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Monitoring Aging Processes of Archival Documents by Means of Quantitative Hyperspectral Imaging: A Part of the Hyperspectral Project at the Nationaal Archief (National Archives of the Netherlands)

ABSTRACT

Archival and library institutions are constantly faced with the great challenge of finding and maintaining a good balance between the public access of historical documents and their conservation. Many tools are used in the conservation field to assess and monitor the suitability of storage and exhibition environments, but a direct verification of the effects of these environments on original documents is still difficult. The Bihanne Project, started in 2006 by the Nationaal Archief (National Archives of the Netherlands), as a branch of the Hyperspectral Project started in 2004, aims at exploring the applications of the hyperspectral imaging technique for monitoring the aging process in documents. Within the Bihanne Project data are taken from both original documents (naturally aged) and specifically prepared samples (artificially aged) to compare aging behaviors of a large number of materials exposed to different conservation treatments and aging conditions. This paper will provide a general introduction to the project and the working principle of quantitative hyperspectral imaging. The procedures followed for the measurement and the analysis are described in detail, and initial results are presented. The high sensitivity of the technique in detecting spectral changes is demonstrated using sample documents artificially aged through light exposure. The results have provided important information for the definition of the application ranges of quantitative hyperspectral imaging not just as an analysis method but as a monitoring tool.

INTRODUCTION

The use of hyperspectral imaging in the archive field is a relatively new subject, although many of its potential applications have already been experimentally addressed using multispectral imaging (Delaney et al. 2005; Kubik 2007, Fischer and Kakoulli 2006). The two techniques are in fact based on the same working principle, however, hyperspectral imaging provides more detailed spectral information and a better reproducibility of quantitative data if a correct calibration procedure is applied. As a consequence, results extracted with a multispectral imaging system can generally be obtained also with a hyperspectral system covering the same spectral range, but not vice versa. The application of this technique on documents has shown to improve the quality and quantity of information obtained by the analysis of the data, opening new perspectives to the diagnosis and study of archival items. This paper concentrates on one particular application, namely the monitoring of aging processes, which represents at the moment an almost unexplored subject of using hyperspectral imaging in the field of cultural heritage.

The research project is dedicated to the memory of our colleague Bihanne Wassink, who prematurely passed away on the 21st of April 2008.

The majority of this contribution focuses on the challenges faced during the practical implementation of the technique as a monitoring tool and on the initial results of the experiments currently carried out. Although a brief introduction of the hyperspectral imaging technique is given here, the reading of introductory texts such as Campbell's *Introduction to Remote Sensing* (2002) and Chang's *Hyperspectral Data Exploitation* (2007) is suggested for a more detailed and technical description of the technique itself.

THE BRANCHES OF THE HYPERSPECTRAL PROJECT

The start of the Bihanne Project can be traced to three particular challenges faced during other research conducted at the Nationaal Archief: 1) The direct verification on documents of the positive effects of air pollutants filtration in storage rooms (Havermans and Steemers 2005); 2) The identification of iron-gall inks in a non-invasive way (Havermans et al. 2003); and 3) The quantification of the effect of temporary and permanent exhibitions on documents.

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Application tests started out using the multispectral technique and they fully proved the high potential of simultaneous recordings of spectral and spatial information of original documents (Havermans et al. 2003). In fact, on one hand, this technique could allow the classification of certain kind of inks and pigments, and in some cases enhance the readability of damaged and erased texts (Goltz et al. 2007). But, on the other hand, it was found unsuitable to distinguish materials with similar spectral characteristics and it was totally insufficient to produce an accurate quantification of spectral changes caused by aging processes. For these reasons multispectral imaging was replaced by hyperspectral imaging, which has much greater potential to achieve all the research goals.

The first applicability studies initiated the division of the Hyperspectral Project in two main branches. The first one is concerned with using the technique to analyze documents, i.e., a single measurement of an object area analyzed for purposes such as materials discrimination, text enhancement, and diplomatic research. The second branch (covered by the Bihanne Project) focuses on exploring the technique's potential as a monitoring tool, i.e., repeated measurements of the same document, performed at different times, are analyzed and compared for purposes such as the monitoring of aging processes, the evaluation of conservation treatments, and environmental conservation actions (Muñoz Viñas 2005).

THE HYPERSPECTRAL IMAGING TECHNIQUE

Hyperspectral imaging is a remote-sensing technique that enables the acquisition of spectral and spatial information of an object, or parts of it, without getting directly in contact with its surface (Elachi and Zyl 2006; de Jong and van der Meer 2004). The same general principle is used in photography and in human vision, where spectral and spatial information are combined to produce an image of a certain scene. For example, when a digital image is acquired by a standard digital camera the end result is generally a color image composed of three overlapping images that are obtained in three discrete spectral channels (RGB). Therefore a digital camera acts as a three-channel multispectral camera, being able to simultaneously acquire all the spectral information of a certain scene in three specific portions of the electromagnetic spectrum. If more than three channels are used, potentially more information about the recorded scene can be obtained (Feller 2001).

