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— *of inventorship (Rule 4.17(iv))*

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— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

(54) Title: DIGITAL ELEVATION MODEL

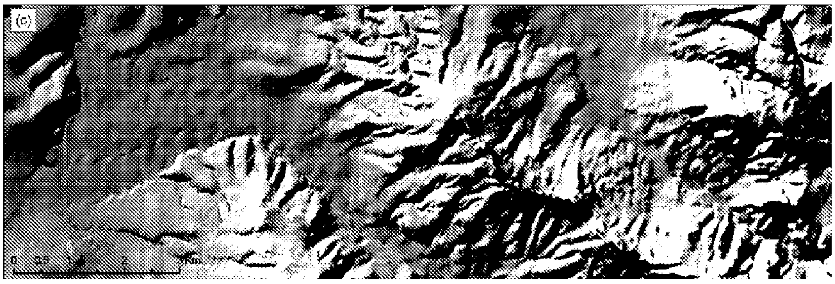

Figure 3

(57) Abstract: A method of producing an enhanced resolution DEM that uses contour data to improve the accuracy of an original DEM is provided in which the original DEM is fused with an intermediate DEM interpolated from contours wherein the intermediate DEM has a resolution higher than the native resolution of the original DEM. The fusion is carried out in a manner that the contour information dominates only in areas where the contour density is significantly higher than the original DEM. The intermediate DEM preferably has a resolution several factors higher than the original DEM. The intermediate DEM may be produced by converting the original DEM to points followed by processing these points using a suitable interpolation tool such that the cells of the intermediate DEM and the modified DEM match substantially perfectly.

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DIGITAL ELEVATION MODEL

FIELD OF THE INVENTION

This invention relates to a digital elevation model (herein abbreviated to DEM) and, more particularly, to an enhanced resolution DEM that is derived from available digital elevation information utilising information that is available independently of the existing DEM.

BACKGROUND TO THE INVENTION

There is a need for enhanced or high-resolution DEMs of geographical regions in respect of which insufficiently detailed information is available in respect of at least parts of the region.

Various techniques have been employed to try and provide enhanced or higher resolution DEMs on the basis of available information that is insufficient to provide for the direct development of a high-resolution DEM.

In one instance an enhanced DEM was interpolated from 1:50000 scale (20m vertical interval) contours using an algorithm developed by the Australian National University. One region in respect of which such a DEM was developed is the Western Cape region of South Africa and that particular DEM will be referred to herein as the WCDEM. Notwithstanding subsequent releases of other DEMs covering specific regions, such as that of the Western Cape, the WCDEM still remains the DEM of choice for many applications for that region. This is mainly due to its relatively high spatial resolution, consistency and accuracy.

Centres for geographical analysis such as the Centre for Geographical Analysis (CGA) in South Africa receive frequent requests for more detailed (i.e. larger-scaled) DEMs.

The idea of combining various sources of elevation data into a single DEM was consequently a logical progression. Experiments showed, however, that incorporating various sources (and scales) of elevation data into existing interpolation algorithms often produces unsatisfactory results. Examples of these are visible “seams” at transition zones between differently-scaled sources; artefacts as a result of inconsistencies between data sources; and grid-like “textures” due to the fusion of data with different sampling resolutions.

Using South Africa as an example, the official 1:50,000 topographical maps that are available and that show the contours and spot heights, remain a primary source of elevation data as it is the only official data set covering the whole country. These 20m (vertical interval) contours and spot heights were digitized by the South African Chief Directorate National GeoSpatial Information (CDNGI) and are freely available to the public.

Recently, the CDNGI has also made available 1:10000 contours (ranging from 5m to 20m vertical interval) and spot heights, which were digitized from the 1:10000 orthophoto map series and the CGA has produced many very high resolution (<20m) DEMs from 1:10000 scaled contour data, where this information is available, and stereographic aerial and satellite imagery. Unfortunately, this data set covers only 43% of South Africa.

In addition, the CDNGI has developed a 25m DEM (also known as the “ORT-files”) covering some parts of South Africa.

Other sources of elevation data covering South Africa include the 1km GTOPO30 DEM; the 90m Shuttle Radar Topography Mission (SRTM); the

30m Global DEM (GDEM) and various large-scale DEMs that were developed for specific projects that are typically restricted to very small areas.

