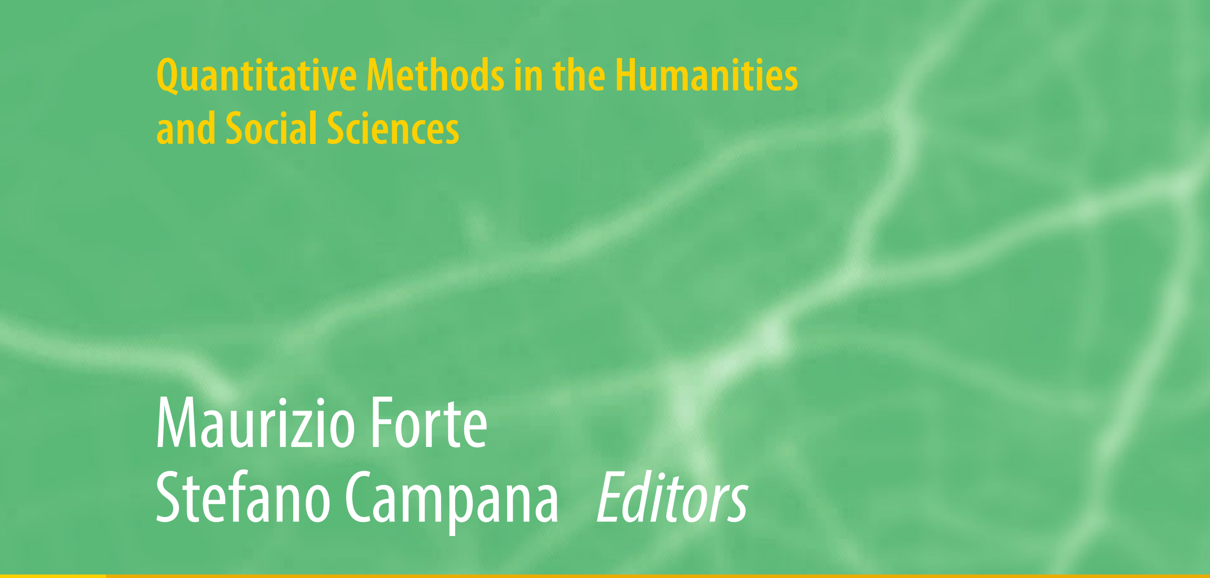

Quantitative Methods in the Humanities
and Social Sciences

Maurizio Forte
Stefano Campana *Editors*

Digital Methods and Remote Sensing in Archaeology

Archaeology in the Age of Sensing

Springer

Quantitative Methods in the Humanities and Social Sciences

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Editors

Digital Methods and Remote Sensing in Archaeology

Archaeology in the Age of Sensing

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Preface

The 1990s will probably be remembered in the history archaeology as the age of GIS. At that time, the introduction of digital technology in archaeological research was in its infancy. Software and hardware had only a limited capacity to integrate the range and complexity of information involved in the archaeological process. In the following decade, however, the archaeological community became gradually aware of the need for a consistency of approach across the whole framework of archaeology, while rapid advances in software and hardware made it possible to envisage a significant renewal of the whole or large parts of the archaeological process. This was the age of the Digital Revolution.

At the same time, remote sensing gained an increasing relevance and application within archaeology and throughout the scientific community. Up to this stage, the definition of remote sensing had focused on the analysis of data collected by sensors that were not in physical contact with the objects under investigation, using cameras, scanners, radar systems, etc., operating from spaceborne or airborne platforms. Now, a wider characterization began to take hold, treating remote sensing as ***any*** nondestructive approach to viewing the buried and nominally invisible evidence of past activity. Spaceborne and airborne sensors (now supplemented by laser scanning) became joined by ground-based geophysical instruments and undersea remote sensing, as well as—for *some* archaeologists at least—by other noninvasive techniques such as surface collection or field-walking survey. Within this broader interpretation, ***any*** method that enables observation of the evidence on or beneath the surface of the earth, without impacting on the surviving stratigraphy, can legitimately be included within the ambit of remote sensing. This and other impulses have also resulted in a rapid growth in multidisciplinary working within and around archaeology and related cultural studies.

From the methodological point of view, the most important change over the past few years has been the burgeoning capacity of archaeologists and cultural historians to collect—relatively easily and quickly—massive 3D datasets at the landscape, local, site, and object scale. Initially, archaeologists did not know exactly how to manage this vast array of 3D information. They readily grasped the idea of its huge potential but did not see how to exploit it. The all pervading presence of the third dimension prompted the need for new perceptions of archaeological features and processes at an intellectual level, in terms of “3D thinking”—or better 4D thinking considered that as archaeologists, we cannot avoid dealing with the chronological dimension—and at a procedural level, challenging long-established approaches to archaeological documentation and therefore to the interpretation process as a whole.

Now, in the early years of the present decade, we feel that we are ready—or at least ***nearly*** ready—to embrace these new methods of recording, interpreting, conceptualizing, and communicating archaeological data and relationships across the passage of time. Technological, cultural, and epistemological advances are enticing us to encompass new and completely different perspectives based on immersive, interactive 3D and 4D environments for managing archaeological data at both the scientific and interpretative levels.

Everybody, in the next few years, will have the opportunity to blend the physical world with a sensory-rich “virtual” world where archaeologists can naturally and intuitively manipulate, navigate, and remotely share interpretations and case studies. Our understanding of archaeology will be taken to a new level, enhancing our capacity to develop interpretations and to present them to fellow specialists and to the general public as simulated scenarios in 4D. Rapid developments in ICT, including hardware and software for immersive environments, will even allow us to communicate and interact with one another through further cultural experiences such as sound, smell, and tactile interfaces. The transformation of the traditional remote sensing in “something else” defines new borders for this research field and suggests a new methodological approach. “Polysensing” rather than “remote sensing” can better define this revolutionary approach. It is quite interesting to notice that archaeology plays as primary actor in this revolution because of its multidisciplinary character and mission.

Welcome in the Age of Sensing!

Durham, NC, USA Maurizio Forte
Siena, Italy Stefano Campana

Acknowledgements

This book is not a proceeding of the conference "The Age of Sensing," but without the conference, we could not have this book. The Age of Sensing has been an extraordinary event and an inspirational opportunity for scholars and students for discussing cutting-edge research projects and applications.

As with most collaborative projects, there are many characters and groups whose assistance has proven crucial to the production of this volume.

