Near-UV Reflectance Imaging: Applications

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Near-ultraviolet imaging has long been thought to be difficult and awkward by many photographers because of the difficulties encountered when using photographic film in the near-UV band. Digital ultraviolet imaging is becoming increasingly affordable and lends itself to a number of interesting applications that have been largely overlooked.

Reflected-ultraviolet imaging is a rather mysterious area of the imaging field. There is relatively little near-UV imagery to be found on the Internet or in the literature compared to near-infrared imagery. There has been no aesthetic use of near-UV imaging to drive technology development as there has been in the near-IR band. Near-UV landscape images are generally not very interesting compared to near-IR photographs that show white clouds against black skies. Some wedding photographers using converted digital cameras shoot in the near-IR to make skin blemishes and imperfections disappear at the longer wavelengths. No one would ever want UV wedding photographs because people's skin has a terrible, almost dirty appearance in the UV band, as shown in Figure 1.

Even though standard black-and-white film has plenty of near-UV response, it must be used in conjunction with a barrier filter that blocks visible light while transmitting in the near-UV. Images taken with black-and-white film and a SCHOTT UG-1 filter will be almost purely near-UV in content, as long as there is sufficient near-UV light available. UG-1 glass has a secondary transmission peak at 750 nm known as a "red leak". Since black-and-white film is quite insensitive to light at these wavelengths and longer, the effect of the red leak on film is negligible. For digital UV photography, it is a serious problem and has resulted in both professionals and amateurs publishing near-UV images that are highly contaminated with red or near-IR content.

The problem with using a barrier filter on a single-lens reflex (SLR) camera is that the photographer cannot compose the shot with the filter in place. The near-UV focus is different from the visible-light focus point, so images may be blurry. The camera has to be prefocused by eye before the filter goes on the lens, and high f-stop settings are used to increase the depth of field. The combination of a filter that blocks the majority of sunlight and a high f-stop setting means that long exposures are required, even with relatively fast film.

Figure 1. *Left image, color; right image, near-UV.*

Electronic imaging in the UV band

As the world transitions to digital imaging, invisible-light photography has followed suit. Photographers have converted standard color digital cameras to the near-infrared band (750 to 1100 nm). The conversion is generally straightforward because the silicon sensors in the cameras are already responsive to near-infrared light, which means that manufacturers of standard color digital cameras have to install a filter to block near-IR to maintain correct color balance. In the aftermarket conversion, the near-IR blocking filter is removed, which allows near-IR light to reach the sensor. Then a barrier filter is used to block any visible light, resulting in digital images that are pure near-infrared. Some cameras converted in this manner can give a continuous live preview in the near-IR band and automatically adjust

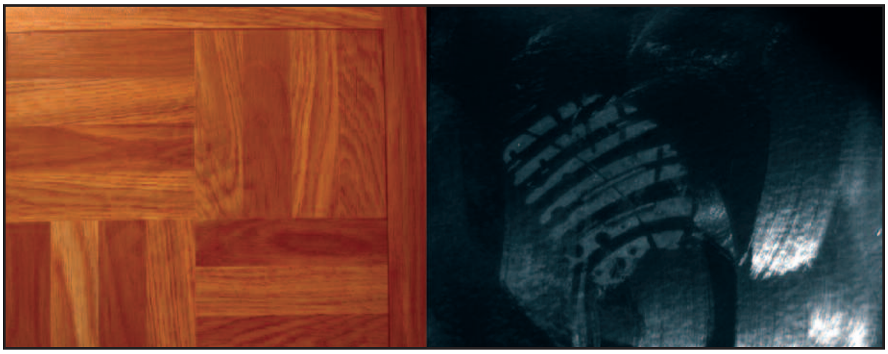

Figure 2. *A vinyl floor tile coated with wax shows a shoe impression. The color image shows only a trace of the print against the tile's pattern (left). In the near-UV image, the wax is no longer transparent and the lines and swirl patterns left by the cloth applicator dominate the image, except where the shoe impression has flattened out the swirl marks.*

the exposure and focus, even with the near-infrared barrier filter in place, making near-IR photography very easy.

Applying these same concepts to digital imaging in the near-UV is problematic because silicon CCDs and CMOS detectors have a great deal of response at wavelengths of 700 nm and longer, but relatively little response in the near-UV band. In the case of commercial digital cameras, the situation is even worse because the imaging sensor itself almost always has a UV blocking layer built into the sensor package window. Trying to push near-UV light through that layer is quite difficult and requires long exposure times. Even though the near-UV content of the scene imaged on the sensor may be many times greater than the red and near-infrared content, the latter dominates the resulting image.

The answer to this problem is twofold. First, one must use a CCD or CMOS sensor that does not have a UV-blocking filter built into either the sensor window or the antireflection coating on the sensor itself. Second, the filter used to block all but the near-UV radiation must not have a significant red leak.

There are several manufacturers offering UV sensitive CCD cameras. There is a fairly large spread in price from low-cost machine-vision UV cameras up to the scientific-grade product. Some of these cameras have back-thinned CCDs, whereby the silicon substrate is thinned down to prevent it from absorbing UV radiation before the photodiodes on the back side can generate carriers that result in photocurrent. The back-thinned CCDs are responsive down to 200 nm and can thus be used for solar-blind imaging, provided that the signal is strong enough. Solar-blind imaging is UV imaging below the UV ozone cut-off at 300 nm. Interestingly, a solar-blind camera will see absolutely no sunlight at sea level.Most solar-blind applications use image intensifiers with UV-sensitive photocathodes to detect the generally very weak signal from solar-blind sources.

