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Editorial

Remote Sensing and Geosciences for Archaeology

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Abstract: Archaeological remote sensing is not a novel discipline. Indeed, there is already a suite of geoscientific techniques that are regularly used by practitioners in the field, according to standards and best practice guidelines. However, (i) the technological development of sensors for data capture; (ii) the accessibility of new remote sensing and Earth Observation data; and (iii) the awareness that a combination of different techniques can lead to retrieval of diverse and complementary information to characterize landscapes and objects of archaeological value and significance, are currently three triggers stimulating advances in methodologies for data acquisition, signal processing, and the integration and fusion of extracted information. The Special Issue "*Remote Sensing and Geosciences for Archaeology*" therefore presents a collection of scientific contributions that provides a sample of the state-of-the-art and forefront research in this field. Site discovery, understanding of cultural landscapes, augmented knowledge of heritage, condition assessment, and conservation are the main research and practice targets that the papers published in this Special Issue aim to address.

Keywords: remote sensing; optical; SAR; geophysics; terrestrial laser scanning; point cloud; GIS; archaeological prospection; pattern recognition; condition assessment

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1. Introduction

The use of remote sensing techniques, by means of either ground-based instrumentations or airborne or space-borne sensors, for archaeological studies—namely, "archaeological remote sensing"—has already a long history of research, scientific publications, and implementation in the field.

Renowned advantages include, but are not limited to:

- The estimation of parameters and surface/subsurface properties without direct contact with the object of study (i.e., non-invasiveness);
- The capability of making remote observations, thereby preventing risks for the operator and reducing costs of in situ investigations;
- The possibility to revisit in time and carry out iterative workflows of data analysis for the purposes of monitoring and condition assessment (e.g., multi-temporal change detection).

The abundant literature (also recently re-examined in review papers, e.g., [1,2]), the proliferation of special issues in international journals (e.g., [3,4]), and the publication of specialist books and manuals (e.g., [5–7]) are three clear indicators suggesting that remote sensing for archaeology is an established discipline, which attracts great interest across different scientific communities (e.g., image analysts, Earth observers, Geographic Information System (GIS) experts, archaeologists, heritage conservators) and has reached a level of maturity by which we are now in the position to assess its achievements and perspectives for future advances.

Therefore, while there is no doubt about the value and existing capability of remote sensing to allow the discovery of new sites, investigation of cultural landscapes, condition assessment of heritage assets, and monitoring and modeling of impacts due to natural hazards and human threats, there is still the need for translating this expertise, spread across the globe, into capacity, best practices, and tools made available widely. In a recent book review [8], for example, I highlighted that this field still lacks of shared standardized methods of data processing tailored for the specific requirements of users.

On the other side, remote sensing is commonly used in archaeology jointly with other geoscientific methods, ranging from geophysical survey methods to GIS, not to forget traditional methodologies of ground-truth and historical data collection. There is a variety of ways researchers and practitioners combine remote sensing and geosciences. Frequently, this depends on local expertise and available instrumentation. Workflows from data capture to data analysis are specifically designed by each research team to suit the questions they aim to address in their case studies. However, lessons learnt from implementation in specific geographic and research contexts can contribute to form a shared methodological basis for wider application.

In the above scenario, the call for papers for publication in the Special Issue *Remote Sensing and Geosciences for Archaeology* that I launched in March 2017 aimed to collect articles on recent work, experimental research, or case studies outlining the current state-of-the-art in at least one of the following topics of remote sensing and geosciences for archaeology:

- archaeological prospection
- digital archaeological fieldwork
- GIS analysis of spatial settlement patterns in modern landscapes
- assessment of natural or human-induced threats to conservation
- education and capacity building in RS for archaeology.

2. Facts and Figures of the Special Issue

A total of 27 submissions were received for consideration of publication in the Special Issue from late April to early December 2017. After rigorous editorial checks and peer-review processes involving external and independent experts in the field, the acceptance rate was 78%.

