On the Use of Google Earth Engine and Sentinel Data to Detect "Lost" Sections of Ancient Roads. The Case of Via Appia

Rosa Lasaponara, Nicodemo Abate, and Nicola Masini

***Abstract*— The currently available tools and services as open and free cloud resources to process big satellite data opened up a new frontier of possibilities and applications including archeological research. These new research opportunities also pose several challenges to be faced, as, for example, the data processing and interpretation. This letter is about the assessment of different methods and data sources to support a visual interpretation of EO imagery. Multitemporal Sentinel 1 and Sentinel 2 data sets have been processed to assess their capability in the detection of buried archeological remains related to some lost sections of the ancient Via Appia road (herein selected as case study). The very subtle and nonpermanent features linked to buried archeological remains can be captured using multitemporal (intra- and inter-year) satellite acquisitions, but this requires strong hardware infrastructures or cloud facilities, today also available as open and free tools as Google Earth Engine (GEE). In this study, a total of 2948 Sentinel 1 and 743 Sentinel 2 images were selected (from February 2017 to August 2020) and processed using GEE to enhance and unveil archeological features. Outputs obtained from both Sentinel 1 and Sentinel 2 have been successfully compared with *in situ* analysis and high-resolution Google Earth images.**

***Index Terms*— Big data, Copernicus, Google earth engine (GEE), Sentinel 1 (S-1), Remote sensing for archeology, Sentinel 2 (S-2).**

I. Introduction

BIG Earth Observation (EO) data emerged in the past few years as powerful tools in archeology serving numerous applications ranging from the archeological discovery and documentation to the monitoring and preservation. In particular, EO technologies offer several advantages in the field of preventive archeology mainly because they provide non-invasive tools capable of significantly reducing time and costs for study and research. EO big data are both resources and tools which pose big challenges to be faced and offer big opportunities, thus opening new research frontiers and enabling innovative applications with an unprecedented value for digital Cultural heritage (CH). Moreover, EO data are also available free of charge, as in the case of Copernicus initiative [1], [2], so that today, archeologists have the possibility and opportunity to use an ensemble of diverse technologies. Nevertheless, the setting up of data processing and methodologies *ad hoc* for archeological investigations is a critical issue along with data interpretation (to identify, extract, delineate, and analyze archeological sites) which need to be tackled by the scientific community to ensure an effective and reliable applicability [3]–[6]. In this letter, Sentinel-1 GRD [1] (S-1) and Sentinel-2 MSIL2A [2] (S-2) data have been used to assess their capability in the detection of archeological features related to some lost sections of the ancient Via Appia, herein selected as case study. This letter is about the assessment of different methods and data sources to support a visual interpretation of EO imagery. Considering that, archeological features generally do not exhibit clear and clean patterns or edges (even in high-resolution data sets), to enhance them, *ad hoc* data processing has been applied both to S-1 and S-2.

Data were processed using the Google Earth Engine (GEE) [7] and then refined in ENVI 5.3 and GIS software. The use of GEE and its data sets was necessary to work with Sentinel's Big Data, without requiring a strong hardware infrastructure.

The Via Appia was one of the most important ancient Roman roads, that connected Rome to Brundisium (Brindisi), which assured the connection to Greece and the East areas and, therefore, was one of the most important ports of ancient Italy. The Via Appia was considered by the Romans as the "Regina Viarum" (queen of the roads), for the enormous economic, military, and cultural impact it had on the Roman society and later on. Still today, Via Appia is universally held, in view of the era in which it was built (late third and fourth century BC), as one of the greatest civil engineering works of the ancient world. Wide sections of the road, particularly in the suburb of Rome, are still preserved and very attractive for archeological tourism [8], [9].

Nevertheless, some sections especially in south of Italy are completely lost, and still today object of numerous researches and lively debates also poorly documented in the historical sources (see Itinerarium Antonini, Tabula Peutingeriana, Medieval Cosmographies of the Anonimo Ravennate and Guidone, and in toponymic "heritage" [10]). As many Roman roads, the Via Appia is now used for most of its length, often below the main modern roads, or in secondary roads not accessible by cars. This makes the Via Appia easy to walk

Manuscript received October 20, 2020; revised December 25, 2020; accepted January 18, 2021. Date of publication February 5, 2021; date of current version December 16, 2021. *(Corresponding author: Nicodemo Abate.)*

Rosa Lasaponara and Nicodemo Abate are with Italian National Research Council (CNR), Institute of Methodologies for Environmental Analysis (IMAA), 85050 Tito Scalo, Italy (e-mail: rosa.lasaponara@imaa.cnr.it; nicodemo.abate@imaa.cnr.it).