The GTOPO30 DEM, SRTM DEM and GDEM are generally considered to be unsuitable for some applications (e.g. flood modeling, geomorphometry, civil engineering) due to their relatively low resolutions (30m or less) and quality. For example, the so-called ASTER-GDEM contains anomalies such as residual cloud patters and stripe effects. ASTER stands for Advanced Spaceborne Thermal Emission and Reflection Radiometer which is a Japanese sensor which is one of five remote sensory devices on board the Terra satellite launched into Earth orbit by NASA in 1999. The instrument has been collecting superficial data since February 2000 and provides high-resolution images of the planet Earth in 15 different bands of the electromagnetic spectrum, ranging from visible to thermal infrared light. The resolution of images ranges between 15 to 90 meters. ASTER data are used to create detailed maps of surface temperature of land, emissivity, reflectance, and elevation.

The so-called SRTM DEM contains some areas with no elevation information at all (i.e. voids). The Shuttle Radar Topography Mission (SRTM) is an international research effort that obtained DEMs on a near-global scale from 56°S to 60°N, to generate the most complete high-resolution digital topographic database of Earth prior to the first release of the ASTER GDEM in 2009. SRTM used a specially modified radar system that flew on board the Space Shuttle Endeavour. The vertical accuracy of the SRTM DEM is, however, relatively high (~6m), which makes it an attractive source for regional applications.

Contours are not ideal for interpolating DEMs as their densities vary with slope gradient. Areas of low relief are particularly problematic as contours are often spaced far apart (horizontally) reducing the reliability of interpolations in such areas. Contour density is further reduced as the vertical interval of the contours increases (i.e. contours with a 5m vertical interval generally produce a better DEM than contours with a 20m vertical interval) and as scale increases (i.e. contours with a 20m vertical interval captured at 1:10000 scale usually contain more detail than contours with the same vertical interval captured at 1:50000 scale).

To alleviate the problem of low contour densities in areas of moderate terrain, additional spot heights are often shown at strategic locations on topographical and orthophoto maps. Although, the quality of a DEM can be improved by incorporating these elevation points in the interpolation process, the combined density of input points (i.e. contour vertices and spot heights) is often insufficient to represent subtle changes in terrain (e.g. floodplains and river banks), particularly in some areas where input points can be several kilometres apart.

There is accordingly a need for the development of a procedure for producing enhanced or higher resolution DEMs from existing information that may not be adequately detailed, in itself, to enable the direct production of a higher resolution DEM.

SUMMARY OF THE INVENTION

In accordance with a first aspect of this invention there is provided a method of producing an enhanced resolution DEM that uses contour data to improve the accuracy of an original DEM, the method comprising fusing, with the original DEM, an intermediate DEM interpolated from contours wherein the intermediate DEM has a resolution higher than the native resolution of the original DEM, the fusion being carried out in a manner that the contour information dominates only in areas where the contour density is significantly higher than the original DEM.

In accordance with a second aspect of this invention there is provided a method of producing an enhanced resolution DEM comprising the steps of:-

1. interpolating a high-resolution DEM from suitable contour data to produce an intermediate DEM;

2. interpolating or resampling an original DEM to the same resolution as the intermediate DEM generated in step **Error! Reference source not found.** to produce a modified DEM;

3. deriving a slope gradient raster from either the intermediate DEM or the modified DEM;

4. adding a small constant value (e.g. 1) to the result of step 3 to ensure that all values are larger than 1;

5. calculating the logarithm of the result of step 4 and saving the result as a new raster;

6. using a mean spatial filter to generalise the result of step 4;

7. normalizing the result of step 6 to a range of between 0 and 1, using linear scaling;

8. multiplying the intermediate DEM values with the result of step 7;

9. inverting the result of step 7;

10. multiplying the result of step 9 with the result of step 1; and,

11. adding the result of step 10 to the result of step 8.

Further features of the invention provide for the intermediate DEM to have a resolution several factors higher than the original DEM; for the original DEM to be the SRTM DEM; for the slope gradient derived in step 3 to be selectively derived from the intermediate DEM or modified DEM with the selection typically being that of which the output is generally better (smoother) and that would commonly be the intermediate DEM; for step 1 to be carried out using a facility selected from TopoToRaster_sa; Spline; Nearest Neighbour; and Kiging with a preference towards TopoToRaster_sa; for step 2 to be carried out by converting the original DEM to points using, for example, the RasterToPoint_conversion tool followed by processing these points using a suitable interpolation tool such as the Sline_sa tool such that the cells of the intermediate DEM and the modified DEM match substantially perfectly; and for step 4 to be carried out using the Plus_sa tool in ArcGIS.

