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Review of Remote Sensing Technologies for the Acquisition of Very High Vertical Accuracy Elevation Data (DEM) in the Framework of the Precise Remediation of Industrial Disasters – Part 1

In the last 10 years, the technological developments have changed the paradigm in remote sensing science. Nowadays, very diverse technologies can be employed to capture and/or extract very accurate terrain elevation data and prepare digital elevation models. This article aims at reviewing the existing remote sensing technologies which could support disaster remediation (by excavation of the soil) with very accurate elevation data acquisition. Ground based technologies (like terrestrial laser scanning, InSAR and SfM) and airborne technologies (airborne laser scanning [ALS], UAV photogrammetric approach, UAV with LiDAR) are reviewed. Their capacities are examined according to the following technical criteria: spatial efficiency, point density, accuracy and applicability in disaster situation.

Keywords: remote sensing, DEM, industrial disaster, remediation, LiDAR, photogrammetry, UAV, accuracy

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1. Introduction

Eleven years ago, on 6 October 2010, Hungary was facing one of the most terrible industrial disasters of its history with the Kolontár red sludge event. Since then, technology has evolved and researches were done on how to handle the remediation work more efficiently. Advantage could have been taken from the existence of geographic information prepared with remote sensing techniques; the preparation of a detailed digital remediation plan and its implementation in the field with navigation technologies and machine control technologies.

This article is the first one of a series of two articles. It provides a general description of the remote sensing technologies and details their capacities. The second article is more specific to the remediation approach by excavation and will really focus on technical problem raised by the foreseen approach.

Varied approaches, based on different kinds of technologies used on diverse carrying platforms are nowadays available, allowing generating DEMs at different scales with different levels of accuracy.[5] The acquisition can be done from the air from different kinds of platforms: with a UAV holding LiDAR, with UAV holding camera or also with airborne laser scanner (ALS) on-board aircrafts. The acquisition can also be ground based with terrestrial laser scanning (TLS) and interferometric synthetic aperture radar (InSAR).[6] What will matter in our case are the advantages of a technology in the context of disaster response and the accuracy of the final DEM product.

First, we give comprehensive information about the qualitative attributes of DEMs. Then, each chapter presents one technology. Literature details six different methods that are routinely used for DTM production. We examine their efficiency and accuracy. Last we conclude about the advantages and disadvantages it offers in the specific scopes of our study.

2. Important concepts related to the technologies and the framework

2.1. Quality criterion for characterising elevation data

The quality of elevation data can be approached using several criteria.

Vertical accuracy is the principal criterion in specifying the quality of elevation data.[7] Horizontal accuracy is another important characteristic for elevation data; however, it

[5] Oluibukun G Ajayi, Akporode A Salubi, Alu F Angbas and Mukwedeh G Odigure, 'Generation of accurate digital elevation models from UAV acquired low percentage overlapping images', *International Journal of Remote Sensing* 38, no 8–10 (2017), 2029–2036; Ivan Lizarazo, Víctor Angulo and Jorge Rodríguez, 'Automatic mapping of land surface elevation changes from UAV-based imagery', *International Journal of Remote Sensing* 38, no 8 (2017), 2603–2622; Zhilin Li, Qing Zhu and Christopher Gold, *Digital Terrain Modeling. Principles and Methodology* (Boca Raton: CRC Press, 2005).

[6] Michel Jaboyedoff et al, 'Use of LIDAR in landslide investigations: a review', *Natural Hazards* 61 (2012), 5–28.

