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Remote sensing archaeology: Tracking and mapping evolution in European scientific literature from 1999 to 2015

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ABSTRACT

This paper discusses the on-going research related to remote sensing archaeology in Europe, since the launch in 1999 of the first high resolution satellite sensor IKONOS. During these 16 years, significant technological improvements have been made both in space sensors as well in other non-contact remote sensing technologies, providing new tools for scientists to search the hidden past. The analysis presented here follows a citation based approach, where useful information is retrieved from the scientific literature. The paper visualises these trends by constructing science maps, based on bibliographic data of established research journals, found in Scopus, ScienceDirect and Web of Science (WoS) search engines. In addition, mapping and clustering analyses were carried out considering the Institutions that applied remote sensing technologies for archaeological purposes, thus providing a better insight and understanding of the current status of remote sensing archaeology in Europe. Time-stamped maps from 1999 until 2015 indicate on one hand that remote sensing technologies are widely accepted and applied by the archaeological community, but at the same time they make clear that substantial gaps still exist amongst European countries. Finally, the popularity of specific terms or the emergence of new terms in scientific literature through time is also presented, providing a synoptic view of the history and development of the remote sensing archaeology discipline. The discussion section analyses the gaps of the current study mainly due to "missing literature". The paper underlines the need for the development of a common depository of all knowledge, acquired by the scientists operating in the field worldwide, to improve the "transfer of knowledge" and therefore harmonise the existing gap between the different scientific fields of remote sensing archaeology.

1. Introduction

The paper aims to synthesize, analyse and visualize the latest research relevant to remote sensing intended for archaeological applications, based on the pertinent scientific literature following a citation-based approach. The term "remote sensing archaeology" includes various types of remote sensing technologies, namely satellite remote sensing, aerial photography, geophysical prospection, and Unmanned Aerial Vehicles (UAVs). Hence, in its broadest sense and in relation to archaeology, remote sensing encompasses methods to discover and map remnants of past civilisations above or below ground level (De Laet et al., 2007).

As Giardino (2011) argues, multispectral and hyperspectral instruments mounted on orbiting and sub-orbital platforms have provided new and important information for the discovery, delineation and analysis of archaeological sites worldwide. A major improvement for archaeological research applications was achieved by the end of the 20th century (1999) with the launch of IKONOS, the first commercial very high-resolution satellite with 1 m spatial resolution. Its importance lies primarily to its potential of providing systematic multispectral data over archaeological sites and monuments (De Laet et al., 2007; Garrison et al., 2008; Di Giacomo et al., 2011; Deroin et al., 2011; Agapiou et al., 2013a, 2014a; Lasaponara et al., 2014).

Since then, satellite remote sensing has been widely applied to numerous archaeological investigations in several parts of the world (Parcak, 2009; Alexakis et al., 2009, 2011; Aqdus et al., 2007, 2008; Lasaponara and Masini, 2006; Altaweel, 2005; Agapiou et al., 2012). The improvements of satellite sensors in terms of spatial and spectral characteristics (e.g. WorldView-2) attracted the interest of even more scientists, who started applying image processing techniques to either identify traces of past human activity (Pappu et al., 2010; Morehart, 2012; Sarris et al., 2013; De Laet et al., 2015), or develop methodologies for systematic monitoring of cultural heritage sites and monuments (Agapiou et al., 2015; Chen et al., 2015).

Aerial images have been systematically exploited for archaeological research from the beginning of the 20th century (Capper, 1907; Crawford, 1923; Keneddy, 1925; Glueck, 1965; Evans and Jones, 1977; Riley, 1987; Bewley et al., 1999; Traviglia and Cottica, 2011), and they

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still continue to provide valuable information to archaeologists. The use of new airborne sensors (such as LiDAR and hyperspectral cameras, e.g. MIVIS) has provided new possibilities for the investigation of archaeological landscapes. “Flights into the past” (see Lasaponara et al., 2011a; Musson et al., 2013) can improve our knowledge providing detail Digital Surface Models (DSMs) in forested areas as well as narrowband hyperspectral signatures for detection of crop and soil marks (Rowlands and Sarris, 2007; Bassani et al., 2009).

UAVs can be seen as the next trend for remote sensing archaeology. Their relatively low cost along with the high resolution data, provided by small sensors attached to these UAV systems (Colomina and Molina, 2014), have demonstrated their potential use in archaeological surveys (Mozas-Calvache et al., 2012; Themistocleous et al., 2015). These technologies motivated researchers to further explore new scientific means in mapping archaeological traces, such as the use of aerial thermography (Casana et al., 2014) and near-ultraviolet images (Verhoeven and Schmitt, 2010).

Moving to ground technologies, geophysical surveys are considered to be very precise in detecting sub-surface remains. Different geophysical processing techniques and equipment (such as ground penetrating radar (GPR), magnetometry and resistivity) are usually integrated together, to maximize the success rate of uncovering archaeological remains (Domínguez et al., 2013; Sarris et al., 2004, 2013; Novo et al., 2014).

Different technologies co-exist in the remote sensing archaeology field and, hence, a different approach might be followed in each case study. It is now frequently observed in literature that these different remote sensing technologies are combined to integrate the overall results into a Geographical Information System (GIS). Archaeological information related with each case study (i.e. archaeological findings; foot surveys etc.) is also imported into the GIS environment to assist the overall interpretation of the results (Luo et al., 2014; Colosi et al., 2009).

