Hyperspectral Imaging in Counterfeit Ink and Banknote Identification

Introduction

Counterfeiting of documents and currency is a pervasive issue, posing significant challenges to law enforcement agencies and financial institutions. Hyperspectral Imaging (HSI) using the Grand-EOS system offers a powerful solution for detecting counterfeit inks on both printed documents and banknotes. This white paper outlines the use of HSI with the Grand-EOS for forensic analysis, highlighting its advantages, methodologies, and real-world applications.

Photon etc
A spectrum of solutions

Benchmark Study Using SWIR Spectroscopy

Our benchmark study leverages the capabilities of the Grand-EOS, a Short-Wave Infrared (SWIR) hyperspectral camera designed for area spectral imaging.

The Grand-EOS features continuous tunability from 400 to 1650 nm and integrates micro and macro modalities. It offers non-polarized wavelength selection with exceptional throughput and efficiency, enabled by Photon etc.'s proprietary filtering technology based on volume Bragg gratings. The system captures hyperspectral data-cubes, providing spatial information along the X-Y axes and spectral information along the Z-axis.

The area spectral imaging technology extracts data-cubes from monochromatic images, eliminating the need for image reconstruction. The camera's adjustable field of view accommodates various applications and sample sizes. Specifically designed for reflectance, transmittance, and luminescence imaging, the Grand-EOS serves both fundamental research and industrial needs effectively for counterfeit inks.

What is hyperspectral data in an area spectral imaging?

Hyperspectral imaging is a technique used to capture and analyze the spectral information of a scene or object. Unlike traditional imaging techniques in the visible range, which capture images in only three spectral bands (red, green, and blue), hyperspectral imaging captures data across hundreds of continuous spectral bands covering the visible and infrared bands of the electromagnetic spectrum. These images are combined into a hyperspectral data cube or image cube. In hyperspectral imaging, each pixel in an image contains information about the emission, reflectance, or transmission of light at different wavelengths. This information can be used to identify and distinguish between materials, identify chemical compositions, and analyze the physical properties at all points of the scene or object being imaged.

Hyperspectral imaging techniques differ in how they capture data:

Point Scanning (Whiskbroom): Captures one spectrum at a time from one pixel at a time using one line of detectors. Hyperspectral data cube is acquired by scanning from one point to another in the field of view.

Line Scanning (Pushbroom): Uses a 2D detector array to capture one spectrum for each pixel on the line at a time. It's faster than point scanning since a hyperspectral data cube is acquired by scanning one line of pixels to another line of pixels.

Area spectral imaging: Uses a 2D detector array to capture 2D areas at a time. Hyperspectral data cube is acquired by scanning one wavelength to another. It's also faster than point scanning since a hyperspectral data cube is acquired by scanning one image at one wavelength to another wavelength. (Figure 1)

Snapshot: Captures the entire hyperspectral data cube in one shot, providing extremely fast data acquisition. It's ideal for dynamic scenes but often has lower spatial resolution.