The published Special Issue contains a collection of 21 articles; one is a review paper on piezoelectric/seismoelectric methods to identify near-surface targets [9], and six are feature papers that were solicited for submission to provide either an overview of specific domains of archaeological remote sensing (e.g., passive airborne optical imaging, [10]) or demonstrations of state-of-the-art remote sensing data [11], research methodologies [12,13], and processing tools and workflows [14,15] for landscape archaeology and archaeological prospection.

Figure 1 compares the geographic distribution of the authors and research teams publishing in the Special Issue (Figure 1a) and of the case studies and demonstration sites (Figure 1b). This is, of course, a sample of the whole scientific community working on remote sensing and geosciences for archaeology and therefore not an exhaustive representation. However, it already provides a glimpse of the widespread expertise of experimental research and field practice, and proves how widely remote sensing is applied to investigate and preserve archaeological heritage.

Figure 2 is a word cloud of the disciplines and scientific domains the authors of the papers published in the Special Issue belong to, as inferred from their affiliations. "Archaeology" is predominant and "geosciences" is the second most populated discipline, as expected due to the specific target of the Special Issue. Nevertheless, it appears that other disciplines are well represented, including "remote sensing", "engineering", "environmental sciences", "cultural heritage", "history", and "geography". This is a further proof of the multi-disciplinary nature of archaeological remote sensing.

In general, two situations are most frequently observed:

1. Groups of different professionals join their efforts to combine skills of image processing and computing science with arts and humanities expertise;
2. Remote sensing specialists or environmental scientists dedicate their research to archaeological topics.