As in any scientific research field, remote sensing archaeology is composed of many subfields and underlying technologies which are related in intricate ways. The “research landscape” of remote sensing archaeology is not static, but a continuous development of technologies and improvements of algorithms. In the near future, new satellite sensors are expected to be launched (i.e. Sentinel missions) providing even more data for archaeological applications. In this frame, the current study aims to document the latest recent trends in remote sensing archaeology. Bibliometric analysis (see Chen, 2006) is used, as it can provide statistical information for remote sensing archaeology surveys, undertaken in Europe and beyond within the last 16 years. Bibliometric analysis may also indicate other important parameters such as the performance of each region in the field of remote sensing archaeology, the spatial distribution of remote sensing archaeology, as well the collaborations between various European institutions through time. Communication through collaboration is a crucial aspect of science and, hence, this paper attempts, for the first time, to indicate the current status of the remote sensing archaeology as a scientific research field, shifting from local applications to the regional (European) and international level. In parallel, the paper discusses the remote sensing technological achievements in relation to the aims and scopes of archaeological science.

2. Methodology

A detailed literature review was carried out, based on the publications of established journals. The Scopus and ScienceDirect scientific databases were used, and the time of publication (1999 — June 2015) was set as the principle search parameter. Specific keywords were retrieved from the title, abstract and keywords of each journal paper. Scopus is the largest abstract and citation database of peer-reviewed literature: scientific journals, books and conference proceedings; it delivers a comprehensive overview of the world's research output in the fields of science, technology, medicine, social sciences, and arts and humanities, Scopus features smart tools to track, analyse and visualize research. As research becomes increasingly global, interdisciplinary and collaborative, search engines such as Scopus can provide an easy way for tracking new papers (Scopus). ScienceDirect is a full-text scientific database which is part of SciVerse and is provided by Elsevier. ScienceDirect refers to 2500 peer-reviewed journals and more than 11,000 books. In summary, it offers more than 9.5 million articles and book chapters (Tober, 2011).

The final keywords selected were: remote sensing archaeology (434 records), satellite archaeology (268 records), aerial archaeology (294 records), geophysics archaeology (294 records) and UAV archaeology (37 records). In total, 1274 different records were indicated in both engines; on average, these are estimated to 85 records per year. Web of Science (WoS) was also explored initially, but the final results were found to be limited (e.g. less than 30 papers for “remote sensing archaeology”). This is because several journals are not listed yet in the WoS database. Nevertheless, even this limited number of articles retrieved from WoS was also found through the Scopus and ScienceDirect engines. Secondary keywords (such as hyperspectral archaeology, crop marks archaeology, space archaeology and GPR archaeology) were also investigated; however these keywords provided fewer results than the more general keywords, discussed above.

Scopus, ScienceDirect and WoS engines provided simple but significant statistics for each journal, such as publications per year and per country. For more detailed analysis of the above mentioned records, the Cite Space software (version 3.9 R9) was used (Chen, 2004, 2006). Details regarding the specific software can be found within Cite Space's manual. Yearly reports (“slices”) from 1999 until 2015 were analysed and exported from the software. The selection criteria for each slice was adjusted to the 50 most cited papers per year, while the nodes were based on the terms and keywords parameters. To map the key institutions and regions related to remote sensing archaeology, another selection was carried out based on institutions (i.e. author and co-authors institutions for each paper).

3. Results

3.1. Search results from database engines

The results of database engines can provide some information related to the scientific field of remote sensing archaeology. As Fig. 1 shows, a linear increase of published material is recorded between 1999 and 2015. This indicates the high importance and the acceptance that remote sensing technologies have gained in the field of archaeological science over the last 16 years.

Using the statistical tools of the various database engines employed in this study, the affiliation of the journals' authors as well the publication journal were extracted for each filtered keyword (remote sensing archaeology, satellite archaeology, aerial archaeology, geophysics archaeology and UAV archaeology). These results were then tabulated and summarized. Fig. 2 (bottom) highlights the top five affiliations (as a country) and the top five publishing journals (Fig. 2, top). As shown in Fig. 2 (bottom), United States of America (USA), Italy (IT) and United Kingdom (UK) are the leading countries where local institutions published results related to the general topic of remote sensing archaeology. Other European countries followed, such as Belgium (BE), France (FR), Greece (GR), Germany (DE) and Cyprus (CY).

The journals publishing the thematic topics, considered in this study, are quite heterogeneous in terms of the core scientific interest that they represent (Fig. 2, top). This thematic diversity is not surprising, if we consider the multidisciplinary character of remote sensing archaeology, which involves researchers with different scientific backgrounds (such as satellite remote sensing, geophysics, photogrammetry, GIS and archaeology). However, the Journal of Archaeological Science (JAS) seems to hold the leading role for all the filtered keywords except from “UAV archaeology” which more cited papers are found at the

