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HYPERSPECTRAL DISCRIMINATION OF ROOFING MATERIALS IN RELATION TO HISTORY

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Abstract

This paper presents the results of a research activity aimed at studying urban areas by means of remotely sensed hyperspectral data acquired over the city of Rome.
The classification of remotely sensed images allowed us to identify different spectral classes referred to materials used for building roofs and to deduce considerations on how the use of building techniques and materials has evolved in space and time, or the architectural composition of building volume. In particular, the classification shows how roof coverings reflect a well defined epoch and how the building style, consolidated over the centuries, granted the privilege to use local materials until the 19th century.
From the 19th century onwards, there is a period when unauthorized buildings and urbanization were rampant, with an indiscriminate and chaotic use of materials like bituminous surfaces, corrugated iron roofing sheets and so on.

Introduction

The images taken by remote sensing over the city allowed us to observe the city from above in a way that we have never seen before, to discover forgotten corners of the urban landscape, where historical squares, domes of churches, and in particular building roofs, are transformed into objects without any secret which can be easily identified on the basis of their geometry, colours and materials. In this way, it contributes to the conservation of the artistic and cultural patrimony in the historical centers of the cities.

Remote sensing represents a major, though still underused, source of urban information by providing spatially consistent coverage of large areas with both high spatial detail and temporal frequency, including historical time series [1; 2]. With increased availability and improved quality of multi-spatial and multi-temporal remote sensing data as well as new analytical techniques, it is now possible to monitor and analyze urban expansion and land use change in a timely and cost-effective way [3]. However, there are some technical challenges in retrieving accurate information of urban expansion and land use changes. A major difficulty in urban remote sensing analysis is caused by the high heterogeneity and complexity of the urban environment in terms of its spatial and spectral characteristics. A successful implementation of remote sensing requires adequate consideration and understanding of these specific urban landscape characteristics in order to fully explore the capabilities and limitation of remote sensing data and to evaluate appropriate image analysis techniques [4]. Cowen and Jensen [5] outlined the relationship between selected urban/suburban attributes and the remote sensing resolutions required to provide such adequate information. Among these issues, the most important technical concern has been the pursuit of finer spatial resolutions of image pixels [6;7;8;9]. It was suggested that remote sensing data with a spatial resolution of 0.5–10 m are required to determine adequately the high frequency detail which characterizes the urban [10].

To this aim, the Daedalus AA5000 MIVIS (Multispectral Infrared and Visible Imaging Spectrometer) instrument, acquired by the Italian National Research Council (CNR) was used. MIVIS is a modular scanning system constituted by 102 spectral channels that use independent optical sensors simultaneously sampled and recorded within the interval comprised between 0.433 and 12.70μm (see Table 1). This instrument, with 4 spectrometers designed to collect radiation from the earth's surface in the Visible (20 channels), Near-IR (8 channels), SWIR (64 channels), and Thermal-IR (10 channels), represents a second generation imaging spectrometer developed for its use in environmental remote sensing studies across a broad spectrum of scientific disciplines [11;12].

Table 1. MIVIS sensor characteristics

Spectrometer	Spectral coverage	Channels	Bands (μm)
I	Visible	20	0.4-0.83
II	Near infrared	8	1.15-1.55
III	Shortwave infrared	64	2.0 -2.5
IV	Thermal infrared	1 0	8.2 -12.7

In addition to a very high spectral resolution, MIVIS also provides a high spatial resolution, with a pixel of 3m x 3m. This allows a detailed analysis when urban objects are to be identified and, in particular, when covering materials such as tiles and bricks, marble materials, asphalt, lead, copper, asbestos-cement, vegetated areas, bare soils are involved. All these characteristics make this instrument remarkably inter-

esting for the study of anthropized areas, enabling an analysis never carried out so far at such an operative level.
In this respect, the results obtained in the classification of hyperspectral data have shown the great potentialities of these tools applied to urban areas, complex situations with a high degree of fragmentation [11;12].
On the basis of these considerations, this paper presents a research activity over the central area of the city of Rome, to discriminate and quantify urban elements and materials, (i.e. surface coatings, not covered structures, urban buildings, depots at open air, vegetation, rivers) by means of remotely sensed MIVIS data, in order to deduce considerations about how the use of building techniques and materials has affected the growth of the city.