Differences between Multispectral and Hyperspectral Systems

On the basis of the number of channels used in the recording, their contiguity, and their spectral separation, it is possible to define the difference between multispectral and hyperspectral imaging techniques. In a multispectral imaging system the number of independent spectral channels is typically not more than ten, and they are not necessarily contiguously distributed. The amount of spectral information acquired with such systems is therefore limited and the classification of certain materials is only possible if significant spectral differences occur.

As compared to multispectral imagers, a hyperspectral imaging system provides a much greater number of spectral channels, which cover the spectral range in a contiguous way, and therefore provide much more complete spectral information. Basically every individual pixel of a hyperspectral imaging recording carries the information of an entire spectral curve, which enables a more efficient target discrimination and further analysis (Grahn and Geladi 2007).

The Development of a New Instrument

The main challenge of applying hyperspectral imaging, or in fact any other analytical technique, to the study of original documents is to obtain the highest amount of information from the analyzed units while limiting any potential damage provoked by handling the documents and by the instrumentation used. Therefore, during the first part of the project great attention was given to the development of a dedicated hyperspectral imager that could fully satisfy the requirements of accuracy, reproducibility, and non-destructiveness. The instrument, a quantitative hyperspectral imager named SEPIA, was developed in collaboration with the company Art Innovation B.V. (Klein and al. 2006). After its construction, periodic measurement commenced for a number of selected original documents, kept in the Nationaal Archief and in some cases provided by other institutions.

This instrument is composed by two wavelength-tunable light projectors, named TULIPS, which illuminate the document from two sides under an angle of 45°. The TULIPS can be tuned through seventy consecutive spectral channels covering the entire range from the ultraviolet (UV, shortest wavelength 365 nm), via the visible (VIS), into the near-infrared (NIR, longest wavelength 1100 nm). The document is imaged by a 4-megapixel, charge-coupled-device (CCD) camera that is mounted overhead at a distance of about 40 cm. In order to avoid any interference by external light the entire setup is enclosed in a climate-monitored darkroom cabinet. The positioning of the optical spectral filters inside the TULIPS is driven by built-in electronic components, which themselves are controlled by software running on an external personal computer. A graphical user interface gives access to all important settings for each spectral channel such as exposure times, gain, and focus position of the camera, and it provides readings for the operating status of the light sources and the environmental conditions inside the cabinet. For more technical information on the operation of the instrument and the results of performance tests please refer to "Quantitative Hyperspectral Reflectance Imaging" by Klein et al. (2008).

In conventional multispectral imaging, the recorded object is illuminated with a powerful white-light source and the different spectral channels are discriminated by placing spectral filters in front of the camera. In contrast, the developed hyperspectral imager achieves spectral discrimination by filtering the light in the light sources, before it hits the object. The great advantage of this approach is that during the recording the document is illuminated not by the entire spectrum (white light), but only by the narrow spectral component used to acquire a particular image. As a result, the document area receives the minimum light energy required for the measurement. This is of highest importance especially if multiple recordings of the same document have to be carried out, for example to monitor aging process, since the recording itself could locally induce accelerated aging if a full-spectrum illumination was used for prolonged times.

The Datacube

Data obtained from both hyperspectral and multispectral imaging is generally represented in a three-dimensional reference system, where the so-called spectral data cube is represented. For every point in this datacube two of the three axes (e.g., X and Y) describe the spatial coordinates of the recorded data (i.e. the surface positions) and the third axis (e.g., Z) describes the optical wavelength (fig. 1).

From the recorded spectral images, the data cube is composed as follows. The pixels of each digital image form a (two-dimensional) matrix of numerical values. After proper calibration of the recorded data, the value of each pixel lies in the range of 0 to 1 and describes the portion of light that is reflected from the corresponding spot on the object at the particular wavelength at which the image was recorded. Each pixel value thus describes a physical quantity, namely the local spectral reflectance of the object.

The entire datacube contains for each pixel the series of numerical reflectance values from all spectral channels, i.e., effectively an entire spectral reflectance curve. For the purpose of a mathematical analysis often an alternative representation of the numerical information contained in the data cube is chosen. The spectral reflectance values of a pixel can in fact be regarded as the elements of a particular vector in a high-dimensional mathematical space. Although being much less intuitive than spectral curves, the representation as such abstract spectral vectors makes it possible to apply a vast array of mathematical tools, developed, for example, to distinguish certain target materials and map their occurrence on the object with pixel accuracy.