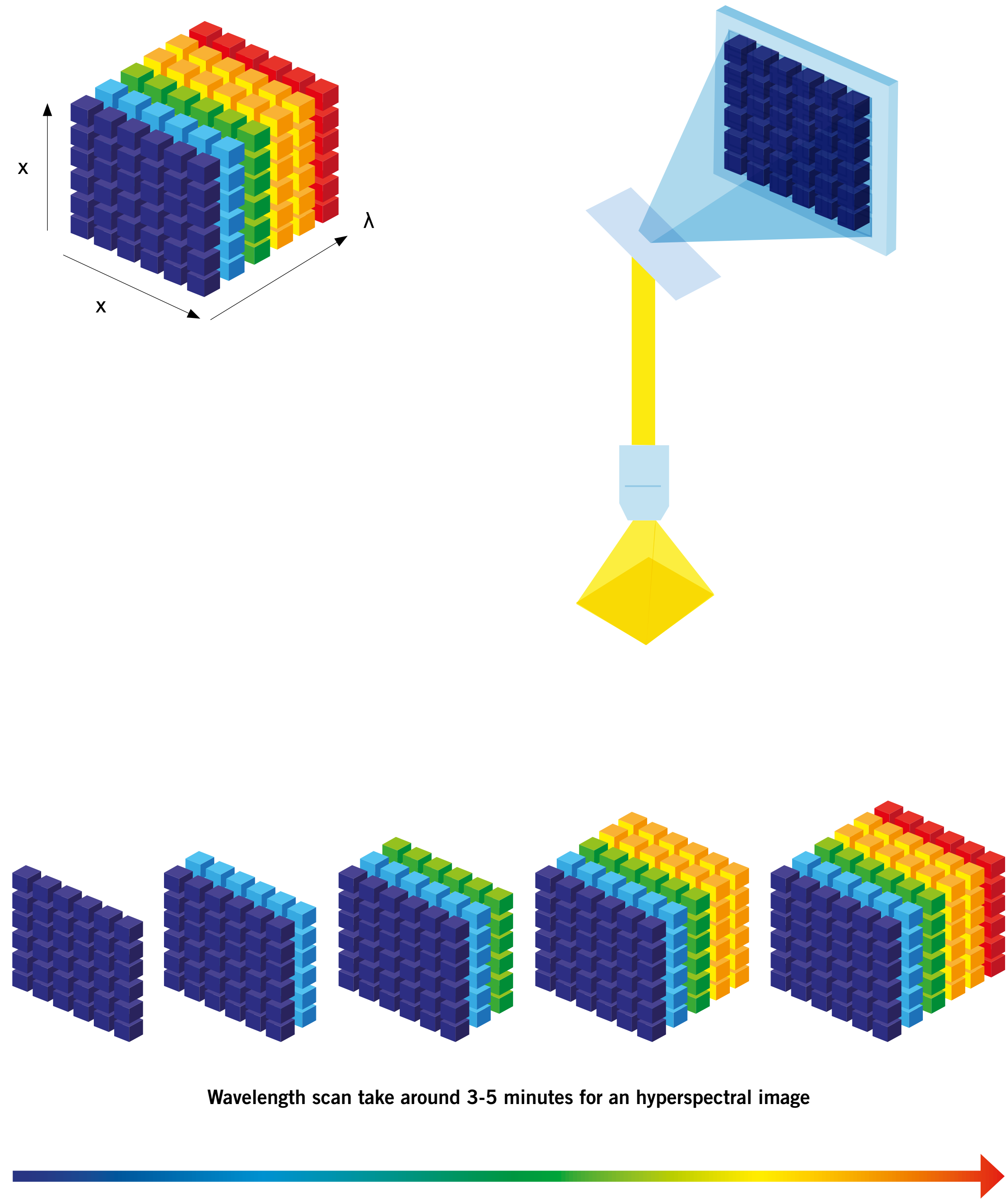

Figure 1. A representation of a hyperspectral data cube in a area spectral imaging system

Grand-EOS™
Area Spectral Imaging

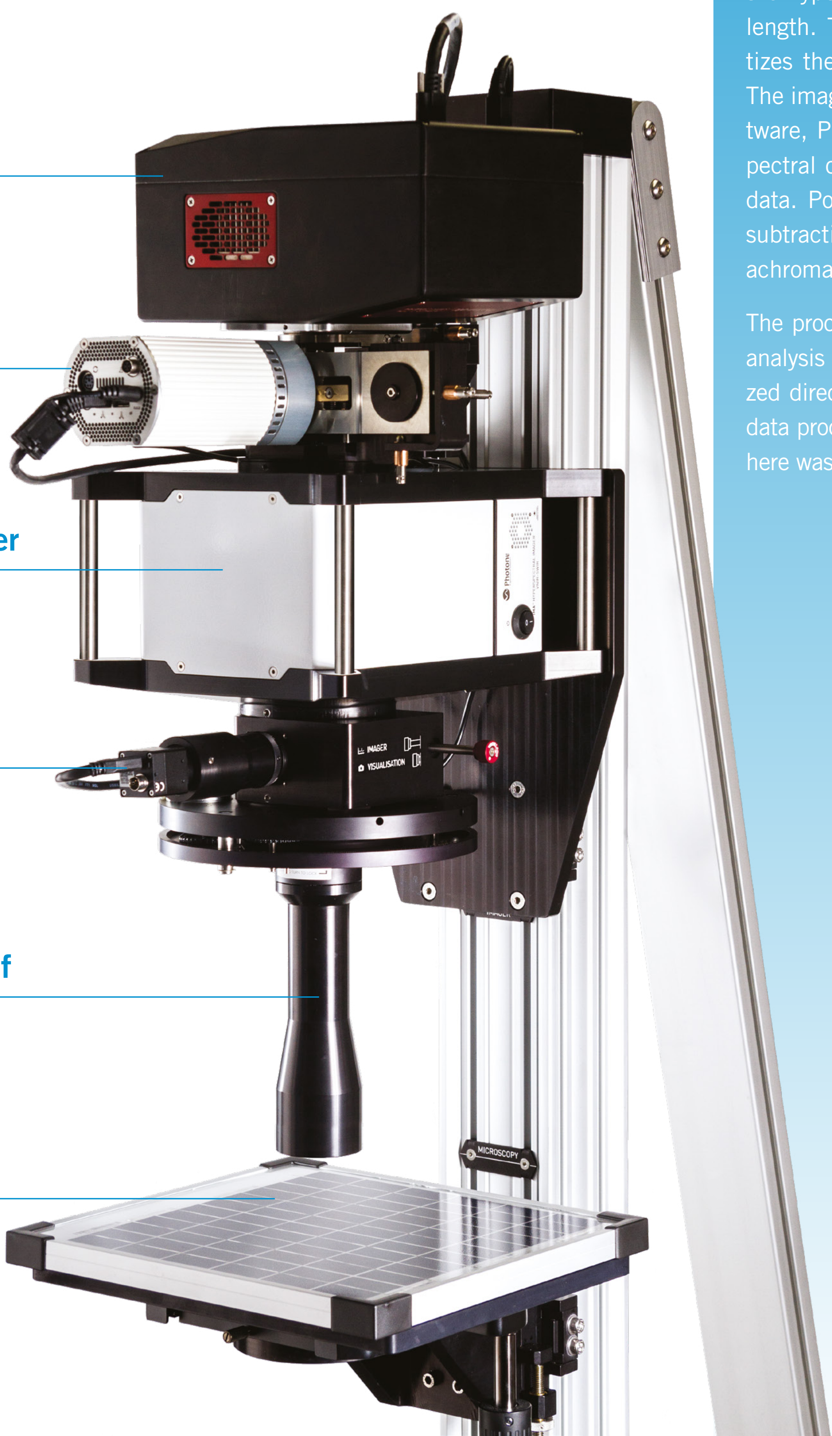

Figure 2. Grand-EOS

Key Features of the Grand-EOS

A sample is placed under the field of view of the Grand-EOS hyperspectral camera.

