved during one second. The lengths of the flight path segments dependent on a velocity of the aircraft. For example, the lengths may be of the order of 50 to 60 metres.

The method 100 comprises step 106 of providing detailed information concerning the flight path 203 of the gravity gradiometer. For example, this information may be provided using a global positioning system (GPS) at suitable time intervals, such as 0.1 to 1 second. Flight path data is provided

in three dimensions and for a plurality of locations along each flight path segment (such as 2, 5, 10 or any other number of locations). The flight path data is then fitted using a curve or spline to approximate the actual flight path of the gravity
5 gradiometer.

Using the provided data regarding the terrain 200 and the flight path 203, theoretical gravity gradient terrain response data are then calculated for a plurality of positions along each of at least the majority of the flight path segments. The number of
10 locations for which the theoretical gravity gradient response is calculated may or may not be the same as the number of locations for which the flight path data is provided for each flight path segment. Figure 2 (a) indicates these locations in the form of vertical lines along the flight path 203. Generally, the
15 theoretical gravity gradient response data may be calculated for any number of locations along the flight path segments, such as two, five or ten or more locations along each flight path segment. In the present example the theoretical gravity gradient response is calculated for more locations at regions in which
20 the terrain surface 202 changes more rapidly than for locations at regions at which the terrain surface 202 changes less rapidly, which will be described in further detail below.

Step 108 of the method 100 comprises calculating the theoretical gravity gradient terrain response data for a plurality of
25 locations along each of the majority of the flight path segments and the calculated data are visualised in the form of dots 204 in Figure 2 (b). These values of the theoretical gravity gradient terrain response are spline-fitted (spline 208) and then integrated substantially along the flight path segments and
30 using the curve or spline fitting flight path data. As mentioned above, a uniform density is assigned for the region between the terrain surface and the datum. The theoretical gravity gradient terrain response is dependent on topographical changes along the

surface 202 of the terrain 200 and may be represented schematically in terms of the area between datum 209 and the spline 208 as shown in Figure 2 (b). The straight portions 210 represent terrain response approximations obtained using

5 conventional point correction methods (one calculated gravity gradient terrain response element per flight segment), and the difference between the straight portions 210 and the spline 208 is representative of an improvement of the method in accordance with an embodiment of the present invention.

10 Step 110 of the method 100 comprises correcting the gravity gradient data using the calculated gravity gradient terrain response data. In this step the calculated gravity gradient terrain response data (processed in the above-described manner) for each flight path segment is subtracted from the

15 corresponding gravity gradient data. Consequently, a variation of a terrain effect along each flight path segment (provided in the form of the plurality of calculated gravity gradient response data along each flight path segment) is taken into account for correcting the gravity gradient data for terrain

20 effects, which improves the estimate of terrain effects which, when removed, enables better detection of small "anomalies" from deeper sources.

Figure 3 shows plot 302 that illustrates a determined cross-section (topography) of a terrain surface over which a gravity

25 gradiometer was flown. Plot 304 illustrates a profile of the flight path of the airborne gravity gradiometer and each dot corresponds to a location representative of a length of a respective flight path segment along which the gravity gradiometer was moved during the period of 1 second

30 (approximately 60 metres in this example). In order to choose an optimum degree of sub sampling of the flight path, without adding unnecessary additional detail, an initial estimate is made of the "rate of change" of the terrain component of the

total gravity gradient signal, and this is used to enable an "adaptive" sampling regime, which relates to the above description of the embodiment visualised in Figure 2 (b).

Figure 4 shows the plot 302 having an area of interest 402 and the adaptive sampling regime. Dots of plot 404 represent locations along flight path segments for which the terrain response is calculated. In order to increase the accuracy, the terrain response is calculated for more locations at or near areas at which the terrain response changes more rapidly than at other areas.

Figure 5 shows also the plots 302, 304 and 306 at a scale that is different to that of Figures 3 and 4. Further, Figure 5 shows plot 508, which illustrates the difference between gravity gradient data that were corrected using one gravity gradient response data point along each flight path segment (conventional method) and a method in accordance with an embodiment of the present invention which uses a plurality of gravity gradient response data points along each flight path segment (in this example 12). In this example, which uses relatively gentle terrain, the difference may be as much as 5 Eo and even larger differences are expected in areas of steeper terrain.

The terrain corrected gravity gradient data may then be plotted as a 2D grid map or further processed in various ways, including inversion modelling, to facilitate interpretation and the location of deposits of valuable material below the terrain surface.