THE BIHANNE PROJECT

The Bihanne Project is divided in two main sections: 1) the study of natural aging process of original documents, and 2) the accelerated aging process induced on sample materials. These two branches of the research are currently used to build two databases that give valuable information about the possible application ranges, limits, and practical procedures to be considered when applying hyperspectral system as a monitoring tool. In the specific case, of the internal exhibition room at the Nationaal Archief, the natural aging of the exhibited documents should be minimal, because each item is allowed to be exhibited for a maximum period of four months per year (53 hours per week) at an illumination intensity of 50 lux. Considering the relatively low light dose accumulated in a single four-month period (42400 lx·h) only very small spectral changes are expected, even for photosensitive materials (Thomson 2000). This is why considerable effort was put in the technical development of both the instrument and the recording procedure to achieve maximum reproducibility and sensitivity of the hyperspectral measurements.

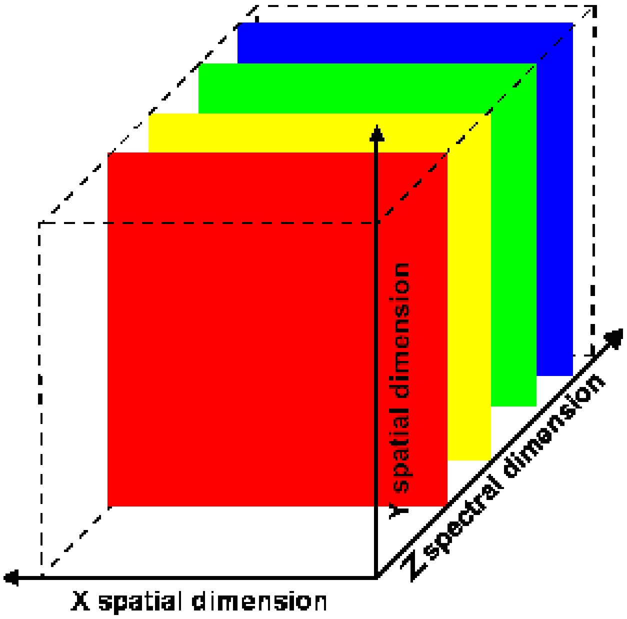

Fig. 1. The three-dimensional shape of the hyperspectral datacube

Measurement reproducibility

One of the major challenges in the Bihanne Project has been to achieve the required reproducibility of the hyperspectral measurements to compare recordings of the same documents made at different times. Over the past three years, the recording and calibration procedures, which are crucial for the measurement reproducibility, have been constantly improved. In particular, the hardware and the control software of the instrument were adapted and a special recording procedure was adopted to minimize the thermally induced drift of the measured values. In order to verify the achieved reproducibility between several measurements of the same document, reference targets are placed within the recorded area. Differences observed between spectral data cubes, recorded for the same document area, can now be related to actual changes of the physical and chemical condition of the document rather than reflecting the imperfections of the apparatus itself.

Another important element taken into consideration for the reproducibility of hyperspectral recordings of documents was the surface of the stage that supports the analyzed sample and thus serves as the optical background of the measurement. In fact, many writing substrates can be translucent to some degree so that the reflectance spectra measured by the instrument are slightly influenced by the background. To give a practical example, when the page of a bound volume is recorded a small amount of the light is transmitted through the measured page and reflected by the underlying pages of the textblock. In a subsequent measurement of the same page, the underlying sheets may have shifted slightly or their reflectance characteristics may have changed, resulting in an interference source for the measured page. In our case the document support received a finish of specially selected flat black paint that is highly light-absorbing over the entire spectral range used by the SEPIA instrument.

The Reference Targets

Generally the calibration of hyperspectral datacubes is based on the comparison of the data obtained from the measured object (having unknown spectral characteristics), to the data obtained from one or more reference targets (having known spectral characteristics), when both are exposed to the same recording conditions. For example, in the airborne scanning of the Earth's surface, reference measurements are carried out by using special target sheets, placed inside the recorded area, or by collecting *in loco* spectral values of homogeneous areas of the ground (Elachi and Zyl 2006). The reference measurements used in the calibration process make it possible to compensate for varying recording conditions (e.g., sun illumination and atmospheric changes) and for possible instrumental errors. Moreover the pixel values in the hyperspectral data cube can be associated with a specific physical quantity such as spectral reflectance.