The sample is illuminated homogeneously by:

- **Wide spectrum lamps such as a halogen lamp for reflectivity mapping**
- **Laser for photoluminescence mapping**
- **UV lamp for fluorescence mapping**

The hyperspectral filter scans the wavelengths reflected or emitted by the sample, building the hyperspectral cube wavelength by wavelength. The visible or infrared camera digitizes these filtered, monochromatic images. The images are transferred to the control software, PhySpec, for assembly into a hyperspectral cube, and for post-processing of the data. Post-processing includes camera dark subtraction, and spectral referencing from an achromatic diffuser.

The processed data can then be exported for analysis in external analysis software or analyzed directly in PhySpec using the embedded data processing functions. Every result shown here was treated within PhySpec.

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Laser for photoluminescence mapping

UV lamp for fluorescence mapping

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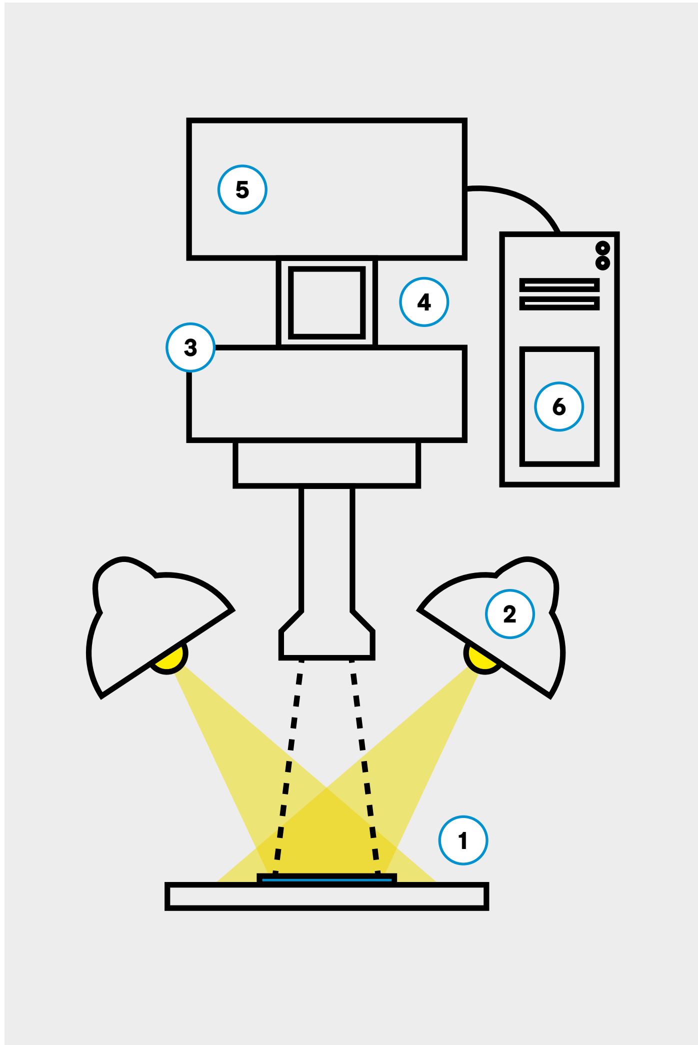
The hyperspectral filter scans the wavelengths reflected or emitted by the sample, building the hyperspectral cube slice by slice.



4 5

The visible (4) or infrared (5) camera digitizes these filtered, monochromatic images.

6

The images are transferred to the control software, PhySpec, assembled into a hyperspectral cube, and the data is pre-processed. Pre-processing includes: camera dark subtraction, wavelength rectification and spectral referencing from an achromatic diffuser.

Figure 3. Schematic representation of the Grand-EOS

Ink test pattern

An ink test was conducted using four different printers and their respective ink cartridges to validate the power of HSI on ink differentiation:

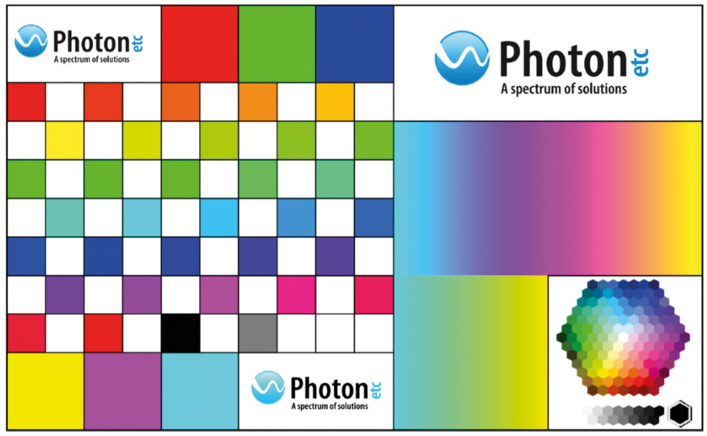
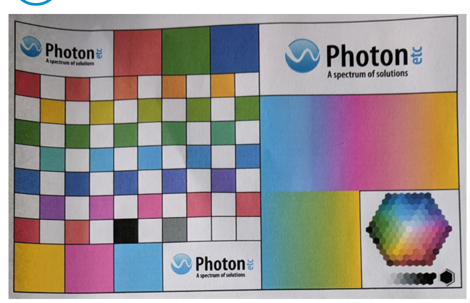