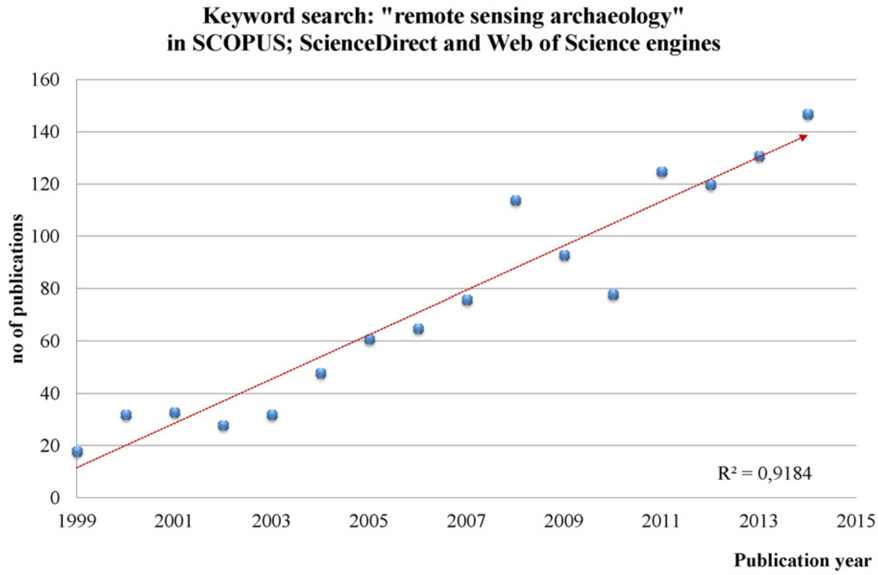

Fig. 1. Final results of publications used in this study from the Scopus; ScienceDirect and WoS engines.

International Society of Optics and Photonics (SPIE) Proceedings". The JAS is followed by several other scientific journals. The list includes the SPIE Proceedings, Archaeological Prospection, Antiquity, Journal of Cultural Heritage, Lecture Notes Proceedings and International Journal of Remote Sensing. The various journals that accept and publish material related to remote sensing archaeology demonstrate the difficulty for readers/scientists to follow and update their knowledge.

3.2. Terms through time

Based on the results of the search carried out in the three main depositories, a citation based approach was followed to investigate further the evolution of literature through time. Using the Cite Space tool, it was possible to track and record the scientific shift of the remote sensing archaeology between 1999 and 2015 (Fig. 3). The size of each circular node in Fig. 3 indicates the total citations that each term received through the period under study (i.e. the number of citations increase with the circle's size). The generic terms "archaeology", "remote sensing" and "geophysics" are the ones to be found most frequently within the relevant literature, followed by the terms "magnetometry", "electromagnetic", "cultural heritage", "aerial archaeology" and "3D GPR". The horizontal axis of Fig. 3 indicates the results for each slice (year). The position of a term within the vertical slice indicates the year that this term was for the first time most cited. For instance the term "archaeology" was most cited by the beginning of 1999 (the lower year limit set for the purpose of this study) and since then was systematically cited within the relevant literature.

It is interesting to note that the term "IKONOS" is firstly observed in this time-zone diagram only in 2008 (i.e. 9 years after the launch of the satellite). Although IKONOS images were used earlier for archaeology (e.g. De Laet et al., 2007), their systematic exploitation, was delayed for almost a decade. As shown in Fig. 3, Landscape archaeology, a term widely used in archaeology (Hritz, 2014), appears for the first time as a highly cited term only in 2009. Radar images ("ALOS Palsar"), "coastal archaeology", "computer vision" and "archaeological index" comprise some of the contemporary terms most frequently used in the relevant literature between 2013 and 2015. The exploitation of radar sensors has only recently been investigated, and this is mainly due to the improvements of the spatial resolution of the satellite sensors (Lasaponara et al., 2011b). In a similar way, "coastal" or even "underwater archaeology" is another recent topic, where new technologies (such as LiDAR) allowed archaeologists to investigate these environments (Chase et al., 2011; Štular et al., 2012). While "archaeological index" has been recently proposed as an image filter to enhance the interpretation of crop marks linked with buried archaeological remains (Agapiou et al., 2013b).

3.3. Time and space

Fig. 4 presents the results of the citation based approach followed in this study. As mentioned earlier, a threshold of the 50 most cited papers was adjusted to the results for each year (slice). According to the results and as demonstrated in Fig. 4 for 1999, the first institutions that published in highly cited scientific journals were limited mainly to Italy and UK. This is not surprising since these two countries have long history and archives of aerial photography and photo-interpretation of vertical or off-nadir images. Sporadic applications (of highly cited papers) dealing with remote sensing archaeology are also found between 2001 and 2005. 2007 could be considered as a milestone for remote sensing archaeology, since several European institutions used and exploited non-contact technologies in a more systematic way. Several institutions from Italy, Greece, France, Germany, Netherlands and especially the UK exploited the potentials of geophysical surveys, satellite archaeology and aerial photography to support archaeological research. Since then, institutions from Spain, Portugal, Turkey, Cyprus and other countries integrated and applied remote sensing technologies for archaeological research. It is important to note that Fig. 4 does not indicate the geographical areas of interest (i.e. archaeological sites) on which remote sensing techniques have been applied, but the institutions that carried out these applications and consequently published their results. From this perspective, Fig. 4 indicates the know-how and experience of the regions related to remote sensing archaeology. It is also becoming evident that some regions only recently were familiarized with these technologies.

Based on the overall results of Fig. 4 (i.e. institutions worked in remote sensing archaeology for the period 1999–2015), a density map was produced at a European level, based on kernels interpolation (Fig. 5). As stated earlier, these institutions are the most cited (i.e. threshold = 50 most cited papers per year from 1999 to 2015) as found from the relative literature examined in this study. Red colour indicates areas with high density of institutions received a high number of citations. Regions with no colour indicate that the total citation number