In our case using a spectrophotometer to obtain reference data from the measured object itself would not provide sufficient accuracy, because such a spot analysis would not produce an effective evaluation of the recording conditions over the total recording surface. In fact the typical inhomogeneity of document surfaces would seriously impede the reproducibility of such type of reference measurements. As an alternative, data sets are recorded directly with the instrument from three types of targets that cover the recorded area in part or completely.

> Primary Reference Target—The primary reference target used is a 128 x 128 mm Spectralon tile that covers the entire field-of-view of the SEPIA instrument (fig. 2). It is provided by the company Labsphere and it has been chosen for its high diffuse reflectivity, as in fact more than 99% of the light is reflected from its surface over a wide range of the light spectrum (230 to 2000 nm). In addition, this calibration standard is provided with a certificate stating its reflectance values according to the standards set out by the National Institute of Standards and Technology. The Spectralon tile is used as the primary reference to correct instrumental errors and provide an absolute, long-term calibration enabling a pixel-per-pixel calibration of the datacubes and a correct evaluation of inhomogeneities of the light distribution over the recording area.
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> Recording Verification Target—In order to detect any major recording malfunctions during the analysis of the investigated documents or test samples, a reference target is placed inside the recorded area of both the documents and the Spectralon (figs. 2–3). This target was realized with a strip of Whatman paper grade number1 (230 x 20 mm) fixed by the two short sides on a 1 mm thick preservation board

Fig. 2. The Recording Verification Target (bottom strip) and the Reproducibility Target (top strip) during the recording of a test document

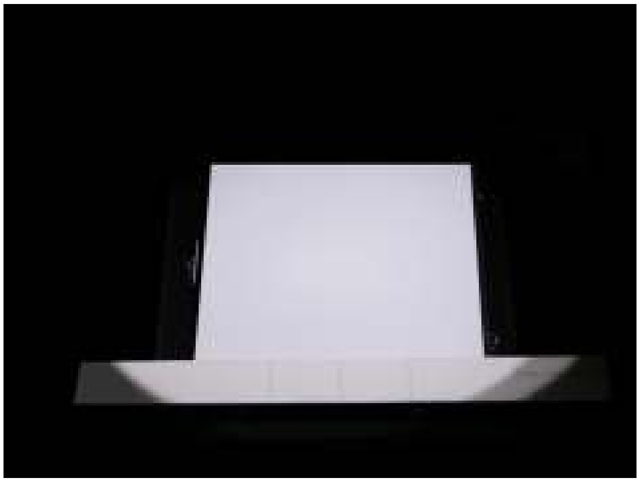

Fig. 3. The primary target (Spectralon) with the Recording Verification Target placed partially on top of it, in the position used for the recording of the document

(with identical dimensions) using Evacon-R adhesive. The fixation of the paper was necessary because its translucency, in combination with an inhomogeneous background, could have caused unpredictable variations of its recorded spectral characteristics, as discussed above. To avoid any changes of the quality of the Whatman paper the adhesive was only applied to the border of the strip, in an area external to the field of view of the imager.

Reproducibility Target—This target is inserted only in the recording of the monitored document or sample test (fig. 2). It is used as a reference to verify that eventually observed spectral changes, found during the comparison of multiple recordings of the same document, would not be caused by a measurement error but by an effective changing of the physical and chemical characteristics of the document. This target is realized in multiple copies with the same procedure used for the Recording Verification Target (described in the previous paragraph) and each of them is associated to one single document recording. Because these targets are constantly preserved in darkness, under optimal climate conditions, and reused only when a new recording of the same document area is performed, they provide a direct reference for the reproducibility of the measurements in time.

The Recording Procedure

The recording procedure used in the Bihanne Project, for monitoring of both accelerated and natural aging processes, is based on daily recording periods of approximately eight hours in which a total of four investigated documents can be analyzed. Each section is divided in thirteen independent recordings of thirty-five minutes. The first two are used to warm up all the components of the instrument and their data are not stored. In the following, a document recording is always calibrated by interpolating the reference data from four Spectralon recordings, namely two recordings made before and two after the document recording itself (table 1). This is why the session starts and ends with two subsequent recordings of the Spectralon target, and between these pairs the documents and the Spectralon are recorded alternately.