[7] ASPRS Guidelines, *Vertical Accuracy Reporting for Lidar Data,* 2004; Xiaoye Liu, Zhenyu Zhang, Jim Peterson and Shobhit Chandra, 'The effect of LiDAR data density on DEM accuracy', *MODSIM07: International Congress on Modelling and Simulation: Land, Water and Environmental Management: Integrated Systems for Sustainability,* 10–13 December 2007.

is largely controlled by the vertical accuracy requirement.[8] If a very high vertical accuracy is required then it will be essential for the data producer to maintain a very high horizontal accuracy.[9] This is because horizontal errors in elevation data normally, but not always, contribute significantly to the error detected in vertical accuracy tests.[10]

Other main criteria like density and distribution of source data are mentioned.[11] Generally speaking, the more accurate and the denser the sampled terrain data are, the more accurate the produced DEM will be.[12] On the opposite, with a reduction in data a more manageable and operationally sized terrain dataset is possible.[13] This last point has to be considered for the terrain model embedded on-board the grading control system for its flowless functioning.

Liu also mentions the importance of the interpolation algorithm for the DEM generation.[14] Even if we are not willing to produce a DEM but instead a TIN, the situation has some similarities and we have to be sure the TIN conversion process is keeping the proper distribution of point density and accuracy; consequently, hereafter we examine and develop a little this issue. TINs are typically used for high-precision modelling of smaller areas, such as in engineering applications, where they are useful because they allow calculations of planimetric area, surface area and volume.[15] The input features used to create a TIN remain in the same position as the nodes or edges in the TIN. This allows a TIN to preserve all the precision of the input data while simultaneously modelling the values between known points.[16] Because nodes can be placed irregularly over a surface, TINs can have a higher resolution in areas where a surface is highly variable or where more detail is desired and a lower resolution in areas that are less variable.[17] In summary TIN models gather and offer all the requested advantages in our case as the mass points and edges will not be touched and accuracy remains unchanged. Also, the point density can be adapted in order to have sufficient point density in irregular areas and sufficient data reduction in flat areas; conciliating best accuracy and density for terrain description and efficiency for the on-board system processing.

2.2. Applicability of the technology in the field condition

If the qualitative aspects evocated above are important, the applicability is also a very important criterion to assess. Disasters often provoke the release of hazardous

8 ASPRS Guidelines, 'Vertical'.
9 Ibid.
10 Ibid.
11 Liu, 'The effect of LiDAR'.
12 Ibid.
13 Xiaoye Liu, 'Airborne LiDAR for DEM generation: some critical issues', *Progress in Physical Geography* 32, no 1 (2008), 31–49; Vaclav Petras, Anna Petrasova, Justyna Jeziorska and Helena Mitasova, 'Processing UAV and LIDAR point clouds in GRASS GIS', *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* XLI-B7 (2016), 945–952.
14 Liu, 'The effect of LiDAR'.
15 ESRI, 'What is a TIN surface?', s. a.
16 Ibid.
17 Ibid.

substance(s), or disturb the environment making it potentially dangerous. The applicability of the measurements approach should be evaluated in this respect.

3. Review of remote sensing technologies

3.1. Airborne laser scanning (ALS)

Airborne Light Detection and Ranging (LiDAR) also called Airborne Laser Scanning (ALS) is a method employing a laser beam emitted from the sensor to the ground (active remote sensing technique). The times of travel between the emission and the several returns of the laser beam are recorded by the system controller. Point cloud data is derived and used for the interpolation and generation of terrain model (TIN, DEM, etc.). Today airborne laser scanning is one of the most effective and reliable means of terrain data collection.[18] ALS surveys are typically designed to have a dense and evenly distributed LiDAR point density over large areas.[19] Large surfaces can be confidently scanned with high efficiency, high accuracy, high density (up to an average of 30–35 point/m^2) and high reliability.[20]

The accuracy of the laser ranging has actually only a limited effect compared to the accuracy of the whole system.[21] The processing of the points also contributes significantly to the achieved accuracy. The coordinate system transformations, the distance of the GNSS base station(s) to the LiDAR system during acquisition, the system calibration, the data alignment after flight to minimise IMU errors, the accuracy of the surveyed control points, how the point cloud is processed using those control points, all of these factors (and others) in total contribute to the actual measurable error in the final deliverable.[22] Axelsson demonstrated that DEMs with very high density (> 1 pt/m^2) and accuracy (mean error of less than 0.05 m) are possible to reach on well-defined surfaces, with appropriated calibration and a flying height of 350 m.[23] Tully mentions a 5 cm absolute accuracy reached with a system with 2.5 cm accuracy flown at an unusual low altitude (150 meters above ground with helicopter).[24] From the references gathered and geodetic equipment limitation (with 2 cm vertical accuracy with RTK L1 & L2), a 5–6 cm absolute vertical accuracy seems a realistic limit.