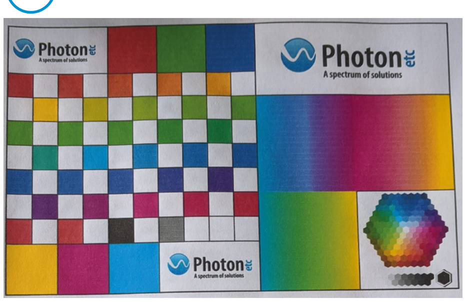
Figure 4. Ink test use for the demonstration

1 **Brother**

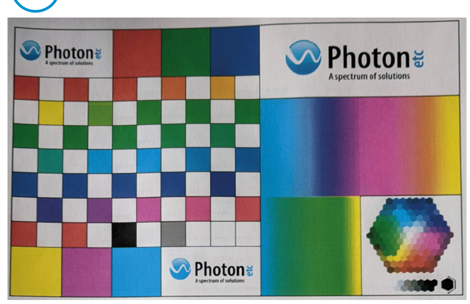
2 **Epson**



3 **HP**



4 **Xerox**



1. Brother MFC J47SDW, Ink: Odoga B-103 (101) ink

2. Epson-276C, Ink: Epson-220 ink

3. HP Envy 4520, Ink: Inktopia 64XL

4. Xerox Workcentre 6515, Ink: LD Product CXE6510SET5AMZ

Figure 5. Printing test on four different types of printers

Notable differences were observed among the printers, primarily concerning ink density—whether the colors appear rich or dull—and how each printer handles color gradients. However, accurately discerning the specific shade of each color presents a challenge when relying solely on unaided human vision or on standard RGB analysis.

Figure 6. Representation of different hues from the four printers used

Photon etc.’s GRAND-EOS provides a high resolution hyperspectral image cube, i.e. a series of monochromatic images with high spectral sampling. The curves here follow the evolution of the printer primary colors, i.e. cyan, magenta, yellow and black (CMYK). The hyperspectral image cubes are analyzed with our PhySpec software. Each image pixel contains a full spectrum from 400 to 1000 nm. Each spectra was referenced with the reflectivity for the copier paper used, thus removing the spectral influence from the paper itself. Considering all four printers, the following results were obtained:

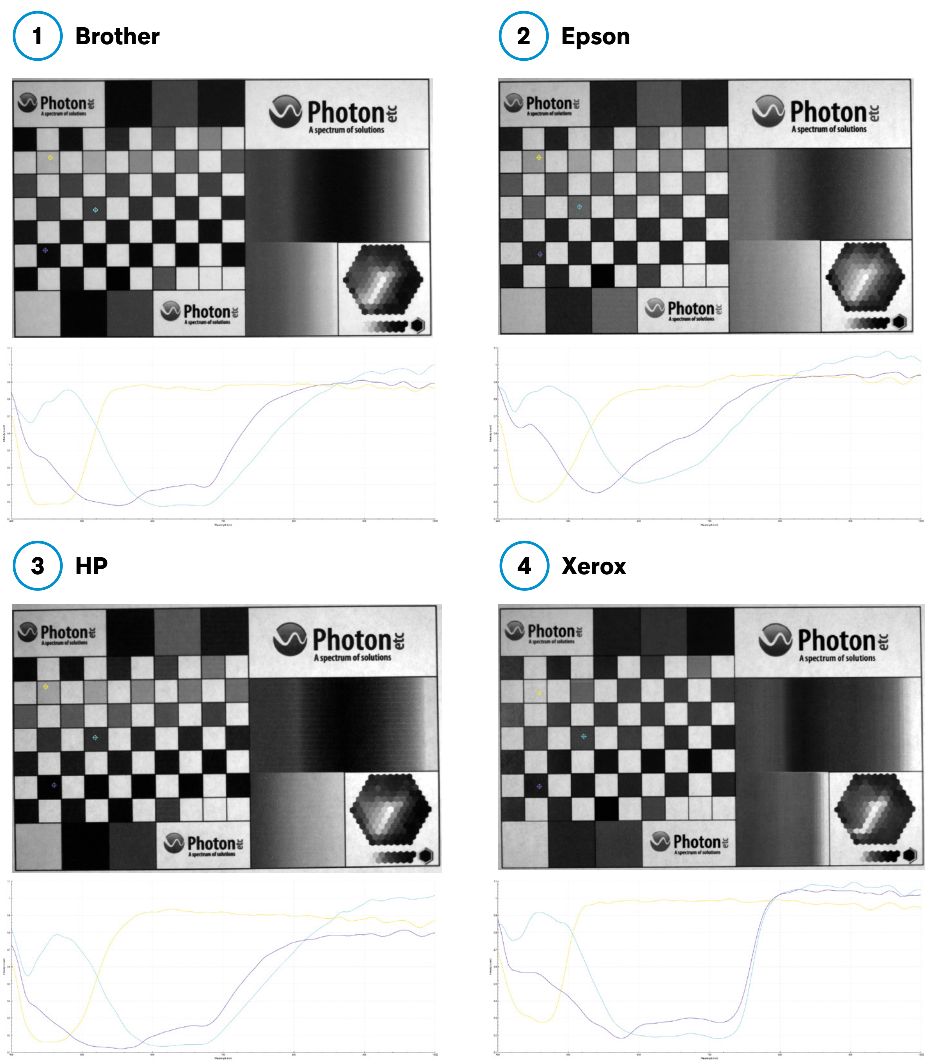


Figure 7. Infrared spectrum of the four tests

Each ink color has striking spectral differences as expected (see Fig. 8-9-10). Inks of the same color exhibit reflectivity spectra with noticeable characteristic features in the visible but also in the near infrared spectrum (above 700 nm). This is particularly true for magenta and cyan. These features can be effectively used to discriminate and identify the different ink.