Nicola Masini is with Italian National Research Council (CNR), Institute of Heritage Science (ISPC), 85050 Tito Scalo, Italy (e-mail: nicola.masini@cnr.it).

Digital Object Identifier 10.1109/LGRS.2021.3054168

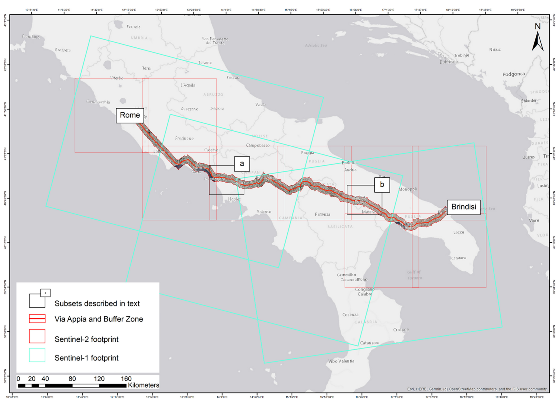

Fig. 1. Study area location (WGS 84 UTM/33N EPSG: 32633).

but hard to find in places where it deviates (for engineering reasons) from the modern road system. In this letter, to assess the potentiality of EO S-1 and S-2, two areas (denoted by a and b in Fig. 1) have been investigated to detect the lost sections of the Via Appia expected to be therein: 1) the current urban centers of Mondragone and Capua (Campania), and 2) Gravina in Puglia and Altamura (Puglia). The main purpose of this letter is not only to test the usefulness of GEE and S-1 and S-2 data set in archeological research but also to set a free and user friendly digital archeology tool "ready to be used" by "digital archeologists" [11]–[16].

II. Method

Aerial- and space-based recognition of archeological features is based on the use of the so-called archeological proxy indicators, generally known as crop, soil, and shadow marks. Soil marks are changes in soil color or texture due to the presence of emerging and shallow remains that can be also visible as microreliefs. Crop marks are changes in crop texture (linked to vegetation height and/or color) caused by the presence of subsoil walls or pits and ditches, which cause differential vegetation growth (increasing or decreasing, respectively). These archeological proxy indicators are very subtle and may be visible in specific conditions due the presence of microreliefs, moisture patterns and /or differential growth of vegetation. Many of these characteristics are closely interrelated so that the brightness of features, and the visibility of archeological marks, is usually linked to several variables, as specific spectral channels and their combinations (spectral indices) useful to enhance vegetation and/or moisture. In addition, it must be considered that there are numerous factors, such as noise, atmospheric contaminations, and so on. that tend to further attenuate or distort the subtle edges and feature linked to subsoil and/or emerging archeological remains. To face these challenges and collect as much as possible information, the enhancement of the features of interest is a mandatory step [11]–[16]. To this aim the use of robust data processing techniques is required, and herein applied to both S-1 and S-2, the latter herein used as available from the ESA web site, already preprocessed (from the calibration to the atmospheric correction).

Related to S-1, it must be considered that a correct identification and interpretation of archeological marks on the basis of radar images is not a straightforward task and requires

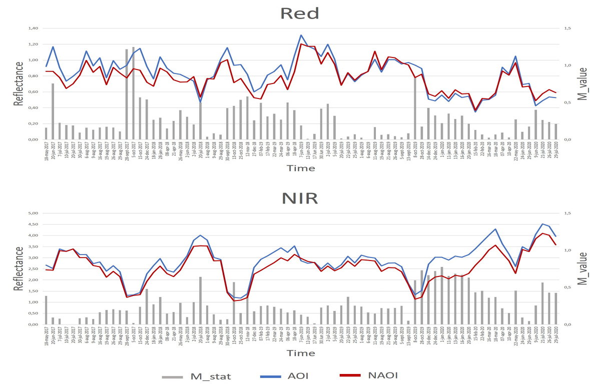

Fig. 2. Example of the S-2 Spectral Signature Analysis (Red and NIR) over time (2017–2020), near Capua. (a) Points where the ancient Via Appia is attested (AOI blue line); (b) Points where the presence of archeological remains of the Via Appia is not expected (NAOI, red line); and M-statistic value.

knowledge about ground surface conditions as well as about the interaction mechanisms between radar waves and surface sensed. The reconnaissance of typical archeological marks (such as crop, shadow, and soil/damp marks) using radar is more complex than optical imaging [13]. The discriminability of archeological marks is a complex issue mainly because linked to very subtle and nonpermanent signals [14], [15] only evident in specific surface conditions, (as for example, vegetation type and phenology, moisture content, etc.) that can be captured using a multitemporal data processing [15]. This requires suitable computing resources from strong hardware infrastructure and facilities or cloud tools, today also available as open and free tools as GEE.