First of all, we are sincerely grateful to a good many friends and colleagues who made a long journey to join the meeting at Duke University, Durham, North Carolina, and who made the publication that developed from it possible.

Particular thanks are offered of course to the University of Siena, the Department of History and Cultural Heritage and the Laboratory of Landscape Archaeology and Remote Sensing for the support provided for the organization of the conference and the Summer School in Siena and Vulci.

Also of great importance to the organization of the conference has been the role played from Melissa Huber, Ph.D. candidate at that time at Duke University who managed greatly the general secretariat making our work much easier before, during, and after the conference. In this respect, we are also particularly appreciative to the assistance of a number of Duke students, throughout the symposium to its sooth running.

The conference was supported by the Trinity College of Art & Science, the Department of Classical Studies, the Department of Art, Art History and Visual Studies, the Trent Foundation grant, Institutional sponsors were ICIP-ICOMOS, NASA JPL and UNESCO (Cultural Sector).

A special thanks to Vanda Gianpaoli and Roberto Rabitti for their very generous and outstanding contribution to the social activity of the conference "The Age of Sensing"

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Cambridge, UK; Siena, Italy Stefano Campana

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About the Editors

Maurizio Forte is William and Sue Gross professor of classical studies art, art history, and visual studies at Duke University. He is also the founder of the DIG@Lab (for a digital knowledge of the past) and Director of the Graduate Program in Classical Studies at Duke. In 2006–2011 was in the advisory board of the UNESCO Remote Sensing Archaeology—Open Initiative. His main research topics are as follows: digital archaeology, classical archaeology, and neuroarchaeology. He was a professor of World Heritage at the University of California, Merced (School of Social Sciences, Humanities and Arts), and director of the Virtual Heritage Lab. He was the chief of Research at CNR (Italian National Research Council) of "Virtual Heritage: integrated digital technologies for knowledge and communication of cultural heritage through virtual reality systems," senior scientist at CNR's Institute for Technologies Applied to the Cultural Heritage (ITABC), and professor of "Virtual Environments for Cultural Heritage" in the "Master of Science in Communication Technology-Enhanced Communication for Cultural Heritage" at the University of Lugano. He has coordinated archaeological fieldwork and research projects in Italy as well as Ethiopia, Egypt, Syria, Kazakhstan, Peru, China, Oman, India, Honduras, Turkey, the USA, and Mexico. Since 2010, he is the director of the 3D Digging Project at Çatalhöyük and since 2014 he is the Director of the fieldwork and digital project Vulci 3000 (Vulci, Italy). He published pioneering books on digital archaeology, virtual archaeology and cyber archaeology.

Stefano Campana is currently faculty member of the University of Siena (Italy), in the Department of History and Cultural Heritage, where he has engaged in teaching and research as senior lecturer in ancient topography. He is specializing in landscape archaeology, remote sensing, GIS, and archaeological methodology for purposes of research, recording, and conservation. His work is focused on the understanding of past landscapes from prehistory to the present day. The principal context for his work has been Tuscany, but he has also participated in and led research work in the UK, Spain, Turkey, Palestine, Iraq and Asia. He has been very active in the international sphere and has established a sound reputation for innovative research. In 2011, he was proposed and admitted as a fellow of the Society of

Antiquaries of London (FSA), and in 2012, he was invited to be a member of the General Management Board of HIST, the Governing Board of the International Centre on Space Technologies for Natural and Cultural Heritage, under the auspices of UNESCO and the Chinese Academy of Sciences. From 2014 to 2016 he was Senior Marie Curie Research Fellow at the University of Cambridge (UK), Faculty of Classics. There, he initiated a totally new project under the title ‘emptyscapes’, aimed at stimulating change in the way archaeologists in the Mediterranean world study the archaeology of landscapes, moving from an essentially site-based approach to a truly landscape-scale perspective.

Introduction

The roots of this book lie in the 5th International Conference on Remote Sensing in Archaeology, the Age of Sensing which took place from October 13 to October 15, 2014, at Duke University within the "From Space to Place initiative."

The initiative started in Beijing on 2004 where took place the first conference organized from the Chinese Academy of Sciences, and in the years, this experience has been developed—independently—from the editors of the present book organizing conferences, workshops, and summer schools in Italy, at Roma and Tuscany (2006), India at Tiruchirappalli (2009), China at Beijing (2012), USA at Berkeley California (2012), France at Marseille (2013), Italy at Siena and Vulci (2014), and of course back to the USA at Durham (2014).[1]

From space to place, initiative could be considered within the framework of current orthodox scientific environment, anarchic, amorphous, and self-referential. To be fair after more than 10 years, it is even difficult to find any other definition than "initiative" to describe it. It is not at all a national or an international association, a scientific society, or whatever. We would probably define it as an ongoing forum aimed to bring around the world every one, sometimes two or three years yet depending from various reasons, the discussion on remote sensing in archaeology, intended from the broader point of view. Priority is given to places where it is more unusual to have the opportunity to put large number of outstanding scientists together or experts belonging to different environments (scientific as well geographic). Moreover, privileged areas are those under threat due to fast and unrestrained economic development, population growth, global warming, environmental pollutions, war, terrorism, and so forth.

After the first experiences, we thought that the publication conference proceedings were unsuitable to deploy the actual meaning of the seminar. Therefore, from the 5th edition of the conference, we decided to change policy (to be fair, we never had any) editing a monograph volume on the main topic of the conference. Therefore, this book is by no means just as a selection of best papers of the 5th

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[1] Campana S., Forte M 2006 and Campana S., Forte M., Liuzza C., 2010.

conference rather than the meeting has been useful to identify a group of authors dealing with themes that would be developed according to the purpose of the present book.

The book opens providing an overview of a leading-edge technology of data recording impacting substantially the last years. The range choice was definitively very wide, lot of technologies had a major influence on archaeology in the last decades, but we decided to focus on laser scanning, terrestrial, and airborne. Indeed, laser scanning from the one hand played a very important role within archaeology, raising new attention on third dimension and form the other hand airborne Lidar provided for the first time a power full tool aimed to explore the ‘black hole’ of landscape archaeology: forested areas. Part “Data Collection and Technology” is organized into two contributions: The first one written by Nicola Lercari (University of California, Merced) provides a rather comprehensive critical overview of terrestrial laser scanning (TLS) in the age of sensing. The second paper written by Rachel Opitz (University of Arkansas) delivers an extended synopsis of the state of the art of the application of airborne laser scanning in archaeology with particular regard to undercanopy case history.