Monitoring Natural Aging

At the moment only a small number of selected original documents are monitored using the hyperspectral technique. These documents, due to their national and international importance, are constantly exhibited in the internal exhibition room of the Nationaal Archief or they are sent to external institutions for temporary exhibitions. The accumulation of data started in the year 2006 and continues to the present time, resulting in more than fifty document areas that have been repeatedly measured before and after their exhibition periods, keeping record of the conditions in which documents were exhibited. The analysis of the data stored in this growing database is still in development and many improvements are constantly performed in order to extract more information from the monitored documents. For this reason, and also because it was necessary to wait a sufficiently long period of

Recordings	Uses	Storage
WU1	Warming up	Erased data
WU2	Warming up	Erased data
01_SPECTRALON-S99	Target used to calibrate Document 1	Stored data
02_SPECTRALON-S99	Target used to calibrate Document 1 & 2	Stored data
03_DOCUMENT 1	Recording of the investigated Document 1	Stored data
04_SPECTRALON-S99	Target used to calibrate Document 1 & 2 & 3	Stored data
05_DOCUMENT 2	Recording of the investigated Document 2	Stored data
06_SPECTRALON-S99	Target used to calibrate Document 2 & 3 & 4	Stored data
07_DOCUMENT 3	Recording of the investigated Document 3	Stored data
08_SPECTRALON-S99	Target used to calibrate Document 2 & 3 & 4	Stored data
09_DOCUMENT 4	Recording of the investigated Document 4	Stored data
10_SPECTRALON-S99	Target used to calibrate Document 3 & 4	Stored data
11_SPECTRALON-S99	Target used to calibrate Document 4	Stored data

Table 1. Daily recording section

Substrates	Writing products	Adhesives	Conservation treatments	Original documents
Whatman paper Grade nr.01	Iron gall ink	Methylcellulose (MC)	Reducing (Tert-butyl-amine borane)	Original document with typewritten text (1941)
Romandruk paper (wood-pulp based)	White lead	Carboxyimethylcellulose (CMC)	Oxidative (Hydrogen peroxide)	Printed book with foxing (late 19th c.)
Eucalipto paper	Copper green	Tylose	Deacidification (Bookkeeper)	Document with iron gall ink (1920's)
Silversafe paper	Brazil wood	Evacon-R		Document with aniline ink (1920's)
Calf skin	Saffron yellow	Gelatine		
Goat parchment				
Cotton				
Linen				

Table 2. Materials actually investigated in the Bihanne Project

time in order to record natural aging processes, preliminary results cannot yet be presented. From September 2009 new analytical tools will be applied to speed up the managing of these data, improving also the quality of the results.

Monitoring Artificial Aging

The acquisition of hyperspectral data from original documents is of extreme importance to understand the natural aging process of their component materials. But in order to predict the long-term effect of certain exhibition or storage environments it is necessary to produce specific aging models by applying accelerated aging to test samples. For this reason within the Bihanne Project a set of artificial samples was manufactured and aged in different ways to create aging models of materials generally found in the production and restoration of archival documents. The hyperspectral measurement of these artificially aged samples is expected to provide valuable information about the type and the intensity of spectral changes that can be expected. In addition, these measurements will help to establish the optimal recording and analysis procedures to be used in standardized monitoring methods in archive institutions. The selection of the materials investigated in this branch of the Bihanne Project is shown in table 2. They are divided in five main categories: substrates, writing products, adhesives, conservation treatments, and original documents. Great attention was given to the use of standardized materials and their production recipes in order to create reproducible samples to be combined in different ways and exposed to different artificial aging process.

Accelerated Aging—All the materials tested until now have undergone three types of artificial aging procedures. The first procedure addresses accelerated light aging of the samples as can be expected to occur during an exhibition period in the internal exhibition room of the Nationaal Archief. In fact, a specifically designed artificial light aging cabinet (ALAC-2) imitates as closely as possible the actual illumination conditions in which original documents are exhibited. Conventional artificial light aging of sample materials is usually performed by using climate chambers fitted with UV filtered Xenon lamps. As opposed to this, the ALAC-2 features four UV free lamps identical to the ones used in the exhibition room (Whitestar UV-P, 12v 50W 4200K). In addition, the same glass cover as used in the showcases, is inserted in the light path between the lamps and the samples. In this way it has been possible to recreate in a laboratory environment the identical spectral characteristics of the illumination used in the exhibition room but with a higher intensity (circa 1200 lux instead of 50 lux). The lamps are fitted with a forced-air cooling system and the temperature at the sample documents is constantly monitored during the aging process in order to exclude any influence of thermal aging of the samples.

The second aging procedure is based on the variation of climate conditions (temperature and relative humidity) to induce aging process on the tested materials. This type of accelerated aging was applied to the samples by using either of two different climate chambers: Heraeus-Vötsch VTRK 150 or the MMM Group Medcenter Climacell-111. Both were programmed to provide different sets of aging cycles, in order to verify differences in their effect on the spectral characteristics of the tested materials.

In the VTRK 150 cabinet the samples were kept at a stable temperature of 80° C for 15 hrs while the relative humidity was cycled three times between 35% and 80%. The second cabinet was programmed to provide a stable temperature of 70° C for 15 hrs and three full cycles of the humidity parameter between 35% and 75% (Bogaard and Whitmore 2002).