GEE is based on the use of the Javascript language to access libraries, resources and datasets, as S-1 and S-2 images provided already preprocessed (see details in the Dataset section of GEE [17]–[21]).

The area of interest was investigated using a GEE script to create a buffer zone of 8 km along the route of the current Via Appia. Sentinel data were processed within the buffer zone, using the computing power of GEE. A total of 743 S-2 and 2948 S-1 images (selected from February 2017 to August 2020, with 01 clouds percentage) were used to focus two subsections of the ancient Via Appia (Fig. 1). For both S-1 and S-2, the processing was addressed to feature enhancement and data reduction to capture archeological features and characterize their spatial and temporal variations in terms of both size and distribution [11], [14]. This was performed using Javascript in GEE to obtain Bands combination, RGB composition, Spectral Signature and Backscattered observation, and PCA [11]. In particular, two classes were identified on the basis of the archeological data and an S-2: 1) areas where the Via Appia is expected by [8]–[10] (AOI) and 2) areas where the Via Appia is not expected (NAOI) (Fig. 2).

Using GEE, the spectral signature (mean and standard deviation) of the two classes was calculated over the entire time span (2017–2020). This enabled the identification of the spectral bands characterized by a significant spectral distance between the two classes using the M-statistic value in the following equation [22]:

$$M = (\mu_1 - \mu_2)/(\sigma_1 + \sigma_2) \tag{1}$$

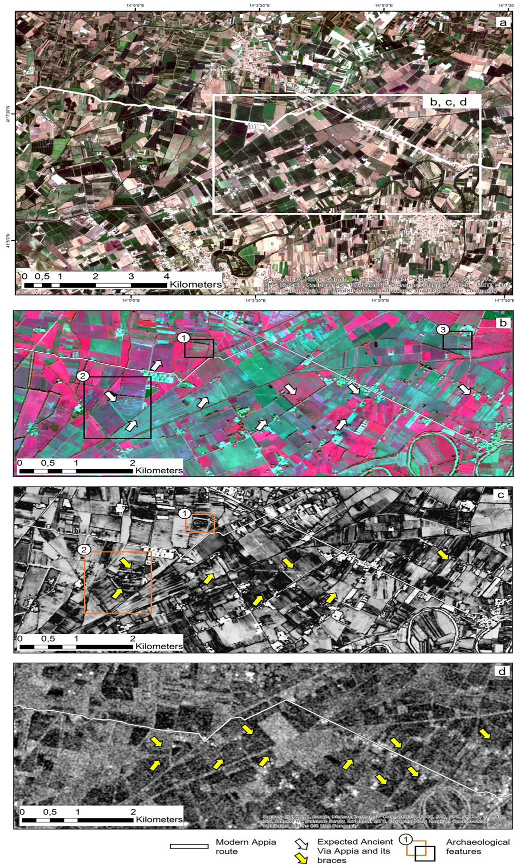

Fig. 3. Via Appia Mondragone–Capua: **(a)** S-2 R: B4, G: B3, B: B2 2017-10-15; **(b)** S-2 R: B8, G: B4, B: B3 mean value 2017-2020; **(c)** Moran's Index 2019-12-14; **(d)** S-1 Sigma0VV_2019-05-03. Arrows point to the linear traces left by the ancient roads, while rectangles mark archeological features (centuriation traces, known archeological sites, or possible new sites).

where μ_1 is the mean value for class AOIs, μ_2 is the mean value for the background, and σ_1 and σ_2 are the respective standard deviation.

