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Image processing and analysis of radar and lidar data: new discoveries in Verona southern lowland (Italy)
Laura Burigana and Luigi Magnini
Department of Cultural Heritage: Archaeology and History of Art, Cinema and Music, University of Padova, Padova, Italy

ABSTRACT
This contribution proposes an evaluation of lidar and radar data processing and its potential in revealing archaeological features within a level plain environment, the southern lowland of Verona (Italy), focusing on evidences dating back to the Bronze Age. Many archaeological sites in the research area, including some of the most outstanding settlements of Terramare Culture, were identified or at least examined through aerial photo observation. Even if in several occasions modern agricultural activities contributed to the discoveries, bringing to the surface artifacts and scarpes of buried layers, this kind of impact has also been progressively deteriorating the archaeological record, hence the proto-historic landscape is now discernible through evanescent marks which cannot be always detected using customary optical sensors. Lidar and radar data analysis has then been considered as an alternative, non-invasive method of investigation on such a vast area.

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Introduction
The southern Verona lowland in Veneto region (Italy) is a portion of the Po plain bordered on the east side by Adige, on the west side by Tregnone and on the south side by Tartaro river. The geological profile is a heterogeneous composition of silty-clay and fine sandy levels. Tacitus, in his Histories, had called this area Palludes Tartars fluminis because of its low morphology and complex hydrography, whose main basin was the Tartaro River, which in the past (especially in pre-Roman age) often conditioned the man’s living choices and his relationship with the territory and the landscape.

In the Early Bronze Age,¹ when the Polada culture was widespread in most part of northern Italy, the plain was sparsely populated and still lacked connection infrastructures, with ample patches of forest left separating the scattered settlements.

During the Middle and Late Bronze Age,² with the development of the Terramare culture, the number of settlements in morphologically depressed areas strongly increased. The land became more extensively exploited for agriculture and also hierarchically organized as a proper “polity”, where the largest settlements³ (conventionally defined, given their relevance in the economic and territorial organization, “first rank” settlements) managed the production and held control of the (both short and long range) exchanges. Those sites were circumscribed by a perimeter bank-ditch system in which a nearby river flow had been steered. Between the Late Bronze Age and the beginning of the Final Bronze Age, the Terramare culture went through a rather sudden crisis caused by various factors such as demographic collapse, climate changes and social/political transformations (Cardarelli 2009). As a result, most part of the settlements are subject to a generalized abandonment.

Only in the Iron Age, a new structured anthropic occupation took place in the territory: the landscape

CONTACT Luigi Magnini luigi.magnini@gmail.com; luigi.magnini@phd.unipd.it
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was re-organized, in some cases (e.g. Perteghelle di Cerea) reactivating Bronze Age settlements (Balista and De Guio 1997, 137–160).

Today Southern Verona Lowland is an area strongly impacted by agriculture, which over time has gradually obliterated (partially or sometimes completely) the oldest anthropogenic traces. Farming has indeed damaged the archaeological deposit even if, on the other hand, it helped to preserve the place from modern building and urbanization. The absence of modern structures allowed archaeologists to observe and analyze the area from a remote perspective: in the last decades settlements, near-site structures, intra-site roads and river links has been spotted and observed through remote sensing.

Since the mid-80s these evidences are object of study of A.M.P.B.V. project (“Alto-Medio Polesine e Bassa Veronese”4) whose preferential research methodology relies mostly on non-invasive techniques, limiting the excavations in favor of the use of remote sensing, surface survey, geophysical prospection and the observation of “open stratigraphic windows” (stratigraphic sections exposed fortuitously during modern rearrangements of the landscape, such as channel excavations).

These procedures have been chosen with the aim of evaluating on a large scale the occupation and exploitation of the territory in southern Verona lowland and northern Polesine, analyzing the structural development of the ancient landscape (near-site/off-site/no-site perspectives). This strategy also required an attentive study of geological and relative dating sequences, as well as paleo-botanical and micro-morphological sampling. Over time, the integrated use of those techniques revealed a vast stretch of territory ideal for the examination of infrastructuralization processes, thanks to the clarity of the evidence as well as the shallow depth at which the archaeological evidence lies. We are thus in a context already known and well studied that can provide, for a methodological research, an adequate sample of reference, but whose information potential can still definitely expand. With the intent to test new means of investigation for the archaeological landscape, we put into comparison the more traditional optical data with two active remote sensing technologies: radar and lidar, that in the last years gained increasing popularity in archaeological science. We applied experimentally, both in the processing and in the pre-processing stage, different filtering and enhancing algorithms, in order to evaluate their effectiveness in improving detection and interpretation of archaeological features in the study area, referred in particular to the Bronze and the Iron Age.

As optical and lidar data, we used a lidar-derived Digital Terrain Model (DTM)5 and a set of aerial orthophotos6 provided by CBV (Consorzio di Bonifica Veronese, the land reclamation authority of Verona), both with a spatial resolution of 0.5m/pixel. As radar data we used an x-band aerial orthorectified Synthetic Aperture Radar (SAR) image, with a resolution of 0.85m/pixel, purchased from Intermap Technologies® in 2012.

Research methods and study area

Radar image processing

The first issue about radar data processing was speckle noise removal. After the interaction with the target, the electromagnetic waves emitted by the sensor are no longer in phase, although still coherent in frequency. This may either be because the waves travel back from different targets at different distances, or the single versus multiple backscattering due to the variance in surface roughness (Qiu et al. 2004, 244–266), or even the movement of the synthesized antenna (Hervet et al. 1998, 1–12). Those out-of phase signals interfere constructively or destructively, producing stronger or weaker signals which, visually, result in a black and white (“salt and pepper”) granular pattern named speckle or fading (Goodman 1976, 1145–1150). When dealing with coherent imaging systems, speckle noise introduces a factor determined not by the object of the analysis, but by the system itself; it is, therefore, important to be able to recognize it as an element belonging to the image (image texture) and not to scene (scenes texture).