The third aging procedure addresses the effects that occur when combining environmental stress and exposure to light. A complete aging cycle according to this third procedure is implemented by sequentially applying to the samples the first aging procedure described above (light) followed by the second (temperature/humidity).

The Recording of the Samples—Each test sample of the used materials was shaped in a rectangle of 120 x 180 mm. This rectangle was then divided in four identical strips of 30 x 180 mm. Each one of these strips underwent a different aging process: natural aging (kept in darkness and used as a reference strip); light aging; climate aging; and light plus climate aging. Recordings of the samples were always carried out before and after every aging cycle in order to be able to measure a progressive changing in the spectral characteristics of the tested materials. To minimize any possible error caused by the positioning of the samples in the area measured by the instrument, a special sample holder was designed (fig. 4).

To reduce the effect of back reflection for translucent materials this holder provides a homogeneous, flat-black surface onto which the samples are mounted. Using eight screws, four sample strips are fixed next to each other on the holder. On top of the samples a grill is placed to press the borders of the sample strips on the holder surface, keeping them flat. This is important because some sample materials, such as parchment, can be considerably deformed by the climate aging. On top of the grill four reference strips with a gray pattern are arranged to verify the working of the instrument. The same grill is also used for the Spectralon calibration recordings, where spacers are used to place it at the same height and position as during the sample recordings.

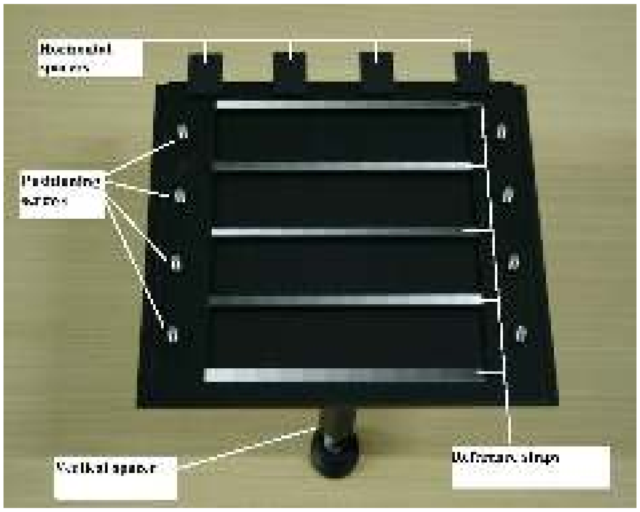

Fig. 4. The sample holder developed to reduce positioning errors of the artificially aged samples when undergoing the recording procedure. A grill fixed on the recording plane with eight screws reduces problems caused by the possible deformation of the samples

RESULTS

The materials tested up until the present time underwent five aging cycles and they were recorded before and after each cycle using the procedure described in the "Recording Procedure" section. The corresponding six recordings are labeled "R0" and "R1" to "R5, where "R0" denotes the zero-measurement before any aging was performed and "R5" the measurement after the fifth aging cycle. An additional recording, labeled "R4-1," was taken after having stored the recorded samples for three days in darkness (i.e., between the fourth and fifth aging cycle). This was done to verify whether any measurable processes occur while the samples are stored in darkness under optimal environmental conditions.

It is beyond the scope of this paper to present and discuss all the results obtained for the tested materials and the different aging parameters. Therefore, only one example was selected to discuss the analysis methods and demonstrate the type of information that can be obtained by using the quantitative hyperspectral imaging technique for monitoring induced aging processes. From the selected sample shown in figure 5, which was cut from a discarded paper document dated 1941, spectral data was extracted from four regions-of–interest (ROIs), which in this case were all defined in the paper substrate in the four differently aged areas. This particular sample was measured seven times over a period of approximately six months, during which it underwent five aging cycles. Each color represents a particular ROI from which the mean values of the pixels, for all the seventy spectral channels, were extracted resulting in a mean spectral curve for each ROI. The ROIs are denoted as follows: R = reference strip; L = light aging; RH/T = climate aging; and RH/T/L = climate aging followed by light aging.