Still further features of the invention provide for attribute errors in the digitized contours and spot heights to be corrected, at least to some extent, before interpolation to produce the intermediate DEM; for spatial errors such as gaps and mismatching of contours at the edges of map sheets to be corrected, at least to some extent, before interpolation to produce the intermediate DEM; for voids in the original DEM to be filled in using elevation values interpolated from the corrected contours and spot heights prior to producing the modified DEM; and for elevation spikes in the original DEM to be removed whilst correcting contours and spot heights.

It is to be understood that in step 5 the use of a logarithmic transformation of slope gradient is important because it produces a better distributed histogram and prevents the dominance of the original DEM during fusion.

Step 6 may also be called a low-pass filter or smoothing neighbourhood operation.

By carrying out the method of the invention, the detail of the original DEM is enhanced and thereby upgraded in hilly and mountainous areas where the horizontal contour interval is higher than the native resolution of the original DEM in question while the integrity of the original DEM is kept in areas of moderate terrain.

In order that the invention may be more fully understood one implementation thereof will now be described in more detail by way of example with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:-

Figure 1 is a schematic illustration of a large area broken up into individual mapping areas;

Figure 2 is an example of hillshades of an area covered by an original SRTM DEM; and,

Figure 3 is an example of hill shades of the same area following processing according to the invention.

DETAILED DESCRIPTION WITH REFERENCE TO THE DRAWINGS

In the example of the invention described below three sets of input data were used to develop, according to the invention, an upgraded DEM of limited areas of South Africa. The methodology to improve the detail of existing DEM used contours available from a Geographical Information System (GIS).

Preference was given to large scale (i.e. 1:10000) contours and spot heights, while smaller scale (i.e. 1:50000) data was only used in areas where large scale data was unavailable. The procedure used combined contours and elevation points with the SRTM DEM (“research-grade” version).

An automated method was developed to detect and correct even the slightest errors in the data. In addition, a methodology was developed to fuse elevation data from different sources and scales so that “edge effects” were minimized.

The main problems experienced with the input data were related to attribute errors in the digitized contours and spot heights; spatial errors such as gaps and mismatching contours at the edges of map sheets; and voids in the SRTM DEM.

Attribute errors refer to instances in which the elevations stored in the “HEIGHT” field of contours and spot heights were incorrectly captured from the original maps. An algorithm was developed and implemented to identify and correct such errors. The algorithm examines vertical profiles (cross sections) created at regular intervals (determined by the extent of the smallest contour) within a specified area to find errors. Each profile is normalized (i.e. the horizontal distance between contours is unified) and tested against a set of topological rules. The algorithm not only identifies incorrect contours (or sequences of contours) but also “corrects” errors by examining each profile.

The corrections were then verified by an operator. About 1% (2926 of 3479217) of the contours that were used as input to the contour interpolation required attribute corrections. Hundreds of spatial edits were required. Spot heights that were likely to be incorrect were identified by comparing their heights to the height of the closest (corrected) contour. If the absolute height difference was more than twice the vertical interval of the contour, then the spot height was labeled as “likely incorrect”. These points were excluded from the interpolation process.

Voids in the SRTM DEM were filled using elevation values interpolated from the corrected contours and spot heights. A similar procedure was used to remove elevation spikes in the SRTM DEM.

The procedure of the invention was developed using a combination of algorithms. The ANUDEM algorithm (as implemented by the Topo to Raster function in ArcGIS) was used for interpolating a DEM from contours and spot heights. ANUDEM is a program that calculates regular grid digital elevation models (DEMs) with sensible shape and drainage structure from arbitrarily large topographic data sets. It has been used to develop DEMs ranging from fine scale experimental catchments to continental scale.

The product, an intermediate DEM, was employed to identify and correct the errors in the SRTM DEM (i.e. voids and spikes). Once corrected, the SRTM DEM was fused with the intermediate DEM using a newly-developed algorithm which ensures that the SRTM DEM is only applied in areas with low densities of contours and spot heights. Although it is recognized that the SRTM DEM is not a true DEM, the fusion procedure reduces the effect of surface objects.