The characterization of spectral signature was the core of the processing: it did enable the selection of the best images (i.e., with highest distance) used as input for the data reduction and statistical analysis based on PCA and LISA, respectively. The three indices Moran, Getis, and Geary [23] of LISA (2) are available in open and commercial software tools as ENVI 5.3.

$$I_i = \left(\frac{z_i}{m_2}\right)\sum_j w_{ij} z_j \tag{2}$$

where the statistic is, for each observation (location) ii, the sum of the relevant expression over the jj index, $\sum_{jgij}$; $m2$ is a constant for all locations; and the weights matrix, W, is typically defined as a contiguity matrix, determined by a distance threshold.

LISA outputs provided indication about the extent of significant spatial clustering and, therefore, enabled us to detect potential anomalies and capture their spatial characteristics. In particular, we used Moran's I not only to better characterize the presence of features and patterns of buried remains but also to enhance their boundaries and improve their recognition and interpretation.

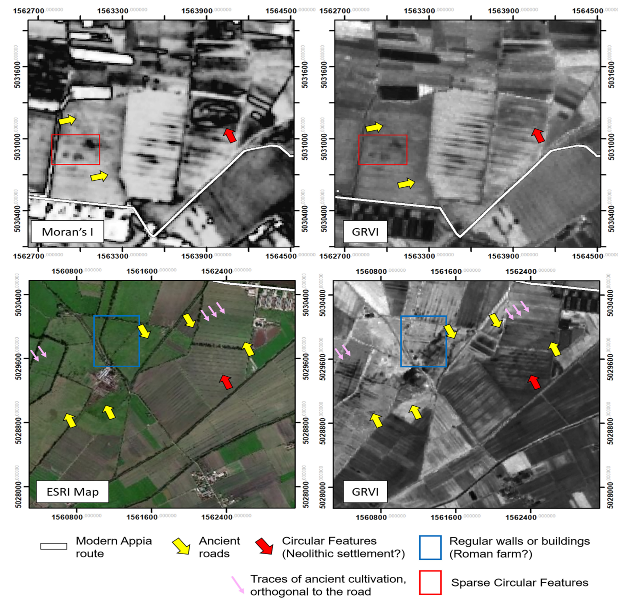

Fig. 4. Comparison of results: Moran's I and GRVI (2019-12-14) zoom on in Fig. 3; ESRI Map (Credits: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN - GIS User Community, with measured grid) and GRVI (2018-10-21) zoom on in Fig. 3.

III. Results

The analysis of S-1 and S-2 pointed out the potential of GEE tools and Sentinel's data to highlight linear archeological traces, even with the limits of the spatial resolution of the S-1 and S-2 data. Figs. 3–6 show the fit between S-1 and S-2 features for the identification of the ancient roads and remains. The section of Via Appia between Mondragone and Capua, near Grazzanise (Caserta), is separated in diverse points from the current modern road [Fig. 1(a)]. The ancient road is visible inside the cultivated fields in the RGB, False Infrared Color images and indices [Fig. 3(a)–(c)], as well as linear traces in SAR data [Fig. 3(d)]. LISA statistics, in particular the Moran's index [Fig. 3(c)], allowed the identification of several linear traces, referable to the ancient Via Appia, secondary ancient roads, and many other features of archeological interest related to ancient buildings and crops. The place (Fig. 3) is known in the bibliography for the crossing of the Via Appia with other important branches, directed toward the main towns of the Roman period and served as a crossroads between the places of the coast and those of the hinterland [8], [9]. The Moran Index [Fig. 3(c)] and the Green Ratio Vegetation Index (Near Infrared/Green) from S-2 images (Fig. 4) highlighted several types of archeological remains. Fig. 4 shows all the strengths of the surveys conducted using S-2.

In particular, the pictures on the top show some archeological features: a road connected to the Via Appia; some circular features are evidenced in the red box (could be huts or tombs); and a complex of circular features (could be a settlement). The pictures on the bottom highlighted the potential of the multispectral data, at 10 m of spatial resolution, compared with the high-resolution RGB provided by ESRI. In S-2 data, there are features not visible in the high-resolution image, in particular, roads (yellow arrows), traces of ancient