It is to be appreciated that various variations of the described embodiments are possible. For example, the gravity gradiometer may be flown at any suitable speed and the gravity gradiometer may take measurements during any suitable time intervals. Further, a suitable number of gravity gradient terrain response data points may be taken into account for correcting the gravity

gradient data for the terrain effects.

The reference that is being made to prior patent documents is not an admission that the disclosure of these documents is part of the common general knowledge of a skilled person in Australia
5 or any other country.

The Claims:

1. A method of processing gravity gradient data indicative
5 of an output generated by an airborne gravity gradiometer that
is moving along a flight path over a terrain, the method
comprising the steps of:

providing the gravity gradient data using the airborne
gravity gradiometer, the gravity gradient data comprising
10 gravity gradient data elements that are associated with
respective flight path segments of the airborne gravity
gradiometer;

providing terrain data indicative of a topography and a
density or a density distribution of the terrain above a datum
15 that is below the surface of the terrain over which the airborne
gravity gradiometer is moved;

providing information concerning the flight path of the
airborne gravity gradiometer in three dimensions;

calculating a theoretical gravity gradient response of
20 the terrain using the provided terrain data and the provided
information concerning the flight path, the theoretical gravity
gradient terrain response being calculated for a plurality of
locations along each of at least some of the flight path
segments of the airborne gravity gradiometer; and

25 correcting the provided gravity gradient data comprising
calculating a difference between the calculated theoretical
gravity gradient terrain response and the provided gravity
gradient data.

2. The method of claim 1 wherein the theoretical gravity gradient response is calculated for a plurality of locations of the gravity gradiometer along each of at least the majority of the flight path segments.

5

3. The method of claim 1 or 2 wherein the gravity gradient data elements are provided in the form of integrals corresponding to respective flight path segments along which the gravity gradiometer moved.

10

4. The method of claim 3 wherein the step of calculating the theoretical gravity gradient terrain response comprises integrating the theoretical gravity gradient terrain response data substantially along respective flight path segments to provide the theoretical gravity gradient terrain response data in the form of integrals that correspond to the respective flight path segments along which the gravity gradiometer is moved.

5. The method of claim 4 wherein calculating a difference between the calculated theoretical gravity gradient terrain response and the provided gravity gradient data comprises calculating a difference between the gravity gradient data elements that are provided in the form of integrals and the theoretical gravity gradient terrain response data that are provided in the form of integrals.

6. The method of any one of the preceding claims wherein the step of calculating the gravity gradient response of the terrain comprises calculating the terrain response for a number of

locations that are closer together in areas in which the terrain response changes more rapidly than in areas in which the terrain response changes less rapidly.

- 5 7. The method of any one of the preceding claims wherein the step of providing flight path information comprises providing flight path data indicative of the location of the gravity gradiometer for a plurality of locations along each of at least some flight path segments.

10

8. The method of claim 7 wherein the step of providing flight path information further comprises fitting the provided flight path data using a curve or spline to approximate the actual flight path segments of the gravity gradiometer.

15

9. The method of claim 8 wherein the step of calculating the theoretical gravity gradient terrain response comprises integrating gravity gradient terrain response data using the curve or spline fitting flight path data.