The first and very important step of the analysis of data was to verify the reproducibility of monitoring measurements. This was done by comparing the mean spectral curves extracted from all six data cubes for the ROI defined on the reference strip (not aged). This part of the document is not artificially aged at all and it is stored in darkness under optimal climate conditions. For this reason a minimal change of the spectral reflectance curve is expected for the ROI defined on this sample. As shown in figure 6, the spectral curves extracted from the six recordings (R0-R5) of the reference strip (R) show indeed only very small differences. They are probably the result of a combination of residual measurement errors of the instrument,

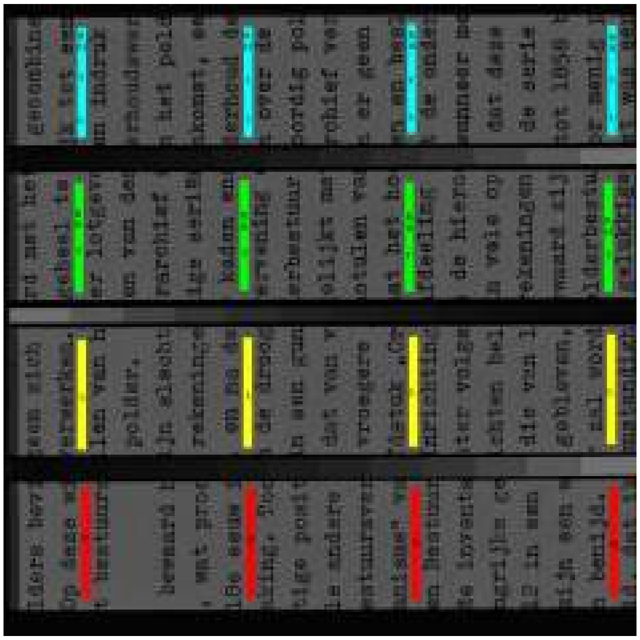

Fig. 5. Selection of four regions-of-interests (ROI) in a hyperspectral datacube of a discarded paper document dated 1941. Each ROI is defined in areas of the document that have undergone different aging process (R: not aged; L: light aged; RH T: climate aging; and RH T L: combination of light and climate aging)

imperfections of the measurement procedures, and possible changes of the sample itself, even when stored under optimal conditions. If in the same measurements larger differences are observed for the spectral curves of the other aged sample strips, this will confirm that this type of change could be caused only by the differences in the aging process of the paper.

Once the reproducibility of the measurement was verified it was also necessary to test the stability of the spectral characteristics of the sample after a period of darkness (fig. 7). In fact it has been reported in the literature that some materials that have undergone accelerated aging can show changing in their spectral characteristics when stored in darkness (Lee et al. 1989; Strilič et al. 2004). This effect is explained by the progression of the chemical reactions, induced by the exposure of certain materials to external energies (such as high temperatures and light), even when the exposure is interrupted (Haillant et al. 2004; Mukherjee 1978). This type of information is thus useful to quantify how long after each artificial aging cycle the corresponding measurement can be performed before the progression of the chemical reactions modify the resulting spectral values (Bukovský and Trnková 2003). In order to verify this, the same document was measured directly after the end of an aging cycle (recording R4) and a second time after three days of storage in darkness (denoted as R4-1 recording). Figure 8 shows that for this type of paper, during such a short period of darkness,

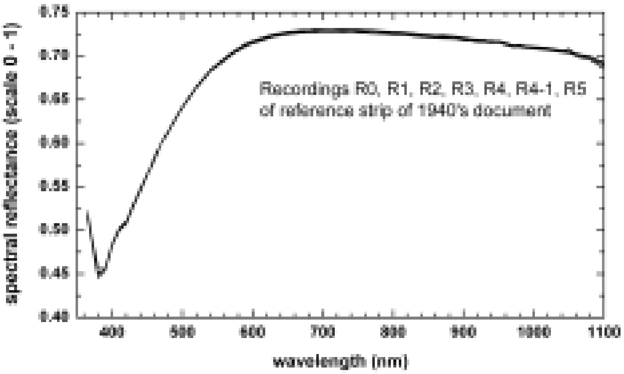

Fig. 6. Mean spectral curves of the not-aged reference strips for the six recordings of the artificial aging tests. All six curves lie very close together, confirming the high reproducibility of the measurement

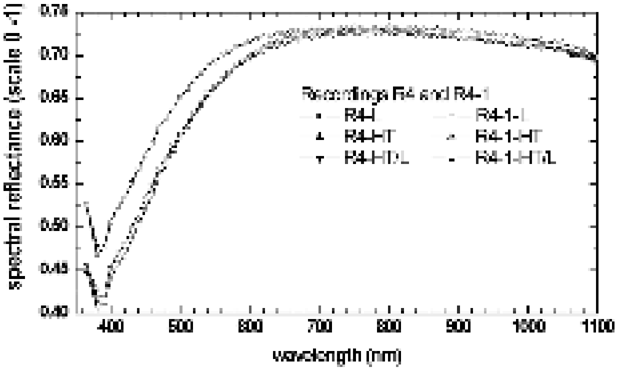

Fig. 7. Comparison of the spectral curves of the aged samples before and after three days of storage in darkness. For all three types of artificial aging: by light (L), by humidity/temperature (HT), and by the combination of both (HT/L); no significant effect of the storage period was measured