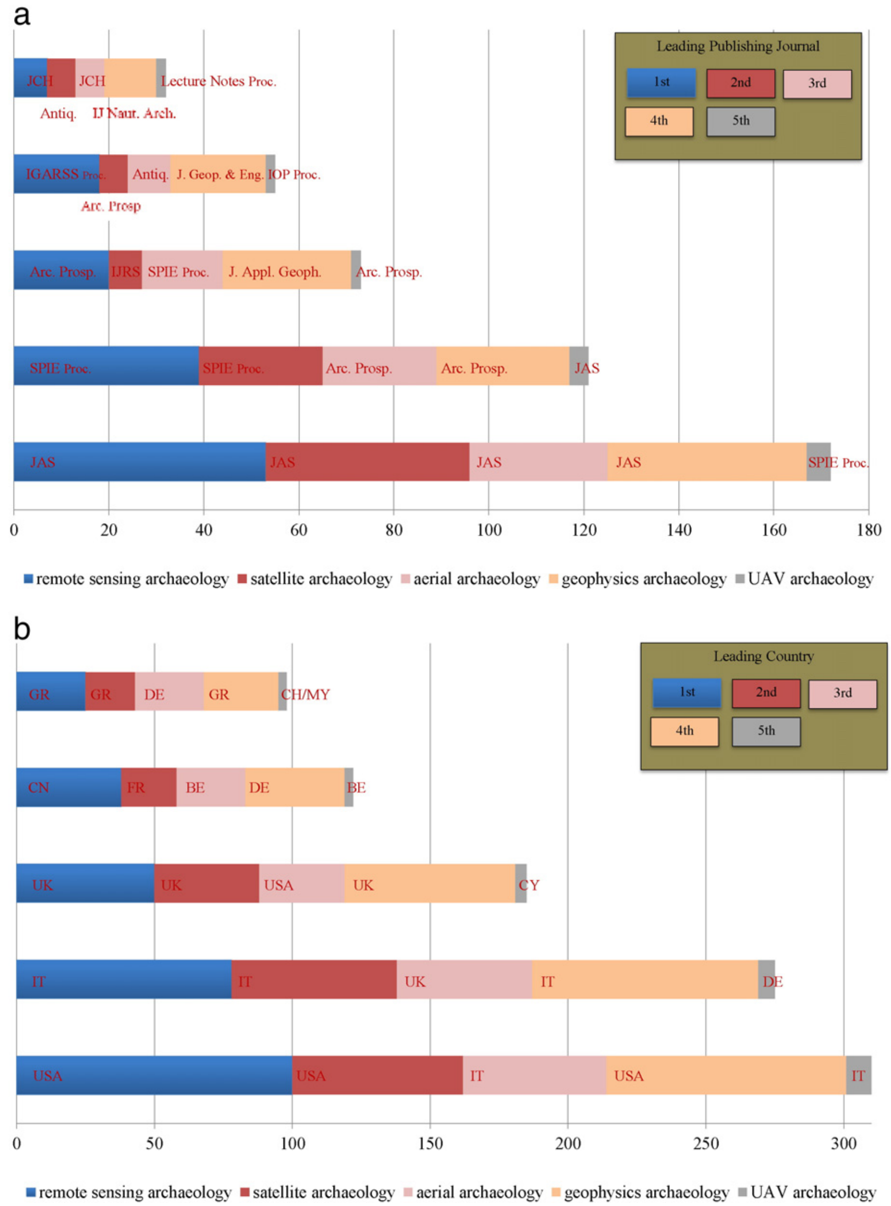

Fig. 2. Top five results related to journals publishing material related with remote sensing archaeology (top) and top five affiliations (as countries) publishing articles in relation to the keywords — terms filtered through the different database engines (bottom).

was very poor. Fig. 5 reveals that remote sensing archaeology is still fragmental at the European level. UK, France, Belgium, Netherlands and Italy are considered to be leading countries for such technologies (indicated as red clusters in Fig. 5). Based on the results from Scopus, ScienceDirect and WoS engines, it is becoming evident the research gap between Western and Eastern Europe. However, this quantitative disparity between western and eastern European institutions does not imply the total absence of relative scientific publications from Eastern Europe. Published material is found for example in local journals and conference proceedings, being however not easily accessible to the wider scientific community (see Section 4 below). Furthermore, these are usually issued in the local language, which does not always permit a direct reading.

3.4. European and word perspective

Moving to a global view of remote sensing archaeology publications (Fig. 6), Europe is by far the most crowded region, where several institutions are emphasizing in the application of remote sensing technologies for archaeological research and publish English-written papers in the three main depositories discussed here. The eastern part of USA presents the greatest activity in the field followed by China, Japan, India and Australia. Fig. 6 indicates the dissimilarity that exists between these areas and other parts of the world (e.g. Africa, Southern America, Middle East etc.). Despite the logical argument that these regions may publish scientific material in local journals (and are therefore not included in the database engines under consideration), still this condition restricts other researchers from appreciating the status of remote sensing archaeology and the exchange of new ideas through publications.

Fortunately, a strong communication between the institutions does exist; this knowledge transfer, mapped in Fig. 7, reflects co-publications between authors from different institutions. Again Europe seems to play a key role to this exchange of knowledge, since several European institutions have collaborated with non-European institutions in different ways. Collaborations between other continents are also mapped (e.g. Australia and North America).