Part “Image and Digital Processing” deals with image and digital processing in relation to visual representation and methodological strategies and sites’ analyses. The first manuscript written by Stacy Curry, Roy Stine, Linda Stine, Jerry Nave, Richard Burt, and Jacob Turner (University of North Carolina) deploys a case study on TLS and ground-penetrating radar (GPR) imaging spatial integration conducted near the third line action at the battle of Guilford Courthouse (American Revolutionary War, March 15, 1781), located at the Guilford Courthouse National Military Park, Greensboro USA-NC. The TLS dataset demonstrated the possibility to discern the concave surface found in the dense overgrown and obstructed wooded area integrating the subsurface feature seen in the GPR data before entering a heavily wooded area. The next paper by Till Sonnemann, Eduardo Herrera Malatesta, and Corinne Hofman (Leiden University) deals with image processing aimed to identify evidence from Unmanned Aerial System (UAS) photogrammetric surveying. The cultural as well the environmental context is tremendously challenging: precolonial settlements in northern Hispaniola (the Dominican Republic). The result is very interesting proving great potential for fast and precise recording of archaeological sites in difficult terrain providing a fast, detailed, and affordable opportunity to monitor changes to the landscape, caused by agriculture, new development, illegal looting, and so forth.

Part “Landscape Representation and Scales” is a quite dense one, facing within landscape studies, theoretical, methodological, and practical issues. The main topics are focused on multiscale landscape study, visibility and emptiness, landscape representation and reconstruction, and accuracy and visual analysis.

Frank Vermeulen (University of Ghent) in his contribution provides an excellent example of critical thinking developing an integrated multiscale and multisurvey approach to the study of the now-rural but formerly urban historical Mediterranean landscapes.

Stefano Campana (University of Siena, Italy) delivers a paper aimed to contextualize and clarify the state of the art of landscape survey focusing on the massive gap in quality and intensity of the research (substantially increased in the last decades) between the analysis of past rural landscapes and past cityscapes; this paper presents a case study aimed to reconcile city and countryside.

Dave Cowley focuses on an analytical review of the causes of gaps, uncertainties, and absences within the archaeological record mainly based on Central and northern Europe but which can be extended to a much broader area.

Heather Richards-Rissetto with her colleagues, Shona Sanford-Long, and Jack Kirby-Miller bring the reader to Copan (Honduras) presenting an stimulating project. Research design and goals instead of being focused on the typical computer-based visualization showing buildings and monuments surrounded by a mass of emptiness in a lunar landscape is aimed developing 3D visualization tool and workflow that have value for examining changes in land use, environment and settlement displaying 3D synchronic patterns visualization as well 4D landscape transformation across time. Back to Europe (Iberia), Edward Triplett uses spatial technologies and particularly the combination of the volumetric and GIS viewshed analysis methods. The case study reveals how between the twelfth and fourteenth centuries, frontier institutions (Muslim and Christian) controlled territory valued landscape visibility as a measurement of security and surveillance, while also acknowledging how vision affected architecture-scale decisions at a military- monastic complex on the frontier.

The contribution Kasper Hanus (Adam Mickiewicz University in Poznań) and Emilia Smagur (University of Sydney), is focused on Cambodia where up to recent time archaeologists have made a substantial progress in the research on the medieval landscape of the urban complex of Angkor neglecting regional survey. This paper presents the large-scale reconnaissance survey based on satellite imagery, which has been implemented to fill the gap in the understanding of the past landscapes in the region. Finally, John K. Millhauser (North Carolina State University) and Christopher T. Morehart (Arizona State University) argue on how Imaging and spatial analysis technologies can revolutionize archaeological methods and archaeologists' perceptions of space. More specifically the use of spatial data in the past recalls the importance of human experience in the representation and description of the empirical world.

Part "Simulation, Visualization and Computing" presents an overview of 3D archaeology, collaborative research, computing, modeling, and supercomputing. Maurizio Forte (Duke University) discusses theory and practice of cyberarchaeology at the intersection of digital embodiment, 3D polysensing environments, and neuroscientific perspectives. The introduction of mass application of virtual reality in research, education, and entertainment is changing completely the human approach to cultural transmission and the reconstruction of the past.

Bill Seaman (Duke University) seeks in his paper to define a new holistic approach to cyberarchaeology including new forms of multimodal sensor hardware to work in conjunction with current sensor systems. Here, we are in the sphere of polisensing systems—parallel multimodal sensing over time—enable the creation of a form of media object that can be given additional metadata and can be explored via state-of-the-art search algorithms, new metamarkup methodologies, and virtual visualization.

Nicoló Dell'Unto (University of Lund—SE) discusses how the development and use of three-dimensional geographic information system (3DGIS) are affecting the way archaeologists retrieve and analyze material detected in the field in support of more accurate archaeological interpretations.

Devin A. White (University of Tennessee) delivers an introduction to the world of high-performance computing, focusing on the present and the future of archaeological supercomputing, using several ongoing projects across a broad swath of the discipline as examples of where we are now and signposts for where we are heading, concluding with some thoughts on the art of the possible, given current and emerging technological trends. One of the goals of this paper is that the reader will come away feeling less intimidated by the idea of using supercomputing to solve archaeological problems and knowing that they can and should take full advantage of the computing power available today as well as help drive how the systems of tomorrow are designed.

Part "Interpretation and Discussion" takes on a central issue of the archaeological debate: how to approach data analysis, interpretation, archiving, and data sharing in large-scale scenarios. Fred Limp (University of Arkansas) presents a comprehensive essay on measurement and the analytical process that characterized our field. Indeed, oversimplifying the process sequence before high-density survey and measurement (HDSM) was observe, interpret/abstract, measure, record, and analyze. HDSM breaks us out of this process in that it pushes us toward a recursive and reflexive engagement with the data, in which we observe, record, measure, analyze, and abstract/interpret repeatedly and in various orders. The growth in the use of HDSM methods is paralleled by increasing applications of computer-based visualization. Effective use of both requires attention to a scholarly digital ecosystem that addresses the archive and reuse of these digital objects and includes strategies to reuse these digital objects in other scholarly representations along with the tools for citation and other aspects of scholarly discourse.