18 Murat Uysal and Nizar Polat, 'Investigating Performance of Airborne Lidar Data Filtering with Triangular Irregular Network (TIN) Algorithm', *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-7 (2014), 199–202; Xiaoye Liu and Zhenyu Zhang, 'Lidar data reduction for efficient and high quality DEM generation', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXVII, Part B3b (2008).

19 Christopher W Bater and Nicholas C Coops, 'Evaluating error associated with LiDAR-derived DEM interpolation', *Computers & Geosciences* 35, no 2 (2009), 289–300.

20 Liu, 'Lidar data reduction'.

21 Mike Tully, 'Just How Accurate is LiDAR?', 2012.

22 Ibid.

23 Peter Axelsson, 'DEM generation from laser scanner data using adaptive tin models', *International Archives of Photogrammetry and Remote Sensing* XXXIII, Part B3 (2000), 85–92.

24 Tully, 'Just how accurate'.

3.2. UAV imagery and photogrammetry

Unmanned Aerial Vehicles (UAVs) have seen an exponential progress in the last decades, thanks to their ability to perform complex tasks on terrain difficult to approach.[25] The technique can provide point cloud data comparable in density and accuracy to those generated by terrestrial and airborne laser scanning at a fraction of the cost.[26]

This technique achieves the best accuracy by using an UAV equipped with GPS/INS device and a camera. Using the external orientations collected by the couple GPS/INS, aerial triangulation software and the images collected, it is possible to calculate the precise external orientation of the images. From the correctly positioned images a dense point cloud can be extracted by dense point matching technique. Finally, the cloud point can be converted in a triangular irregular network (TIN).

The common processing pipeline for the DEM generation depends on several factors such as overlapping, flight altitude, camera resolution, etc. Variations in these parameters affect the final accuracy of the model obtained and many works[27] have analysed the effects of each of them. As a general rule, the horizontal relative accuracy is considered to be two times the GSD and the vertical relative accuracy is three times the GSD. As a rule of thumb, the absolute vertical accuracy of a map will be around three times worse than its absolute horizontal accuracy.[28] Pix4D source mentions 3 times the GSD.

In a white paper we found that in average 2/3 of the test points lie within 2 GSD and ¾ of the test points are within 3 GSD, reaching the same level as best possible results theoretically achievable with any photogrammetry method, even when using lower quality UAV imagery (Pix4D white paper). Ajayi tested the accuracy of DEM produced from low percentage overlapping images and a flight at 50 m AAG. The horizontal and vertical accuracy are respectively of 4.67 cm and 11.51 cm.[29]

So in practice the vertical absolute accuracy can be lowered by flying low. Nevertheless, for the benefit of the accuracy, this approach is lowering the acquisition efficiency. And secondly, absolute accuracy still remains limited by the accuracy of the GCPs used in the triangulation process (few centimetres). As a consequence, the UAV imagery and photogrammetry approach can reach few centimetres accuracy but it is rather convenient for a site size of one to several hectares.

[25] Juan J Ruiz, Luis Diaz-Mas, Francisco Perez and Antidio Viguria, 'Evaluating the Accuracy of DEM Generation Algorithms from UAV Imagery', *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-1/W2 (2013), 333–337.

[26] Jonathan L Carrivick, Mark W Smith and Duncan J Quincey, *Structure from Motion in the Geosciences* (Wiley-Blackwell, 2016).