Hengl (2006) suggested the use of Equation 1 to calculate the appropriate cell size when interpolating DEM from contours. When applying Equation 1 on contours of various intervals and scales, and in various types of terrains within South Africa, the “optimal” resolution varied between 5m and 50m. Consequently, it was decided to produce the DEM at a 5m resolution to ensure that no topographical variation becomes lost as a result of cell size. Producing the upgraded DEM of the invention at 5m resolution will also enable the incorporation of other DEM (e.g. those that were created using stereo images and LiDAR) in the future.

Equation 1:-

$$p = \frac{A}{2 \cdot \sum l}$$

where *p* is the pixel size; *A* is the total size of the study area; and *l* represents the contour length.

An example of the method of the invention was then carried out as follows in order to improve the quality of the 90m resolution SRTM DEM by using 1:10000 scale contours using ArcGIS software. The steps carried out are the following.

1. Interpolate a 5m-resolution DEM from the corrected contour data using, in this instance, the TopoToRaster_sa tool, to create an intermediate DEM.

2. Upscale (interpolate) the SRTM DEM to 5m-resolution by converting it to points using the RasterToPoint_conversion tool. A 5m modified DEM could then be interpolated from these points using an interpolation tool, in this instance, the Sline_sa. Care was taken to set the SnapRaster to the intermediate DEM generated in step **Error! Reference source not found.** to ensure that the cells of the two DEM match perfectly.

3. Derive a slope gradient raster (degrees) from the contour-interpolated intermediate DEM using the Slope_sa tool.

4. Add a small constant value (e.g. 1) to the result of step 3 to ensure that all values are larger than 1 in preparation for the next step. The Plus_sa tool in ArcGIS proved to be ideal for this operation.

5. Calculate the logarithm, using the Log10_sa tool, of the result of step 4 and save the result as a new raster.

6. FocalStatistics_sa (mean with a 11x11 cell kernel) is used to generalise the result of step 4.

7. Normalise the result of step 6 to a range between 0 and 1, using linear scaling. This can be done using the SingleOutputMapAlgebra_sa tool.

8. Multiply the interpolated intermediate DEM's values with the result of step 7 using the Times_sa tool.
9. Invert the result of step 7 using the SingleOutputMapAlgebra_sa tool.
10. Multiply the result of step 9 with the result of step 1 using the Times_sa tool.
11. Add the result of step 10 to the result of step 8 using the Plus_sa tool.

To determine the accuracy of the upgraded DEM, elevation values were systematically compared to reference elevations. Highly accurate (centimetre) LiDAR points, obtained from the South African aerial survey company, Southern Mapping Company (Pty) Ltd, were used as reference data. A total of 177 reference points were randomly selected from a range of LiDAR campaigns covering diverse terrain types and geographical areas in South Africa (compare Figures 2 and 3 of the accompanying drawings).

To determine vertical accuracy, the mean absolute error (*MAE*) and root mean square error (*RMSE*) for the resultant upgraded DEM were calculated using Equations 2 and 3 respectively.

Equation 2:-

$$MAE = \frac{\sum |x_i - x_j|}{n}$$

where MAE is the mean absolute error; x_i is the DEM's elevation value; x_j is the reference point's elevation value; and n is the number reference points.

Equation 3:-

$$RMSE = \sqrt{\frac{\sum (x_i - x_j)^2}{n}}$$

where $RMSE$ is the root mean square error; x_i is the DEM's elevation value; x_j is the reference point's elevation value; and n is the number reference points.

The results of the accuracy assessments are summarized in Table 1.

Table 1

PRODUCT	MAE(m)	RMSE(m)
SRMT DEM	4.6	43.4
Upgraded DEM	2.2	10.2

It is clear from the results that the upgraded DEM according to the invention performed significantly better than the SRTM DEM in terms of MAE and RMSE.

A qualitative assessment also revealed that some of the artefacts (e.g. banding, tiger stripes, and wave effects), that are frequently present in contour-interpolated DEM are reduced when the SRTM fusion is performed as will be quite apparent from a reference to Figures 2 and 3 of the drawings.