Study area

The site taken into consideration for this study belongs to the territory of the city of Rome. The test area covers a north-south transect of km by 147.12 km^2 along the Tiber river (see Figure 1).

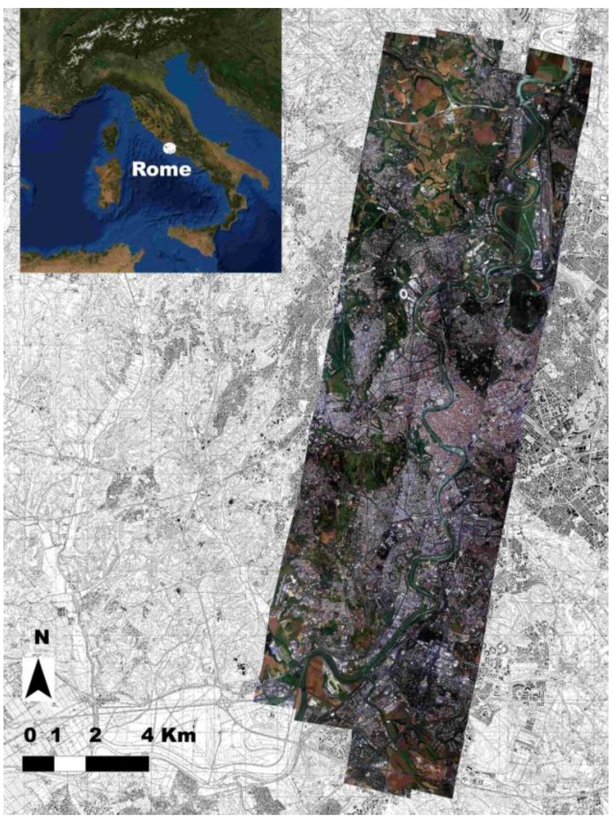


Figure 1. Territorial framework of the study area

Materials and Methods

Herein are presented the aerial survey and MIVIS images characteristics (see Table 2).

Table 2. List of the materials and data used in this research

Data type	-MIVIS data -Format .hdr
Details	- 4 strips - Date: 19 June 2004 - Flight time: 10:41 - Surface acquired: 187,52 km^2 - Covered Area (km2): 147,12 km^2 - Resolution: 3x3 m
Process	- Geometric correction; - Enhancement; - Georeferentiation (UTM WGS84); - Mosaicking; - Classification.

The MIVIS data were calibrated according to the procedures described by Bianchi et. al. [1996].
Not having reflectance measurements to the ground and information on the characterisation of the column of air between the sensor and the ground at our disposal, the calibration method known as IARR (International Average Relative Reflectance), described in [14], was used. It consists in dividing the radiance spectrum of each pixel of the flight line by the average spectrum of the whole scene. This procedure is a variance of the so-called criterion known as *"flat field calibration"*, which approximately removes solar irradiance, atmospheric absorption, scattering effects and any other residual noise from the instrument [14;15;16].

Data were classified in order to obtain a thematic map to which is associated, besides the spatial information, a semantic information which specify the so-called class. The data, radiometrically corrected, were classified using the Spectral Angle Mapper (SAM) approach. It is an automated method which permits rapid classification and mapping of the spectral similarity of image spectra to reference spectra [17]. The SAM algorithm implemented in ENVI software [18] takes as input a number of *training classes* (training areas) or reference spectra from ASCII files, specific ROIs (Regions Of Interest), or spectral libraries. As far as this study is concerned, the input spectra were extracted from ROIs accurately identified in the MIVIS image.
Inside each ROI, areas having different morphological characteristics were selected: flat surfaces or ones with different exposure slopes, to best represent the variability of the area taken into consideration [18;19].