Yellow

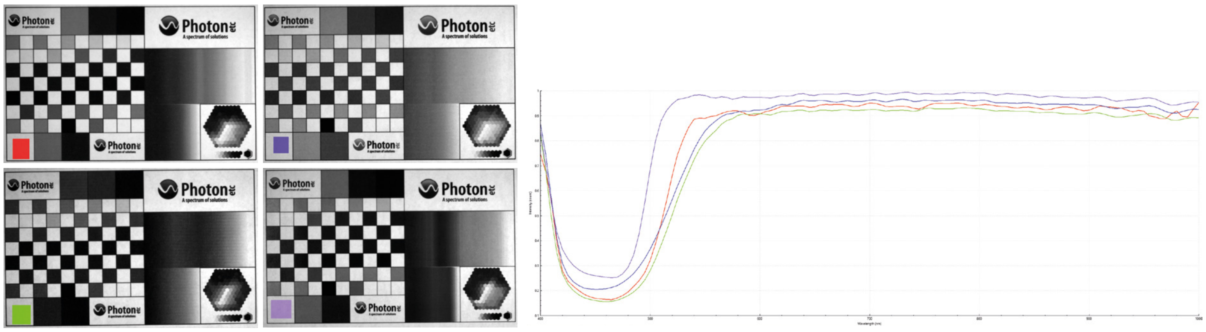


Figure 8. Yellow spectrum of the four inks test

Magenta

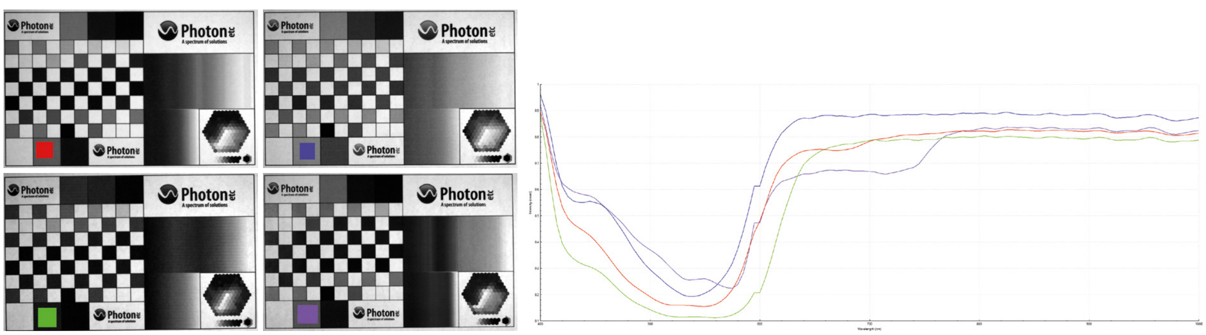


Figure 9. Magenta spectrum of the four inks test

Cyan

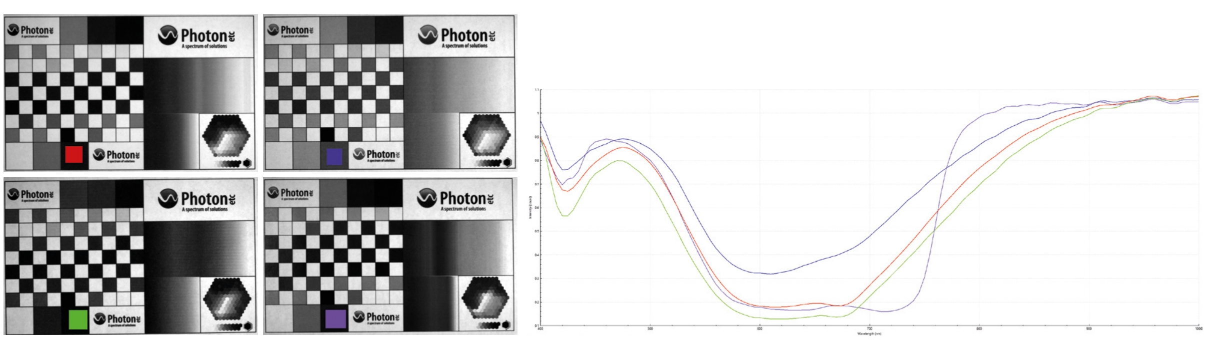


Figure 10. Cyan spectrum of the four inks test

Black

Among the four inks tested, two black inks can be differentiated based on their disappearance in the short-wave infrared (SWIR) spectral region, as demonstrated by the SWIR capabilities of the GRAND-EOS. Apart from one specific black ink family, all other inks become fully transparent within the SWIR spectral range.