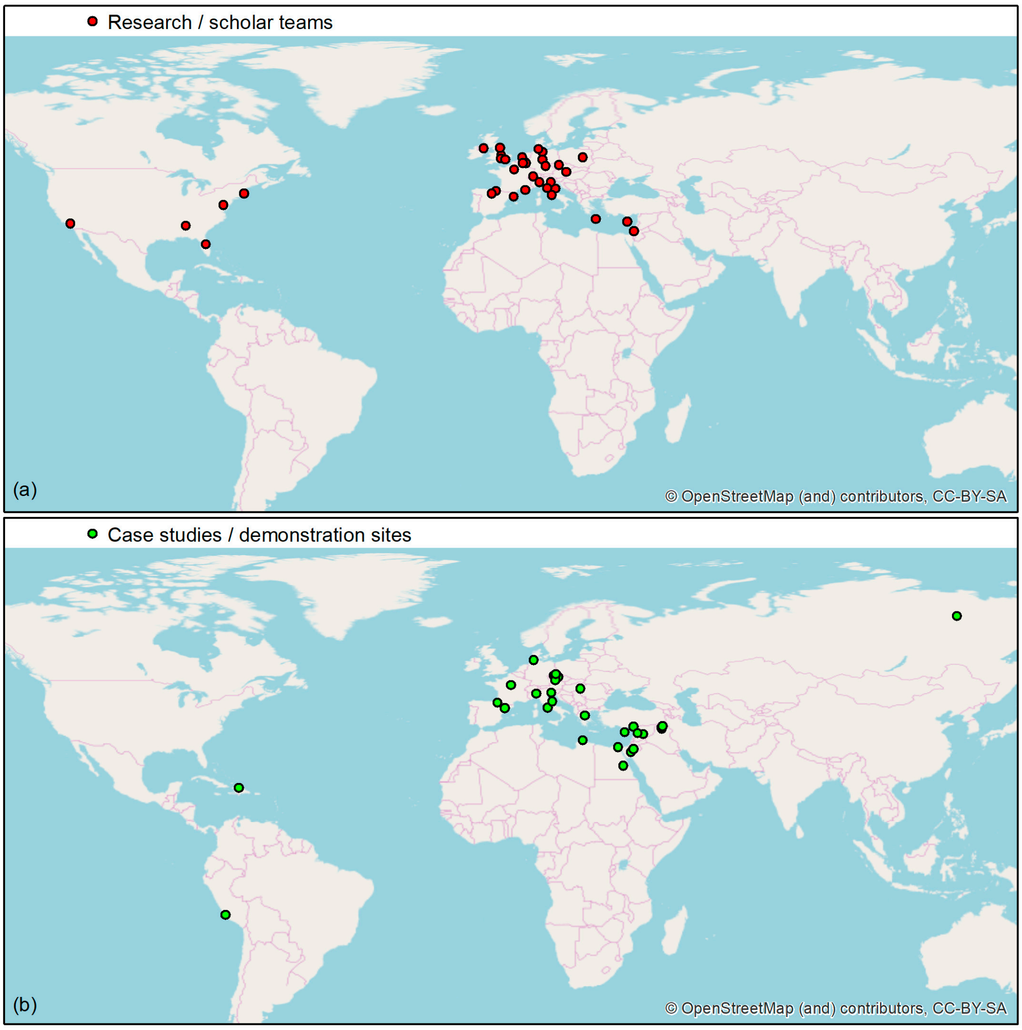

Figure 1. Geographic distribution of: (**a**) authors and research teams publishing in the Special Issue; (**b**) case studies and demonstration sites that are discussed in the papers.

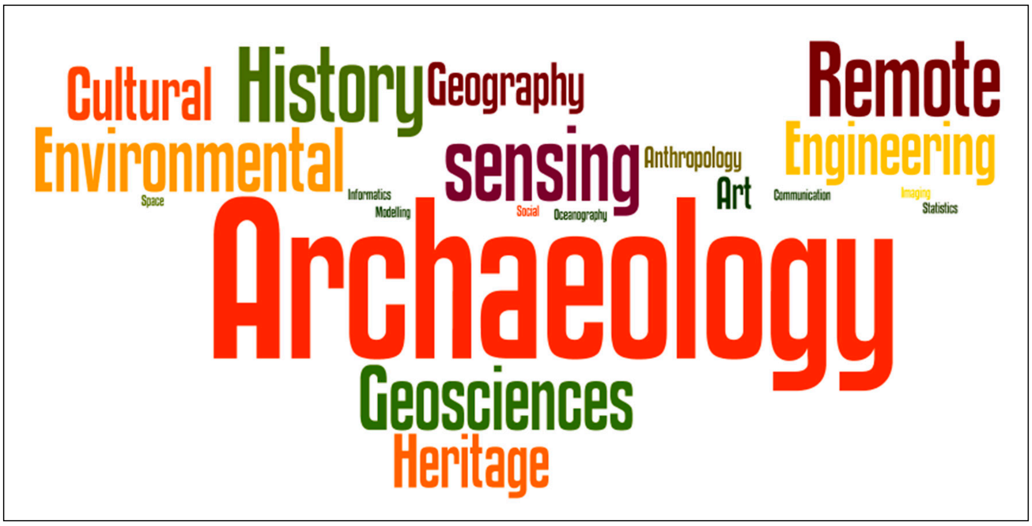

Figure 2. Word cloud of the disciplines and scientific domains the authors publishing in this Special Issue belong to [9–29], as inferred from their affiliations.

Similar evidence has been found in review exercises of specific domains of archaeological remote sensing based on decades of published literature [1]. In this regard, it is worth mentioning that the Special Issue includes examples of international, collaborative efforts between teams of scholars, academics, and/or cultural institutions for remote sensing-based studies on archaeology and heritage of developing countries or crisis zones [12–14].