In this phase of the method, 9 ROIs corresponding to other surfaces were identified (see Table 2). A brief description follows.

Table 2. Classes and their description

Classes		Description
1	**Tiles and bricks**	They are made of a natural material, namely clay, with the addition of coloring substances. They represent the older roofing material mainly used for civil buildings [20].
2	**Travertine and grits**	This material is an "artificial stone" obtained by mixing in appropriate proportions cement, other stony materials like gravel or common stones, water and additive substances[20].
3	**Bituminous surfaces**	They are covering waterproofing membranes made of sheets whose composition in bitumen-polymer They represent one of the systems used to cover industrial buildings [20].
4	**Metallic surfaces**	Unlike other metallic materials known since ancient times, in particular alloys aluminium have been only recently used specially to roof industrial buildings [20].
5	**Roads**	They are covered by a bituminous material made of a mixture of hydrocarbons having natural or pyrogenic origin; this material plays the role of binder, as it joins inert elements[20].
6	**Treed surfaces**	Areas mostly covered by trees with deciduous leaves or evergreen (planes, pines and ilexes).
7	**Lawns**	Areas covered by vegetation with the prevailing presence of herbaceous vegetation.
8	**Bare soils**	Unvegetated areas, awaiting use (for sowing or urbanisation).
9	**Water bodies**	This means Tiber river, but it is also referred to small artificial lakes and surfaces dedicated to pools.

Data Analysis and Discussion

The figure 2 shows the results of the classification of the MIVIS image referred to a study area in 9 spectral class, achieved by the Spectral Angle Mapper (SAM) [18]. From a preliminary visual analysis, defined by Foody [2002] as the first and the most important step of accuracy assessment of methodology, a good discrimination of the ground surfaces can be observed which shows the good potential of the MIVIS data for the discrimination of different surfaces. Moreover, the maps provides interesting information about the extension and the direction of the urban development, in particular the development of covering materials in time and space.

The classification results were then evaluated by calculating the matrix of confusion [21; 22], designed to verify or "to test" the performances of the classifier, obtained from ROIs accurately identified in the scene, integrated with the visual analysis of additive synthesis in RGB (Red, Green, Blue). The elements of the matrix in Table 3, represent the number of pixels belonging to a class compared to the reference data.

Table 3. Confusion matrix

Classes	1	2	3	4	5	6	7	8	9
1	**94,38**	0,54	0	0	0,14	0	0	1,45	0
2	3,48	**94,76**	1,84	8,02	0,08	0	0	1,59	0
3	1,31	0,77	**54,34**	11,22	17,20	0	0	0	0,01
4	0	2,47	8,98	**77,50**	5,58	0	0	0	2,00
5	0,16	0	34,84	2,96	**74,82**	0,14	0	0	0,03
6	0	0	0	0	0,02	**65,08**	35,91	0	0
7	0	0	0	0	0	30,52	**63,96**	0	0
8	0,67	0,08	0	0	1,84	1,80	0,13	**96,97**	0
9	0	1,39	0	0	0	0	0	0	**97,96**
10	0	0	0	0,29	0,14	2,47	0	0	0

The values of the main diagonal of the confusion matrix represent the examples of agreement between the classification and ground truth class, whereas the values found off the diagonal represent pixels classified incorrectly. Moreover, two kind of errors can be calculated: errors of Omission and errors of Commission. The first ones are shown in the columns of the confusion matrix. They represent pixels that belong to the ground truth class but the classification technique has failed to classify them into the proper class. The second ones are shown in the rows of the confusion matrix. They represent pixels that belong to another class and that are labelled as belonging to the class of interest.
By analyzing Table 3, it is possible to notice that the average classification accuracy obtained corresponds to 80,32%, whereas most classes were found with an accuracy ranging from *Lawns (63,96%)* to *Water (97,96%)*, except for the class *Bituminous surfaces (54,34%)* and *Unclassified* in black. The differences between *Bituminous surfaces* and *Roads (74,82%)* (protective covers, sheathings, etc.), depends on the fact that both are mainly composed of bituminous materials (mixtures of hydrocarbons of natural or