Speckle reduction techniques can be basically divided in two main categories: non-coherent or multi looking integration and adaptive image (post-image formation) restoration techniques. The first category, which consist in dividing the azimuth bandwidth of the radar spectrum into a specific “number of looks”, was not taken into account for this research, since currently many SAR systems already integrate few looks during the image formation to assos a minimum improvement of the image quality. We chose instead, considering Gagnon and Jouan observations in their comparative study of speckle filters (Gagnon and Jouan 1997, 80–91), to focus our attention on post-image filters in order to find the best processing method to adopt for our research area. We thus tested, on a sample area near Castello del Tartaro site, a frequency filter based on stationary “a trous” wavelet transform and four spatial filters: Lee (Lee et al. 1994, 313–340), Frost (Frost et al. 1982, 157–166), Gamma and Kuan (Kuan et al. 1985, 165–177) (see Figure 1).

As an evaluation criterion to assess each filter effectiveness, we chose three statistical indices based substantially on the mean and the variance (that can be
automatically obtained by means of any software that can perform statistical computation) values of a uniform portion of the sample:

- the Equivalent Number of Looks (ENL), the increase of which implies a greater capacity of the filter to smooth the “peaks” in a flat area.

**Figure 1.** Visual comparison of a radar image sample treated with different filters.
The Speckle Suppression Index (or SSI), based on the following equation:

$$SSI = \left[ \frac{\sqrt{\text{variance} (I_f)}}{\text{mean} (I_o)} \right] \ast \left[ \frac{\text{mean} (I_o)}{\sqrt{\text{variance} (I_o)}} \right],$$

where $I_f$ and $I_o$ stand respectively for the filtered and the original image. This index has values inferior to 1 with a significant noise reduction (Sheng and Xia 1996, 1159–1161).

The SMPI, a more recent Speckle Suppression Index which takes into account the preservation of the average value of the image pixel. SMPI has been developed to address the risk of unreliability when the average value is overestimated by the filter (Shamsoddini and Trinder 2010, 239–244).

$$\text{SMPI} = Q \ast \left[ \frac{\text{variance} (I_f)}{\text{variance} (I_o)} \right],$$

where $Q = 1 + |\text{mean} (I_o) - \text{mean} (I_f)|$.

Lower values of SMPI indicate a better filter performance in terms of both the average value preservation and the noise reduction (Wang, Go, and Xiaojing 2012, 341–346).

Lidar image processing

Lidar-derived DTM analysis focused on an empirical evaluation of different types of relief enhancement processing, with the purpose to find the most suitable algorithms for a flatland archaeological landscape. Since the ultimate intent was a methodological evaluation, we turned most of our attention to already (at least partially) investigated sites, in order to retain some historical-interpretative “reference points” in our survey. We worked at two different observation scales: large-scale analysis covered the whole research area of southern Verona lowland; small-scale analysis focused on four sample-areas, corresponding to three of the four largest Terramare settlements currently known in the northern Po Plain (Fondo Paviani, Fabbrica dei Soci and Castello del Tartaro) and to the main infrastructure in the area attributable to the same chronological span: the so-called SAM (Strada su Argine Meridionale, meaning “road on southern embankment”).

Fondo paviani

The first traces of Fondo Paviani settlement came to light in 1974 after deep agricultural plowing (Fasani and Salzani 1975, 259–281). The site’s first perimeter system consisted only in a shallow ditch, possibly associated with a modest fence. At a later time during the Late Bronze Age, the site platform was enclosed in a more solid structure (the bank-ditch system still detectable through remote sensing). In this phase Fondo Paviani would have grown up to 16/20 ha, properly becoming a central place with political control over the surrounding territory and over the commercial exchanges at both short and long range (attested by a number of Mycenaean pottery fragments) (Cupitò, Leonardi, and Dalla Longa 2014, 99–102; Cupitò et al. 2015, 357–376).

Castello del Tartaro

Since 1994 the researches on this site have been conducted by the AMPBV project team. The ancient

| Filter       | Kernel | Software | ENL   | SSI   | SMPI  |
|--------------|--------|----------|-------|-------|-------|
| NONE         | –      | –        | 4.83  | 0.84  | 0.84  |
| Lee          | 3 × 3  | ENVI     | 6.8   | 0.74  | 0.74  |
|              | 5 × 5  |          | 8.79  | 0.68  | 0.67  |
|              | 7 × 7  |          | 10.49 | 0.68  | 0.67  |
| Frost        | 3 × 3  | ENVI     | 6.58  | 0.84  | 1.47  |
|              | 5 × 5  |          | 8.15  | 0.78  | 1.35  |
|              | 7 × 7  |          | 9.29  | 0.72  | 1.6   |
| Gamma        | 3 × 3  | ENVI     | 6.79  | 0.84  | 0.84  |
|              | 5 × 5  |          | 8.76  | 0.75  | 0.74  |
|              | 7 × 7  |          | 10.41 | 0.7   | 0.68  |
| Kuan         | 3 × 3  | ENVI     | 6.48  | 0.86  | 0.95  |
|              | 5 × 5  |          | 6.86  | 0.84  | 1.27  |
|              | 7 × 7  |          | 8.05  | 0.77  | 0.84  |
| Wavelet      | –      | IRIS     | 10.89 | 0.67  | 1.2   |
| Wavelet + median | 7 × 7 | IRIS     | 15.26 | 0.56  | 0.62  |
landscape of Castello del Tartaro has been investigated by means of stratigraphic sections analysis, small excavations and field surveys. Three distinct chronological phases were identified in a time stretch from the Middle Bronze Age 1 and Late Bronze Age 2. The site platform is about 11 ha large and has a sub-rectangular shape. Southeast at close proximity a sub-trapezoidal space, limited by a ditch, was functionally interpreted as a corral (De Guio, Whitehouse, and Wilkins 1997, 154–167). In the same direction is still partially visible the outline of a net of concentric narrow canals, connected to each other by transverse channels departing from the site. The traces of such a complex agricultural system (presumably structured during the Late Bronze Age site’s acme) testifies a well-developed hydraulic management, focused on intensive crop, horticulture and a widespread manuring (De Guio et al. 2015, 309–312; Balista et al. 2016, 53–102).