3. Overview of the Special Issue Contributions

The papers published in the Special Issue cover a wide spectrum of techniques: satellite Synthetic Aperture Radar (SAR) imaging [11,16,17]; optical remote sensing from high to very-high resolution space-borne sensors [12,13,18–21]; geophysics including magnetometer surveys, Ground Penetrating Radar (GPR), geoelectric resistivity measurements, multi frequency Electromagnetic Induction (EMI), piezoelectric/seismoelectric methods [9,22,23]; photogrammetry [24]; terrestrial laser scanning and three-dimensional (3D) point clouds [25,26]. Some of the papers also explore the benefits of combining different approaches, e.g., optical remote sensing, aerial imagery and geophysical prospection [27,28], 3D surveys, and reconstruction in GIS environment [29]. In other cases, the focus is the demonstration of automatic detection tools and workflows [14,15].

Each paper explores successes and challenges that are consequential from the use of the above remote sensing and geoscientific techniques. In the following paragraphs, the main features of the Special Issue papers are highlighted.

3.1. Satellite Optical Remote Sensing

Building upon the renowned capability of satellite optical imagery (mostly sourced from commercial providers) to be an objective source of information to assess the condition of heritage at risk, the contributions by Danti et al. [12] and Rayne et al. [13] demonstrate how archaeologists and heritage professionals—with skills of remote sensing or supported by image analysts—can exploit large volumes of very high-resolution images to undertake systematic regional-scale efforts of damage mapping and assessment, leading to site-scale investigations and multi-temporal change detection. Both the teams of scholars have addressed the challenge of building site databases that could enable spatial and temporal querying of the results. These papers discuss how their experiences contribute to the standardization of methodologies for digital recording and metadata compilation, the use of shared terminology, and accurate classification with a logged level of uncertainty.

In particular, the implementation in the iconic sites of Nimrud in northern Iraq, Palmyra, and the Old City of Mosul in Syria offers a selection of incidents that highlight the results that Danti et al. [12] achieved with a methodology integrating satellite-based assessments with ground-based observations and open-source information. The methodology is flexible enough for addressing aspects of cultural heritage crises in other conflict zones, as it offers various alternatives for providing or publicly attributing sources of reliable information in cases where direct ground-based observations are unfeasible.

Rayne et al. [13], instead, focus on the value of combining multi-temporal satellite imagery with published data to create a detailed set of database records for a single site. They also discuss how the mapping of site disturbances at an extensive scale across cultural landscapes should integrate multi-temporal image interpretation, land-use mapping, and field surveys.

Anthropogenic impacts on the preservation of archaeological heritage are also the subject of the other three papers, two of which present results achieved with very high-resolution (open-source) optical satellite and aerial imagery [18,20], and the third paper freely accessible Landsat time series [19].

Interestingly, the geographic focuses of the studies by Chyla [19] and Parcak et al. [20] are located in Egypt. Despite the different data and methodologies used, both papers show examples of impacts on Egyptian archaeological heritage due to the expansion of agriculture and urbanization, which represent sources of threat for conservation in addition to natural processes characterizing the local fluvial environment. The authors of these papers demonstrate how satellite-based assessments can be used to support decision-making before sites disappear or are irreversibly damaged.

For early warning and prevention, Agapiou et al. [18] propose a novel methodology for the detection of archaeological looting incidents based on a set of indices and processing operations (e.g., vegetation indices, fusion, automatic extraction after object-oriented classification) of high-resolution WorldView-2 multispectral satellite imagery and RGB high-resolution aerial orthorectified images.

3.2. Airborne Optical Remote Sensing

From the papers introduced in the previous section, it is clear how archaeologists rely on satellite imagery. However, airborne optical remote sensing still stands as another important source of information, especially for archaeological reconnaissance, prospection, and landscape archaeology. Despite operational costs and permission to fly, airborne facilities are highly competitive solutions for archaeologists who want to investigate cultural landscapes, owing to the spatial resolution of the onboard sensors and the fact that targeted surveys can be undertaken instead of imagery acquisition according to pre-defined observational scenarios and fixed acquisition parameters.