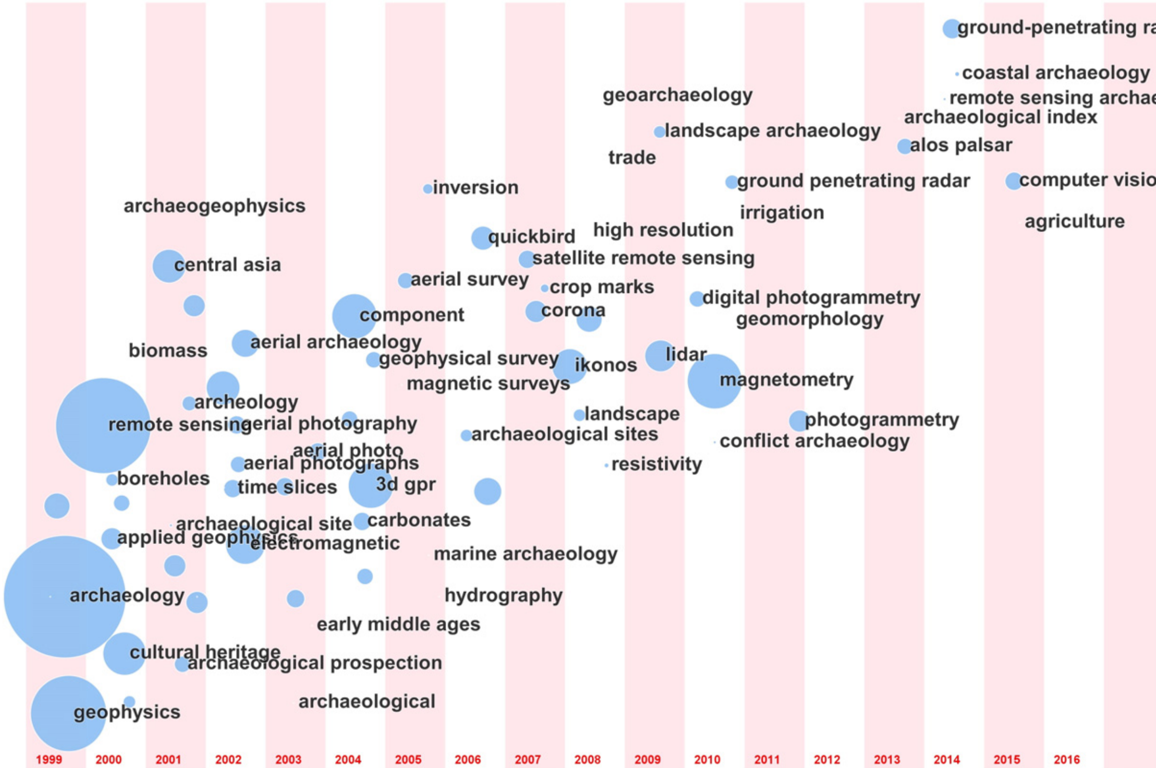

Fig. 3. Time-zone diagram indicating the top cited terms for the period 1999–2015. The size of the node indicates the total number of citations while the year where each node appears indicates the first time (year) that this term was most cited. The distance between each node indicates the relation between these nodes (terms) as found in the literature.

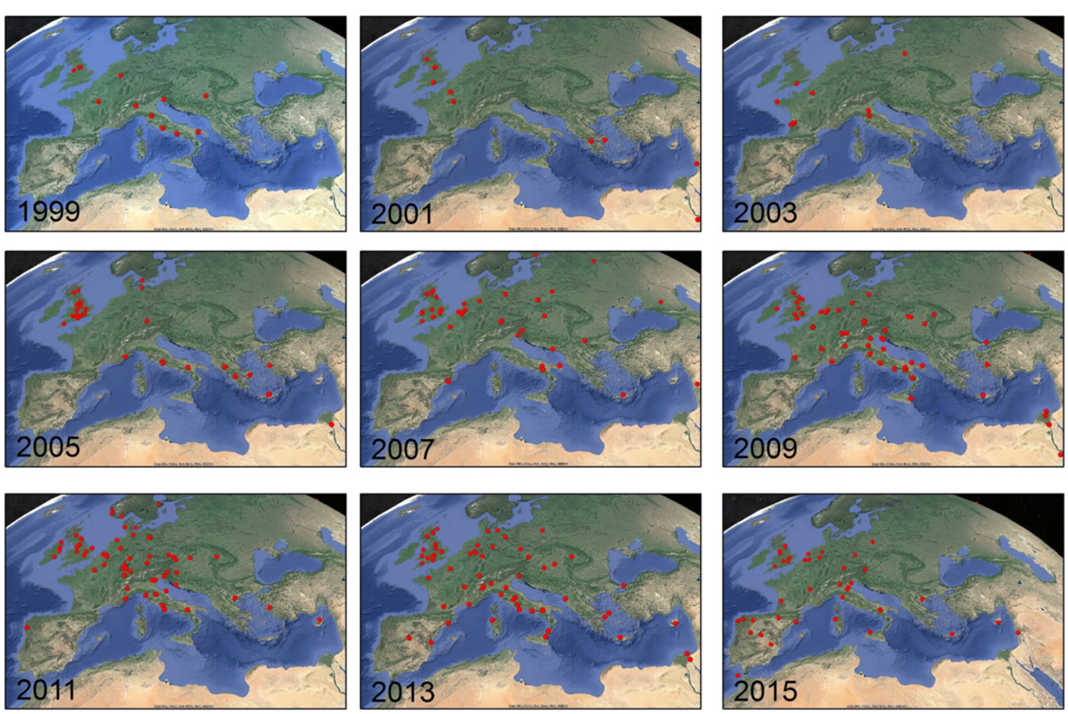

Fig. 4. Visualization of the countries/institutions employing remote sensing techniques for archaeological research covering the chronological span between the years 1999 until 2015 (2 years interval).