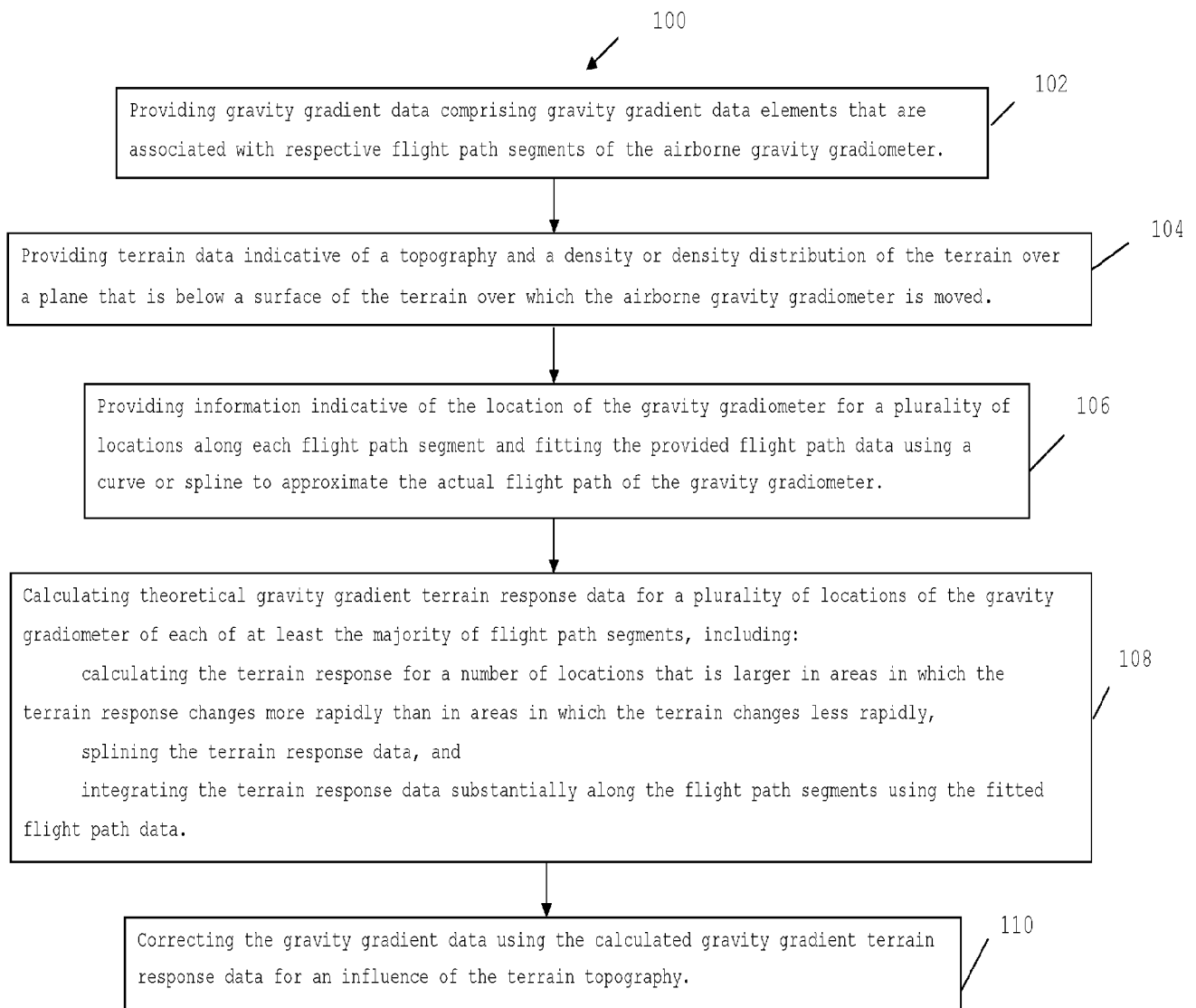
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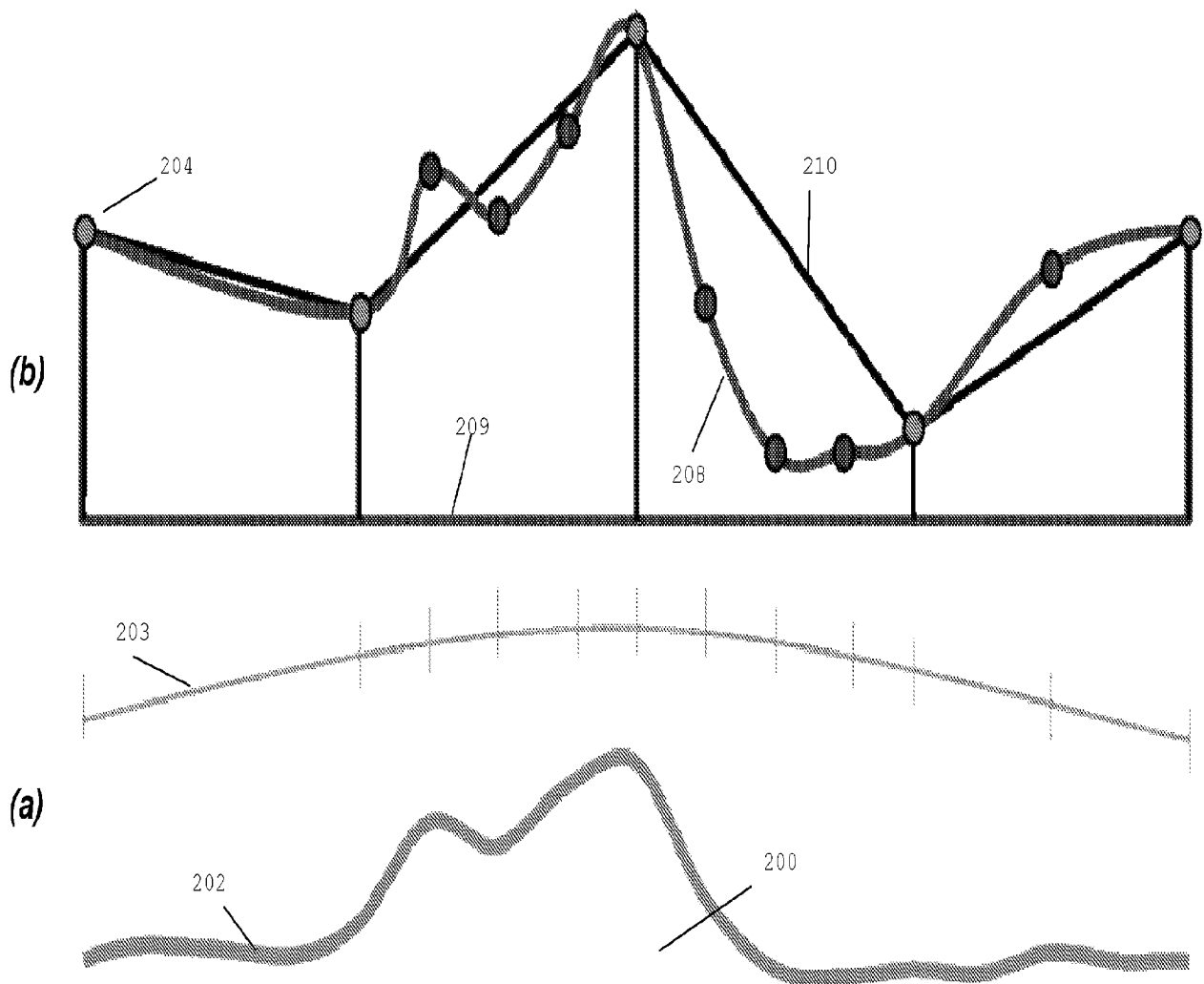
10. The method of any one of the preceding claims comprising selecting a spacing between locations along the flight path for which the gravity gradient response of the terrain response is calculated.