**Fabbrica dei Soci**
The settlement’s life span is dated between Middle and Final Bronze age. Similarly to Fondo Paviani and Castello del Tartaro, Fabbrica dei Soci is characterized by a small bank and a shallow ditch, here about 5 m and 7 m wide. The AMPBV team identified, within the intra-site anthropic layer, a sub-ellipsoidal (extended approximately 1–1.5 ha) which was associated with a possible earlier phase of the settlement, prior to the implementation of the bigger perimeter system. Along the eastern half of the embankment, where was hypothetically located an access, flowed the artificial canal also in connection with an “inter-channel” depressed area. The site has gone through several degradations, contextually to two post-abandonment river sedimentation cycles and short reactivation stages (Balista and De Guio 1997, 137–160).

**SAM**
The SAMis the longest and most important proto-historic connection identified during project AMPBV investigations (Balista et al. 2005, 97–151). The southern stretch of the road probably had as main function the protection of the vast cultivated space surrounding Castello del Tartaro from flooding (Balista et al. 2005, 97–151; Balista et al. 2016, 53–102). The contiguous northern stretch, oriented towards Fondo Paviani, presumably served also as a proper inter-site connection. Along the main trace four branches, three of which had been previously spotted through aerial photo observation (research by Betto 2013) and probably contextual to some changes of the local hydrography, have been identified.

- In order to perform our evaluation, the following visualization techniques were tested:
  - Shaded relief, or hillshade: For our comparison we implemented shaded relief both in mono (single band) and multi-directional (RGB composite of three bands) mode.
  - PCA: More images treated with hillshade from different light source locations were processed as a set of linearly correlated variables through Principal Component Analysis or PCA (Estornell et al. 2013, 83–89).
  - Contrast stretch: Image enhancing through histogram manipulation, in order to improve the image contrast by changing (stretching) the range of the pixel values (Gonzalez and Woods 2008, 115–138).
  - Local Relief Model (LRM), developed by Ralph Hesse (Hesse 2010, 67–72) to extract the local small-scale relief while excluding larger landscape forms trough a sequence of smoothing and edge-detection operations.
  - Sky View Factor (SVF), based on the use of diffuse lighting, indicates the portion of the sky visible from an observation point (Zakšek, Oštir, and Kokalj 2011, 398–415).

Hillshading, multi-directional hillshading, SVF and PCA were implemented with RVT® (Relief Visualization Toolbox), an open source application designed by the Research Centre of the Slovenian Academy of Sciences and Arts (ZRC SAZU). We instead used ESRI ArcGis to compute LRM, after integrating the appropriate toolbox available from Novak (2016). We carried on our small-scale analysis dividing each sample area into multiple sub-elements with an archaeological significance. Those elements were thus listed into tables, in which were reported:

- the given interpretation;
- whether the trace is part of the site, or is located in the off-site area, or if it is a connecting element (such as a road);
- when in the presence of terrain discontinuities, it has been specified whether the trace is the result of a contribution (positive relief) or of a removal (negative relief) of soil;
- among the soilmarks have been distinguished those in which the water drainage is apparently favored by the quality of the soil, and those in which it is instead inhibited.

We proceeded analyzing the processed images by means of autoptic analysis before synthesizing the results in overall comparative histograms. Observing the various elements extracted from the four archaeological contexts, we attempted a visibility evaluation for each enhancing technique, assigning values between 0 and 2 (0 = not visible; 1 = partially visible; 2 = visible).
Results

Large-scale analysis of radar data

In the rural area of Castagnaro municipality, halfway between fund Stangheletti (from where come finds related to both the Terramare and the Sub-Apennine culture) (Belluzzo and Tirabassi 1996, 79–145) and Val Nova where, during some surveys, fragments of Bronze Age pottery emerged (Capuis et al. 1990, 246), the radar image (see Figure 2) shows a dark elliptical soilmark, possibly a former ditch, surrounding an area of about 11 ha and connected to two fossil river beds, one going north and one going southwest. A hypothetical emissary is also visible on the east side. Although particularly evident in the radar data, this anomaly is only partially detectable in the orthophoto (where is also noticeable, directly to the southeast, an oval lighter patch). This could possibly be a so-called interpretative trap: the diachronical overlapping of hydrological marks can be interpreted by means of a radar sensor with many uncertainties because of the microwave signal (although limited) ground penetration. Nevertheless, because of its location (close to two Bronze Age sites), size (comparable to some Terramare settlements in Verona lowland), and shape (very similar to a perimeter ditch), this anomaly is, in our opinion, worth mentioning and will hopefully be object of future field investigations.