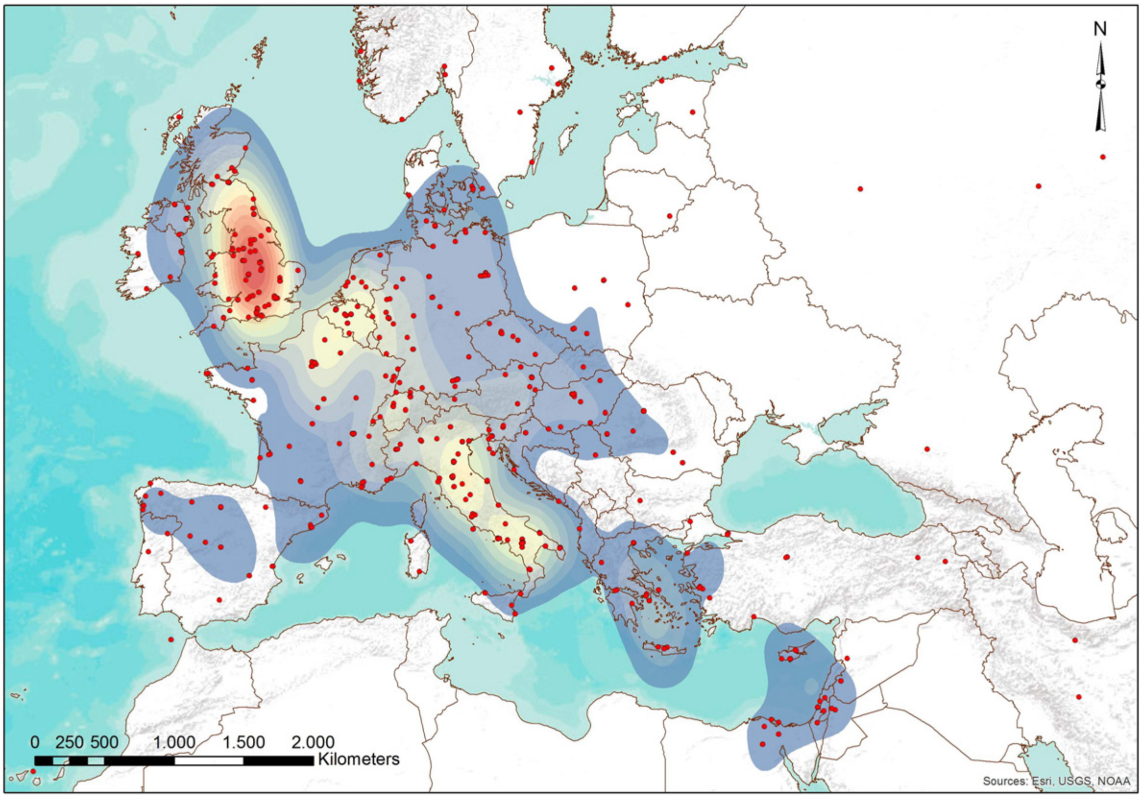

Fig. 5. Density map indicating clusters according citations for remote sensing archaeology in European level. Red colour indicates areas with high density of institutions received a high number of citations. Regions with no colour indicate that the citation number was very poor.

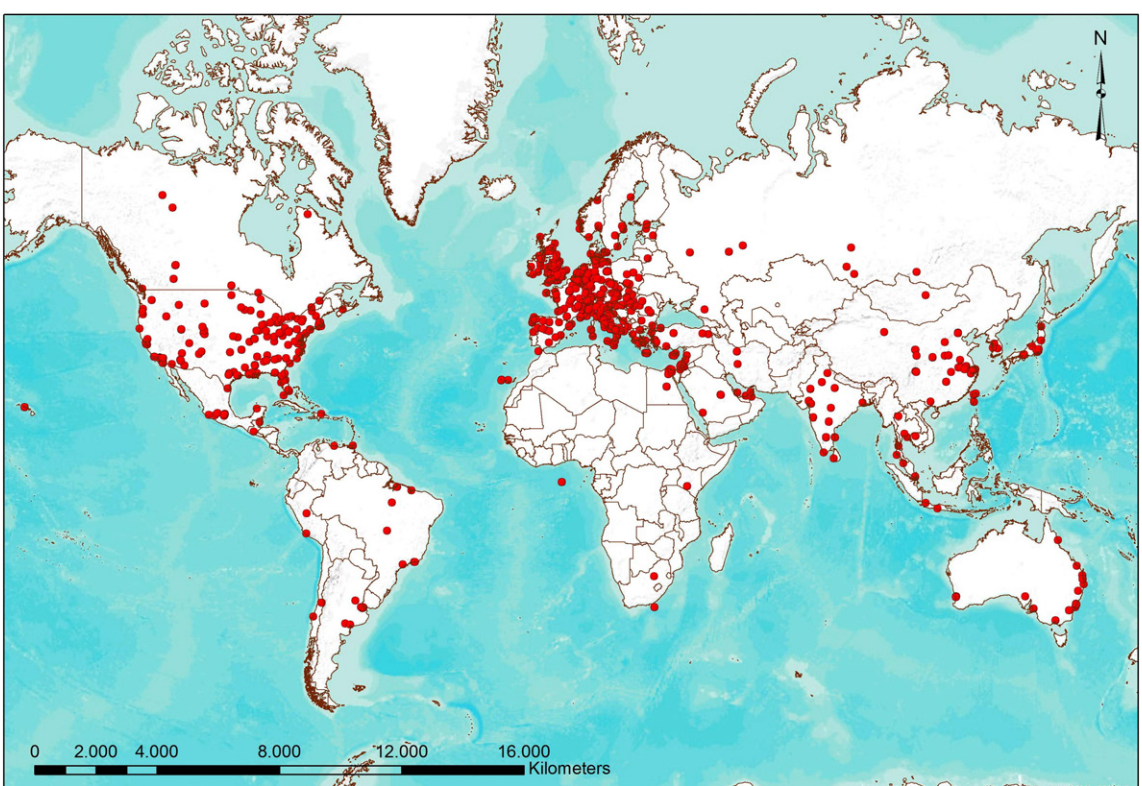

Fig. 6. Visualization of remote sensing archaeology scientific publications worldwide.

