LASER-INDUCED FLUORESCENCE FOR ASSESSMENT OF CULTURAL HERITAGE

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ABSTRACT

Remote imaging measurements of laser-induced fluorescence have been performed, with application towards cultural heritage. Measurement campaigns have been performed at, e.g., the Coliseum in Rome. Differences in fluorescence spectra from different points were found and images corresponding to different features could be produced for thematic mapping.

1. INTRODUCTION

Laser-induced fluorescence can be used in diverse applications. It is used in laser medicine [1], but can also be applied remotely [2] to study, e.g., vegetation status [3] or cultural heritage [4-5].

2. MEASUREMENT SET-UP

Measurements are performed using the mobile lidar system of the Lund Institute of Technology [6] and the mobile lidar system of CNR-IFAC [7].

Pulsed laser radiation is directed to the target spot, where fluorescence is induced. The laser beam can be steered wherever desired. When it hits the target, molecules are excited to higher energy levels. When they relax, they emit fluorescence light, which may show different features dependent on the material. Since the target is a solid material, the energy levels are smeared out and the return signal does not show any sharp features. Instead, small differences in the spectra have to be analyzed.

The fluorescence light is gathered by a receiving telescope, on the same optical axis as the transmitting optics. The signal is sent through a long-pass filter to block the exciting wavelength and guided by an optical fiber to a spectrometer with a gated CCD camera which records the spectrum. The measurement is averaged over a number of laser shots to reduce the noise.

When the spectrum in a point is gathered, the laser spot is directed to the next point. The spectrum from this spot is recorded and the laser beam is moved again, and so on. In this way, an area is scanned and imaging is accomplished.

The Swedish system is originally intended for differential absorption lidar measurements, but is also well suited for remote fluorescence. The system is built inside the cargo compartment of a Volvo F610 truck and is thus fully mobile. A motor generator, towed by the truck, ensures that measurements can be performed at any location. The laser source is a frequency tripled Q-switched Nd:YAG laser at 355 nm or alternatively an optical parametric oscillator system, which can produce wavelengths between 220 nm and 1.7 μm, although usually only the ultraviolet wavelengths are used.

The laser beam is directed through a beam expander and to the air through a roof-top dome, where a computer-controlled folding mirror can be used to direct the radiation to the desired spot. The spot size on the target, 50-100 m away, is typically about 5 cm. The fluorescence light is gathered by the same folding mirror and directed to a 40-cm-diameter Newtonian telescope which focuses the radiation onto the tip of an optical fiber, connected to the spectrometer. The spectrum in the wavelength range 280-810 nm can be detected. The measurement is averaged over a number of laser shots (typically 100 shots, corresponding to 5 seconds) to reduce the noise.

The Italian system is a dedicated fluorescence lidar system (FLIDAR), housed in a Fiat Ducato van and powered by a motor generator. Pulsed laser radiation from a 10 Hz XeCl excimer laser at 308 nm is used, with a spot size on target of 2 cm at a typical range to the target of about 20 m. The fluorescence light is gathered with a 25-cm-diameter Newtonian telescope and directed through an optical fiber to a spectrometer and a 512 channel linear photodiode array detector. The spectrum in the wavelength range 300-800 nm is gathered by merging two acquisitions, one in the range 300-600 nm and the other in the 500-800 nm range. A spectrum is recorded in about 1 minute (averaging over 30 laser shots).

3. MEASUREMENT CAMPAIGNS

Measurements have been performed at sites of importance for the cultural heritage. Recent measurements include the castle Övedskloster in southern Sweden [8], the amphitheater Coliseum in Rome (see Fig. 1) and the Lateran Baptistery in Rome.

Fig. 1. Measurements at Coliseum. The Swedish lidar system is seen on the right and the Italian system is on the left, closer to the monument.

The measurement campaign in Rome was performed over a two week period in February 2005. Measurements were performed at night, not to disturb the daytime activities, e.g. tourism, at the sites. Note that the gating of the detectors is efficient enough to suppress the ambient light, so technically the measurements could have been performed in daytime, as has been done in most previous campaigns.