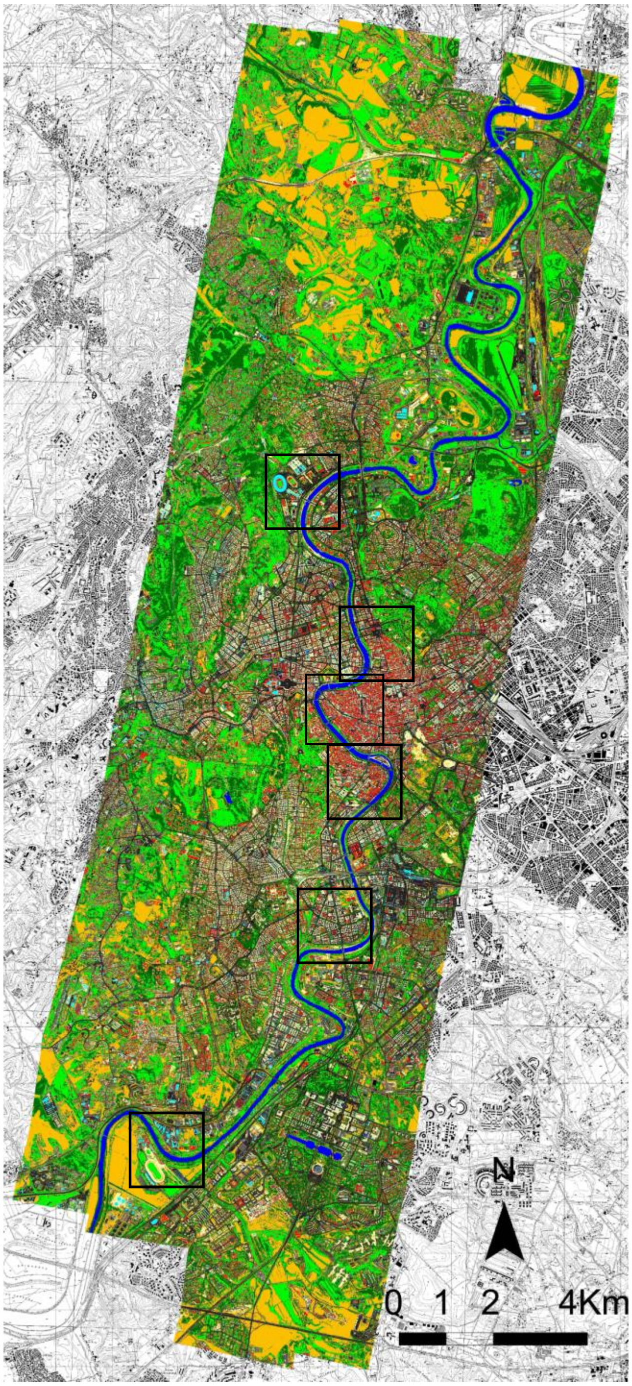
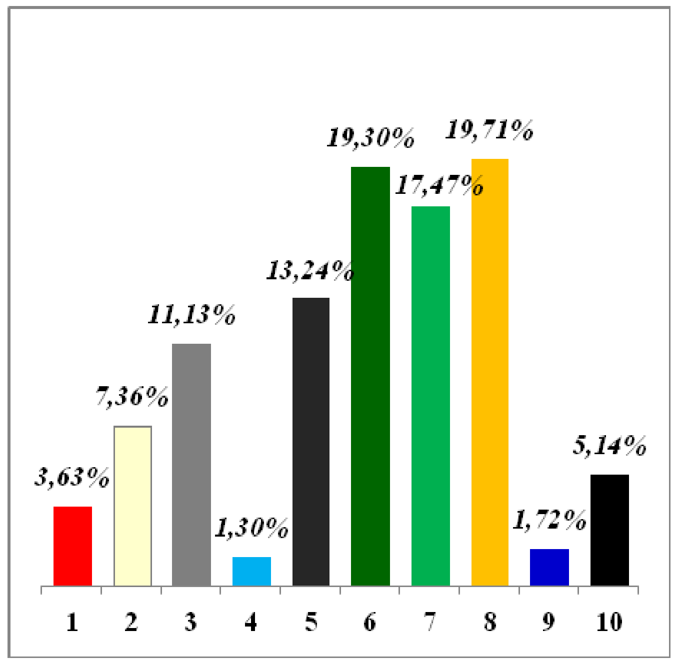


