OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 14, No. 7-8, July-August 2020, p. 333 - 337

Reflectance spectra of plant leaves obtained by remote sensing

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The paper presents the results of studies on the detection of plants infected by parasites, from a remote distance, basing on the spectral reflectance. The possibility to detect infection by parasites of nut leaves (small areas 1-2 mm) from remote distance was shown.

(Received October 23, 2019; accepted August 18, 2020)

Keywords: Reflectance, Reflectance Spectra, Remote Sensing

1. Introduction

Studies of the spectral reflectance allow us to identify organic objects from a remote distance. A review of spectroscopy techniques in early detection of plant disease is presented in the work [1]. It was shown that visible (VIS) and infrared (IR) spectroscopy is one of the most promising non-invasive techniques for early detection of plant disease. Spectral reflectance analysis can be very useful in detecting plant stress due to changes in the absorption of incident light in the VIS and IR range of the electromagnetic spectrum. It was noted that VIS spectrum region 400-650 nm was used to report differences between healthy and affected tissues in plants. The reflectance properties of an individual leaf depend on the interaction of pigment content, leaf structures, and water content with electromagnetic radiation. The review of advanced techniques for detecting plant diseases is presented in this work [2]. The spectroscopic and imaging techniques (fluorescence spectroscopy, VIS-IR spectroscopy, fluorescence imaging, and hyperspectral imaging) are described in detail. It was shown that VIS and IR spectroscopy can be used as a rapid and non-destructive method for the detection of plant diseases. The multispectral radiometer and airborne multispectral scanner for the identification of panicle blast in rice from remote distance (300 m height) were used. The four spectral bands of 400–460 nm, 490–530 nm or 530–570 nm, 650–700 nm, and 950–1100 nm was utilized for scanning. In work [3] the remote sensing is defined as an indirect assessment technique that can monitor vegetation conditions from a distance and evaluate the spatial extent and patterns of vegetation characteristics and plant health. It was noted that spectral reflectance measurements for an early diagnosis of symptoms in Nicotiana debneyi plants at different stages of tomato mosaictobamovirus infection and observed a decrease in leaf reflectance due to a reduction of chlorophyll content 10 days after inoculation. For the same experiment, visual symptoms of the presence of the pathogen were observed only two weeks later. Measurements can be taken from a distance at which single leaves cannot be observed with imaging sensors mounted on elevated platforms, drones, aircraft, or satellites. Remote sensing represents a valid tool to detect early infections, since they can identify a few infected plants within orchards or fields. It can be a tool to quickly analyze many plants and eradicate primary infections early, thereby avoiding secondary spreads.

In work [4] was shown that lichens from the subarctic zone can be identified by the spectral reflectance. The reflectance spectra of species were measured in the laboratory using spectroradiometer in the range from 350 to 2500 nm. The distance from the spectroradiometer to the investigated objects was 130 cm, and the lichens were illuminated by a 1000W lamp from a distance of 110 cm. The common spectral features and principal differences of investigating species were obtained using this method. In work [5] the Photochemical Reflectance Index (PRI) was examined in a corn field over multiple growing seasons using the miniature fiber optic spectrometer and the solar irradiance as the incident light. All spectral observations were acquired at nadir, at a height of approximately 1 m above the canopy. An additional spectrometer was used to measure the reference panel continuously in order to monitor detailed changes of irradiance during the field days. In work [6] an unmanned aerial vehicle was used to study the reflectance spectra of plants. All reflectance spectral measurements were made with a portable spectrometer which has a nominal spectral range from 350 to 1000 nm. The dimension of the area sampled at the ground can vary between 0.5 and 12 m, considering a flight altitude ranging from 5 to 50 m. All the above methods have a high accuracy of measurement of the reflectance spectra, but they are designed to study large areas and use large spectral instruments. In work [7] studies of the fluorescence of oil films on the water surface from a remote distance are presented, using a set of narrow-band interference filters instead of a spectrophotometer. This obtained the spectral dependence of the fluorescence of an oil drop with a volume of 1 ml on the water surface from a distance of 15 m.