Nevertheless, inherent biases and limitations need to be accounted for. After a clear statement about the concept of 'landscape archaeology' and an agile introduction to 'passive' remote imaging, Verhoeven [10] provides an insightful discussion of these biases, in particular those caused by sub-par sampling strategies, cost, instrument availability, and post-processing issues. Technological and methodological aspects are clearly explained within the overall framework of the archaeological theory relying on the capture, documentation, and interpretation of archaeological records, in conjunction with field data, in order to corroborate an archaeological hypothesis. The paper therefore sets out where we are in this domain of archaeological remote sensing. As such, it is worth reading not only by mature scholars, but also by beginners who can learn research methodology and how to go beyond the mere use of these technologies as black boxes.

3.3. Satellite and Airborne Synthetic Aperture Radar (SAR) Imaging

SAR imaging has been used for archaeology since the 1980s. A quick search through the specialist literature proves that, already a decade ago, the remote sensing community had achieved a good understanding of the capabilities of SAR for archaeological prospection, either via implementation on real case studies or in laboratory experiments (see specific SAR papers in [6]). Furthermore, a recent review exercise clearly highlighted a ramp-up in indexed peer-review publications using SAR data in archaeology in the last 30 years [1]. Therefore, it cannot be stated that SAR is novel in archaeological remote sensing. Instead, the novelty nowadays lies in the use of new imaging modes (mostly from new or current space missions) and higher spatial resolution and more accurate derived products, as well as the development of methodologies integrating multi-source SAR data. It is with regard to these aspects that the papers published in the Special Issue [11,16,17] offer interesting evidence of scientific research achievements.

Gade et al. [17] presents probably the first published example of the use of high- to very high-resolution SAR images acquired by the German Aerospace Center (DLR) constellation TerraSAR-X, including the Staring Spotlight mode, to detect and monitor the condition of lost coastal heritage in intertidal flats. The application on a constantly changing environment—where conditions of visibility of the archaeological remains and traces are discontinuous—proves how the tasking of satellite acquisitions is as important as the capability to extract features from the images after signal processing.

The TerraSAR-X constellation is also an example of a SAR mission equipped with twin satellites (TerraSAR-X and TanDEM-X in this case) providing data for the generation of high-resolution and accurate Digital Elevation Models (DEMs) with different spatial resolutions (e.g., processed at 2 m from High-Resolution Spotlight mode). In Cilicia, Rutishauser et al. [11] were able to extract cross-sections of height values (profiles) for the detailed analysis of the topography across riverbeds and paleo-channels from the TanDEM-X DEM mosaic covering the study region. The DEM-based analysis of silted up riverbeds and historic CORONA imagery allowed the first indications for the reconstruction of former river channels, when there was only limited coring available.

In the current international scenario of SAR missions, the European Space Agency (ESA) constellation Sentinel-1 cannot be forgotten. This is a space mission providing free and consistently acquired time series of SAR images with a large swath, high revisiting time of up to six days and a spatial resolution of 5 m by 20 m in Interferometric Wide (IW) swath mode. Sentinel-1 data therefore can be valuable to feed into studies of landscape archaeology and wide-area monitoring activities. It is with this purpose that Comer et al. [16] experimented with Sentinel-1 images to detect and measure landscape disturbance threatening the world-renowned archaeological features and ecosystems of the Lines and Geoglyphs of the Nasca and Palpa World Heritage Site in Peru. Multi-scale and multi-band analysis was also achieved thanks to targeted airborne surveys that were undertaken with the National Aeronautics and Space Administration (NASA)/Jet Propulsion Laboratory (JPL) Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) platform. In particular, these data allowed the authors to assess the impact on local heritage due to a known event that occurred in December 2014.

3.4. Automated Methods of Data Processing

As recalled in Section 1, a step forward in the use of remote sensing data is the development of robust automated methods for data processing to extract features of archaeological significance or to estimate parameters, and ease their uptake by the user community. The contributions by Sonnemann et al. [14] and Traviglia and Torsello [15] provide an interesting glimpse of the research currently being carried out on this topic.