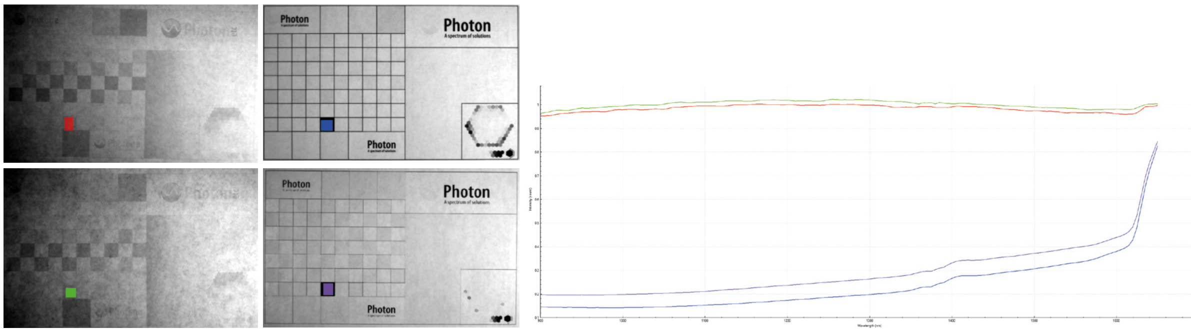


Figure 11. Black visible and infrared spectrum of the four ink tests

These results hold substantial implications for forensic document analysis. By establishing an extensive database, the origin of a document can be traced to the specific ink cartridge used. Additionally, pen inks display varied spectral signatures (not depicted here), suggesting a broad applicability of this method. The GRAND-EOS can verify whether two documents were printed with identically composed inks, providing a powerful tool for verifying the authenticity and origin of printed materials.

Observations

The fine spectral signature of CMYK base colors for inkjet printers varies depending on the printer used and the supplier of the ink. The different inks can be easily distinguished and identified.

Most inks vanish in the short-wave infrared spectrum, except for one studied family of black ink. Visible CMOS sensors can be used with success in this application without the need to use more expensive SWIR cameras.

The Grand-EOS hyperspectral imaging system can extract the fine spectral signature from any pixel over a large field of view. There is no need to move the object under test during the acquisition of hyperspectral data.

Analysis of 200 French Francs 'Montesquieu' Banknotes

In our second experiment, the GRAND-EOS hyperspectral imaging system was used to analyze 'Montesquieu' banknotes, 200 French Francs. For this study, two banknotes were purchased from collectors in 2020. Among them, one was sold as genuine (#658738, allegedly real), and one was sold as fake (#974195, allegedly fake).

Figure 12. 200 French Francs 'Montesquieu' banknote

Initial Observations in the Visible Spectrum

Initially, all two banknotes exhibited similar behavior in the visible spectrum from 400 nm to 700 nm, making it challenging to distinguish between the genuine and fake notes based on this wavelength range. However, from 700 nm to 1000 nm, while the reflectivity of the fake is almost constant, the reflectivity of the real notes increases monotonically. This feature could be used as a first criteria to discriminate the fake from the real notes.

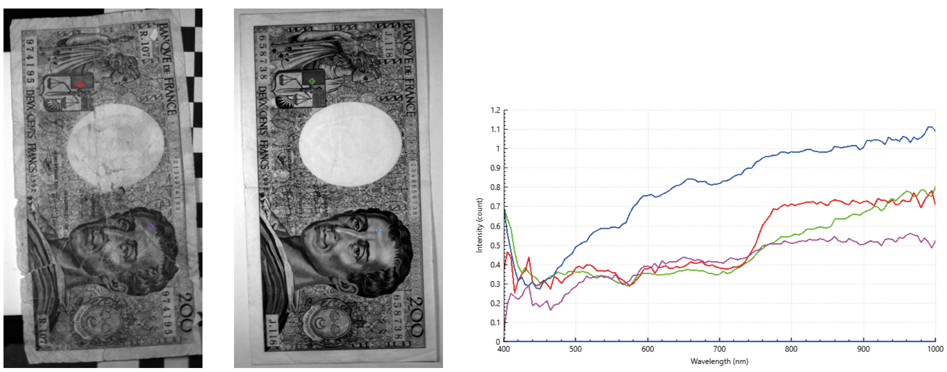


Figure 13. Visible spectral of the two banknotes (#974195, allegedly fake; #658738, allegedly real)

Significant Differences in the SWIR Spectral Range

When analyzed in the short-wave infrared (SWIR) spectral range however, the behavior of the banknotes changed significantly in the full spectrum. The colors of the allegedly real banknote #658738 remained visible in the SWIR, while they the allegedly fake banknote #974195 vanished completely. This is particularly demonstrated at 1500 nm (see figure 15) where the person with heraldry is faded in the allegedly real banknote #658738 versus the allegedly fake #974195 where it is still quite visible.