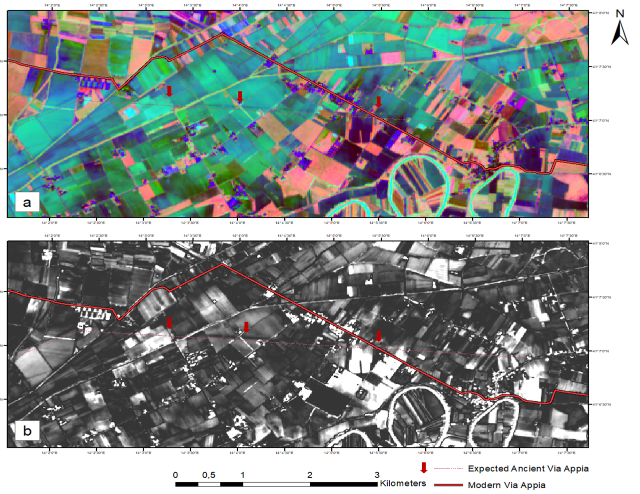

Fig. 5. Via Appia Mondragone–Capua: **(a)** Sentinel-2 (all images) PCA-RGB composite (R: First Component 71,784% inf., G: Second Component 20,702% inf., B: third Component 6,718% inf.); **(b)** Moran's Index applied to the PCA (**a**).

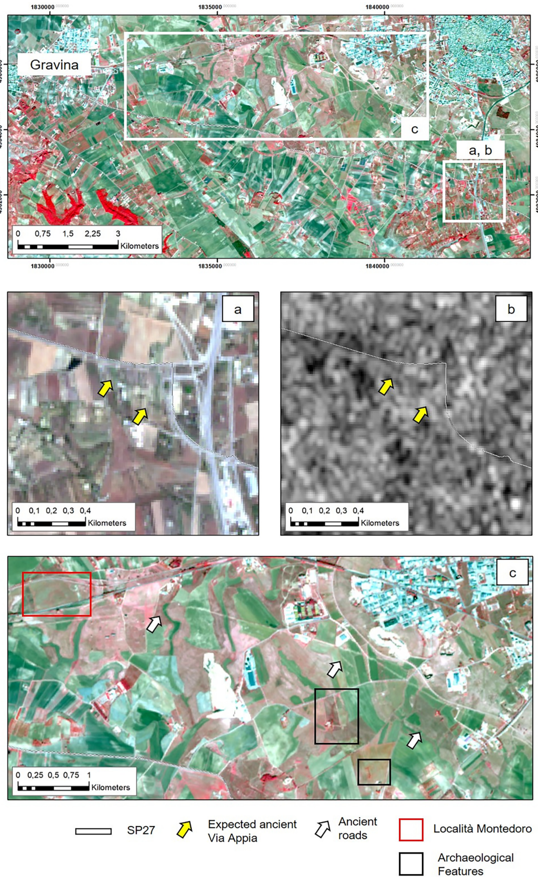

Fig. 6. Via Appia Gravina in Puglia–Altamura (False Color Infrared 2017-10-15). **(a)** RGB 2019-06-29; **(b)** Sentinel-1 Sigma0_VH 2019-05-04. **(c)** FCIR 2017-10-15 subset.

cultivation (pink arrows), structures (blue box), and circular compounds (red arrow).

The data reduction processes based on the PCA of Sentinel 2 provided excellent results for the ancient Via Appia located in the Capua area.

A good result was also provided by the Moran index applied to the RGB composed of the first three Principal Components, which shows a strong spatial correlation in the area where the Via Appia was expected (Fig. 5).

The characterization of the lost section of the Via Appia in the Apulia Region (close to Gravina and Altamura towns) was more complex compared with the one in the Caserta area [Figs. 1(b), 3, and 4]. Several studies suggested that the route of the ancient Via Appia almost entirely coincides with the modern road named SP27, with a few points of separation between the two roads (Fig. 6). Fig. 6 clearly pointed out that both S-1 and S-2 were useful to identify the linear features of the Via Appia and other minor ancient roads between the Gravina and Altamura towns. Moreover, both S-1 and S-2 highlighted circular or subcircular features (see red box in Fig. 6) linked to the Neolithic settlement and the late antique necropolis of Montedoro [24].

The features inside the black box in Fig. 6 are not known from the bibliography and can be considered as a new discovery probably related to buried ancient settlements or hill fences, built along the main roads. The discovery of settlements, stations, necropolis, and farms, dated back from prehistory to modern age, is quite frequent along roman roads, because often the Roman roads (as in the case of Via Appia) were built over already existing routes used for centuries before the Romans.