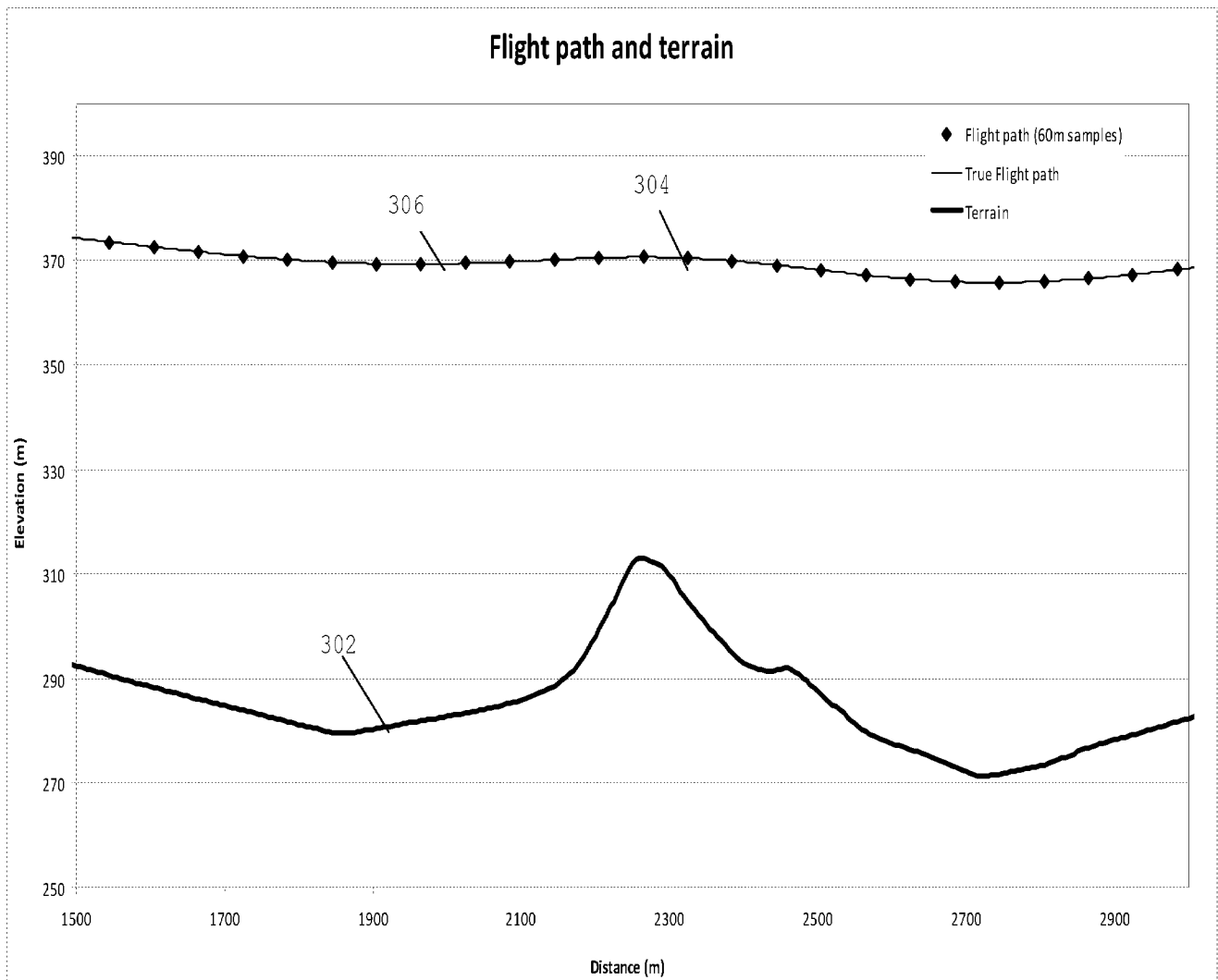
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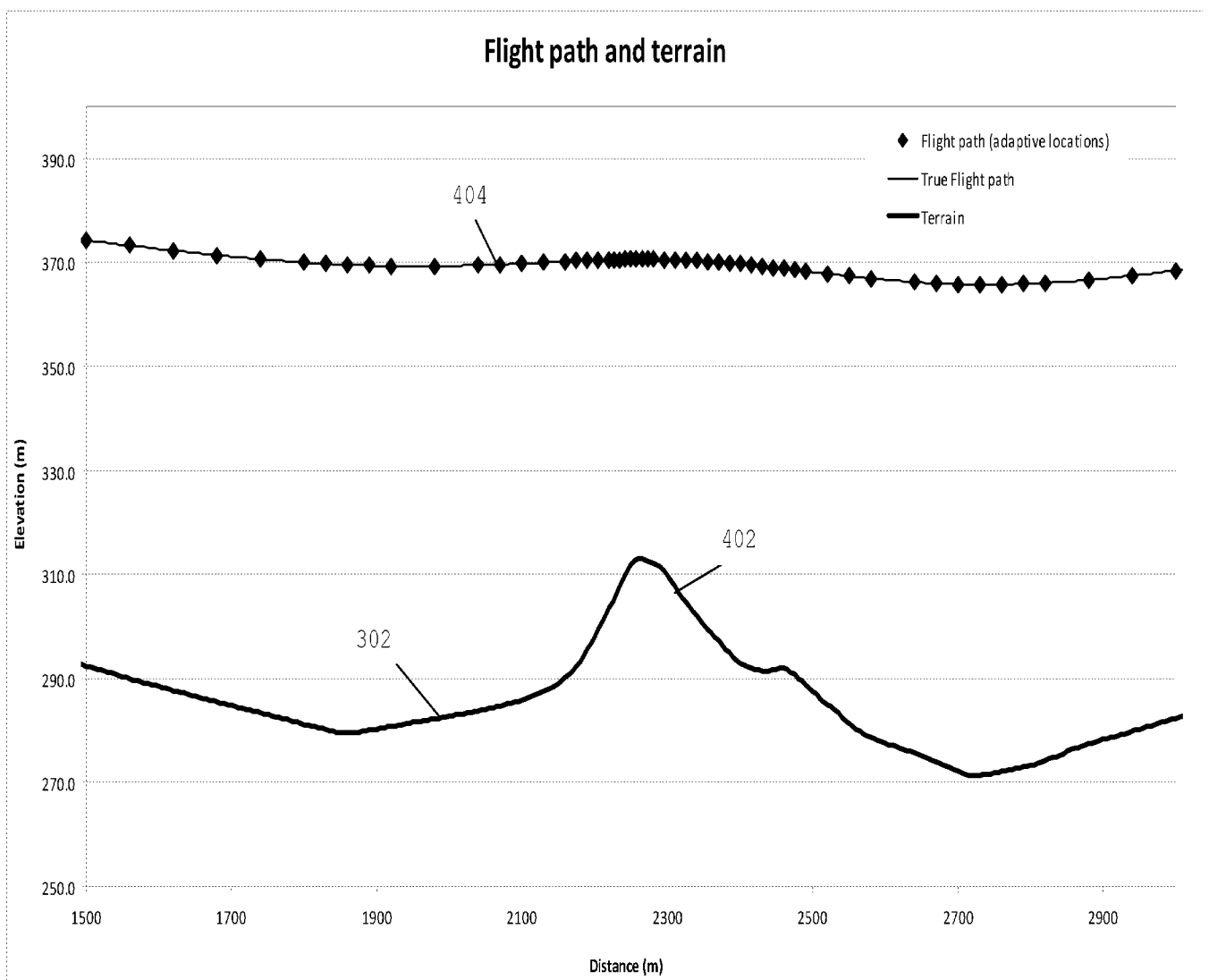
11. The method of claim 10 wherein selecting the spacing is performed as a function of a change in the gravity gradient data along the flight path.