Large-scale analysis of lidar data

Castel di Macaccari

In the municipality of Gazzo Veronese, less than a kilometer northeast Maccacari town, in the early 1990s the Archaeological Group of Gazzo Veronese (contextually to the excavation of drainage ditches) discovered a cluster of concentrated ceramic fragments and sporadic archaeological evidences distributed on the surface (Salzani 1993, 81–91). In this area (see Figure 3(b–f)), the DTM shows the sub-circular light patch (see Figure 3(f), drawn in green) of a high ground (from which the local toponym “Castel di Macaccari” probably derives), southwest-northeast oriented and about 8 ha wide. Stretching the image contrast a dark linear element also emerges along its perimeter (which in the orthophoto looks like a pale soilmark, see Figure 3(a,f) drawn in red); the “castle” mark is touched southwest by the faint trace of an alleged paleo-channel (see Figure 3(f), drawn in blue), whereas a broader and more pronounced one reaches the perimeter southwest. This anomaly seems to precede the actual land division, indeed the modern tangent channel apparently adapts to the raised platform. The finds unearthed in the 1990s and the similarity of the trace, in shape and proportions, with other large Terramare sites in the area (in particular Castello del Tartaro) makes Castel dei Macaccari a site of interest which
Figure 3. Castel di Maccacari (Gazzo Veronese): orthophoto (a); multi-directional hillshade (sun elevation: 30°) (b); 30° sun elevation hillshade, azimuth 45° (c); DTM contrast stretch (d); PCA 1, 2 and 3 RGB combination (e); and interpretative drawing (f).

Figure 4. Finilone (Gazzo Veronese): DTM (contrast stretch) (a); false-color LRM (b); equalized orthophoto (c); hillshade (azimuth: 45°; sun elevation: 30°) (d); and interpretation drawing (e).
could withhold the remains of a first rank Terramare settlement.

**Finilone**

This proto-historic site, near San Pietro in Valle in Gazzo Veronese municipality, is partly known since the late 1960s, and was firstly discovered through aerial photography in 1988 by Stefano Calzolari (Calzolari 1989; Ferri and Calzolari 1989). A paleo-channel (see Figure 4(f), drawn in blue) surrounds on three sides a lighter colored patch that measures approximately 2.5 ha (see Figure 4(f), drawn in light green). It was supposed that the small peninsula of the settlement had been produced by an ancient river branching off into multiple channels (Tozzi and Harari 1990). The site area is not covered by the available radar data. In the lidar image (see Figure 4(a,b,d)), the settlement perimeter structure is not visible, whereas stands out rather vividly the paleo-riverbed, a tributary of the Tione, which connect the site with a circular anomaly (see Figure 4(f), drawn in dark green) having a diameter of about 130 m. The location and the connection between these two elements are similar to Fabbrica dei Soci and its necropolis Franzine Nuove; the circular shape finds comparison with the area of Mantua and, within the study area, the site of Perteghelle (Cerea).

**La Vallona**

La Vallona’s proto-historic necropolis was discovered in the mid-1980s by the Archaeological Group of Ostiglia (Ferri and Calzolari 1989). The orthophoto (see Figure 5(a)) shows in the site area a rectangular space of about 4 ha (see Figure 5(d), drawn in green) enclosed between two fossil riverbeds (see Figure 5(d), drawn in blue); into that space some elliptical

![Figure 5. La Vallona (Ostiglia): Equalized orthophoto (a); radar (b) and lidar image (c); and interpretative drawing.](image-url)
soilmarks (see Figure 5(d), drawn in red) of variable size stand out. The soil patch seems to expand to the south, possibly because of a ground leveling. The lighter area, probably due to the presence of sandy soil (and thus a higher reflectivity) is visible in the radar image too (see Figure 5(b)). From an aerial view La Vallona can be compared to Corte Finilone, even if lacking a perimeter contour. Nevertheless, its angular shape suggests, as in the case of Finilone, that the river course had been artificially adjusted at some point in the past. Another difference from Finilone is perceivable observing the lidar data (see Figure 5(c)): here the visibility changes drastically, also because of another leveling in the northern portion which makes almost impossible to discern any feature, except for the thin and light strip left by the river to the north, also visible in the optical and in the radar data. Within the light rectangle is visible, both in the DTM and in the orthophoto, a darker and irregular mark (see Figure 5(f), drawn in dark green) enclosing an area of about 2 ha; given its position the anomaly could be worth further investigations.

Figure 6. Massaua (Villabartolomea): orthophoto (a); PCA 1, 2 and 4 RGB combination (b); multi-directional hillshade, sun elevation: 30° (c); DTM contrast stretch (d); and interpretative drawing (e).
Massaua
In proximity of Villa Massaua, in Villabartolomea municipality, in the early twentieth century, Alessio De Bon reported of a small proto-historical settlement. From 1954 archaeological excavations were carried on under the supervision of Maria Fioroni, who found evidences referable to the Bronze Age (Capuis et al. 1990, 233; Belluzzo and Salzani 1996). In the orthophoto (see Figure 6(a)), the site looks like a darker rhomboidal area of less than 1.5 ha (see Figure 6(f), drawn in dark green) delimited by a wide darker band (see Figure 6(f), drawn in light green), which is part of a paleo-channel more easily distinguishable in the radar image. In the DTM (see Figure 6(b–d)), a relieved area stands out at the intersection of two extinct rivers (see Figure 6(f), drawn in blue).

Small-scale analysis of radar and lidar data

Fondo Paviani
In the radar image (see Figure 7(a)), the site platform has a darker shade, possibly because of a higher organic concentration whereas the ancient hydrography sand deposits look like clear and thin lines. The drop in resolution due to the filtering makes many details less clearly distinguishable compared to optical and lidar data; feature identification, however, is even harder in the unfiltered image, where speckle noise hampers the observation. In the lidar image treated with LRM, the most discernible elements are local fossil riverbeds running around and across the site, including the Menago paleo-channel. This method, however, also highlighted older traces, like small channels coeval to the settlement and the perimeter moat. Hillshade (see Figure 7(d)) has proven to be particularly useful in revealing convexities, like the boundary embankment; it also put to evidence an uneven thickness of the site platform, that looks higher at northeast. Those same anomalies are somehow visible, though much more faintly, in the image treated with SVF, by means of which the only evident trace is the palaeo-Menago. DTM contrast stretching (see Figure 7(c)) also put in evidence an extended (almost 15 ha) depressed area, maybe an old basin, directly west of the settlement. This anomaly is not currently dated, nor directly relatable to the site’s chronological sequence, but lays apparently under an Iron Age flood paleo-channel mark (see Figure 7(b)), meaning it could belong to an earlier phase and possibly be contemporary with the site (Table 2).