Jakob Kainz (University of Vienna) presents an approach combining archaeological excavation with geophysical prospection. This is achieved by a combination of magnetometry, magnetic susceptibility, ground-penetrating radar (GPR), and pXRF measurements, on archaeological features before and during excavation. The aim is addressed to establish the full archaeological potential of the various prospection methods as these measurements can help corroborate excavation results as well as providing further archaeological data that cannot be seen by the excavator's eye.

Willem Vletter (University of Vienna) and Sandra Schloen (University of Chicago) provide an original contribution aimed to validate chronological interpretation of airborne laser scanning (ALS) data in reconstructing historical road and path networks in forested areas. The chronological model makes use of both the Harris Matrix Composer (HMC) and the Online Cultural and Historical Research Environment (OCHRE), developed at the University of Chicago.

Part “Cultural Resource Management: Communication and Society” confronts a broad subject characterized by several declinations: cultural resource management (CRM), public archaeology, theory and practice of digital archaeological communication, museums and sensing, and social outcome.

Eva Pietroni (Italian National Research Council) argues that despite the exciting perspectives opened in education and in terms of social and economic growth, research in the domain of virtual museums has not reached a sufficient level of maturity, such as cinema or game sectors. There is still a disconnection between the research, that develop tools with little interest in their wide application, and the industry, that build ten-year plans addressing the market. Given the need for enhancing the emotional and cognitive impact of virtual museums, some criteria and good practices are discussed, exemplified through concrete case studies, among which the *Tiber Valley Virtual Museum*, dealing with engaging storytelling, embodiment, and novel solutions in the interaction design and in the integration of media.

Riccardo Olivito (Scuola Normale Superiore), Emanuele Taccola (University of Pisa), and Niccolò Albertini (Scuola Normale Superiore) in their contribution provide a critical view of virtual immersive environments delivering through the case study of the agora of Segesta, an excellent example on how this technology can play a key role for the archaeological practice allowing the visualization and analysis in real time of different types of data and the interaction with them.

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Part I
Data Collection and Technology

Terrestrial Laser Scanning in the Age of Sensing

Nicola Lercari

Abstract For more than a decade, Terrestrial Laser Scanning (TLS) has been a primary remote sensing technique for disciplines related to archaeology, architecture, built heritage, earth science, metrology, and land survey. The increasing precision, range, and survey speed of TLS make this technology even more viable for large-scale data capturing in the Age of Sensing. This chapter reviews the state of the art of Terrestrial Laser Scanning in 2015 with the aim to assess its applications in a context of lower data capturing costs for alternative technologies, such as new commodity sensors, Image-based 3D Modeling, Unmanned Aerial Systems (UAS), optical 3D scanning, and Airborne Laser Scanning. More specifically, TLS still maintains a fundamental role in the documentation and interpretation of archaeological contexts at intrasite scale: (i) Terrestrial Laser Scanning delivers high-fidelity data of surfaces and structures of buildings as well as ultra-precise measurements of the morphology of stratigraphic layers; (ii) research in remote sensing proved that TLS point clouds can be successfully interpolated with data recorded with other instruments and techniques, such as magnetometry, Ground Penetrating Radar, Unmanned Aerial Vehicles, Image-Based Modeling, in order to generate hybrid documentation and new knowledge on natural and cultural heritage sites. Inevitably, the current advancements in TLS bring new questions. For example, how can micro-differences only visible in the point clouds change the analysis and interpretation of layers and buildings? How to improve the monitoring and conservation of a site via automated analysis of TLS data? How to enhance the mapping process of built-heritage using data segmentation or semi-automatic feature extraction of TLS point clouds? This chapter proposes a new approach to TLS based on multi-modal capture workflows, semi-automated post processing, online archiving, and online visualization and management of point clouds with the aim to open new horizons for digital archaeology, architectural survey, and heritage conservation.

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Overview of New Data Capture, Processing, and Visualization Systems in Relation to Terrestrial Laser Scanning

The second half of the 2010s witnesses a deep transformation in the domain of data recording, data processing, and visualization. A number of cutting-edge remote sensing technologies and methods are now production-ready tools that can be deployed in the fields, do the job, and challenge established survey technologies, such as Terrestrial Laser Scanning. The Age of Sensing is characterized by the rapid diffusion of cost-effective and incredibly versatile technologies such as computer vision-based 3D scanners, inexpensive cameras and sensors, mobile or web apps for real-time processing, and interactive platforms for data sharing in the cloud. Commodity sensors, such as accelerometers, three-axis gyroscopes, proximity sensors, ambient light sensors, and Global Positioning System (GPS) receivers are becoming ubiquitous in smart phones, cameras, household electronics, cars, and wearables.

As of the beginning of 2015, new generations of sensors are ready to go mainstream while their manufacturers openly express the ambition to transform the way people interact with the real world through their digital devices.

Great examples of the new era of commodity sensors are: (i) revolutionary optical 3D scanning solutions, such as the Structure Sensor, now available for smart phones and tablets users to be employed in the digitization of objects, interior environments, and artifacts; (ii) low-cost motion tracking technologies, such as the Intel RealSense, embedded in new tablets and laptops that promise to change the way users interact with computers (Intel RealSense 2015); (iii) commodity thermal imaging sensors, such as the Seek Thermal XR camera, which enable smart phones to detect infra-red light and record thermal information opening new possibilities for basic spectral analysis for the masses (Seek Thermal 2015).

The effects of the mass diffusion of sensing technologies on the society at large are yet to be assessed. What is already clear is that new, low-priced, and increasingly powerful tools for data capture, processing, and visualization have started to transform the field of remote sensing and its applications.

This new scenario opens research opportunities linked to the development of novel methods, bringing scholars to experiment hybrid techniques and workflows that integrates more established tools, such as TLS, with cutting-edge technologies often developed by small, start-up companies, research centers, or universities.

The following sections of this chapter will analyze in detail the transformational shift described above, especially in regards to Terrestrial Laser Scanning. The aim is to ponder new advancements in the fields of data recording, processing, and simulation and discuss whether TLS still matters today.

Alternative 3D Capture Systems

In the Age of Sensing, TLS is no longer the only viable solutions to survey heritage sites, buildings, and archaeological excavations in 3D.

Image-based 3D modeling techniques, also known as Structure from Motion (SfM), have long proved viable for the documentation of heritage (Pollefeys et al. 2001; Remondino and Menna 2008), stratigraphic layers in archaeological excavation (Doneus and Neubauer 2005a, b; Forte et al. 2012), and artifacts (Kersten and Lindstaedt 2012).