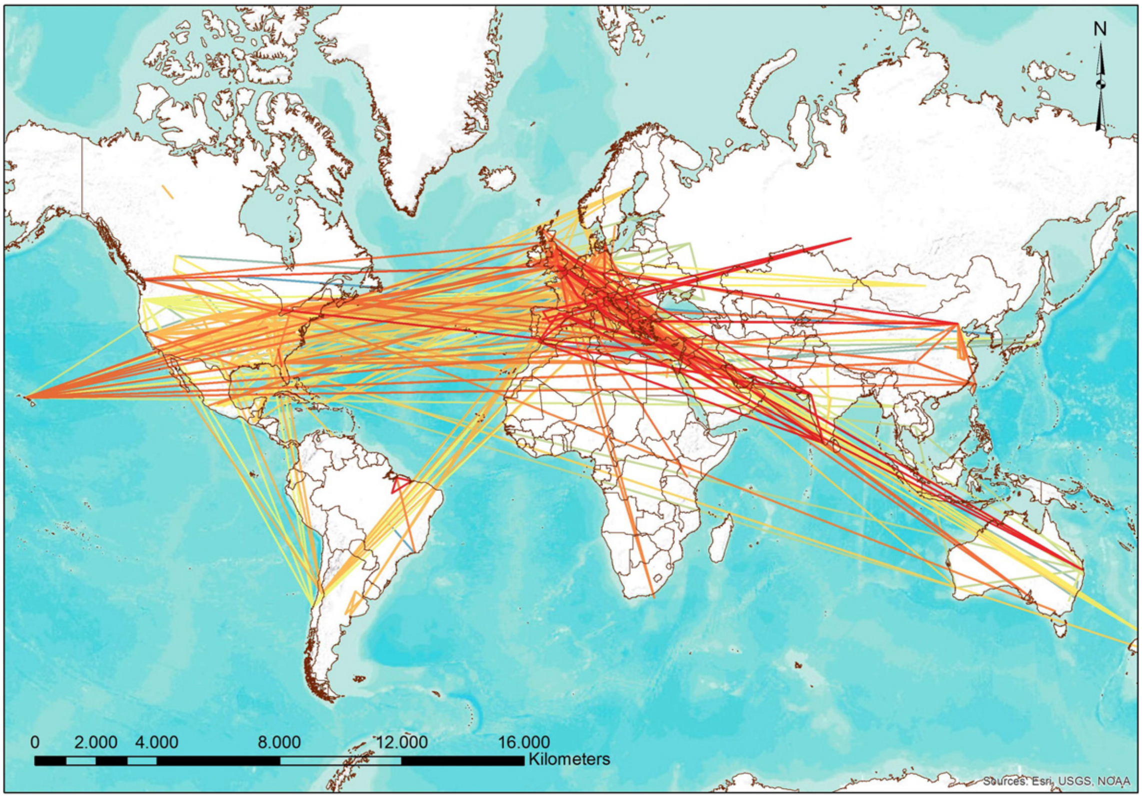

Fig. 7. Visualization of institutions exchange and transfer of knowledge in global level.

4. Discussion

4.1. The citation based approach and missing literature

In this study, a citation-based approach was performed. The logic beneath is that citations represent the impact of scholars' research (Garfield, 1973). As discussed earlier, the study included only English-written publications and, hence, the results are only indicative of the current state of the art. Since the results are based on the citation score, it is expected that the trends will change after a period of time, since recently published papers require some time to becoming highly cited papers. Furthermore, the current study is by no means exhaustive, since it focused on three main scholar depositories: Scopus; ScienceDirect and WoS. However, it should be noticed that even though other engines do exist, such as Google Scholar, the metrics provided from those could not be used mainly due to the "noise" of the outcomes. As Bauer and Bakkalbasi (2005) argue, Google Scholar can give a full account of what material it is indexing and how often that index is updated, but it cannot be considered a true scholarly resource in the sense that WoS and Scopus are.

Another critical parameter is the missing literature that is not recorded here. This missing literature reflects conferences, workshops, round tables and various collections dealing with remote sensing archaeology. These databases include, for example, the Archaeological Institute of America (AIA), Society for American Archaeology (SAA), American Anthropological Association (AAA), European Association of Archaeologists (EAA), Aerial Archaeology Research Group (AARG), European Association of Remote Sensing Laboratories (EARSeL), Computer Applications of Archaeology (CAA), British Archaeological Reports (BR) or even PhDs and MA/MSc theses. Indeed, in recent years there has been an increasing number of remote sensing specific panels and sessions, showing how much the field of remote sensing is growing, as well the rich diversity of research across Europe and elsewhere. Although, this literature should not be underestimated, the authors have knowingly avoided excluding such information for two reasons, as explained next.

- In this study a citation-based approach was followed. Therefore, it is practically impossible (under the current status of how publication procedures work) not only to track, but to go one step forward and identify the citations of these papers. Even a detailed attempt to collect as much information as possible will skew the final outcomes.
- Many of these conference or workshop articles consist only a part of the publications in scientific peer reviewed journals.

The present study renders plausible the need of a scientific depository for remote sensing archaeology, where all kinds of publications of the field could be detectable and accessible for the researchers.