Fabbrica dei Soci
Observing the stretched DTM (see Figure 8(d)), the ancient perimeter appears as a low sub-circular relief detectable by means of all the tested processes, although resulting more evident in LRM and SVF (see Figure 8(a)) visualizations. Old river bars and the site platform are also distinguishable. The latter looks partially compromised by a ground leveling northeast, probably a recent agricultural intervention.

Figure 7. Fondo Paviani (Legnago): filtered (wavelet + median) radar image (a); equalized orthophoto (b); DTM contrast stretch (c); multi-directional hillshade (sun elevation: 30°) (d); and schematic drawing of remotely sensible features (e).
Table 2. Fondo Paviani: visibility through different data processings and visualizations.

| Element          | Type     | Relief | Drainage | Orthophoto | DTM contrast str. | DTM hillshade | DTM multi hillshade | DTM hillshade PCA | DTM LRM | DTM SVF | Filtered radar | Not filt. Radar |
|------------------|----------|--------|----------|------------|-------------------|--------------|---------------------|-------------------|---------|---------|---------------|-----------------|
| 1. Site platform | Site     | –      | –        | 1          | 0                 | 0            | 0                   | 0                 | 0       | 0       | 2             | 2               |
| 2. Embankment    | Site     | Positive | Favored  | 2          | 2                 | 2            | 1                   | 2                 | 1       | 1       | 0             | 0               |
| 3. Ditch         | Site     | Negative | Inhibited | 2          | 2                 | 2            | 2                   | 2                 | 1       | 2       | 2             | 2               |
| 4. Menago        | Hydrography | Negative | –        | 0          | 2                 | 1            | 1                   | 1                 | 1       | 0       | 0             | 0               |
| 5. Basin(?)      | –        | Negative | –        | 0          | 2                 | 1            | 1                   | 1                 | 1       | 0       | 0             | 0               |
| 6. SAM Infrastructure | Infrastructure | Positive | Favored  | 2          | 2                 | 2            | 0                   | 0                 | 1       | 0       | 2             | 2               |
| 7. Western paleo-channel | Hydrography | Positive | Inhibited | 2          | 2                 | 2            | 2                   | 2                 | 2       | 1       | 2             | 2               |
| 8. Southern paleo-channel | Hydrography | Negative | Inhibited | 2          | 2                 | 2            | 1                   | 2                 | 2       | 1       | 2             | 2               |
| 9. Southeastern paleo-channel | Hydrography | –        | Inhibited | 2          | 1                 | 2            | 2                   | 2                 | 1       | 0       | 2             | 2               |
| 10. Site platform | Site     | –      | –        | 1          | 0                 | 0            | 0                   | 0                 | 0       | 0       | 2             | 2               |
| 11. Embankment   | Site     | Positive | Favored  | 2          | 2                 | 2            | 1                   | 2                 | 1       | 1       | 0             | 0               |

Note: 0: not visible; 1: partially visible; 2: visible.
(given the abrasion correspondence with the modern fields limits). Therefore, it is not possible to observe the alleged access to the site, visible in the optical data as a soilmark. Multi-directional hillshading (see Figure 8(b)) manages to show clearly a branch of the Tartaro river cutting across the site platform. It cannot be determined solely by remote sensing whether this episode followed or preceded the settlement life cycle. In the first case, it may have been a digression dating back to a post-abandonment phase in which the riverbed, lacking an embankment maintenance or being affected by agricultural scrapings, changed its course; in the second case, the digging of the ditch around the site would have steered the river flow along the perimeter. About 500 m southeast both in lidar and optical data (see Figure 8(c)), we spotted a sub-circular relief connected to the site’s perimetral trench through a thin fluvial trace. Since this anomaly shares approximately shape, extension and distance from the main site with Fabbrica dei Soci necropolis, Franzine Nuove, the same function has been hypothesized for this area; alternatively, another plausible use could have been specialized agriculture. In the radar image, the same anomaly, like Franzine Nuove, looks like a dark patch. The Tartaro paleo-channel is also identifiable and its course can be visually followed to the perimeter ditch. On the eastern side of the site area, the archaeological palimpsest is more chaotic and thus difficult to interpret with the exception of some minor paleo-channels (Table 3).

Castello del Tartaro

Radar image shows only very faint marks relatable to the settlement, with the exception of two dark streaks attributable to the ancient path of Tregnone: one circling the site, one (apparently older) a few hundred meters north. A presumed dampmark, possibly a canal, departs from the site to the southwest. Other ancient rivers, southwest-northeast oriented, are also visible: they probably were tributaries of Tregnone, since their traces interrupt when they reach the bigger paleo-channel. In the lidar image (see Figure 9(b–d)), the most noticeable feature is the elliptical platform of the settlement, surrounded and crossed by paleohydrographic shallow incisions. What remains of the perimetral bank gain visibility implementing shaded relief, whose effectiveness can be further improved increasing the vertical exaggeration value. It is noticeable an interruption of the perimetral structure at southeast, where the modern human activity impacted the most, with many ablations and swaps of land. In SVF visualization low terrain elevations are less visible; southeast can be detected the linear embankments of a nineteenth-century canal, whose trace continues to the north. Agricultural channels are partially visible through LRM, too, especially in the eastern region near the curve of SAM trace, which being lightly raised stands out in the image as a lighter band. In close proximity to the site, again at an approximate distance of 100 m southeast, a weak anomaly appears by means of contrast manipulation: its a dark trace with a sub-quadrangular shape, north–south oriented, that