[27] Brance Hudzietz and Srikanth Saripalli, 'An experimental evaluation of 3D terrain mapping with an autonomous helicopter', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXVIII-1/C22 (2011), 137–142; Olivier Küng, Christoph Strecha, Pascal Fua, Daniel Gurdan, Michael Achtelik, Klaus-Michael Doth and Jan Stumpf, 'Simplified building models extraction from ultra-light UAV imagery', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXVIII-1/C22 (2011), 217–222; Masahiko Nagai, Ryosuke Shibasaki, Dinesh Manandhar and Huijing Zhao, 'Development of Digital Surface and Feature Extraction by Integrating Laser Scanner and CCD Sensor with IMU', *Center for Spatial Information Science, The University of Tokyo* (2004), 655–659.

[28] Franck Schroth, 'Accuracy in Drone Mapping: What You Need to Know', *Drone Life,* 07 February 2017.

[29] Ajayi et al., 'Generation'.

3.3. SfM approach

The SfM method solves the camera pose and scene geometry simultaneously and automatically, using a highly redundant bundle adjustment based on matching features in multiple overlapping offset images.[30] It differs fundamentally from conventional photogrammetry, in that the geometry of the scene, camera positions and orientation is solved automatically without the need to specify a priori, a network of targets which have known 3-D positions. The author mentions SfM as an inexpensive, effective and flexible approach to capturing complex topography.[31]

Unlike traditional photogrammetry, the camera positions derived from SfM lack the scale and orientation provided by ground-control coordinates.[32] Consequently, the 3-D point clouds are generated in a relative 'image-space' coordinate system, which must be aligned to a real-world, 'object-space' co-ordinate system. In most cases, the transformation of SfM image-space coordinates to an absolute coordinate system can be achieved using a 3-D similarity transform based on a small number of known ground-control points (GCPs) with known object-space coordinates.[33] To conclude, compared to the photogrammetric approach, SfM needs longer calculation time, cumulate the measurement errors from the SfM approach, errors inherent to transformation, and like the other methods the GCP measurements errors. Similar thoughts are provided by Lucieer with SfM approach and transformation to real world coordinate system.[34]

3.4. UAS equipped with LiDAR sensor

The LiDAR technology employed here is very similar to the one employed with ALS. Sensor and associated equipment (GPS, IMU) is miniaturised to be hold by a UAV or UAS platform. As an active remote sensing technique, UAS LIDAR has the advantage to penetrate the vegetation and find bare earth (whereas UAS equipped with cameras meet some limitations on this aspect). LiDAR sensors are increasingly getting attention in UAS mapping.[35]

The found references agree on the fact that LiDAR UAS is still an emerging technology[36] and that one issue related to using LiDAR sensors on UAS is the limited performance of the navigation sensors used on UAS platforms.[37] Consequently, the accuracy of the UAS LiDAR point cloud is lower than the one of a dense point cloud

30 Matthew J Westoby, James Brasington, Neil F Glasser, Michael J Hambrey and John M Reynolds, ''Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications', *Geomorphology* 179 (2012), 300–314.

31 Ibid.

32 Ibid.

33 Ibid.

34 Ruiz et al., 'Evaluating the Accuracy of DEM'.

35 Arko Lucieer, Sharon Robinson, Darren Turner, Steve Harwin and Josh Kelcey, 'Using a micro-UAV for ultra-high resolution multi-sensor observations of Antarctic moss beds', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXIX-B1 (2012), 429–433.

36 Ibid.

37 Ibid.

extracted from images flown at similar AGL. To tackle this issue, the advanced UAS LIDAR applications are using a LIDAR sensor in conjunction with a camera system to beneficiate from the higher accuracy brought by photogrammetry techniques.[38] At best, one can expect to obtain a point cloud accuracy of 5 to 10 cm.[39]

The remediation method we are developing is only applicable in open space area because it is only in this case feasible to predict, plan and implement the moves of the grading equipment. So it makes no sense to take advantage of the penetration capacities of a LIDAR sensor in this situation. At similar coverage efficiency level, UAV imagery offer better accuracy, lower costs and simpler processing workflow.