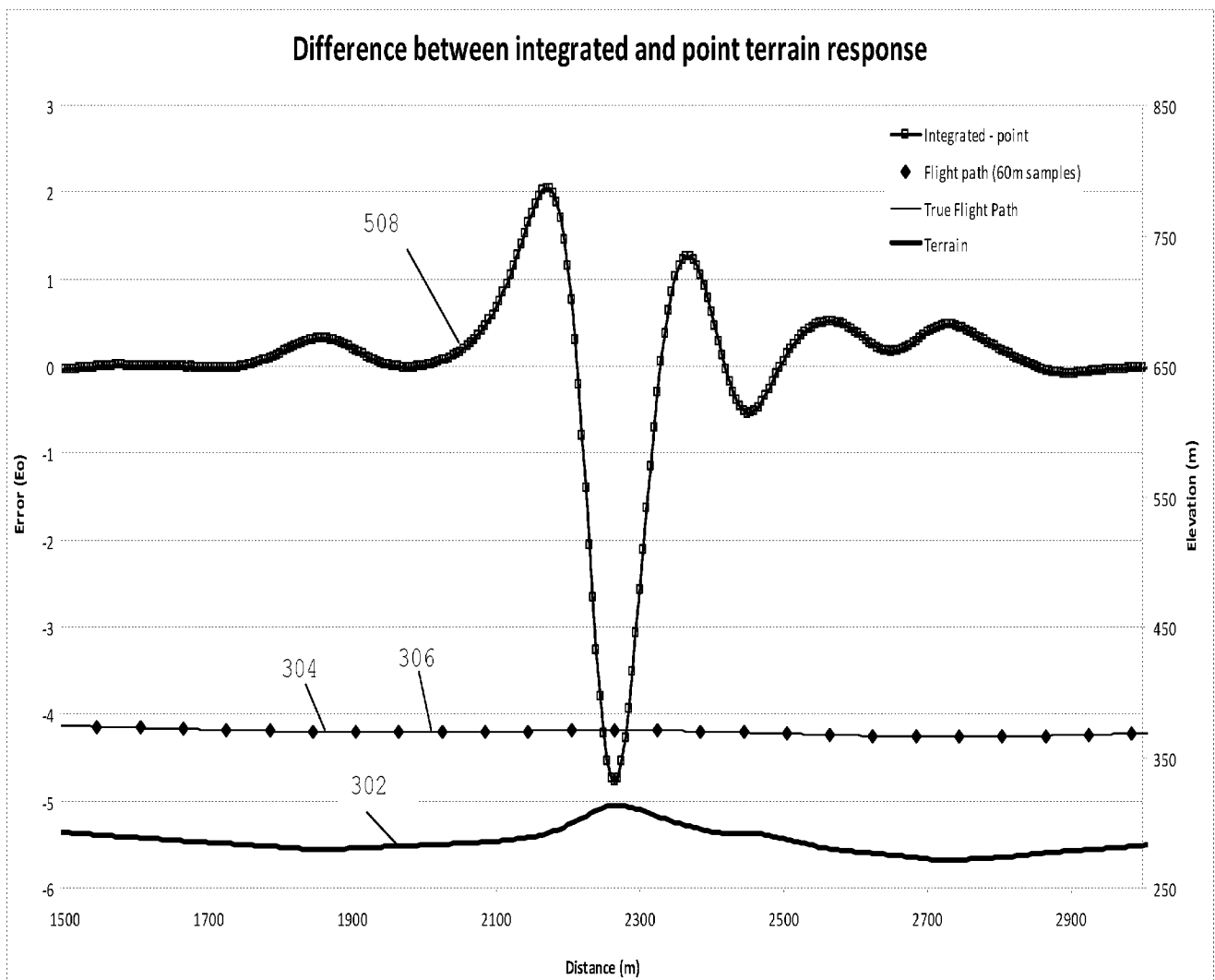
12. The method of claim 9 wherein selecting the spacing is performed as a function of a change in the gravity gradient response of the terrain that is initially calculated for some of
5 the locations.