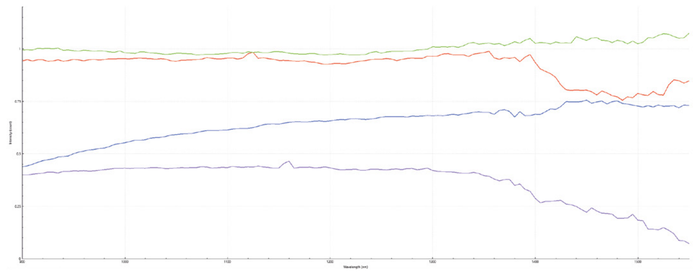


Figure 14. SWIR spectral analysis of the SWIR spectrum of the banknotes (900 nm up and 1500 nm down)

Principal Component Analysis (PCA) Insights

The Principal Component Analysis (PCA) algorithm was employed to further analyze the spectral data in the VIS. PCA separates the spectra of the image into principal components and evaluates the strength of each component in every pixel of the data cube. A pixel whose spectrum closely matches component 1 will score high on this component. The false-color images are then assembled using the relative weight of a set of the three major components in the red, green, and blue channels. Elements with the same false color share similar spectral features, indicating a similar composition. The difference in the visible spectrum is noticeable. These two components are present in different areas of the real (right of figure 15) and allegedly fake banknotes (left of figure 15).

Figure 15. Visible PCA with False color image with components 1, 2 and 3

In the SWIR spectral range, PCA identified the different families of black ink used in the three notes. It also enhanced the structure of the background through the transparency of the copier paper in the SWIR spectral range. The PCA demonstrates quite striking the difference between the allegedly fake (left of figure 16) and the allegedly real (right of figure 16). There are almost no similarities in the location of the red green and blue components between the two notes.

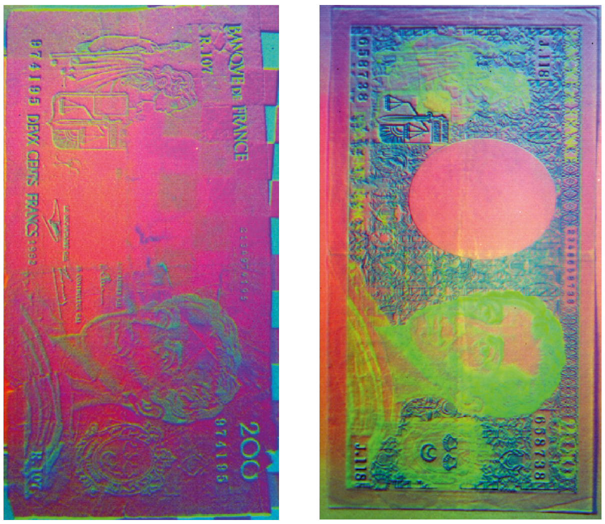


Figure 16. Visible PCA with False color image with components 1, 2 and 3

Observations

VIS and SWIR hyperspectral wide-field imaging can reveal significant differences in seemingly identical banknotes that cannot be detected by the human eye.

The technique can identify even high-fidelity counterfeit banknotes comparing spectral signatures one different areas of the notes.

PCA analysis in the VIS and the SWIR further enhances the spectral differences between the two banknotes making the detection of counterfeit banknotes more obvious.

Combined with the analysis of inks from the first part of our study and with a proper reference database, it means that one could determine which printer was used to print each individual note and trace the origin of the note and trace the origin of the banknote.

Software - PHySpec

PHySpec is Photon etc.'s proprietary software for instrument and camera control. PHySpec provides a sequencer with measurement automation as well as analytical tools for rapid extraction of sample information. Its multithreaded architecture expedites processing complex algorithms as well as the acquisition, visualization, import, and export of data.

Every tool comes with a complete PHySpec user manual and unlimited licenses.

See below for a few highlights of our software:

Broadband video recording (including metadata like timestamps or exposure time)

Sequential acquisitions defined by the user via software:

Automatic data acquisitions, analysis and handling: parameters predetermined by user

Allows user to define custom spectral range, wavelength step size, exposure time

Hyperspectral imaging analysis toolbox:

Pixel-spectrum visualization tools

Hyperspectral data processing (dark subtraction, normalisation, smoothing, curve fitting, binning, cropping, spectral map)

Hyperspectral files exportable in HDF format (.H5) and fits (compatible with other softwares)

Spectrum data files exportable in HDF format (.H5), Envi BIL format, and CSV (excel compatible)