The aim of this work was an application of remotely measured reflection spectra of plants infected by parasites with a small size (1-3 mm) to distinguish healthy leaves from infected ones.

2. Experimental setup

The experimental setup for the study of reflectance spectra of plants from a remote distance (Fig. 1) is based on a telescopic system (1), a set of narrowband interference filters (2), a digital camera (3), and a white LED module (4).

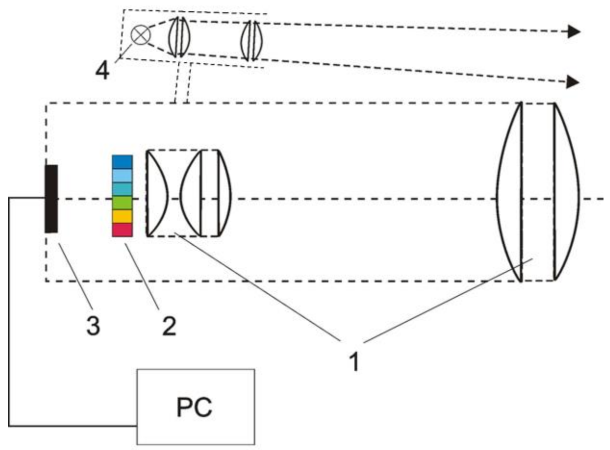


Fig. 1. Experimental setup: 1) Telescopic system, 2) Set of narrowband interference filters, 3) Digital camera matrix, 4) White LED module

The signal of the LED (4) is projected by the optical system on the surface of the studied object. Light reflected by the object passes through the set of narrowband interference filters (2) and is projected onto the matrix of the digital camera (3). The telescopic system is based on the input lens (1:10, focal distance F = 750 mm) with a resolution of 35 l / mm, and on the short-focus objective of 6.3^x with the focal distance of F = 8 mm. The narrowband interference filter set (Edmund Optics) consists of 18 filters with wavelengths: 420 nm, 430 nm, 442 nm, 455 nm, 470 nm, 486 nm, 500 nm, 515 nm, 532 nm, 546 nm, 560 nm, 580 nm, 594 nm, 610 nm, 636 nm, 650 nm, 671 nm, and 685 nm. Spectral dependencies of narrowband interference filters are presented in Fig. 2.

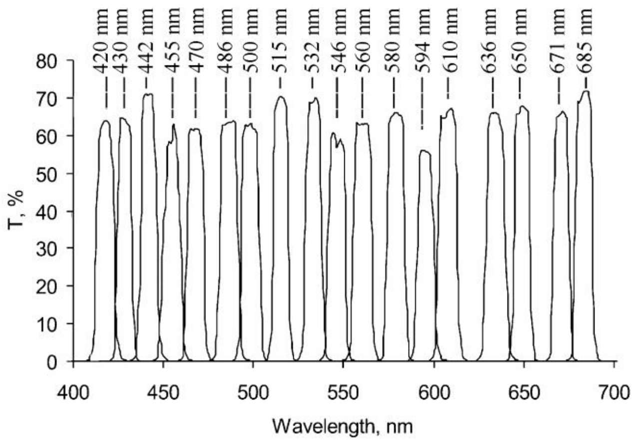


Fig. 2. Spectral dependencies of narrowband interference filters

The white LED module CREE LED CMA 1840 was used to illuminate the studied objects. The relative spectral power of the white LED module is shown in Fig. 3.