3.5. Terrestrial laser scanning (TLS)

Terrestrial laser scanning (TLS) is a ground-based, active imaging method that rapidly acquires accurate, dense 3D point clouds of object surfaces by laser rangefinding.[40] The static systems are operated from atop a surveying tripod and commonly employed for the as-built documentation of industrial plants, the recording of cultural heritage sites, the measurement of natural processes, structural deformation measurements,[41] natural deformation measurements, planning applications.[42]

Two main types of applications should be distinguished: 1. hard surface topographic surveys with data collected at engineering level accuracy (industrial survey); and 2. topographic surveys with data collected at lower level accuracy.[43] In industrial surveying, a terrestrial laser scanner measures the distance to an object surface with a precision in the order of millimetres[44] at a relatively close range (50–200 meters). Topographic surveying is performed with longer range scanners,[45] the ranging accuracy of the equipment is then higher (15 mm at 6000 m range for a RIEGL VZ-6000, for example).[46] In 2010, Cuartero reports the fact that standards for error evaluation have not been established yet for the TLS instruments. Consequently, the accuracy specifications given by laser scanner producers in their publications were hardly

[38] Grzegoz Jóźków, Charles Toth and Dorota Grejner-Brzezinska, 'UAS Topographic mapping with velodyne LiDAR sensor', *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* III-1 (2016), 201–208.

[39] Markus Hillemanna and Boris Jutzi, 'UCalMiCeL – Unified intrinsic and extrinsic calibration of a multi-camera-system and a laserscanner', *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* IV-2/W3 (2017), 17–24; GIM-International, *UAS-based Lidar: A Market Update.*

[40] GIM-International, *The Current State of the Art in UAS-based Laser Scanning.*

[41] Ibid.

[42] Derek Lichti, 'Terrestrial Laser Scanning', Special issue. *Remote Sensing* (2011).

[43] Reha M Alkan and Gökçen Karsidag, 'Analysis of the Accuracy of Terrestrial Laser Scanning Measurements', *FIG Working Week,* 2012.

[44] Caltrans, Surveys manual, 'Terrestrial laser scanning specifications', June 2018.

[45] Sylvie Soudarissanane, Roderik Lindenbergh, Massimo Menenti and Peter Teunissen, 'Scanning geometry: Influencing factor on the quality of terrestrial laser scanning points', *ISPRS Journal of Photogrammetry and Remote Sensing* 66, no 4 (2011), 389–399.

[46] Andreas Kellerer-Pirklbauer, Arnold Bauer, Herwig Proske, 'Terrestrial laser scanning for glacier monitoring: Glaciation changes of the Gößnitzkees glacier (Schober group, Austria) between 2000 and 2004'. 3rd Symposion of the Hohe Tauern National Park. *Conference Volume for Research in Protected Areas,* 97–106.

comparable[47] and experience showed they should be considered cautiously. Nowadays, TLS are capable of superior point positioning accuracies compared to ALS.[48] The most recent review work done on TLS mentions that the accuracy of the instruments is in the range of that obtained by a total station.[49] The final absolute accuracy of the end product will finally depend on the accuracy of the GPS ground control points (around 2 cm at the best) plus the several millimetres or centimetre (varying with the range, angle and equipment) inaccuracy of TLS equipment.