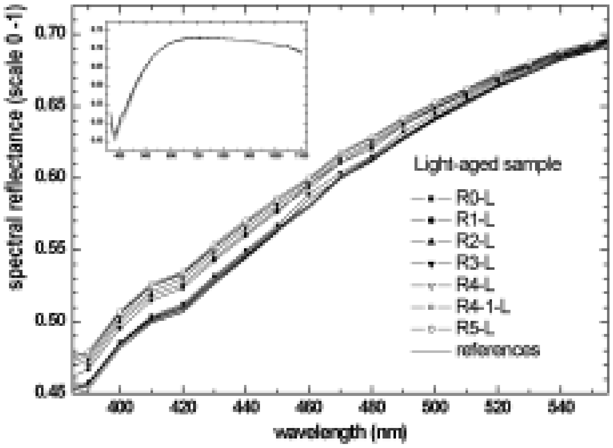

Fig. 8. Spectral curves of light-aged samples for different numbers of aging cycles applied. For comparison, the corresponding curves of the reference sample are plotted as plain lines. Insert: Overview of entire wavelength range. The most significant changes are in the blue-green range of the visible part of the spectrum

the spectral values have not changed in a relevant manner. In fact, the ones extracted from the three different aged areas (L; RH/T; RH/T/L), from recordings R4 and R4-1, overlap almost perfectly over the entire spectrum.

In order to verify possible spectral changing of these values after longer periods of darkness, the same samples will be recorded again after six months of storage. Figure 8 shows the spectral curves of the light-aged sample strip for the recordings R0 to R5. The light aging applied between two subsequent recordings corresponds to approximately one month of exposure in the exhibition hall of the Nationaal Archief. With progressive aging the curves show a small but systematic increase of the reflectance values of the paper in the visible region of the spectrum, whereas the values in the infrared remain practically constant. The total change in the reflectance curves between the R0 and the R5 recording is only about 2% in the visible range; however, this is still about five times more than the variation observed for the same recordings on the reference strips. From this it can be concluded that with the quantitative hyperspectral technique it is possible to identify spectral changes incurred after an exhibition period of only one or two months.

Since the reflectance curves mainly change in the visible violet-blue region of the spectrum (400–500 nm), the effect of the light aging is potentially visible to the human eye as bleaching of the paper (Neuvirt 2005; Schaeffer 2001). Due to the high spectral resolution of the hyperspectral imager, the spectral curves can be used to calculate the CIELAB color indices $L^\star$, $a^\star$, and $b^\star$ and, from those, the color difference (ΔE) of the sample between any two recordings. For the standard illuminant D65, the difference in the spectral curves of the sample in the R5 and in the R0 recording corresponds to a color difference of $\Delta E = 1.35$ for the equivalent four months of exhibition. For a trained person, in direct comparison and at sufficient light levels, a color difference of $\Delta E >= 1$ can be distinguishable whereas for the average human observer a threshold of $\Delta E >= 3$ is more typical. This means that after applying light aging corresponding to only one or two months of exhibition, the induced spectral change can already be measured with the instrument while it is not yet visible, even for a trained person in good lighting conditions.

CONCLUSIONS AND CURRENT DEVELOPMENTS

Preliminary results obtained by the Bihanne Project, with both natural and artificial aging, have already shown that quantitative hyperspectral imaging has a great potential as a monitoring tool for archival documents. The most promising result of this research is the possibility to measure minute changes of the reflectance spectra even after short exhibition periods in optimal environmental conditions and provide a map of their distribution. The experiences accumulated until now with this project have also shown that the quality of the data, the accuracy and sensitivity of the instrument used, and above all, the reproducibility of the recordings over a period of several months, are crucial parameters when applying hyperspectral imaging as a monitoring tool. A considerable part of the research described in this paper addresses the development of suitable recording procedures that minimize the risk of measurement errors. Such procedures are still being improved in order to obtain a final standardization for the application of the hyperspectral imaging technique in the normal working flow of archives and libraries.

Current research within the Hyperspectral Project at the Nationaal Archief addresses the further improvement and simplification of the recording procedure so that more samples can be measured without compromising the accuracy. A second important and very challenging issue is the development of new, efficient methods for comparing, with maximal spatial resolution, the data cubes of multiple recordings of the same object taken at different times. The goal is based on the measurement of the original and the artificially aged samples to develop aging models of different material systems and identify the most representative spectral channels to be used for monitoring purposes. Such information will provide conservators with the knowledge required to apply the quantitative hyperspectral imaging technique in the most efficient way to monitor the condition of historic documents even with less advanced and easily affordable instruments.

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