From the quantitative and qualitative assessments it is clear that the upgraded DEM of the invention are significantly more accurate than the SRTM DEM. The higher resolution of the upgraded DEM also enables the inclusion of more terrain detail.

Experiments conducted in the manner described above therefore showed that SRTM DEM quality in areas of moderate to steep terrain can be significantly improved when the SRTM DEM ("research-grade" version) is used in combination with contours and elevation points in relatively flat areas.

The ASTER-GDEM was also considered for this purpose, but accuracy assessments indicated significant deviations from the reference data. This observation is supported by others who have found that the SRTM DEM is superior to ASTER-GDEM. The 25m CDNGI DEM (also known as the "CDSM ORT-files") will likely be incorporated in future editions of the method of the invention, but only once verifications and corrections have been completed.

Also, other sources of information such as ASTER DEM, river lines, epipolar DEM (derived from high-resolution stereo aerial photographs and satellite imagery) and LiDAR data may well become a part of the method of this invention.

Numerous variations may therefore be made to the example of the invention described above without the scope hereof.

CLAIMS:

1. A method of producing an enhanced resolution DEM that uses contour data to improve the accuracy of an original DEM, the method comprising fusing, with the original DEM, an intermediate DEM interpolated from contours wherein the intermediate DEM has a resolution higher than the native resolution of the original DEM, the fusion being carried out in a manner that the contour information dominates only in areas where the contour density is significantly higher than the original DEM.

2. A method as claimed in claim 1 comprising the steps of:-

   1 interpolating a high-resolution DEM from suitable contour data to produce an intermediate DEM;

   2 interpolating or resampling an original DEM to the same resolution as the intermediate DEM generated in step **Error! Reference source not found.** to produce a modified DEM;

   3 deriving a slope gradient raster from either the intermediate DEM or the modified DEM;

   4 adding a small constant value (e.g. 1) to the result of step 3 to ensure that all values are larger than 1;

   5 calculating the logarithm of the result of step 4 and saving the result as a new raster;

   6 using a mean spatial filter to generalise the result of step 4;

   7 normalizing the result of step 6 to a range of between 0 and 1, using linear scaling;

   8 multiplying the intermediate DEM values with the result of step 7;

9 inverting the result of step 7;

10 multiplying the result of step 9 with the result of step 1; and,

11 adding the result of step 10 to the result of step 8.

3. A method as claimed in claim 2 in which the intermediate DEM has a resolution several factors higher than the original DEM.

4. A method as claimed in either one of claims 2 or 3 in which the original DEM is the SRTM DEM.

5. A method as claimed in any one of claims 2 to 4 in which the slope gradient derived in step 3 is selectively derived from the intermediate DEM or modified DEM with the selection being that of which the output is better (smoother).

6. A method as claimed in any one of claims 2 to 5 in which step 1 is carried out using a facility selected from TopoToRaster_sa; Spline; Nearest Neighbour; and Kiging.

7. A method as claimed in any one of claims 2 to 6 in which step 2 is carried out by converting the original DEM to points followed by processing these points using a suitable interpolation tool such that the cells of the intermediate DEM and the modified DEM match substantially perfectly.

8. A method as claimed in any one of claims 2 to 6 in which step 4 is carried out using the Plus_sa tool in ArcGIS.

9. A method as claimed in any one of the preceding claims in which attribute errors in the digitized contours and spot heights are corrected to some extent before interpolation to produce the intermediate DEM.

10. A method as claimed in any one of the preceding claims in which spatial errors including gaps and mismatching of contours at edges of map sheets are corrected to some extent before interpolation to produce the intermediate DEM.

11. A method as claimed in any one of the preceding claims in which voids in the original DEM are filled in using elevation values interpolated from the corrected contours and spot heights prior to producing the modified DEM.

12. A method as claimed in any one of the preceding claims in which elevation spikes in the original DEM are removed whilst correcting contours and spot heights.