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Figure 8. Fabbrica dei Soci (Villabartolomea): SVF (16 directions, search radius: 20m) (a); multi-directional hillshade, sun elevation: 30° (b); equalized orthophoto (c); DTM (contrast stretch) (d); and schematic drawing of remotely sensible features (e).
| Element | Type       | Relief   | Drainage | Orthophoto | DTM contrast str. | DTM hillshade | DTM multi hillshade | DTM hillshade PCA | DTM LRM | DTM SVF | Filtered radar | Not filt. radar |
|---------|------------|----------|----------|------------|------------------|---------------|---------------------|------------------|---------|---------|----------------|----------------|
| 1. Embankment | Site       | Positive | Favored  | 2          | 2                | 2             | 2                   | 1                | 2       | 0       | 0              | 0              |
| 2. Ditch    | Site       | Negative | Inhibited| 2          | 2                | 2             | 2                   | 2                | 2       | 2       | 2              | 2              |
| 3. Site platform | Site       | Positive | Favored  | 0          | 2                | 2             | 2                   | 2                | 2       | 2       | 0              | 0              |
| 4. Site access (?) | Site       | –        | Inhibited| 2          | 0                | 0             | 0                   | 0                | 0       | 0       | 0              | 0              |
| 5. Tartaro (tributary) | Hydrography | Negative | Inhibited| 2          | 2                | 1             | 2                   | 1                | 2       | 1       | 2              | 2              |
| 6. Fossil river branch between FS and FN | Hydrography | Negative | Inhibited| 2          | 2                | 0             | 0                   | 1                | 1       | 1       | 0              | 0              |
| 7. Fabbrica dei Soci fossil river bed hydrography | Negative | Inhibited| 2          | 2                | 2             | 2                   | 2                | 2       | 2       | 2              | 2              |
| 8. Fabbrica dei Soci fossil river bump hydrography | Positive | Inhibited| 2          | 2                | 2             | 2                   | 2                | 1       | 0       | 2              | 0              |
| 9. Northern tributary hydrography | Positive and negative | Inhibited| 2          | 2                | 2             | 2                   | 1                | 1       | 1       | 1              | 1              |
| 10. Southern tributary hydrography | Positive and negative | Inhibited| 2          | 2                | 2             | 2                   | 1                | 2       | 1       | 1              | 1              |
| 11. Franzine Nuove necropolis | Site       | –        | –         | 2          | 2                | 0             | 0                   | 0                | 0       | 0       | 0              | 0              |
| 12. Southwestern road stretch infrastructure | Infrastructure | Favored | 2          | 1                | 1             | 1                   | 1                | 0       | 0       | 0              | 0              |
| 13. Southwestern circular paleo-channel | Off-site   | Negative | Inhibited| 1          | 2                | 1             | 1                   | 1                | 1       | 0       | 1              | 1              |
| 14. Southeastern bump | Off-site   | Positive | –         | 0          | 2                | 1             | 1                   | 1                | 0       | 0       | 1              | 1              |

Note: 0: not visible; 1: partially visible; 2: visible.
surrounds an area of about 5 ha. It could have been an enclosing structure, currently still not relatable with the settlement sequence, it seemingly precedes the modern channel, by which it is in part overlapped (Table 4).

**SAM**

In its southern section (SAM 1), the road (see Figure 10) has a northwest-southeast orientation and follows an almost straight line for about 1,2 km. It is visible in the DTM by means of all compared treatments, but not in the radar image. Near the Canal Bianco, less than 400 m east, the SAM resumes its path northbound (SAM 2). After about 200 m the main route crosses the BRANCH 1, which is less pronounced and slightly narrower. In the lidar data, the relation between these elements is not easily observable because of an interruption, due probably to modern plowing, in correspondence of the intersection. Nevertheless, they look quite similar. BRANCH 1 is clearly visible in both the lidar and the radar image (even if more faintly in the latter); it then continues north for about 600 m. The road remains visible, in all data types, for about 600 m, then it bifurcates in two opposite directions. Although distinguishable in orthophotos, the western branch does not show in any lidar image; a part of the eastern branch is almost obliterated, whereas the rest appears in all the DTM treatments, but not in the radar. The next stretch (SAM 5) is only visible by means of optical data. In close proximity to the Tregnone paleo-channel, SAM undergoes a deviation of almost 90°, following the ancient river course along its left bank (SAM 6), but 200 m before such interruption the road intersects almost perpendicularly another trace (fully visible in the orthophoto and partially in the lidar and the radar data) that goes to the west in Castello del Tartaro direction, which was interpreted as a possible branch of the SAM (BRANCH 2). Another branch (BRANCH 3) departs from the main trace and proceeds with a double-curved shape until it reaches the modern Tartaro; it is present in all the available data. The last branch (BRANCH 4) lies at short distance from Ponte Moro, and is detectable, as well as in the optical and the radar data, in three lidar visualizations: contrast stretching, hillshading (both mono-directional and multi-
| Element                      | Type       | Relief | Drainage | Orthophoto | DTM contrast str. | DTM hillshade | DTM multi hillshade | DTM hillshade pca | DTM lrm | DTM svf | Filtered radar | Not filt. Radar |
|------------------------------|------------|--------|----------|------------|-------------------|---------------|---------------------|-------------------|---------|---------|----------------|-----------------|
| 1. Site platform             | Site       | Positive | –        | 2          | 2                 | 2             | 2                   | 2                 | 2       | 2       | 1              | 1               |
| 2. Embankment                | Site       | Positive | Favored  | 2          | 2                 | 2             | 2                   | 2                 | 2       | 2       | 1              | 1               |
| 3. Ditch                     | Site       | Negative | Inhibited| 2          | 0                 | 0             | 0                   | 0                 | 0       | 0       | 0              | 0               |
| 4. Drove way (“Big Road”)    | Infrastruct.| Inhibited| 0        | 2          | 0                 | 0             | 0                   | 0                 | 0       | 0       | 0              | 0               |
| 5. Southwestern paleo-channel| Hydrography| Negative | Inhibited| 2          | 1                 | 1             | 1                   | 1                 | 2       | 1       | 1              | 1               |
| 6. Road (?) to southwest     | Infrastruct.| Favored | 0        | 1          | 0                 | 0             | 0                   | 0                 | 0       | 0       | 0              | 0               |
| 7. Paleo-Tregnone            | Hydrography| Negative | Inhibited| 2          | 2                 | 1             | 2                   | 1                 | 2       | 1       | 2              | 1               |
| 8. Canals (1st phase)        | Infrastruct.| Negative | Inhibited| 1          | 0                 | 0             | 1                   | 0                 | 0       | 0       | 0              | 0               |
| 9. Canals (2d phase)         | Infrastruct.| Negative | Inhibited| 2          | 1                 | 1             | 1                   | 0                 | 1       | 1       | 1              | 1               |
| 10. Canals (3d phase)        | Infrastruct.| Negative | Inhibited| 2          | 1                 | 1             | 1                   | 0                 | 1       | 1       | 1              | 1               |
| 11. Corral                   | Near-site  | Negative | Inhibited| 2          | 2                 | 1             | 0                   | 1                 | 2       | 1       | 0              | 0               |