Image files exportable in HDF format (.H5), JPEG, PNG, FITS and BMP

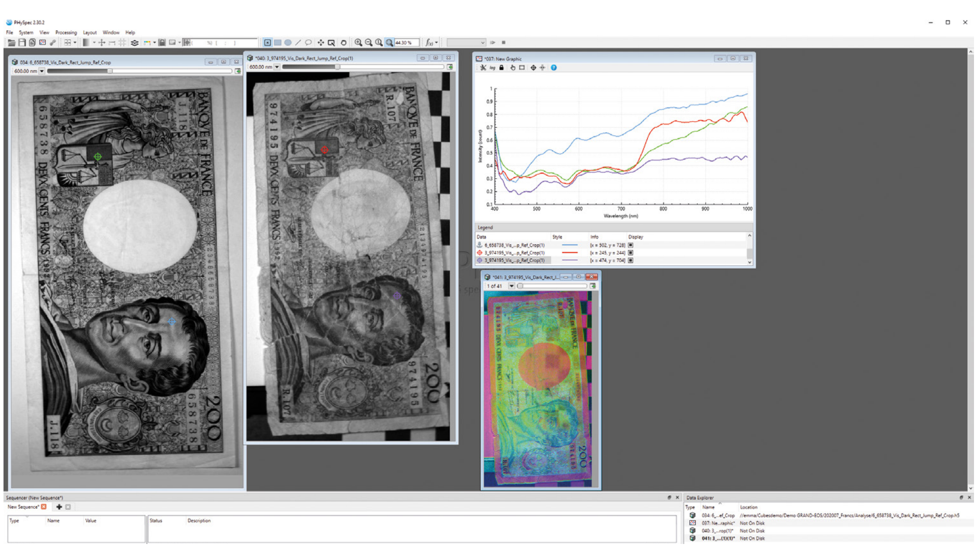
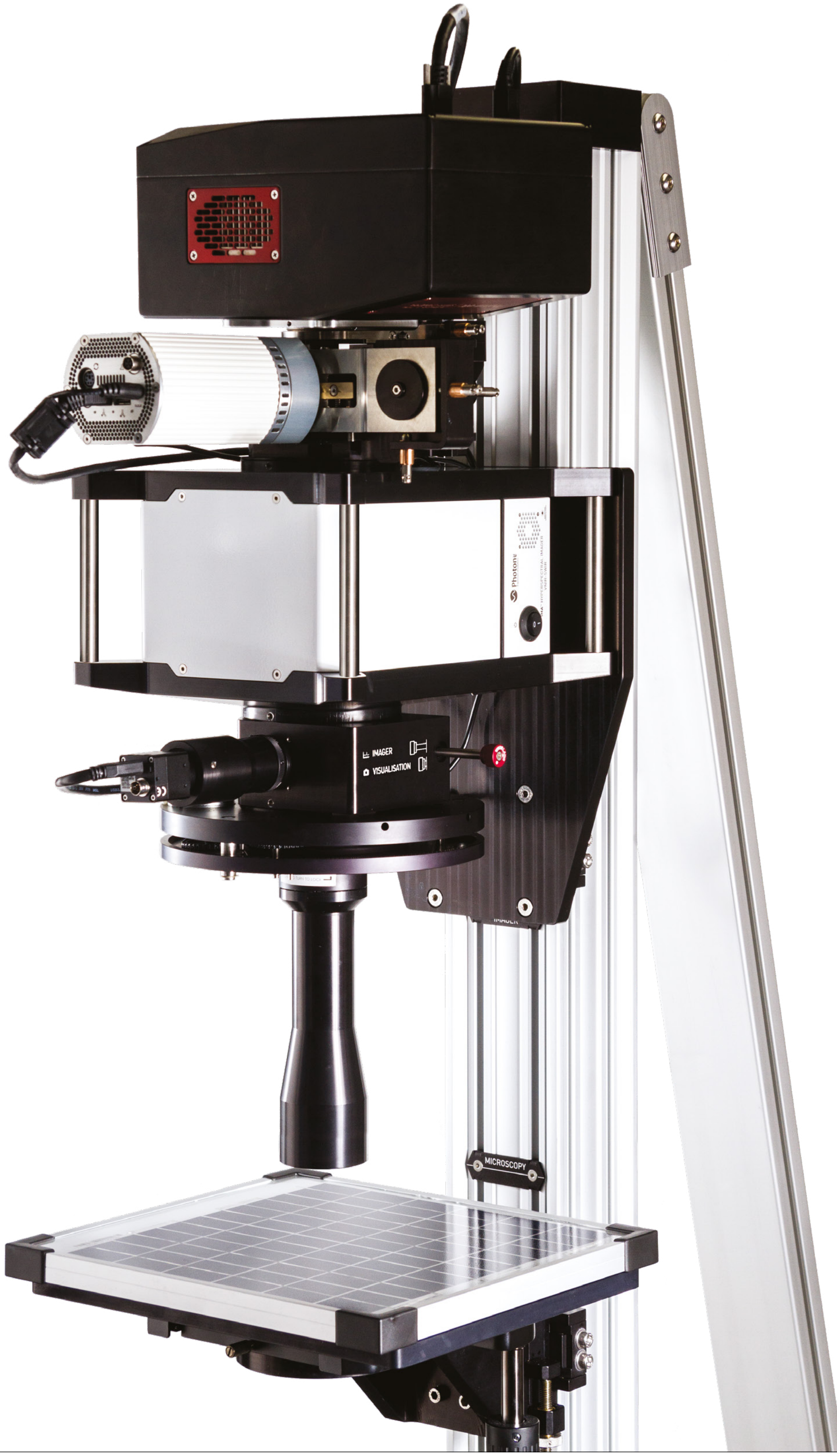


Figure 17. PHyspec software analysis data


IMAGER
VISUALISATION
MICROSCOPY

Conclusion

The application of the GRAND-EOS hyperspectral imaging system in forensic science represents a significant advancement in the identification of inks and counterfeit banknotes. Through detailed spectral analysis across SWIR ranges, this system can distinguish between genuine and counterfeit materials with high precision, uncovering subtle differences undetectable to the naked eye or traditional imaging techniques.

Coupled with advanced analytical software such as PhySpec, we are able to process and interpret complex hyperspectral data, making it a robust tool for forensic investigations. By leveraging the hyperspectral imaging system's ability to analyze inks and materials, forensic experts can also build comprehensive databases to trace the origins of documents and banknotes.

The adaptability of the GRAND-EOS system to incorporate additional techniques like UV fluorescence further extends its applicability beyond inks and paper to other materials such as fabrics and organic traces. This versatility makes it an invaluable asset for any forensic laboratory.

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A spectrum of solutions