Because of the low oblique angle of transmitted signals TLS could show some limitations with certain field situations. Incidence angle has an effect on data quality.[50] The laser footprint increases significantly as the incidence angle increases so normal incidence is recommended.[51] In the literature, many applications were done in canyons, quarries, glaciers, river beds were the laser bean could find vertical surfaces and/or be positioned from above helping with the incidence angle. Applications in flat plain terrain presenting small irregularities (micro topology) are less mentioned.[52] In contrast to ALS which acquires the data at near nadir view angles and thereby yield a relatively homogenous point distribution, TLS generates an irregular distribution of points.[53] The TLS points concentrate around the scanner and density decreases inversely proportional to the square of the distance to the scanner location.[54] So one can assume that a more consequent number of scans have to be done in flat terrain in order to ensure a correct accuracy and point density repartition. LiDAR impulses can also be reflected back to the scanner by obstacles and therefore shadows occur in the 3D point cloud.[55] This is an issue in areas with more rugged topography.[56] To mitigate these effects and to generate a 3D point cloud with a larger spatial extent, multiple TLS scans with different viewsheds can be combined in a single dataset.[57] Due to the irregular point distribution and the shadowing effect of obstacles, the separation of ground and non-ground points obtained by TLS is more complex than

47 Riegl, 'Data Sheet RIEGL VZ-6000', 01 September 2017.

48 Aurora Cuartero, Julia Armesto, Pablo Rodríguez and Pedro Arias, 'Error Analysis of Terrestrial Laser Scanning Data by Means of Spherical Statistics and 3D Graphs', *Sensors* 10, no 11 (2010), 10128–10145.

49 Ananda Fowler and Vladimir Kadatskiy, 'Accuracy and error assessment of terrestrial, mobile and airborne LiDAR', *ASPRS 2011 Annual Conference Milwaukee, Wisconsin,* 1–5 May 2011.

50 Ibid; Andri Baltensweiler, Lorenz Walthert, Christian Ginzler, Flurin Sutter, Ross S Purves and Marc Hanewinkel, 'Terrestrial laser scanning improves digital elevation models and topsoil pH modelling in regions with complex topography and dense vegetation', *Environmental Modelling & Software* 95 (2017), 13–21.

51 Ibid.

52 Most probably because LIDAR ultra-high accuracy measurements find limited interest in regular terrain; Sanna Kaasalainen, Anttoni Jaakkola, Mikko Kaasalainen, Anssi Krooks and Antero Kukko, 'Analysis of Incidence Angle and Distance Effects on Terrestrial Laser Scanner Intensity: Search for Correction Methods', *Remote Sensing* 3, no 10 (2011), 2207–2221.

53 Fowler, 'Accuracy'.

54 Weiming Xie, Qing He, Keqi Zhang, Leicheng Guo, Xianye Wang, Jian Shen and Zheng Cui, 'Application of terrestrial laser scanner on tidal flat morphology at a typhoon event timescale', *Geomorphology* 292 (2017), 47–58.

55 Fowler, 'Accuracy'; Baltensweiler, 'Terrestrial'; Thomas Hilker, Martin van Leeuwen, Nicholas C Coops, Michael A Wulder, Glenn J Newnham, David L B Jupp and Darius S Culvenor, 'Comparing canopy metrics derived from terrestrial and airborne laser scanning in a Douglas-fir dominated forest stand', *Trees* 24 (2010), 819–832.

56 Mike Pinkerton, 'Terrestrial Laser Scanning for Mainstream Land Surveying', *International Federation of Surveyors, FIG Congress 2010,* Sydney, Australia, 11–16 April 2010.

57 Fowler, 'Accuracy'.

for ALS data.[58] Finally, TLS is a very viable option in large open areas which require efficiency of data collection at a level of accuracy not obtainable by LiDAR (or a scale where the cost of LiDAR cannot be justified).[59] In a study, 7 ha were surveyed in 5 hours by 2 surveyors.[60]

Regarding the applicability of TLS to our goals, there are several limitations we could mention. The first one is the necessity to be in the field to perform the measurements which can be a concern if the polluted material is hazardous for health. The second concern is the fact that the campaign should be carefully planned in order to avoid any shadow area; in particular as the shadow would appear in some place where the terrain is irregular and where accuracy elevation model is expected. So a prerequisite would be to do terrain reconnaissance to plan the measurement campaign. Usually, it is not the most efficient approach. The last constraint is to really carefully consider the oblique angle effect and again carefully plan the scanning geometry.