The Coliseum, officially known as the Flavian amphitheater, was inaugurated in year 80 A.D. It is mainly constructed with travertine, quarried in nearby Tivoli. The stone has in many parts deteriorated and the need for ongoing control and analysis of the material is vital for the conservation and maintenance of the monument, which is now also a great tourist attraction.

The Lateran baptistery is connected to San Giovanni in Laterano, the cathedral of Rome and the oldest church of Christianity. It was constructed in the 4th century A.D. and is a brick building. It has been rebuilt many times and the façades thus consist of many construction phases. The building is the property of the Vatican state, and is part of the Laterano territory.

4. ANALYSIS

The resulting data from a scan is three-dimensional (two spatial dimensions and wavelength). To create easy-to-understand images the data must be reduced to two dimensions. This can be done by applying some sort of function to each spectrum, so that the wavelength dimension is reduced to a single value. Then it is possible to create a false-color coded image that can show differences between different regions in the studied area (thematic mapping).

The function applied to the spectra can be chosen in several ways. By choosing, e.g., the mean value in a certain wavelength band, the wavelength dimension is reduced to a single value. However, this is generally not enough to describe the differences in the spectra. By choosing more wavelength bands and combining them (e.g. one band divided by another) more subtle variations can be focused on. Also, instead of the mean value in a band, one may choose the maximum value in the band or the minimum value, the integral over that band or the slope of the curve in the band. It is always desired to use dimensionless quantities, since all outer factors that may affect the absolute value of the detected fluorescence, such as laser intensity fluctuations, angle of incidence, etc. are then divided away. Only the shape of the spectrum is then evaluated, the absolute intensities are neglected. In some cases this is not desired, so special care has to be taken in each case.

Normalizing the spectra is another way of disregarding absolute intensities. This can be done in several ways, e.g. each spectrum may be divided by its maximum value (max-normalization) or the area under the spectrum (integral-normalization). Another way may be to regard each wavelength as a sample and normalize with regards to the maximum value for that wavelength in the data set (lambda-normalization).

It is also possible to make correlations between different spectra and thus find points with similar spectral features.

Usually, the spectra have only small differences, although certain materials have characteristic fluorescence features. Chlorophyll has strong fluorescence features in the near infrared area, around 700 nm.

In this context, it is important to have collaborations between physicists and partners from architectural conservation science and the archeological fields, who can interpret the results and draw relevant conclusions.

4.1 Principal Component Analysis

Principal component analysis (PCA) is a systematic way to find the most significant differences between (in this case) the spectra. Each spectrum has 1024 channels, which means that there are 1024 different variables. Then there are a number of samples, represented by the spectra that have been taken in the scan. Each sample has a certain value for each variable.

The PCA algorithm projects the data onto a new set of variables, called principal components (PCs). This is done such that the variance in the data along the first PC is maximized. Then the second PC is created, orthogonal to the first one, maximizing the residual variance, and so on. Each PC has a set of values for the wavelengths, called loadings. Each spectrum can be expressed as a linear combination of the PC loadings, and the factors are called the score values for the sample. This procedure reduces the complexity of the samples, because usually no more than 4-5 PCs are needed to describe the data, the rest is noise. By forming functions of the scores for the different PCs, new information can be extracted from the data.

5. RESULTS

In Fig. 2 the fluorescence spectrum from four different points on a part of the northern façade of Coliseum is shown for 355 nm excitation.

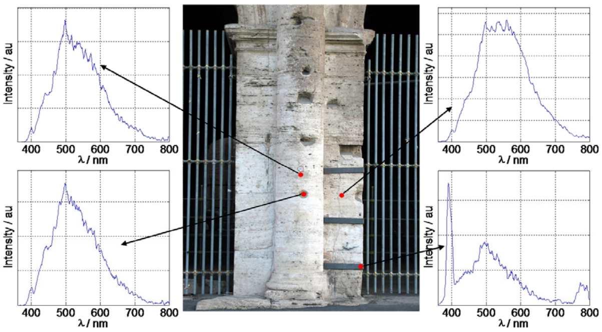

Fig. 2. Fluorescence spectra from different points on the northern façade of Coliseum.