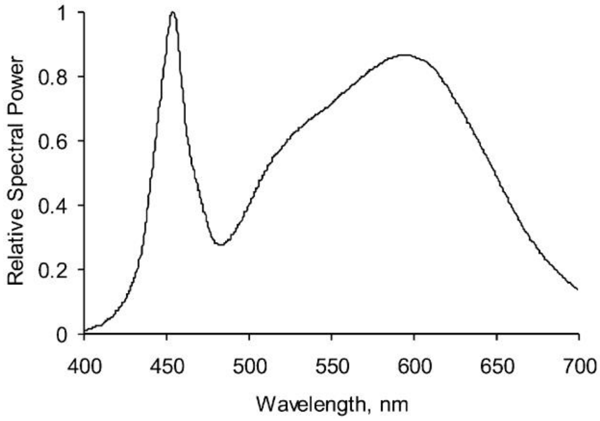


Fig. 3. The relative spectral power of the LED module CREE LED CMA 1840

A monochrome digital camera CCD1545M ThorLabs is used to record the optical signal (3, Fig. 1). It is necessary to calibrate the CCD camera due to nonlinear characteristics of the spectral sensitivity of digital cameras [7-8]. The relative spectral sensitivity of the digital camera was investigated using a monochromator MDR-23. The studies were carried out for wavelengths resolved by a set of narrowband interference filters (Fig. 2). The signal at the output of the monochromator was measured using a photodetector S120C-PM100USB ThorLabs. Instead of the photodetector, the digital camera was placed in the same axial plane without any optical lenses for each measurement. The images for each selected wavelength were recorded using the same values for exposure time and intensity of the light signal. All 18 recorded images were processed in a graphical editor to obtain the image brightness in conventional units from 0 to 255 of the grayscale. Image brightness depending on the wavelength enables the relative spectral sensitivity of the digital camera used. The relative spectral sensitivity of the digital camera is presented in Fig. 4.

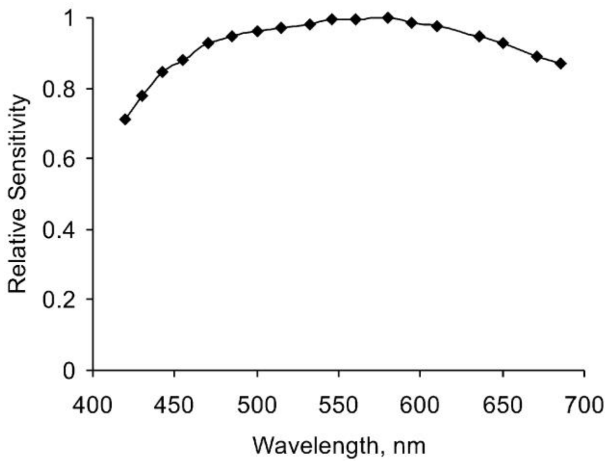


Fig. 4. The relative sensitivity of the monochrome digital camera CCD1545M ThorLabs

The method of reflectance spectra studied from a remote distance is based on the recording images of an object through each of the narrowband interference filters. The software of the used digital camera allows determining signal brightness (from 0 to 255 of the grayscale) for any selected point of the recorded image. Computer processing of all 18 recorded images allows obtaining the brightness of reflected signal depending on the wavelength. Thus, the relative spectral distribution of reflectance of the studied object can be obtained from a remote distance.

3. Results and discussion

Walnut leaves infected by parasites were chosen as the objects of research. The studies were conducted in the absence of external radiation, which allows the experiment to be as close as possible to the identification of objects in the night. The object studied was located at the distance of 15 m, and was illuminated by the radiation of the white LED (4, Fig. 1). Fig. 5a shows the image of the nut leaf infected by the parasitic mite *Eriophyes tristriatus* [9]. Theses mites make small hard blisters that are about 1.5 mm in diameter on the leaf surface. As an example, Fig. 5 shows the images of the surface of the nut leaf recorded through narrowband interference filters using the colour digital camera.