4.2. Satellite archaeology or space archaeology?

Due to its interdisciplinary nature, research on remote sensing archaeology topics may appear in sources that are part of various academic disciplines. Thus, it is not rare to find through literature a variety of different terms, related to remote sensing archaeology, such as "satellite archaeology" and "space archaeology", or "airborne archaeology" and "aerial archaeology". This has a great impact on researchers tracking articles and books, published with differing search terms.

A standardization of terms, related with the variety of aspects of remote sensing, can tackle this issue, although this should not in any case considered as an easy task. The interoperability and simplification of the data themselves can support this aspect, but the different heterogeneous problems of the data should be firstly solved (semantic heterogeneity; schematic heterogeneity; syntactic heterogeneity).

It is important also to highlight the fact that the two fields of geophysical and aerial/space based remote sensing are quite different, and therefore are not yet merged. Furthermore, these fields are not as connected (e.g. fusion of data) as many think they should be for archaeological research. This "fusion" of data has been and will be, in the near future, a hot topic for remote sensing applications in archaeology. Although attempts have been made to integrate or fuse ground and aerial/space based data (e.g. Sarris et al., 2013), there is still a long way before getting there. However, space technology is moving really fast and several achievements are expected to be applied in the forthcoming years. An example is the new world Digital Elevation Model of TanDEM-X, the very high resolution of WorlView-3 with 31 cm pixel resolution or even the multi-temporal images (5 days) from Sentinel 2 sensor.

4.3. Future of remote sensing

An important question which arises from the results of the above bibliometric analysis is related to the future of remote sensing archaeology as a science itself. Remote sensing for archaeology, regardless of the technological tools and procedures employed for each case, seems to be widely accepted and established through time. New technologies (such as radar satellite images, interferometry and LiDAR) have already been applied at various archaeological sites (Štular et al., 2012; Gaber et al., 2013; Tapete et al., 2015). New satellite sensors, such as Sentinel missions, are also expected to support archaeological research in the near future (Agapiou et al., 2014b). The WordView-3 sensor with a spatial resolution of 31 cm highlights the latest achievements of space technology. Using data with such an improved quality, scientists can seek even more elaborate details for sub-surface remains and a better understanding of archaeolandscapes.

However, at the same time, significant gaps exist at a European as well as at the global scale. A critical aspect of the gap observed in Europe is not limited only to transfer of knowledge, but also to the improvement of existing scientific practices. Although remote sensing as a science itself acquires information from distance, there is a great need for ground truth verification of the results as well for calibration of the instruments or improvements of existing algorithms. From this perspective, it can be argued that methodologies applied in a specific archaeological environment might not adequately work in other sites (Beck, 2007). In addition, archaeological surveys and findings should always be linked with the interpretation results of the remote sensing data. In this way, a fruitful communication between archaeology and remote sensing (and vice versa) can be achieved.

It is also very common to perceive that archaeological questions and actual archaeological needs do not exactly match within the framework of existing remote sensing sensors. For instance, research related with the detection of mineral deposits was until recently based mainly on ASTER datasets with spatial resolution of 15 m; this was due to the capability of the sensor to record the MIR and SWIR part of the spectrum. Only lately, with the launched of WorldView sensors, scientists can work with very high resolution multispectral data in this specific part of the spectrum.

Consequently, remote sensing archaeology, as a scientific research field per se, needs to be able of merging technological improvements of remote sensing sensors with archaeological questions and archaeological needs; and this is to improve the quality of information retrieved from remote sensing data.

5. Conclusions

This paper presents the current status of remote sensing archaeology based on statistical analysis of published, English-written, journal papers, found through the Scopus, Science Direct and WoS engines. Future work may assess the performance of other existing databases such as Google Scholar.

Remote sensing technologies are used to support archaeologists in providing useful information for sub-surface remains, for documentation of sites and landscapes, for monitoring of cultural heritage sites. This initiative, which started approximately 16 years ago (i.e. 1999), became a trend and its course, development and evolution have been tracked through the relevant literature, where several new papers have been published dealing with one or more aspects of remote sensing, archaeology and cultural heritage.

Remote sensing technologies and image analysis algorithms have been merely applied in different archaeological and cultural heritage contexts with different rates of success. Along with the technological achievements of remote sensing sensors, new topics of interest have been also raised, and alongside, new terminology alluding those areas of interest emerged. This terminology includes, amongst other, archaeolandscapes, coastal archaeology, radar images.

As in any science, remote sensing archaeology needs further experimentation to be aligned with the initial archaeological questions, as well as to improve the quality of information provided back to archaeologists. The literature, recorded by the present study, reveals the involvement of an increasing number of archaeologists in the field of remote sensing technologies, a fact that reflects their awareness for the usefulness of these tools for their research. Indeed, remote sensing is growing, as well the rich diversity of research across Europe and elsewhere, as this is observed by the several remote sensing specific panels and sessions organised each year. This awareness should be also linked with the development of more user-friendly software of remote sensing processing tools. Furthermore, this can be seen as an indication of overlapping the boundaries of conventional archaeological procedures and traditional archaeological concerns attributing increasingly a completely new approach to the research of ancient landscape. In addition, remote sensing archaeology can be considered as an innovative approach for monitoring and protecting both existing sites of cultural interest and previously unsuspected buried archaeological remains. Driven from these technological innovations, the archaeologists started addressing new questions to guide their research, which can only lead to further improvement of all the sciences and technologies involved.

This promising, wide-spread, knowledge is an indicator of what to expect in the near future: even more institutions working on remote sensing data to support archaeological investigations and cultural heritage and, at the same time, a truthful transfer of knowledge can be achieved.

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