IV. Discussion and Conclusion

In this letter, we focus on the use of GEE to process multitemporal S-1 and S-2 data sets (as a "friendly user tool" for archeologist) to detect some lost sections of ancient roads, using as case study the Via Appia (in South of Italy). For the purpose of our investigations, we propose an "easy-to-use" methodological approach following the recommendations by the European Space Agency on the Copernicus Program website, GEE. According to this vision, the data processing approach was mainly based on the use of features enhancement as PCA and LISA, along with visual interpretation of RGB and spectral indices and ancillary data [8]–[10], [24]. The use of GEE and the ancillary data (available from the archeological bibliography) was of fundamental importance in the processing of multitemporal S-1 and S-2 data sets devised for the identification of the best satellite-based products for the detection of features of archeological interest, as shown by the graphs and figures in the text. This tool was useful to easily calculate the reflectance/backscattering values of the identified classes (e.g., in Fig. 2) in dozens of Sentinel images, which was necessary in order to choose the best data to enhance the visibility of archeological features in PCA and LISA operations.

The comparison of the results obtained from S-1 and S-2 for the two sections of the Via Appia, herein investigated, highlighted that the reconnaissance of the typical archeological marks (crop, shadow, and soil/damp marks) is more complex using radar than optical imaging. This is due to a greater number of parameters that characterize SAR data, including the: 1) characteristics of the radar system as operating frequency, polarization, angles, viewing geometry (ascending or descending), and so on; 2) characteristics of the surface, in terms of land cover type, topography, relief, dielectric constant, moisture content, and conductivity; and 3) archeological features in terms of buried or emerging remains, their geometric structure, orientation, building material, and so on. The parameters that have a key role in the interactions between radar and target are 1) surface roughness; 2) radar viewing and surface geometry relationship; and 3) moisture content and dielectrical properties of the target. The roughness is usually the dominant factor in a radar picture, but it is very important to consider that it is not an absolute characteristic but it depends on the wavelength and on the incidence angle of radar signal which is another crucial parameter. S-1 does provide useful additional information complementary to those provided by S-2. Results jointly obtained from S-1 and S-2 have been successfully compared with *in situ* analysis and high-resolution EO data as Google Earth images. The multipurpose integration (result assessment and improvement) of diverse data source and EO technologies can offer a *continuous improvement* of *knowledge* thought a *scalable and modular approach* oriented to collect and puzzle pieces of information on past human activities thus has opening new possibilities, unthinkable only a few years ago for Cultural Heritage.

The methodology herein proposed can be promptly reapplied to cultural properties with different characteristics and located in diverse geographical areas, and allows us to fully exploit the spatial resolution of the two sensors and their strengths. In particular, thanks to the use of the GEE, satellite image processing, which requires high-level hardware, becomes accessible to everyone.

EO technologies are noninvasive and very reliable not only for the discovery of lost archeological remains/sites but also useful to investigate cultural landscapes, assessing the condition of archeological features that is a mandatory step for the preservation and management of cultural properties and historic sites. The great amount of remotely sensed data, today also available at very high spatial resolution (from aerial and satellite platforms), at low cost or free of charge (Google Earth), opens new strategic challenges in the field of remote sensing for CH and archeology. There is no doubt that EO big data will significantly change the scientific approach, data analysis, and methodologies for the discoveries of unknown archeological sites even if this poses several critical issues, as those linked to data processing and interpretation, for transforming data into useful information.

As a whole, the use of S-1 and S-2 multitemporal data set and GEE for archeology offers great potentiality even if critical challenges are still to be faced to improve our capacity to uncover unique and invaluable information, from site discovery to studies focused on the dynamics of human frequentation in relation to environmental changes. Moreover, EO technologies can enable advanced performances and new operational applications specifically addressed to security and risk of archeological remains in particular and Cultural properties in general.

References

[1] *Sentinel-1*. Accessed: Oct. 18, 2020. [Online]. Available: https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-1-sar

[2] *Sentinel-2*. Accessed: Oct. 18, 2020. [Online]. Available: https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi

[3] A. Traviglia and A. Torsello, "Landscape pattern detection in archaeological remote sensing," *Geosciences*, vol. 7, no. 4, p. 128, Dec. 2017.

[4] A. Agapiou, D. Alexakis, and D. G. Hadjimitsis, "Potential of virtual Earth observation constellations in archaeological research," *Sensors*, vol. 19, no. 19, p. 4066, Sep. 2019.

[5] A. Agapiou, D. Alexakis, A. Sarris, and D. Hadjimitsis, "Evaluating the potentials of Sentinel-2 for archaeological perspective," *Remote Sens.*, vol. 6, no. 3, pp. 2176–2194, Mar. 2014.