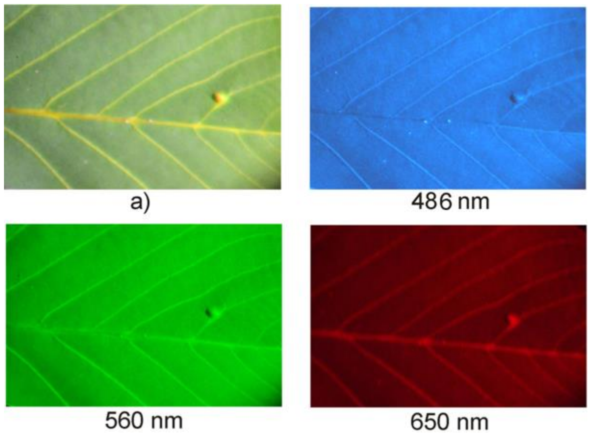


Fig. 5. Images of the nut leaf infected by parasitic mite Eriophyes tristriatus obtained from the distance of 15 m (color online)

To study the reflectance spectra, images were recorded using the CCD1545M ThorLabs monochrome camera. All images were recorded at the same exposure time of 95 ms. As an example, Fig. 6 shows the image of the nut leaf on the computer screen recorded through the interference filter of 560 nm.

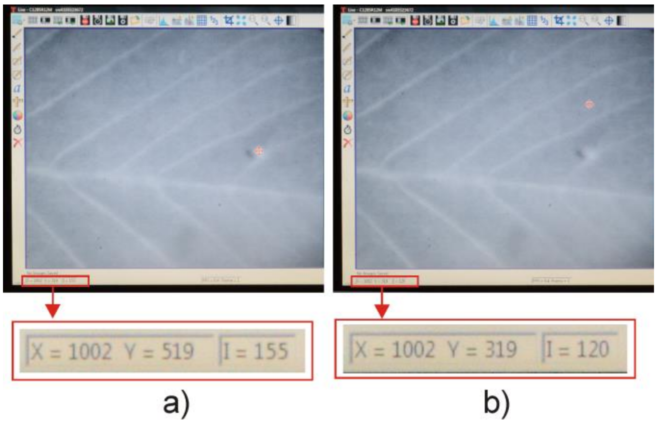


Fig. 6. Image processing of the nut leaf recorded through the interference filter of 560 nm

To process the image of the leaf area infected by the parasitic mite *Eriophyes tristriatus*, the cursor is positioned in the center of the blister (Fig. 6a). The coordinates in pixels and the brightness of the image in grayscale (I=150) are shown on the screen. The brightness of uninfected area was measured on a healthy place of the leaf (Fig. 6b). The obtained values of brightness I are recalculated taking into account the transmission of the narrowband interference filter (Fig. 2), the LED spectral distribution (Fig. 3), and the spectral sensitivity of the digital camera (Fig. 4). Similar measurements are carried out for images recorded through each of the narrowband interference filters. Fig. 7 shows the relative spectral dependence of the reflectance of the surface of the nut leaf infected by the parasitic mite *Eriophyes tristriatus* (curve

1, dashed line) and the healthy surface of the nut leaf (curve 3, dashed line), obtained from a remote distance of 15 m.

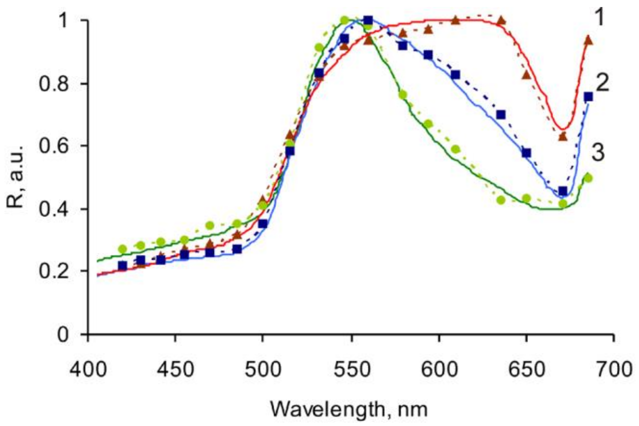


Fig. 7. Relative spectral dependencies of reflectance of the nut leaf obtained were using the monochromator (solid lines) and from the remote distance (dashed lines): 1) infected by parasitic mite Eriophyes tristriatus, 2) infected by parasitic fungus Microstroma juglandis, 3) non- infected area (color online)

The reflectance spectra of nut leaves infected by the parasitic fungus *Microstroma juglandis* [10-11] were studied. The first signs of *Microstroma juglandis* appear in the middle of May: a wax-like bloom in the form of spots up to 2 cm in size forms on the back of the leaves, and the color of the leaf changes on the front surface.