3.6. Interferometric synthetic aperture radar (InSAR)

Compared to the other techniques, the Interferometric Synthetic Aperture Radar (InSAR) is relatively new.[61] The ground based SAR is a radar-based terrestrial remote sensing imaging system[62] making use of the phase information contained in the Synthetic Aperture Radar (SAR) images. It consists of a radar sensor that emits and receives a burst of microwaves, repeating this operation while the sensor is moving along a rail track.[63] The imaging capability is achieved by exploiting the Synthetic Aperture Radar (SAR) technique.[64] By exploiting the interferometric capability of centimetre-wavelength microwaves, this technique has high sensitivity in the region of submillimetres to millimetres.[65] It is a long-range measurement device, which can work up to some kilometres.[66] SAR measures in two dimensions. The development of InSAR allowed to measure in 3 dimensions (stereo-radargrammetry). Instead of cameras being used as in photogrammetry, radargrammetry is achieved from active

58 Pinkerton, 'Terrestrial'; Helmut Panholzer and Alexander Prokop, 'Wedge-filtering of geomorphologic terrestrial laser scan data', *Sensors* 13, no 2 (2013), 2579–2594.

59 Hilker, 'Comparing canopy metrics'.

60 Ibid.

61 Emilio Rodríguez-Caballero, Ashraf Afana, Sonia Chamizo, Albert Solé-Benet and Yolanda Canton, 'A new adaptive method to filter terrestrial laser scanner point clouds using morphological filters and spectral information to conserve surface micro-topography', *SPRS Journal of Photogrammetry Remote Sensing* 117 (2016), 141–148; O Monserrat Hernández, *Deformation measurement and monitoring with Ground-Based SAR* (PhD dissertation, Universitat Politècnica de Catalunya, 2012).

62 Zou Weibao, Li Yan, Li Zhilin and Ding Xiaoli, 'Improvement of the Accuracy of InSAR Image Co-Registration Based On Tie Points – A Review', *Sensors* 9, no 2 (2009), 1259–1281.

63 Dario Tarchi, Haraksim Rudolf, Guido Luzi, Leandro Chiarantini, Peter Coppo and Alois J Sieber, 'SAR interferometry for structural changes detection: a demonstration test on a dam', *IGARSS,* Hamburg, Germany, 1999, 1522–1524; Giulia Bernardini, Pier P Ricci and Francesco Coppi, 'A ground based microwave interferometer with imaging capabilities for remote measurements of displacements'. *Proceedings of the Galahad Workshop within the 7th Geomatic Week and the 3rd International Geotelematics Fair (GlobalGeo),* Barcelona, Spain, 20–23 February 2007.

64 Ramon F Hanssen, *Radar Interferometry* (Dordrecht: Springer, 2001).

65 Rodríguez-Caballero, 'A new adaptive'.

66 Ibid.

radio detection and ranging (RADAR).[67] The technique is mainly used to monitor a wide range of deformation phenomena, ranging from a few millimetres per year up to metres per day. If deformation is not in the focus of this study, the generation of digital surface models (a prerequisite to deformation monitoring) is.

By exploiting the phase of the coherent radar signal, interferometry has transformed radar remote sensing from a largely interpretive science to a quantitative tool, with applications in cartography, geodesy, land cover characterisation and natural hazards.[68] InSAR has been recognised as a potential technique for generating digital elevation models (DEMs) by using the phase component of the complex radar signal[69] and the measurement of ground surface deformations.