Figure 2. Classification of remotely sensed MIVIS images acquired from an altitude of m 1.500

pyrogenic nature). These materials are mixed with consistent synthetic products (atactic polypropylene); as far as road are concerned bitumen is instead blended with inert matters as a binding compound. As a consequence, where the road cover is in good condition the asphalt emerges and the above classes tend to mingle spectrally, where instead the inert matter emerges due to wear the two classes tend to separate [11]. Therefore the classification accuracy of 74,82% of the class *Roads* reveals the spectral predominance of the compound "inert matters" over the compound "bitumen" so indicating the asphalt's state of wear of the road cover in the area investigated.

Tiles and bricks (94,38%) class tends to be confused with that of *Bare soils (96,97%)* mainly in the nearest neighbour areas characterized by the presence of large areas of clayey soils. Similarly significant is the spectral confusion between *Travertine and grits (94,76%)* and *Metallic surfaces (sheets) (77,50%)* classes, due to the lead oxidation which tends to become similar to travertines and the other light construction stones [11]. This is an aspect which can be particularly noticed in some domes of the city.

Table 4. Class distribution



In the MIVIS scene, the visual analysis of the classification (Figure 2), allowed us both to identify, with a good level of detail, the distribution of the different spectral classes and to deduce considerations herewith reported.

The critical observation of the processed MIVIS scenes was also an occasion for reflection on the systematic processes of urban deterioration. Countering the centuries-old image of the *Tiles and Briks (3,63%)* covered roofing, characteristic of much of the old city (Trastevere and Vaticano, at the center of the image) are the neurotic and fragmented expression of the new areas of the contemporary city, spontaneous or not (Portuense, Trullo and Magliana, outskirts of city), where signs of clashing superimposition - of a vague technological character - prevail. The cover gives the impression of a no- man's land, a space of fortuitousness and

rejection, which is perceptible in the chaotic use of material: *Bituminous surfaces (11,13%), Metallic surfaces (1,30%).*
Finally, at the top and bottom of the classification MIVIS, away from the city center, where the city becomes less densely built, dominated by the main *Roads (13,24%)* linking the city with the countryside.

The first strong imprint of nature is that of the Tiber river, *Water bodies (1,72%).* With its meandering loops, the river has divided the scene into two sections. It is absolutely the most defined shape, made up of a single cluster of pixel, classified with an accuracy which is equal to 97,96%.

At the centre of the image is the Tiber Island (*Insula Tiberis)* which lies in the middle of Tiber river: *natural ford, it was essential to the erection of permanent installations on the surrounding heights of peoples (the Etruscans and the Sabines) who inhabited along the Tiber river in the 8th century B.C* [23] (see Figure 3).

It was entirely built in *Travertine* and the Island profile suggested to arrange of the external perimeter in shape of war ship, with the embankments equipped for the moorings and with an obelisk as the main tree. It is connected to the left and right banks of the Tiber river through Fabricio and Cestio bridges whose construction dates back to 62 B.C.

Figure 3. Tiber Island

The *Tiles and bricks* in this historic cure place belong to roof coverings of the edifices still standing today. Among these, it is worth mentioning the Fatebenefratelli Hospital (brothers, engage in good works) whose origins date back to 1548; St. Giovanni Calibita church with its small baroque bell tower and the medieval tower; the church of St. Bartolomeo which was erected in the 10th century [23].