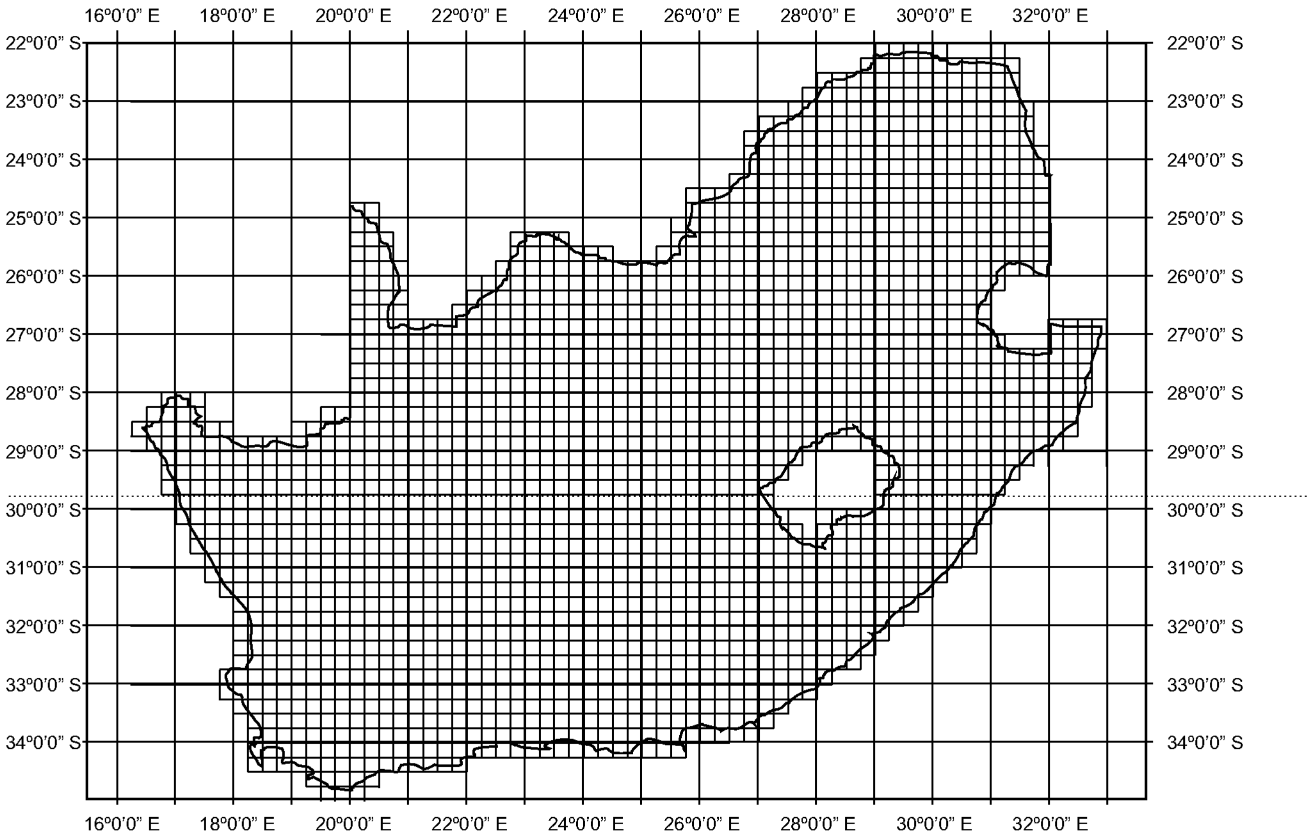
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Figure 1