Montserrat brings very interesting elements of information and concrete figures regarding the influence of the reflectors on the performance of a DSM.[70] He first mentions that the performances of a DSM are rather a function of the average reflector available in a scene; then he mentions strong reflectors are very rare in a natural scene. As a consequence, the majority of the pixels of an interferogramme will not have the researched performance and DSM will not have a uniform coverage. For a typical surface covered with grass (with a high phase noise standard deviation equal to $\pi/5$ rad) the standard deviation of the error in elevation (σz) is in the order of meters. For instance, at a distance of 1200 m the σz is equal to 5.2 m. This accuracy is clearly insufficient compared to the goal of our study. Secondly, Montserrat mentioned that disambiguation is achieved with the help of a DSM.

InSAR data processing consists in image co-registration, interferogram generation, phase unwrapping and geocoding.[71] The resolution of equation and post-processing is a complex task which make infererogramme generation a not straightforward process.

4. Analysis and discussion

The table below recapitulates the advantages and disadvantages of the technologies.

Table 1: Comparison of technologies
Source: Compiled by the authors.

Technology	Advantage	Disadvantage
TLS	Higher accuracy	Point density Accuracy decreases when range increase; occlusion effects = lot of shooting points necessary, not appropriate for extended areas Not appropriate for dangerously contaminated areas

67 Ajayi et al., 'Generation'.
68 Paul A Rosen, Scott Hensley, Ian R Joughin, Fuk K Li, Søren N Madsen, Ernesto Rodríguez and Richard M Goldstein, 'Synthetic Aperture Radar Interferometry', *Proceedings of the IEEE* 88, no 3 (2000), 333–382.
69 Monserrat, 'Deformation'.
70 Rodríguez-Caballero, 'A new adaptive'.
71 Monserrat, 'Deformation'.

Technology	Advantage	Disadvantage
ALS	Efficiency over extended areas Point density	Vertical accuracy limit near 5 cm
InSAR		Point density as natural terrain has insufficient number of good reflectors Requires DSM for post-processing and interferograms' generation
UAV photog-rammetry	Low cost – good solution for several hectare areas Point density Accuracy improves when flight altitude is lowered	Spatial efficiency decreases when flight altitude is lowered
UAV LiDAR	Point density	Vertical accuracy not competitive with ALS or photogrammetry Efficiency

As described in the part addressing quality attributes of DEMs, point density and its regular distribution are key quality factors for an elevation model. To this end, aerial remote sensing approaches should be favoured as they ensure the best distribution of the point density in the point cloud; which is not the case with the ground base approaches. Additionally, ground base approaches could not be reliable in case of an environment made hazardous or dangerous by technological disaster. Taking the remediation specificities and challenges, two technologies are of interest: the UAV photogrammetry and ALS. ALS is favoured for extended areas, the UAV approach is favoured for small to medium scale areas.

Table 2: Technical specifications and recommended technologies
Source: Compiled by the authors.

Technical specifications	Recommended technology
Few Ha, mm or cm vertical accuracy	UAV photogrammetry at low altitude
Few Ha, cm accuracy	UAV photogrammetry
Few km^2, cm accuracy	UAV photogrammetry (reaching the limit of efficiency)
>10 km^2, 1 cm accuracy	No technical solution
>10 km^2, 5 cm accuracy	ALS

5. Conclusions

This study demonstrated the advantages offered by aerial remote sensing technologies (ALS and UAV photogrammetry) over terrestrial survey methods because they allow the production of sufficiently dense point clouds with homogeneous distribution. Moreover, terrestrial approaches have high chances to be not practicable in case dangerous substances spill or the environment is too much hazardous to operate with the measurements.

UAV photogrammetry is efficient for covering small to medium sized AOIs. When the surface of the AOI increases over several km^2 only ALS technology offers sufficient efficiency. For the sake of absolute vertical accuracy, ALS can nowadays achieve at best 5 cm. Vertical absolute accuracy with UAV and photogrammetry varies with the pixel size; commonly 2–3 GSD can be achieved. The efficiency of UAV and photogrammetry approach decreases when AAG decreases and the technique is not appropriated for extended AOI (superior to 10 km^2).

Additionally, TIN size issues should be considered to find the compromise between light data allowing fast processing but qualitative data for sufficient accuracy.

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