Immediately striking is the existence in the *city centre* [23], adjacent to the great loop of the river, of a densely built-up area, showing up as spectrally compact and homogeneous, with a tangled skein of narrow streets (see Figure 4). This authentic and distinctive heart of the city is characterised by the prevalence of pitched roofs mostly covered with *Tiles.*

Pitched brick roofs, the standard design for centuries and which here show up in a repeated geometry of pixels, are also a feature of religious buildings. The MIVIS image shows a composition unit, "the heart of Rome", with spatially contiguous and spectrally homogeneous pixels because of pitched brick roofs (see Figure 4).

Figure 4. "The heart o Rome" Pantheon and Piazza Navona

Here MIVIS image provides an overview of Roman Architecture such as domes and bell towers, squares and fountains with their rich symbolic significance, whose supremely sophisticated shapes can be easily identified.
For example the Pantheon, "temple of all the gods", originally built by Marcus Agrippa and destroyed along with other buildings in the great fire of Rome in 80 A.D [23]. It was subsequently rebuilt during the reign of the Emperor Hadrian. Remarkably well preserved, it is constructed mainly of a pozzolanbased concrete with a brick veneer. Its dome symbolizes the celestial sphere, the huge opening or 'oculus' not only serves as the temple's light source, but is symbolic of the Sun.

The history of Rome spans more than twenty centuries and, for this reason, this part of the city reflects the stratification of several epochs. To the north-east side of the city, there is the Baroque style which found its secular expression in the form of grand palaces built of stone and roofed with tiles. Baroque palaces were built around an entrance sequence of courts, anterooms, grand staircases, and reception rooms of sequentially increasing magnificence (see Figure 5).

Figure 5. Piazza del Popolo

An example of Baroque architecture and town planning can be found in Piazza del Popolo at the apex of a triangular area known as the Tridente which gets its name from three streets - Via di Ripetta, Via del Corso and Via del Babuino - that arrow out of Piazza del Popolo like a trident's prong (see Figure 5). The piazza, one of Rome's most impressive, is an elegant neoclassical showpiece which was originally laid out to provide a grandiose entrance to the city. The MIVIS image shows the circular shape of Piazza del Popolo, a compact cluster of *pure pixels* belonging to *Roads* class, which contrasts with the few pixels of *Travertine* class, the basis of the Flaminian Obelisk. In the centre is the Flaminian Obelisk which was built to celebrate Pharaoh Rameses II (1232-1220 B.C.) and was transported to Rome by Emperor Augustus [23]. The classification accuracy is also shown by the characterization of *Water bodies* class, as can be seen from the 4 basins at the lower corners of the obelisk.

There is a sequence of urban expansions dating back to pre- and post-unification periods which can be easily identified thanks to large buildings for government ministries: Viale Trastevere (Ministry of Education 1870), Via Arenula (Ministry of Justice, 1889), Via Flaminia (Ministry of Marine, 1859). These imposing constructions are notable for their austere tone, regularity of shape and flat roofs covered with *Travertine and grits.*
Large buildings for government ministries are visible alongside residential areas, with straight roads flanked by houses, in Prati district behind Castel S. Angelo; industrial buildings are introduced to the Testaccio district; the Janiculum Hill is the focus of new residences for the upper and middle classes. Other sub-urban areas are located in Aventino and Monteverde quarters.

The city continued to expand southwards where highly urbanized areas are concentrated within the Garbatella quarter, along Via Ostiense and outside Porta San Paolo (see Figure 6). These extensions to the city, often of mediocre architectural quality made by an army of speculating entrepreneurs referred to as "*palazzinari"* (posh block builders), are recognisable from the banal regularity of their chessboard streets, lack of green areas, use of flat roofs, and the boring repetitiveness of the houses (see Figure 6).

Figure 6. Via Ostiense

This is the culture of the 20th century, which sees the spread of white-painted plaster walls and with flat roofs that are a sort of "*fifth wall"*. This was a building culture, at a time of feverish expansion, that was generally careless, largely ignored roofs as a significant feature, and laid waste to every tradition, including traditional skills in construction, thanks to the ease in handling the new materials (reinforced concrete, steel).