[6] D. Tapete and F. Cigna, "Appraisal of opportunities and perspectives for the systematic condition assessment of heritage sites with copernicus Sentinel-2 high-resolution multispectral imagery," *Remote Sens.*, vol. 10, no. 4, p. 561, Apr. 2018.

[7] *GEE*. Accessed: Oct. 18, 2020. [Online]. Available: https://earthengine.google.com/

[8] L. Quilici and S. Q. Gigli, Eds., *La Via Appia. Iniziative e Interventi per la Conoscenza e la Valorizzazione da Roma a Capua*. Roma, Italy: L'Erma di Bretschneider, 2002.

[9] F. Ruffo, *La Campania Antica, Appunti di Storia e di Topografia*. Bologna, Italy: Danaro Libri, 2010, pp. 52–63.

[10] L. Piepoli, "Il percorso della via Appia antica nell'Apulia et Calabria: Stato dell'arte e nuove acquisizioni sul tratto Gravina-Taranto," *Vetera Christianorum*, vol. 51, pp. 239–261, 2015.

[11] N. Abate, A. Elfadaly, N. Masini, and R. Lasaponara, "Multitemporal 2016-2018 Sentinel-2 data enhancement for landscape archaeology: The case study of the Foggia province, Southern Italy," *Remote Sens.*, vol. 12, no. 8, p. 1309, Apr. 2020.

[12] S. Zanni and A. D. Rosa, "Remote sensing analyses on Sentinel-2 images: Looking for roman roads in srem region (Serbia)," *Geosciences*, vol. 9, no. 1, p. 25, Jan. 2019.

[13] F. Chen, J. You, P. Tang, W. Zhou, N. Masini, and R. Lasaponara, "Unique performance of spaceborne SAR remote sensing in cultural heritage applications: Overviews and perspectives," *Archaeol. Prospection*, vol. 25, no. 1, pp. 71–79, Dec. 2017.

[14] A. Elfadaly, N. Abate, N. Masini, and R. Lasaponara, "SAR sentinel 1 imaging and detection of palaeo-landscape features in the mediterranean area," *Remote Sens.*, vol. 12, no. 16, p. 2611, Aug. 2020.

[15] F. Chen, R. Lasaponara, and N. Masini, "An overview of satellite synthetic aperture radar remote sensing in archaeology: From site detection to monitoring," *J. Cultural Heritage*, vol. 23, pp. 5–11, Mar. 2017.

[16] R. Lasaponara, R. Yang, F. Chen, X. Li, and N. Masini, "Corona satellite pictures for archaeological studies: A review and application to the lost forbidden city of the Han-Wei dynasties surveys," *Geophysics*, vol. 39, no. 1, pp. 1–20, Nov. 2018.

[17] A. Agapiou, "Remote sensing heritage in a petabyte-scale: Satellite data and heritage Earth engine applications," *Int. J. Digit. Earth*, vol. 10, no. 1, pp. 85–102, Jan. 2017.

[18] H. A. Orengo *et al.*, "Automated detection of archaeological mounds using machine-learning classification of multisensor and multitemporal satellite data," *Proc. Nat. Acad. Sci. USA*, vol. 117, no. 31, pp. 18240–18250, Jul. 2020.

[19] *GEE S2*. Accessed: Oct. 18, 2020. [Online]. Available: https://developers.google.com/earthengine/datasets/catalog/COPERNICUS_S2_SR#description

[20] *GEE S1*. Accessed: Oct. 18, 2020. [Online]. Available: https://developers.google.com/earthengine/guides/sentinel1#sentinel-1-preprocessing

[21] *Sentinels Dataset*. Accessed: Oct. 18, 2020. [Online]. Available: https://www.copernicus.eu/it/accesso-ai-dati/piattaforme-tradizionali-di-accesso-ai-dati

[22] L. Luo *et al.*, "Identifying linear traces of the Han dynasty great wall in Dunhuang using Gaofen-1 satellite remote sensing imagery and the Hough transform," *Remote Sens.*, vol. 11, no. 22, p. 2711, Nov. 2019.

[23] L. Anselin, "Local indicators of spatial association-LISA," *Geographical Anal.*, vol. 27, no. 2, pp. 93–115, Sep. 2010.

[24] D. Venturo, "Altamura (bari), montedoro," *Taras*, vol. 15, no. 1, pp. 29–30, 1995.