In particular, Sonnemann et al. [14] applied a chain of image registration with a set of pre-processed, very diverse datasets, to combine multispectral bands to feed two different semi-automatic direct detection algorithms: a posterior probability and a frequentist approach. The method was tailored to generate maps that, with statistical significance, could address the question about the probability of finding archaeological evidence across the landscape and identifying sites in the Dominican Republic. Although not validated, the trials presented in the paper demonstrate the experimental attempt made by the authors towards automation in the context of multi-source data (e.g., satellite imagery, airborne surveys) which is one of the current challenges in remote sensing and geosciences.

Traviglia and Torsello [15] instead applied a workflow of feature extraction and detection implemented in ©Matlab to estimate the location and periodicity of dominant linear features on georeferenced images depicting the cultural landscape in northern Italy that had been engineered with land cadastration since Roman times. The trials suggest that this approach provides the accurate location of target linear objects and alignments signaled by a wide range of physical entities with very different characteristics, which also can be later interpreted against historical documentations, old maps, and in situ archaeological evidence.

3.5. Geophysical Techniques of Archaeological Prospection

The level of penetration of geophysical techniques in archaeological practice is such that several manuals and textbooks are published and disseminate best practices on how to carry out geophysical surveys in archaeological field evaluation according to established and shared standards [30,31]. The type of information that these techniques collect to investigate sites of archaeological potential is broadly classifiable as "geoscientific", since the outputs from the field surveys are measurements of parameters and properties of soil, subsurface materials, and buried objects.

In this regard, the contributions published in this Special Issue offer an interesting sample of case studies scattered across Europe.

Garcia-Garcia et al. [22] analyze the validity of a geoarchaeological core survey to check the archaeological interpretations based on geophysical results in the Roman site in Auritz/Burguete and Aurizberri/Espinal, Navarre, Spain.

Křivánek [23] showcases examples from the Czech Republic where different geophysical techniques were combined (i.e., surface magnetometer, resistivity survey) and integrated with other remote sensing methods (e.g., aerial photo-documentation, LiDAR) to address archaeological questions in different archaeological and environmental contexts. One of the sites is interestingly located close to a modern infrastructure. Achievements and limitations are discussed.

In addition, Agapiou et al. [27] focus on integration. In particular, in the demonstration site of Vésztő-Mágor Tell in the eastern part of Hungary, the authors run a workflow of data integration and fusion consisting of nine steps, including data capture, regression models to examine more than 70 different vegetation indices, cross-check and validation with GPR, and in situ magnetic gradiometry measurements.

Kalayci et al. [28] integrated geomagnetic, electromagnetic induction and GPR, historic aerial imagery, and Remotely Piloted Aerial Systems, as well as very high-resolution space-borne sensors, to discover differences in layouts of Early and Neolithic settlements in Thessaly, central Greece, and to investigate commonalities as a way to understand Neolithic use of space. In this way, the authors detected and characterized different aspects of the hindered prehistoric settlements that could have been overlooked by using only one geophysical approach.

The last contribution of the Special Issue focused on geophysics is a review by Eppelbaum [9] of piezoelectric/seismoelectric methods to capture piezoelectric and seismo-electrokinetic phenomena manifested by electrical and electromagnetic processes that occur in rocks under the influence of elastic oscillations triggered by shots or mechanical impacts. Reporting some examples from mining geophysics in Russia and an ancient metallurgical site in Israel, the author demonstrates that piezoelectric/seismoelectric anomalies may be analyzed quantitatively via advanced and reliable methodologies developed in magnetic prospection.