Note: 0: not visible; 1: partially visible; 2: visible.
directional) and LRM. After 530 m eastwards the SAM diverts about 45° towards Fondo Paviani (SAM 7). This last section is visible in the orthophoto and in the lidar image processed with contrast stretching, hillshading and LRM, which also put in evidence a differentiation between the southern part (not visible relief) and the northernmost (visible relief). Two distinct chronological phases were, therefore, supposed for this final stretch (Table 5).

**Conclusions**

Southern Verona lowland has been for a long time object of remote sensing analysis and many ground surveys, revealing an articulated fossil landscape partially damaged and partially unearthed by modern transformations. Recently, technological development and purchase cost reduction granted access to data acquired through a wide range of sensors, encouraging new strategies for the archaeological research. In this paper, we approached two aerial detection technologies, lidar and radar, with the purpose of finding more specific application cases. During our comparative study, we found new landscape elements with some potential archaeological value: infrastructures (the Northern branch of the SAM in the direction west-BRANCH2), settlements (the platform emerging in Castel di Maccacari site, the ellipsoidal area between Stangheletti and Valnova of Castagnaro, detected in the radar image), as well as anomalies whose identity could not be clearly established, but that still have a meaningful relation with other evidences and well-known

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**Table 5.** SAM: visibility through different data processings and visualizations.

| SAM    | ortho | DTM contrast str. | DTM hillshade | DTM multi hillshade | DTM hillshade pca | DTM lrm | DTM svf | Filtered radar | Not filt. radar |
|--------|-------|-------------------|---------------|---------------------|------------------|--------|--------|----------------|----------------|
| SAM 1  | 2     | 2                 | 2             | 1                   | 1                | 2      | 1      | 0              | 0              |
| SAM 2  | 2     | 2                 | 2             | 1                   | 1                | 2      | 0      | 1              | 0              |
| SAM 3  | 2     | 0                 | 0             | 0                   | 0                | 0      | 0      | 0              | 0              |
| SAM 4  | 2     | 2                 | 2             | 2                   | 2                | 2      | 1      | 0              | 0              |
| SAM 5  | 2     | 0                 | 0             | 0                   | 0                | 0      | 0      | 0              | 0              |
| SAM 6  | 2     | 1                 | 1             | 1                   | 1                | 1      | 0      | 0              | 0              |
| SAM 7  | 2     | 0                 | 1             | 0                   | 0                | 1      | 0      | 1              | 1              |
| BRANCH 1 | 2   | 2                 | 0             | 1                   | 1                | 2      | 0      | 0              | 0              |
| BRANCH 2 | 2   | 1                 | 1             | 1                   | 1                | 1      | 1      | 1              | 0              |
| BRANCH 3 | 2   | 1                 | 1             | 1                   | 1                | 1      | 0      | 1              | 0              |
| BRANCH 4 | 2   | 1                 | 1             | 1                   | 1                | 0      | 0      | 1              | 0              |

Note: 0: not visible; 1: partially visible; 2: visible.
archaeological sites (the sub-circular relief southeast Fabbrica dei Soci, Fondo Paviani western depressed area, or the sub-rectangular shape intercepted by the corral of Castello del Tartaro). The nature of these anomalies will be hopefully clarified through focused field investigations.

As for the methodological development, all visual supports required, in order to visualize the faintest traces, a combination of contrast stretching and lightness manipulation. Additionally, performing relief analysis on the DTM gave better results setting a high Vertical Exaggeration value (8 or even 9).