Differences between the spectra can be seen. The lower right spectrum is taken from a steel clamp where the sharp peak at 390 nm is due to an anti-corrosion treatment chemical applied to the surface. In the other three spectra, the differences are more subtle. The upper right spectrum shows a broader structure than the two on the left. The two left ones are very similar, although still some difference may be noticed, e.g. studying the slope of the curve between 500 and 600 nm.

With an area analysis of a scan over this area, it is easy to find the metal points, as these are clearly different than the other points. The result is seen in the left part of Fig. 3. On the right in Fig. 3, points with a strong positive slope in the region 500-550 nm are shown. Some distinct areas can be recognized as similar in this aspect.

Fig. 3. The left picture shows that the metal bars are easily singled out and in the right picture the points with a large positive slope at 500-550 nm. The frames correspond to the measured area and the brightest pixels correspond to the points with the largest values.

As mentioned above, chlorophyll has characteristic fluorescence features. In Fig. 4 the spectrum from a point on Coliseum with algal growth is shown for 355 nm excitation. There is a large peak at around 700 nm which corresponds to the presence of chlorophyll.

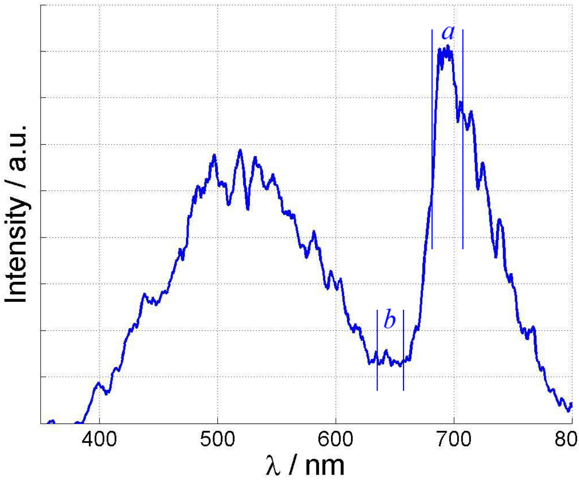

Fig. 4. The spectrum from a point with algal growth.

The points with algal growth are thus easily singled out and an image showing points with algal growth can be produced. Here, the intensity value in the wavelength region 680-705 nm (*a*) is compared to the intensity in the region 635-655 nm (*b*). As can be seen from Fig. 4, a point with chlorophyll content will have a higher intensity in the *a*-band than in the *b*-band, whereas the opposite will be true for a spectrum without chlorophyll. The result can be seen in Fig. 5. It is noted that the most intense chlorophyll signal is detected from a stone with rough surface and large cavities, giving good living conditions for the biodeteriogens.

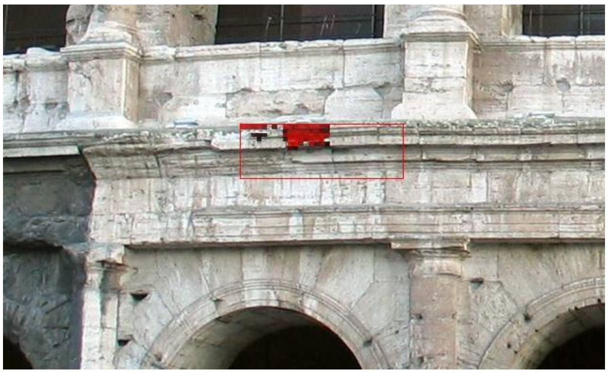

Fig. 5. Chlorophyll on an area on Coliseum. The frame indicates the measured area and the brightest pixels correspond to the points with highest chlorophyll signal.