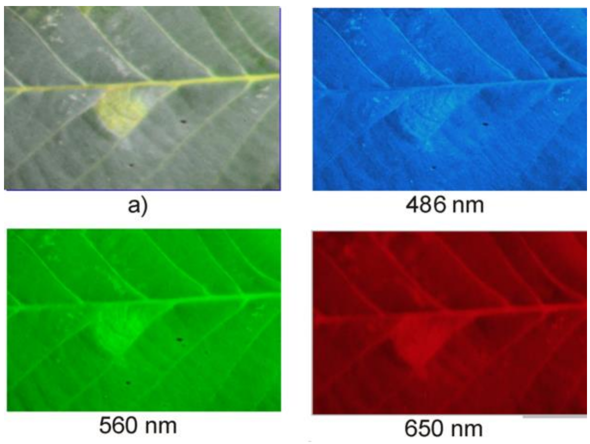
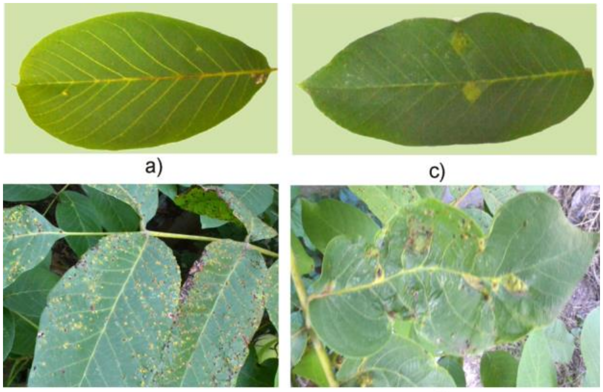


Fig. 8. Images of the nut leaf infected by the parasitic fungus Microstroma juglandis obtained from the distance of 15 m (color online)

Fig. 8 shows the image of the surface of a nut leaf infected by *Microstroma juglandis* (Fig. 8a) and images recorded through narrowband interference filters using a color digital camera. Fig. 7 shows the relative spectral dependence of reflectance of the area of the nut leaf infected by *Microstroma juglandis* (curve 2, dashed line) obtained from a remote distance of 15 m.

As can be seen from Fig. 7, the reflectance spectra of non-infected and infected parts of the nut leaf have sufficient differences, allowing the identification of parasites from a remote distance. To evaluate the experiments, the spectral dependencies of the reflectance of those objects were obtained using a monochromator. Fig. 7 shows the relative spectral dependences of reflectance of healthy and infected surfaces of the nut leaves obtained using a monochromator (solid lines), and from the remote distance (dashed lines). As can be seen from Fig. 7, the spectral dependencies of reflectance obtained from remote distance do not completely coincide with the same values obtained using the monochromator. Variations in spectral characteristics were dependent on several factors: a discrete set of interference filters and a lower precision digital camera compared to the power meter of the monochromator. However, as can be seen from Fig. 7, the spectral dependence of the reflectance of the infected parts of the nut leaf (dashed lines) obtained from a remote distance closely correspond to the results obtained using a monochromator. This allows identifying infected plants from a distance in the early stages of disease. It should be noted that the leaves from the same branch of a walnut tree were used in the each separate experiment. Initially, parasite-infected leaves were examined from a remote distance. At the second stage, the reflection spectra of the infected and non-infected surfaces of each leave were studied using a monochromator. The next experiment was conducted using a different pair of leaves from another branch infected with the same parasites. The reflection spectra for both healthy and infected leaf surfaces were different in all experiments, even conducted within one day. As it was noted in work [1] the reflectance properties of individual leaves depend on the interaction of pigment content, leaf structures, water content, and absorption by photosynthetic pigments. Also, the changes in reflectance spectra due to the plant diseases and pathogens can be clarified by impairments and the variation of chemical composition inside the affected tissue. In the work [3] was shown that with the increasing altitude of acquisition of spectral reflectance issues such as atmospheric effect, pixel heterogeneity of the sensor, and acquisition geometry must be considered when analysing the signal. Also, the spectral signature of vegetation is influenced by leaf area, spatial arrangement, roughness and optical, dielectric, or thermal characteristics of the vegetation elements. However, deviations in the reflection spectra obtained remotely from the spectra observed by monochromator were within 6-8% (similar to the deviations in Fig. 7) in every separate experiment.