As shown in Figure 7, the surface classified as *Metallic surfaces (sheets)* of the Auditorium Parco della Musica is worthy of note. It is a large public music complex on the north side of Rome, located between Villa Glori, Parioli hill and Villaggio Olimpico quarter, planned by Renzo Piano, Italy's foremost architect, and inaugurated in 2002. This is an example of how "roofing systems" have undergone, over the last few years, strong transformations involving both the exterior aspect and its role in building composition, and ever more sophisticated building technologies able to adapt to the specific purposes for which a building was commissioned, with an architecture not confined to shaping a building (see Figure 7).

Figure 7. Auditorium Parco della Musica

Its structure is that of three large "beetle-shaped buildings" of different dimensions, roofed with lead sheets, arranged around a large open-air amphitheatre which is the central performance area. From a compositional point of view, the roofing is no longer simply something that provides overhead protection, but blends with the perimeter walls and uses complex curves thanks to advanced technology that allows designers ever increasing flexibility and freedom. There is no doubt that this architecture was exceptional, but other smaller-scale buildings provide examples of a happy combination of creative invention and expression, compositional balance, and the skilful use of technology.

As the eye moves towards the outskirts to the south and north of the MIVIS image, one can notice that roof coverings are characterized by a considerable heterogeneity of pixels. This spatial and spectral complexity is due to the variability of sizes, shapes and materials used. The spatial complexity is due to the variability of sizes and covering shapes, whereas the spectral complexity is due to a wide range of construction materials, which are very similar to each other.

These outlying districts with evident characteristics of areas created and developed spontaneously in the sixties, present now a situation of environmental disorder, where residential buildings, industrial sheds, sports facilities, open-air depots and vegetable gardens randomly stand side by side, and which are the result of speculative evaluations of the contemporary city (see Figure 8). The brick-tile roof, typical element which characterized residential buildings erected in the sixties, started falling into disuse and roofs gradually became a "*no man's land"*, result of casualty, often ignored by town planners. *Bituminous surfaces* and *Metallic surfaces sheets* appeared on the scene. On the whole the image shows great variability from pixel to pixel to which corresponds a high degree of fragmentation of shapes and materials of surfaces.

Figure 8. Magliana

The lack of homogeneity in type and size of the constructions shows up clearly, with many of the same elements to be seen everywhere, and the architecture appears to be a mere assembly of standardised parts. Recurrent components are outside stairs, verandas, roller shutters, jutting balconies, cantilevered roofs. This is a building style developed spontaneously in the twenty years from 1965 to '85: the Magliana district is an example (see Figure 8).

Treed surfaces are highly concentrated in the areas of the Villa Borghese Park, Villa Glori Park, the Janiculum Walk (Passeggiata del Gianicolo), defining the borders of the areas between the city dating back to the post-unification period and the suburbs. In the southern district of the city,

named EUR, there is a wide green area surrounded by huge marble buildings built around an artificial lake.
Moreover, the classification highlights a large number of *Lawns* and *Bare soils*. These are grounds left free of constructions, the last remnants of the hybrid environment - simultaneously agricultural and urban, city married to campagna - that was Rome.

New roof coverings made of light, opaque or transparent materials are now available on the market. These materials offer sometimes impressive decorative solutions, such as corrugated iron roofing sheets, fibre-cement sheets, polycarbonate or textile fibres. However, the increasing attention to environmental sustainability issues has led to use roof coverings made of natural or environmentally friendly materials

Conclusions

The MIVIS data acquired over the city of Rome allowed us to demonstrate, in an original and innovative manner, how it was possible to characterize and quantify the roofing surfaces and to deduce considerations on the aerial view of the city, Especially, attention was focused on how the use of the techniques of building and roofing materials has evolved in space and time.

Contrasting with the old city, showing up as homogeneous and continuous in terms of roofing materials and styles, is a more random city. The pitch of brick-tile roofs, which has down the centuries characterized construction methods and is still used today, tends to merge into the landscape– which now resembles an obstacle course.

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