Even though optical data can be more easily interpreted by a human observer because of a larger amount of visual attributes (brightness, color and texture) in order to distinguish feature boundaries, lidar data highlighted several features (both near-site and off-site), some of which not visible in orthophotos if not as weak traces (as in the case of Castel dei Macaccari or the anomalies spotted nearby the first rank Terramare sites) or were not visible at all because of vegetation coverage (for instance, at Corte Finilone). Except for the contrast stretch (where, as well as in the original image, the boundaries between each object and its background are defined by different brightness values), all the lidar processing techniques we tested on our study area codify this kind of information in the form of contours (even in the shaded relief visualization the shadows projected, given the scarcely accentuated local morphology, look more like lines than areas), focusing on specific characteristics determined both by the chosen treatment and its settings. These techniques simplify and, therefore, make more legible some shapes in the image; however, a smaller number of features are visible. The most commonly employed treatment here, hillshade, in our comparison gave the best results with positive reliefs. It can point out to the observer threedimensional details with the aid of artificial lighting whose source can be positioned (setting sun height and azimuth values) in order to highlight even the less-accentuated reliefs. An advantage of hillshade at ground level is that even the projected shadows are thin and do not cover (as happens in the analysis of mountain territories) significant portions of the image. A well-known drawback depends on the mono-directionality of the artificial light, which does not allow to visualize linear objects parallel to the radiation direction, with the risk of neglecting some details and thus compromise the interpretation. Nevertheless, the lidar data processing that turned out less performing in our comparison is SVF that could not express its full potential in planar landscape, even if it managed to highlight some major discontinuities like some deeper ditch. As a diffuse light treatment SVF has the advantage of identifying features lying in all directions with the possibility to add, with RVT, an anisotropy effect. The problem is that in presence of almost flat surfaces (as in our case), where only the most grazing irradiation can expose terrain discontinuities, in the ultimate combination from all search direction some traces appear too faintly to be recognizable. That cannot be helped even implementing the anisotropic SVF, as the effect of anisotropy is determinable only along the azimuth and not the zenith. The limit in visibility given by the one-sided illumination of hillshade was more effectively overcome by Principal Component Analysis or by the simple combination in RGB bands of the image processed from three different directions, specifically selected by the operator in order to highlight as much as possible the features in the scene. PCA gave the best results, as expected, in its first components, even if the falsely positive or falsely negative relief effect may be less immediate to interpret; on the other hand, in some cases, this effect helped to notice details otherwise less obvious. These two combinations of hillshaded images exposed effectively a large number of anomalies, turning out particularly suitable for irregular or polygonal shapes detection. Indeed both the multi-directional hillshade and PCA gave the best results with paleo-channel bumps and with the raised platforms of Terramare sites. The best solution for the thinnest reliefs visualization, such as embankments or ditches and relict channels, has proven to be the LRM, which was in fact designed in order to highlight, by operating at local level, minor terrain discontinuities. Along with the contrast stretch, LRM indeed resulted as the most helpful DTM processing technique to highlight the SAM trace. Overall, lidar analysis (in particular through histogram manipulation) proved to be useful for the identification of almost as many anomalies as the orthophoto, providing a large number of new information on the area of interest (Figure 11). Unfortunately, in some cases modern leveling works cancelled some threedimensional traces which are instead visible in optical or radar data, for this reason a cross-validation is in any case strongly advisable.

Basing on the quantitative comparison between the processed data types, radar data showed, in this context, a smaller number of features; this is most likely due to both the scene and the image quality. In the first case, the composition (partial presence of silts) and the moisture of the soil probably attenuated significantly the microwave signal; nevertheless, the flat land allows a good angle of incidence and, therefore, a more intense reflection. In the second case, the radar image characteristic speckle noise could not be limited without affecting the image quality since filtering, however carefully weighted, always reduces to a certain extent the spatial resolution. Despite the not entirely ideal conditions, archaeological traces were found in the form of connective elements, relict hydrography in particular. Terramare settlements are recognizable by their perimeter structures looking like light (banks) or more frequently dark marks (moats),
rarely visible at the same time: this could depend on the contrast with the proximal terrain reflectivity. Because of the microwave capability of ground penetration, radar can provide information about artifacts or larger scale structures not emerging on the surface, especially when said surface (like in our case) has been repeatedly scratched by ploughings over time. As a downside, it is in some cases difficult to discern features intercepted by the signal at different depths. For this reason, radar images can sometime display “fake” shapes that put at risk a visual interpretation based on Harris principles of succession. Cutting edge technologies such as multiband radar may help in the future to overcome this limit, making easier to decipher palimpsests in radar mapping. Experimentation in this direction for archaeological purposes at the time being is still under development. Lidar and radar investigations, however, are gaining increasing popularity, which hopefully will lead to some useful experience and more accurate observations.

**Notes**

1. 2300/2050–1700/1650 BC.
2. 1650/1600–1170–1150 BC.
3. With an extension of over 5 ha.
4. Northern and central Polesine, Southern Verona lowland.
5. Lidar acquisition by Blom CGR of Parma (Compagnia Generale Ripreseeree, General Aerial Shooting Company), 2008–2010.
6. Taken by CGR of Parma (Compagnia Generale Ripreseeree, General Aerial Shooting Company) in 2012.
7. The fourth first rank settlement actually known, Lovara, was excluded because it is now covered by modern buildings preventing a remote sensing analysis.
8. Castle of Macacari.
9. The site is included in AMPBV project research area although being located in the province of Mantua.
10. VE (Vertical Exaggeration) = HS (Horizontal Scale)/VS (Vertical Scale).

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No potential conflict of interest was reported by the authors.

**Notes on contributors**

Laura Burigana obtained the master degree in Archaeology in 2015 at University of Padua with a thesis about image processing applications in archaeological research. Her recent scientific activity primarily focuses on the study of innovative means of investigation and restitution of archaeological landscapes through remote sensing, geographical information systems and digital image manipulation.
Luigi Magnini (PhD) is a specialist in landscape archaeology. His main research interests include remote sensing and multi-sensor object-based image analysis applied to archaeological features detection. He is coordinator of the Unipd funded “STEMPA Project” focused on the proto-historic village of the Bostel of Rotzo (VI). He is also member of the coordination team of the student project “Horus” on the application of aerospace technologies to the archaeological research.

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