What is remarkable is that one can now digitize an entire indoor environment in real-time using commodity 3D data capture systems based on depth cameras technologies or structured light devices. The effects of Microsoft Kinect sensor have been largely documented (Zhang 2012); especially in regards to data capture accuracy (Khoshelham 2011), and mapping of indoor environments (Khoshelham and Elberink 2012). The performance of low-cost 3D scanning devices has also been assessed in relation to their employment in the cultural heritage domain (Guidi et al. 2007).

In 2015, it is now possible to 3D capture, process, and virtually reconstruct both the built environment and objects in real-time using sensors, such as Microsoft Kinect or Structure Sensor by Occipital (Structure Sensor 2015) combined with mobile devices (Raluca Popescu and Lungu 2014). A Structure Sensor records colored triangular mesh of its surrounding space or objects—located within 2 or 3 meters from the device—in a matter of seconds. It uses an iPad, or smartphone, to process the captured data, render its geometry, and align multiple point of views in real-time (Fig. 1).

The possibility to capture, process, and instantaneously visualize the 3D scans on a mobile device implies that the survey of built heritage or archaeological sites can potentially be verified on the go. Differently than TLS, this capability makes data post-processing inexpensive and fast.

Fig. 1 Structure Sensor uses iPad for real-time data processing—courtesy of Occipital

A foreseeable effect of this new technology is that dense data capture becomes now available to anybody who owns a tablet or smartphone and is willing to spend few hundred additional U.S. dollars to purchase a Structure Sensor. There is no doubt that this capability will open new horizons for community-based heritage preservation performed by cultural associations, volunteers, students, and local communities. More broadly, one can envision that heritage diagnostics of the built environment or the digital documentation of archaeological remains could be immediately discussed on site, few instants after the survey is completed.

A discourse on alternative 3D capture systems need to go beyond a cost-benefit analysis of purchase price, survey time, and ease of use. Thus, this chapter needs to assess whether the new optical scanning solutions also challenge TLS in regards to data fidelity. One can now record, align, and process in real-time very precise colored point clouds of the interior of a building or the shape of complex objects using a DPI8 scanner developed by DotProduct (DPI8 2015). This hand-held 3D scanner is operated via the operating system Android and relies on a low-cost tablet PC for processing data in real-time. DPI8 delivers fairly accurate measurements within a range of 0.6–5 m when used with optimal ambient conditions. In February 2015, the author of this chapter had the opportunity to test a DotProduct scanner for a test survey of the interior of a warehouse located at Fort Mason Center, in San Francisco, during the *REAL 2015* conference (REAL 2015). Such preliminary testing showed that a DPI8 optical scanner is able to deliver precise data when scanning the interior of a building, which has been evenly lit. Undoubtedly, further testing on DPI8 is needed to call this portable 3D capture system a mature technology for heritage documentation. Given a price tag of few thousands of U.S. dollars, it is relevant to mention that the data fidelity of this optical scanner is acceptable if compared to a TLS unit, such as a FARO Focus^{3D} X330, which costs about ten times more (FARO Focus^{3D} X330 2015). No doubt, DPI8 already presents the characteristics needed to become a leading technology in the domain of artifacts digitization and documentation of interiors of buildings.

The current revolution of data capture platforms is not solely related to indoor surveys and artifacts scanning. New tools for landscape surveying and built environment 3D mapping are now available. Such new systems combine lightweight Unmanned Aerial Vehicles (UAVs), uncalibrated cameras, and Image-based 3D Modeling software, posing major challenges to the viability of TLS for what concerns intersite documentation or landscape surveying.

In 2015, advanced 3D mapping standalone software, such as Pix4D, allows scholars, architects, and heritage practitioners to perform accurate 3D mapping of entire sites and landscapes (Pix4D 2015). Other cloud-based UAS platforms, such as DroneDeploy (DroneDeploy 2015) provide archaeologists, land surveyors, and geoscientists, with new effective tools for 3D mapping cultural landscapes and natural environments simply using Android or iPad devices to manage mission planning, data capturing, and server-based data processing. Currently, the most widespread technique for the 3D documentation of archaeological heritage is the standalone Image-based 3D modeling software Agisoft Photoscan Pro (Photoscan 2015). In the Age of Sensing, the popularity of this technology is so widespread that Photoscan is becoming a standardized method for intrasite and intersite documentation. Photoscan provides archaeologists and conservators with an incredibly efficient workflow that reduces the cost and time of single context data recording, while enhances on-site data-driven discussion and interpretation (Forte et al. 2015, pp. 45–46) (Fig. 2).

The viability of standalone and cloud-based UAS platforms for 3D documentation in archaeology—specifically Photoscan Pro and DroneDeploy—were positively tested in the summer 2015 at the archaeological sites of Çatalhöyük and Boncuklu Höyük, in Turkey. In the field season 2015, a DJI Phantom 3 Pro multirotor copter equipped with a 4K RGB camera and DroneDeploy server-based mission planning was employed to conduct several missions for indoor survey inside the permanent shelters (Lercari and Lingle 2016), as well as for outdoor 3D mapping survey (Forte et al. 2016). Such UAS operations were aimed to enhance the 3D survey of Çatalhöyük buildings for conservation and monitoring purpose. UAS data capture was also employed to 3D map the landscape of Çatalhöyük and its environs with the goal to provide further understanding of the site's relationship with other Neolithic settlements in the Konya plain, such as Boncuklu Höyük.

The above mentioned survey methods open new horizons for heritage conservation and documentation in a time of decreasing funding for archaeological excavation or cultural heritage preservation. Thus, micro UAS platforms challenge commercial photogrammetry or airborne LiDAR services in relation to intersite surveys. Their capability to render the morphology and multispectral properties of heritage sites and landscapes with high accuracy and in a cost-effective way, allows the new multi-sensor data capture systems to also challenge laser scanning in regards to intrasite documentation.