In Figs. 6 and 7 areas on the Lateran baptistery are shown. In these pictures, differences can be seen, due to the presence of different types of bricks. There is also difference between the bricks and the surrounding mortar. In both Figs. 6 and 7, the pixels indicated have spectra with a slightly wider structure, that do not fall off as fast towards longer wavelengths.

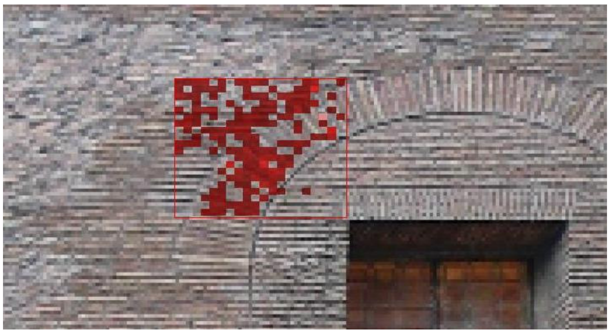

Fig. 6. An area on the Lateran baptistery. The mineralogical composition of the bricks in the window arch differ from the re-used bricks within.

6. CONCLUSIONS

Our measurements show that laser-induced fluorescence is an efficient method for conservation assessment. Measurements are made remotely and are completely non-destructive. Information that can be extracted include detection of biodeteriogens and characterization of different materials. The data from our Rome campaign is now in the process of being fully analyzed.

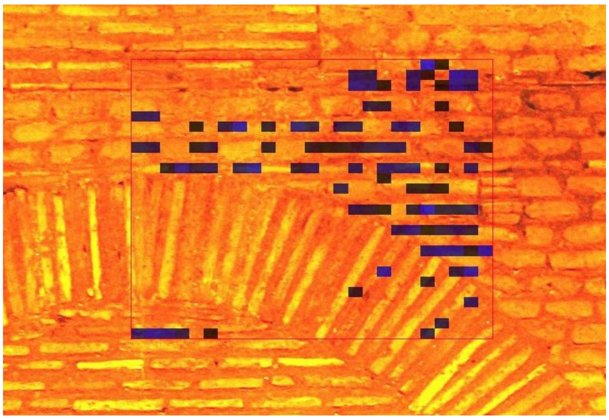

Fig. 7. An area on the Lateran baptistery. Differences between different types of bricks can be detected and bricks can be distinguished from mortar.

REFERENCES

1. Svanberg, S., New Developments in Laser Medicine, *Physica Scripta*, Vol. T72, 69-75, 1997.

2. Svanberg, S., Fluorescence Spectroscopy and Imaging of Lidar Targets, Chap. 6 in T. Fujii and T. Fukuchi (eds.), *Laser Remote Sensing*, CRC Press, Boca Raton, Florida, 2005.

3. Svanberg, S., Fluorescence Lidar Monitoring of Vegetation Status, *Physica Scripta*, Vol. T58, 79-85, 1995.

4. Weibring, P., et al., Fluorescence Lidar Imaging of Historical Monuments, *Applied Optics*, Vol. 40, 6111-6120, 2001.

5. Lognoli, D., et al., Fluorescence Lidar Imaging of the Cathedral and Baptistery of Parma, *Applied Physics B*, Vol. 76, 457-465, 2003.

6. Weibring, P., et al., Versatile Mobile Lidar System for Environmental Monitoring, *Applied Optics*, Vol. 42, 3583-3594, 2003.

7. Cecchi, G., et al., Remote Sensing of Chlorophyll *a* Fluorescence of Vegetation Canopies: 1. Near and Far Field Measurement Techniques, *Remote Sensing of Environment*, Vol. 47, 18-28, 1994.

8. Grönlund, R., et al., Fluorescence Lidar Multispectral Imaging of Historical Monuments – Övedskloster, a Swedish Case Study, proceedings of Lacona VI, Vienna, Austria, 21-25 September 2005, to appear.