**Fig. 1**

**Fig. 2**

**Fig. 3**

**Fig. 4**

**Fig. 5**

INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2013/001096

A. CLASSIFICATION OF SUBJECT MATTER

G01V 7/06 (2006.01) G01V 3/38 (2006.01) G01V 3/40 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

INSPEC, GOOGLE: EPODOC, WPI, Full text authorities - TXTUS5, TXTUS4, TXTUS3, TXTUS2, TXTUS1, TXTUS0, TXTEP1, TXTGB1, TXTWO1, TXTAU1, TXTC A1: (G01V3/38/LOW/IC/CC/EC OR G01V3/38/IC/CC/EC OR G01V7/06/IC/CC/EC);(OR GRADIOMET+, (GRAVITY 2D GRADIENT?), (AEROMAGNETIC D SURVEY+), GRAVIMETER+, MAGNETO_METRIC?, (GRAVITY W SURVEY+)); (OR AIR+, FLIGHT+); (OR LOCAT+, PATH, SEGMENT?); (OR TOPOGRAPH+, (DENSITY D DISTRIBUT+)); (OR SPLIN+, CORRECT+, (CURVE 2W FIT+)) and similar terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	



Further documents are listed in the continuation of Box C



See patent family annex

* "A"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 15 November 2013	Date of mailing of the international search report 15 November 2013
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustalia.gov.au Facsimile No.: +61 2 6283 7999	Authorised officer Firoozeh Rabbani AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 0262832287

INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/AU2013/001096
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2006/0036367 A1 (BREWSTER) 16 February 2006	1-5, 10-12
A	Refer to the whole document and in particular to [0024]-[0028], [0043], [0049]-[0050], [0052]-[0053], [0059], [0086]-[0087]; Fig. 1, 5 & 6 As above	6-9
X	LI, Y et al., "Terrain correction and its effect on 3D inversion of airborne gravity gradiometry data", In R. J. L. Lane (editor), 2010, Airborne Gravity 2010 - Abstracts from the ASEG-PESA Airborne Gravity 2010 Workshop: Published jointly by Geoscience Australia and the Geological Survey of New South Wales, Geoscience Australia Record 2010/23 and GSNSW File GS2010/0457, pg 131-141, retrieved on 04 February 2013. Retrieved from the Internet URL: www.ga.gov.au/image_cache/GA17945.pdf	1-6
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X	LANE, R., "Integrating ground and airborne data into regional gravity compilations", in R.J.L. Lane, (editor), 2004, Airborne Gravity 2004 - Abstracts from the ASEG-PESA Airborne Gravity 2004 Workshop: Geoscience Australia Record 2004/18, pg 81-97, retrieved on 04 February 2013. Retrieved from the Internet URL: www.ga.gov.au/image_cache/GA16642.pdf	1-12
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A	US 2006/0004519 A1 (HUMPHREY et. al.) 05 January 2006 Refer to the whole document and in particular to para [0029]-[0030], [0044]	3-5

INTERNATIONAL SEARCH REPORT Information on patent family members		International application No. PCT/AU2013/001096	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
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		US 7542850 B2	02 Jun 2009
		WO 2006011997 A2	02 Feb 2006
End of Annex			
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001. Form PCT/ISA/210 (Family Annex)(July 2009)			