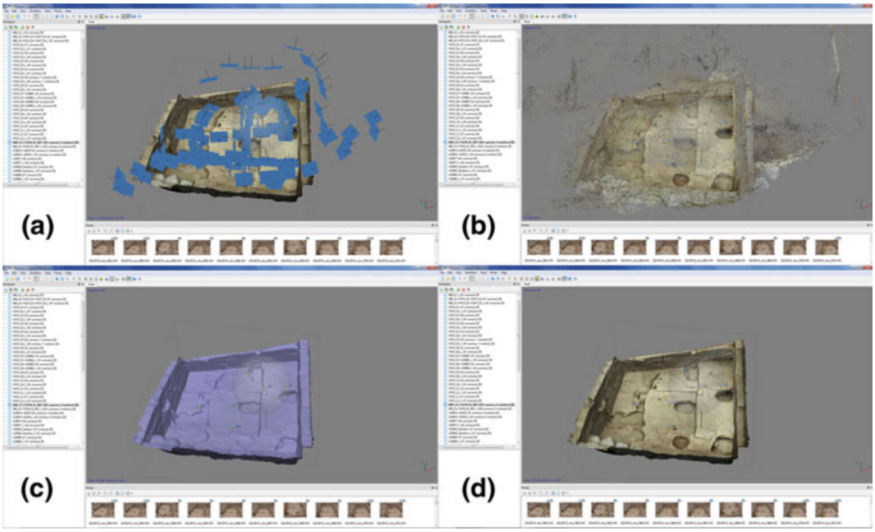

Fig. 2 Processing of 3D data captured at the UNESCO site of Çatalhöyük, Building 89 in Agisoft Photoscan showing. **a** Camera positions and ground control points. **b** Georeferenced dense cloud. **c** Edited triangular mesh in *Wireframe mode*. **d** Optimized triangular mesh in *Shaded mode*

The Historic Buildings and Monuments Commission for England—also known as Historic England or English Heritage—provides surveyors with thorough guidelines with the aim to help identify the best application scenarios for Airborne LiDAR, TLS, or other 3D capture methods in relation to different deliverables and specific precision and accuracy goals (Crutchley and Crow 2009).

Currently available technologies give surveyors the advantage to cut the duration of the survey process from data capture to final delivery by one order of magnitude. For instance, one can now fly an affordable thermal camera, such as a FLIR Tau 2, and a compact RGB camera, such as a mirror-less Sony RX100, mounted on a consumer multi-rotor UAW manufactured by DJI (DJI 2015) or 3D Robotics (3DRobotics 2015) for few thousands of U.S. dollars (FLIR&DJI 2015).

The current major shift in 3D mapping and 3D modeling is due to proven computer vision technologies based on Structure from Motion (SFM) and Dense Stereo Matching (DSM) algorithms (Verhoeven 2011; Verhoeven et al. 2012; De Reu et al. 2013; De Reu et al. 2014). SFM and DSM proved to be reliable technologies that can be used to process large datasets of aerial photographs captured by uncalibrated digital cameras mounted on lightweight aircrafts flying GPS waypoint missions.

Nonetheless, the main disadvantage of the new 3D capture technologies is that the new 3D scanners mostly rely on depth cameras or electro-optical sensors that still do not work outdoors, or at night, or underperform in scenarios where the subject is overexposed or not evenly lit. Thus, the quality and accuracy of the new 3D digitizers highly depend on environmental conditions such as the temperature, illumination, and reflectivity of the area of interest. One needs to notice that such constraints may be overcome by future technological development, but currently represent a strong drawback to the adoption of the new 3D capture technologies in many professional fields and academic disciplines. One also needs to underline that some of the above mentioned limitations might apply to traditional laser-based data capturing tools. For instance, digital archaeological work at the UNESCO site of Çatalhöyük, in Turkey, proved that the documentation of stratigraphic layers may be very complex or not feasible when an high-accuracy optical laser scanner (e.g. Minolta Vivid 910) was employed in the field to document the stratigraphy of a complex midden sequence (Forte et al. 2015, pp. 43–44). When compared to optical technologies, time-of-flight and phase comparison laser scanners are less affected by adverse lighting conditions; the accuracy and precision of such scanners can decrease in heavily lit scenarios, unless such equipment is specifically manufactured for long-range and outdoor usage. More broadly, one also needs to mention that extremely hot or cold temperatures can affect the majority of data capture sensors. Extreme environmental conditions may become an issue for surveyors. For example, the author of this chapter has often experienced TLS equipment warnings and shutdowns while scanning archaeological heritage inside the permanent shelters of Çatalhöyük where air temperature may be above 45° C in a hot summer afternoon.

In terms of survey range, the new commodity 3D scanners offer very limited options when compared with time-of-flight or phase comparison TLS technologies. Optical and TLS structured light data capture systems have very limited survey range—usually from 0.5 m to maximum of few meters from the sensor—and present a number of constraints that make them not very feasible for large sites or whole-building surveys (Fig. 3).

Moreover, mass consumers are not very interested in expensive or complicated calibrations operations or data fidelity. These propensities are reflected in the way the new commodity data capture tools are designed and built. The new 3D digitizers are rarely rugged enough to perform well outdoors or in the fields and do not support custom color and sensor calibration.

A comprehensive cost-benefit analysis of the alternative technologies and methods discussed in the previous pages goes beyond the scope of this chapter, but will need to be examined in future publications.

User-Oriented Data Processing and Open-Source Software

In the Age of Sensing, data processing is also more effective, faster, user-friendly, and occasionally freely available. For instance, the end-to-end 3D platform developed by Matterport allows users to perform the following with great ease Matterport (2015): (i) to scan and upload 3D data via a Matterport Pro 3D camera, an optical solution for data capturing, or simply via any mass-market mobile devices equipped with a Matterport 3D capture app; (ii) to automatically process the captured data in the cloud