In the daytime, the reflectance spectra can be measured in sunlight and the construction of the spectral dependence of the reflectance is carried out considering the spectral distribution of sunlight. The use of compact and low power LEDs will also allow monitoring at night. The high resolution of the optical system and the ability to identify the reflectance spectra of small objects (~ 1 mm) will make it possible to detect plant diseases at the earliest stage. As an example, Fig.9a shows the image of a nut leaf infected by *Eriophyes tristriatus* in May, when only 2 infected places are observed, the size of which does not exceed 2 mm. Fig. 9b shows a nut leaf on the same tree affected by *Eriophyes tristriatus* in early October without any treatment.



a) c) b) d)

Fig. 9. Nut leaves infected by Eriophyes tristriatus (a - at the beginning of May, b - at the beginning of October) and Microstroma juglandis (c - at the beginning of May, d - at the beginning of October) (color online)

As is shown in Fig. 9b, a big part of the leaf surface is infected by *Eriophyes tristriatus* in October. The walnut leaf infected by *Microstroma juglandis* in May (Fig. 9c) is completely infected without treatment at the beginning of October (Fig. 9d). When leaf damage reaches an extensive stage (Fig. 9b and Fig. 9d), their detection can be obtained with good accuracy, using the methods proposed in [4-6]. However, at the initial stage of infection (Fig. 9a), when the size of the infected area is about 1mm, such a small surface can make an insignificant contribution to the study of the reflectance using the technique proposed in [4-6]. In this case, the detection of plant disease at an early stage can be difficult.

In this work, the experiments were carried out in the laboratory under the illumination of objects only with white LED radiation, which corresponds to the detection of plants from a remote distance at night. In the daytime, the reflectance spectra of plants can be obtained considering the spectral distribution of solar radiation, as was proposed in work [5].

Some investigations remained out of the study in this work. To carry out the full-scale investigations it is necessary to study the plant spectral reflectance depending on species, age, and environmental factors. This allows studying the repeatability (or deviation) of the measurements (such as presented in Fig. 7) obtained using the proposed experimental setup and methodology. This is the aim for future investigations.

4. Conclusion

Studies have shown that the infection of nut leaves with parasites can be detected at the earliest stage, when the size of the infected area is about 1mm. Using modern compact unmanned aerial vehicle (UAV) for the visual monitoring requires using compact telescopic system and a CCD camera. Placement of a set of compact narrowband interference filters between the optical system and the CCD camera allows not only visual monitoring but also registering reflectance spectra of the vegetables. The UAV can also be equipped with a device for spraying anti-parasitic reagents, which allow treating locally infected areas at an early stage of infection of plants. This will allow, along with the economic benefits, a reduction in environmental poisoning with pesticides and herbicides.

Acknowledgments

Author gratefully acknowledges support provided by the National Agency for Research and Development of Republic of Moldova and the Moldova State University through the projects #20.80009.5007.12, #15.817.02.34A, and #20.80009.7007.05.

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