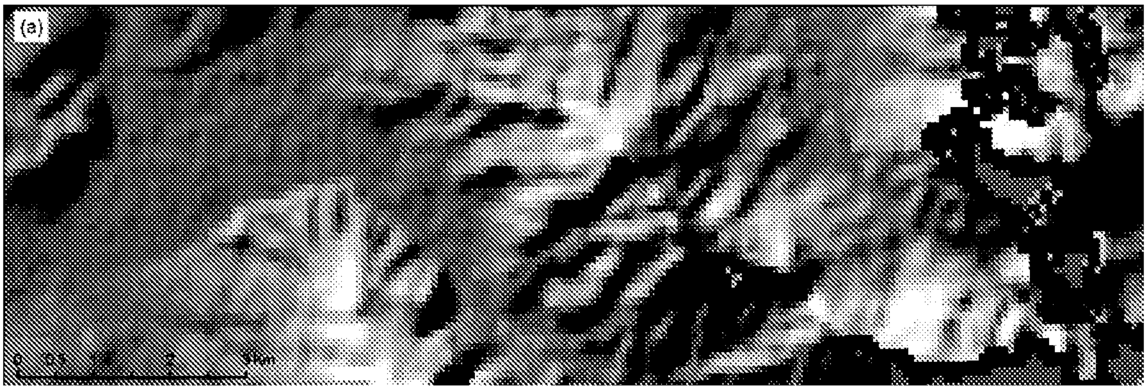

Figure 2

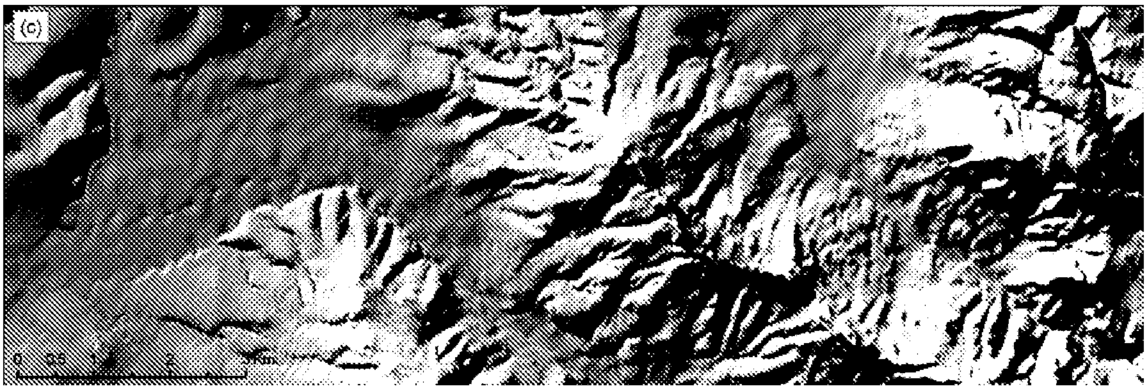

Figure 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2013/051117

A. CLASSIFICATION OF SUBJECT MATTER
INV. G06T17/05
ADD.

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)
G06T G01C G01S

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)

EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	HARIS PAPASAIKA ET AL: "Fusion of Digital Elevation Models Using Sparse Representations", 5 October 2011 (2011-10-05), PHOTOGRAMMETRIC IMAGE ANALYSIS, SPRINGER BERLIN HEIDELBERG, BERLIN, HEIDELBERG, PAGE(S) 171 - 184, XP019167022, ISBN: 978-3-642-24392-9	1-12
Y	abstract section 1.1; pages 171,172 section 3.1, 3.2; pages 176,177 pages 182,183 ----- -/--	2

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

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Date of the actual completion of the international search

17 July 2013

Date of mailing of the international search report

25/07/2013

Name and mailing address of the ISA/
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Meinl, Wolfgang

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	STANISLAV BEK ET AL: "Optimization of interpolation parameters when deriving DEM from contour lines", STOCHASTIC ENVIRONMENTAL RESEARCH AND RISK ASSESSMENT, SPRINGER, BERLIN, DE, vol. 25, no. 8, May 2011 (2011-05), pages 1049-1055, XP019982284, ISSN: 1436-3259, DOI: 10.1007/S00477-011-0482-8	2
A	abstract section 2.3, 2.4; page 1051 -----	1,3-12
A	FERAS M ZIADAT: "Effect of Contour Intervals and Grid Cell Size on the Accuracy of DEMs and Slope Derivatives", TRANSACTIONS IN GIS, vol. 11, no. 1, February 2007 (2007-02), page 67, XP055071640, ISSN: 1361-1682, DOI: 10.1111/j.1467-9671.2007.01033.x abstract sections 2, 3.2; pages 69-73 -----	1-12
A	US 2003/154060 A1 (DAMRON JAMES J [US]) 14 August 2003 (2003-08-14) abstract paragraphs [0002], [0004], [0030], [0035], [0036], [0061] -----	1-12
A	KARKEE M ET AL: "Improving quality of public domain digital elevation models through data fusion", BIOSYSTEMS ENGINEERING, ACADEMIC PRESS, UK, vol. 101, no. 3, October 2008 (2008-10), pages 293-305, XP025644712, ISSN: 1537-5110, DOI: 10.1016/J.BIOSYSTEMSENG.2008.09.010 [retrieved on 2008-10-23] abstract; figure 1 pages 293-296 -----	1-12

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2013/051117

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2003154060 A1	14-08-2003	NONE	