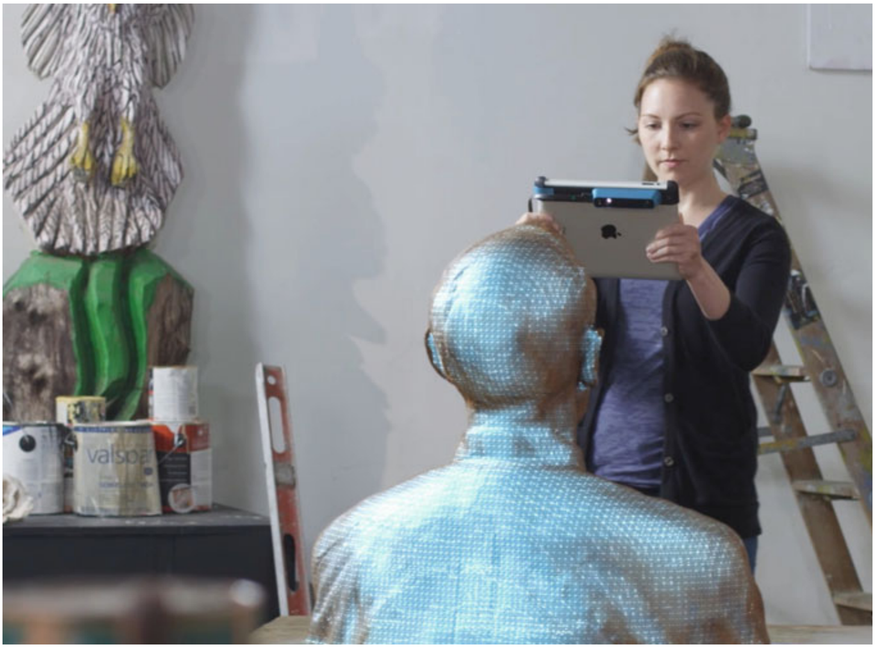

Fig. 3 Indoor usage of the Structure Sensor to record artworks—courtesy of Occipital

using Matterport Cloud Service; (iii) to enable anybody to interact with and share the processed data using a web browser or mobile app (Matterport). The functionalities of the Matterport platform make this tool a comprehensive and very easy to use system able to 3D map the world, display content on virtual reality headsets, such as Oculus Rift (Oculus Rift 2016), HTC Vive, Samsung Gear VR (Samsung Gear VR 2016), or the Web, while enable mass mobile technologies to become 3D capture systems.

Sequoia is a multiplatform, standalone software that allows to easily reconstruct the surface of large point clouds made of several billions of points. Sequoia is able to convert huge data sets of laser scanning data and particle data to triangular mesh geometry in few minutes (Sequoia 2015). The start-up company Thinkbox Software developed Sequoia's architecture to handle massive amounts of laser scanning data through a progressive processing workflow. The result of this approach is that Sequoia is able to visualize the final result of the processing even before all the data is loaded. Moreover, this software is able to handle huge data sets that can be larger than the actual memory available in the computer where the processing is performed. Sequoia also allows users to perform operations such as smoothing, decimation, color and texture projection on mesh (Thinkbox 2015).

One of the exceptional aspects of Sequoia is that this application makes large point clouds processing accessible and easy to handle even for non-experts in TLS data processing. In fact, Thinkbox Software developed this application for architecture, engineering and construction markets with the goal to directly compete with more established data processing platforms such as the 3D authoring tools developed by 3D Systems (3D Systems 2015).

In regards to 3D Systems' products, one needs to spend few words on Geomagic Design X, formerly known as Rapidform XOR. In the Age of Sensing, Geomagic Design X is one of the most advanced point cloud processing software capable of combining the parametric approach of Computer Aided Design (CAD) software with advanced 3D data scan processing capability. Nonetheless this tool is part of a specialized software platform primarily created for reverse engineering and manufacturing projects, Geomagic Design X is user-friendly and presents a number of functions able to automatically extract features and components directly from the point clouds. The applications of Geomagic Design X for the documentation and mapping of sites and the drawing of artifacts are endless; one can employ Geomagic Design X for point cloud to CAD operations. This allows surveyors to generate accurate maps of entire sites or sections of walls and facades starting from TLS survey data. One can also use Geomagic Design X for authoring precise 2D drawing of artifacts and other material culture objects that were previously scanned (Geomagic Design X 2015). The main downsides of the commercial software referenced above are: (i) the high cost for acquiring the license of these proprietary platforms; (ii) the ongoing cost for maintaining them; (iii) the closed-source code; (iv) commercial strategies non-quite friendly to educational institutions.

In the Age of Sensing, viable alternative solutions to the above-mentioned software are available free of charge. MeshLab is an free software application for mesh and point cloud data editing that is incredible popular among scholars, educators, cultural institutions, and private firms involved in the digital documentation of heritage sites and 3D data processing (Cignoni et al. 2008).

The widespread diffusion of MeshLab is due to the powerful tools and filters it provides to its users (Fig. 4) (MeshLab 2016). This software is distributed under GNU General Public License. MeshLab is the product of the invaluable dedication and cutting-edge research of the Visual Computing Laboratory at CNR-ISTI research center. What is remarkable about MeshLab, is that it is developed by a team of scholars committed both to develop free software for cultural heritage as well as to advance virtual heritage research (Callieri et al. 2011; Dellepiane et al. 2012; Siotto et al. 2014).

CloudCompare is a multiplatform open-source solution for 3D point cloud editing that can be also employed to process triangular mesh (Girardeau-Montaut 2011; CloudCompare 2015). This software was initially created in 2004 in the division for Research and Development of the public utility company Électricité de France (R&D E.D.F. TP 2011). In 2009, CloudCompare was released as free software under GNU General Public License. CloudCompare architecture exploits octree structure techniques to visualize and handle large point cloud data sets (Chien and Aggarwal 1986). This application offers a large variety of cloud processing algorithms spanning mesh-cloud comparison, registration, resampling, color and picture projections, and interactive or automatic segmentation. CloudCompare is especially relevant for evaluation and comparison of 3D Data (Scollar and Giradeau-Montaut 2012; Rajendra et al. 2014) (Fig. 5).

Viable workflows for data capture and processing rely on: (i) transparency of the data acquisition process, (ii) use of open file formats (e.g. Wavefront .obj or Polygon

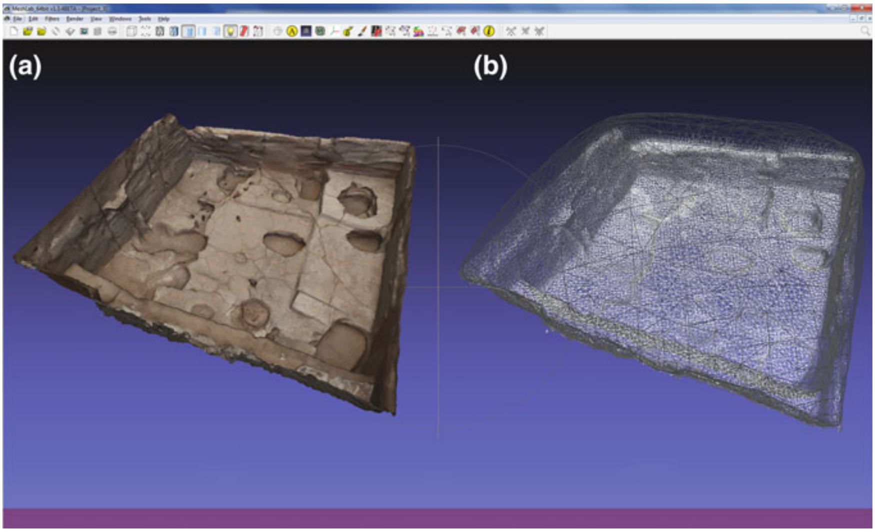

Fig. 4 Triangular Mesh of Çatalhöyük Building 89 in MeshLab. **a** Flat mode view with lighting. **b** Wireframe mode view showing poisson surface reconstruction