3.6. Laser Scanning, 3D Reconstruction, and GIS

Significant technological advancement is currently being achieved in the remote sensing and geoscience domains of laser scanning, manipulation of cloud points, and modeling. As rightly recalled by Poux et al. [26], point clouds and derivatives are changing the way curators, cultural heritage researchers, and archaeologists investigate heritage and collaborate on its understanding.

Guidi et al. [29], in this regard, provide a demonstrative example. Based on a proper mix of quantitative data originated by current 3D surveys and historical sources, such as ancient maps, drawings, archaeological reports, restrictions decrees, and old photographs, the authors were able to achieve a diachronic reconstruction of the ancient Roman Circus of Milan that, at present, is completely covered by the urban fabric of the modern city. The hypothesis of temporal evolution and transformation of the monument is presented via an easy-to-understand visual output.

The accessibility of information stored in point clouds and derived models is crucial for dissemination among end-users. Poux et al. [26] propose a classification method that relies on hybrid point clouds from both terrestrial laser scanning and dense image matching, and feeds into a WebGL prototype enabling different heritage actors to interact in a collaborative way. The geometric reconstruction, therefore, serves as a digital platform for storing and sharing relevant information and for easing communication with and between end-users.

Multi-disciplinarity is also at the base of the paper published by Drap et al. [24]. Medieval archaeologists and computer science researchers collaborated towards a connection between 3D spatial representation and archaeological knowledge, by integrating observable (material) and non-graphic (interpretive) data.

In addition to promoting understanding, digital 3D recording enables timely, iterative, and repeatable documentation of heritage to inform decision-making on its conservation. Corso et al. [25] show how terrestrial laser scanning can be used by practitioners and heritage bodies to document and monitor the heritage for which they are responsible; to map present conditions and assess visible impacts of weathering and deterioration processes; and to extract information to design mitigation and preservation measures.

4. Key Messages for Future Research

The wide portfolio of methodologies, data, and techniques presented in the contributions published in this Special Issue proves that remote sensing and geosciences for archaeology are currently vibrant research and practice domains, with expertise spread across the globe and teams fully exploiting the capability of remote sensing to investigate sites and landscapes in different geographic, social, and environmental contexts.

It is clear that there is no barrier for techniques—based on either space-borne, airborne, or ground-based instrumentation and sensors—to be employed in the field, to carry out experimental test of new functions and facilities, or to exploit known capabilities to accomplish professional, research, and institutional tasks (e.g., prospection, recording, condition assessment).

In this regard, satellite imagery (particularly from optical sensors and open-source platforms) is a clear example, since it has become a facility fully embedded in standardized routines for mapping and monitoring heritage. SAR, on the other side, is a stimulating research arena. While there are still difficulties for this technology to be utilized by non-expert users, the technological developments offering novel imaging modes and processing methods are triggering forefront research paving the way for a wider spectrum of applications.

Landscapes remotely sensed using different bands of the electromagnetic spectrum are ideal test sites for researchers and archaeologists to focus on signal processing and analysis to extract information not otherwise achievable, except via ground investigations. When archaeologists have access to different geophysical techniques, they tend to combine them to improve the level of data acquisition and the amount of information. However, this abundance of information leads, on one side, to the challenge of developing strategies and methods to fuse information and, on the other, to the need to isolate and extract the relevant information from the unnecessary and redundant.

Automation plays an important role, since it allows the operator subjectivity to be counterbalanced, and the time spent for data processing to be decreased. As a consequence, archaeologists and image analysts can concentrate more on archaeological interpretation and product generation.

In this regard, more efforts should be made towards the sharing of processing routines tailored to archaeological applications and their embedding within software or open platforms. Moreover, there is a need for more publications showing successful stories of the conversion of experimental methodologies into best practices, as well as the discussion of 'bad practice' examples where current methodologies are not adequate enough and improvements are needed.

Interestingly, the majority of the Special Issue papers prove that different professionals tend to team up to share expertise and technical skills to better address archaeological questions and/or facilitate the dissemination and sharing of information.

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