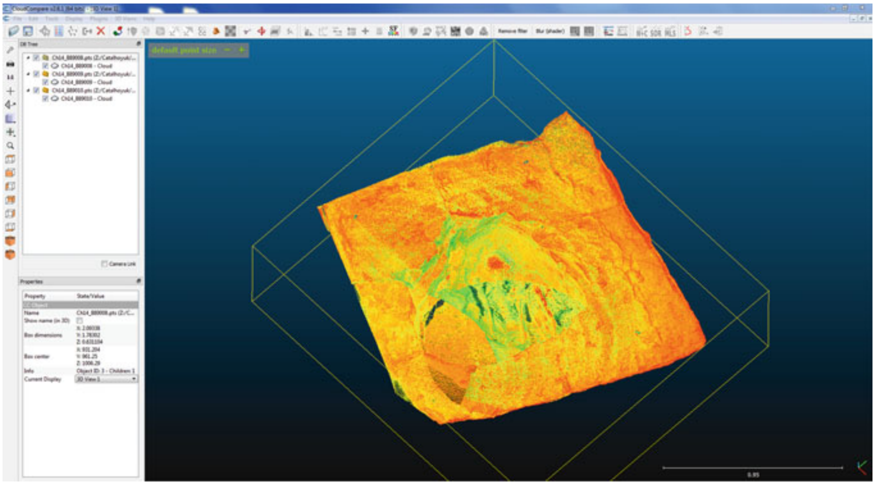

Fig. 5 Çatalhöyük Feature 3484 point cloud analysis and comparison in CloudCompare

File Format .ply) or manufacturer-independent file formats (e.g. ASTM E57 .e57), (iii) delivery of data that can be processed and visualized with open source or free software, (iv) open access to the end results (Lercari 2010). These four factors determine the sustainability of a workflow or technology over time and apply to both TLS and new tools available in the Age of Sensing.

3D Web Visualization and Cloud Services

To further advance this discussion on data recording and processing methods in the Age of Sensing, one has to mention that the increasing diffusion of high-speed networks—such as *next generation* wired connections able to transfer data at 10 or 100 Gb/s or Long Term Evolution (LTE)-A mobile connections able to download data at 1 Gb/s—create new opportunities to process 3D data in the cloud or to render complex 3D scenes directly over the Internet.

Web-based 3D reconstruction services have been utilized for years (Vergauwen and Van Gool 2006), but the availability, effectiveness, and versatility of the cloud services now available for 3D data processing have greatly expanded since the 2010s. In addition, the wide diffusion of open web 3D standards such as X3D (X3D 2015) and WebGL (WebGL 2015) and open-source frameworks, such as X3DOM (Behr et al. 2009; X3DOM 2015), has made it possible to visualize 3D data natively on a web browser, without the need to install additional plug-ins. These new scenarios are enabled by empowered web browsers (e.g. Mozilla Firefox 38.0 or Google Chrome 50.0) that are able to directly access the graphics card's acceleration capabilities to perform online, real-time rendering of 3D content (Evans et al. 2014).

Previous work demonstrates the potential of a complete workflow from the field to the 3D web. TLS data were captured at a natural heritage site, then processed, and finally simplified to be suitable for web visualization using X3D, WebGL, and X3DOM standards (X3DOM 2015; Silvestre et al. 2013).

New scholarship shows the potential of 3D visualization of cultural heritage data on the web using WebGL and SpiderGL (Callieri et al. 2015); as well as custom systems, such as 3DHOP, designed to optimize the online visualization of 3D cultural objects (Potenziani et al. 2014). While cloud computing tools have been used for years in the visualization of 3D cultural data in online virtual environments (Lercari et al. 2011), cloud platforms for 3D data processing and visualization are relatively new.

In recent years, big corporations in the field of remote sensing and 3D authoring software (e.g. Leica, FARO, and Autodesk) have engaged in the development of new cloud-based systems able to process, visualize, mark-up, and share point clouds and triangular mesh over the Internet. Autodesk Recap 360 or Recap 360 Ultimate (Autodesk Recap 2015), FARO SCENE WebShare Cloud (SCENE WebShare Cloud 2016), Hexagon Imagery Programme (HxIP 2015), and Leica CloudPro (CloudPro 2015) are good examples of new commercial cloud platforms created for online 3D data processing, visualization, and sharing of TLS or ALS data.

These new commercial cloud processing and interactive visualization systems enable surveyors, clients, and collaborators, to remotely access and share survey data on buildings, landscapes, and even entire sites. Moreover, these cloud platforms make it possible for stakeholders to work together to create and share mark-ups and interpretations of the TLS post-processed data.

As of 2015, many different models are available for 3D processing and visualization in the cloud. Web-based cloud services, such as Autodesk Recap 360, allow users to process and visualize both TLS and IMB 3D content using their Internet browser (Fig. 6). In addition, the hybrid standalone and cloud-based software Autodesk Recap Ultimate provides further options for TLS automatic data registration and processing. The cost of Autodesk cloud services is U.S. dollars 500/year per user for Recap 360 and U.S. dollars 2000/year per user for Recap 360 Ultimate (Recap 2015).

FARO Technologies also offers a Platform as a Service (PaaS) cloud-based hosting solution that promises to revolutionize access to TLS data online. In fact, FARO SCENE WebShare offers to its users incredibly easy to use tools aimed at data processing, managing, and sharing 3D data directly in the cloud. SCENE WebShare offers different levels of subscriptions that target Small Enterprise (€1.490/year for 100 GB of storage or 1000 scans), Medium Enterprise (€2.950/year for 200 GB of storage or 2.000 scans), and Large Enterprise (€7.750/year for 500 GB of storage or 5.000 scans) (SCENE WebShare Cloud 2016).