Recently, Fuji came out with a variation on its popular S-3 digital SLR camera. This camera, called the S-3 UVIR, is designed to be responsive from 380 nm to about 1100 nm so that it can be used for UV and near-IR imaging. After extensive testing, it was found that it has relatively little near-UV response, especially when used in conjunction with filters that pass UV light in the 330 to 380 nm band. It is actually much better suited to near-IR imaging.

Ultraviolet filters

One commercially available filter used in conjunction with silicon imaging sensors for near-UV imaging is the Baader Venus filter. This terrific filter is used by astronomers to photograph cloud patterns in the Venusian atmosphere. The clouds are sulfuric acid, which is strongly absorbing in the UV band, so a great deal of contrast appears in these photographs. The Baader has an extremely small red leak which is less than 0.1 percent of the peak transmission at 360 nm, and is better suited for use with silicon sensors than UG-1. It is possible to use filters with red leaks as long as the leak is plugged by the use of a second filter. The second filter, typically made of blue glass, will stop the red leak without destroying the UV transmission.

To create pure near-UV images without the use of a barrier filter the illumination source must be rich in ultraviolet radiation with as little visible or near-infrared light as possible and ambient light must be reduced to or near zero. If reflected-UV images are desired, it is critical that the scene or object not be fluorescent to any great extent.

Ultraviolet light sources

Most UV imaging applications require an external source of UV illumination unless the object of interest is something like a laser beam, a high-temperature flame, or a high-voltage corona discharge that generates its own UV radiation. The most common UV illumination sources used for imaging are direct sunlight, gas discharge lamps and ultraviolet LEDs.

The solar spectrum is rich in near-UV light because of the very high temperature of the photosphere. The atmosphere has fairly high transmission in the visible band but begins to cut off radiation below 400 nm, with a hard cut-off at 300 nm

Figure 3. *Left image, color; right image, near-UV.*

due to the ozone layer. For many near-UV imaging applications direct sunlight is an excellent UV source.

There isn't much near-UV light indoors since most modern window glass is designed with UV-blocking coatings. Indoor near-UV applications require something other than conventional incandescent or fluorescent lights because they are generally designed to minimize near-UV which fades wallpaper and fabrics and isn't used for human vision. The standard for artificial near-UV sources has historically been the mercury gas discharge tube. Mercury has a strong spectral line (known as the i-Line) at 365 nm which is a useful wavelength for many imaging applications. There is another line at 254 nm that can be used for illumination in solar-blind UV applications. These mercury discharge lamps are often coated internally with a filter material that appears nearly black to the eye. This filter is like a Wood's glass in that it blocks visible light while transmitting UV light. It should be noted that there is a red leak in these filter coatings which makes the lamps unsuitable for use with silicon-based imaging sensors unless a barrier filter is used.

Xenon lamps also generate substantial quantities of near-UV radiation, and are used in some UV light sources in conjunction with a Wood's glass filter or something similar. The short-arc xenon lamps can be used to produce a directed beam of light with suitable optics since the light is emitted within a tiny volume, typically about a cubic millimeter. Deuterium discharge lamps are another commonly used UV source. All will produce radiation below the glass cut-off at 300 nm.

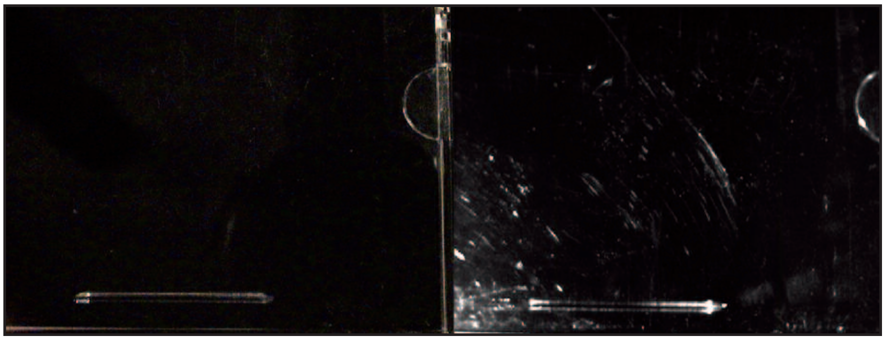

Figure 4. *Left image, color; right image, near-UV.*

Since that radiation is fairly harmful, it may be advisable to block it using an uncoated BK-7 glass window for near-UV imaging applications.

Ultraviolet LEDs

In the last few years, UV LEDs based on gallium nitride semiconductor alloys have emerged as a very serious challenge to gas discharge lamps. These devices have many advantages over gas discharge lamps: spectral purity, long lifetimes, high beam intensities, shock and vibration resistance, and high-voltage power supplies are not required.

Manufacturers are developing ever-brighter LEDs at ever-shorter wavelengths. The LEDs are very spectrally pure and emit radiation out of a very small surface area. LED arrays are commercially available and can be made to form well-collimated beams of UV light. Some of the smaller UV LEDs come encapsulated in plastic packages that have lens geometries molded in, as is the case with many standard visible light LEDs. Forming a tightly focused beam is difficult with cylindrical lamp sources.

Ultraviolet optics

Standard glass optics do not perform well below about 320 nm. The glass BK-7, for example, has a 70 percent transmission point at about 325 nm at 1 mm thickness. In a 3 mm thickness, the transmission drops to 34 percent. Fused silica, or quartz, transmits quite well down to about 250 nm, making it a nice lens and window material for UV imaging systems, although it is difficult to shape because of its hardness. Special lenses created specifically for UV imaging have been made of materials like quartz and calcium fluorite.

Conventional wisdom is that if one is doing UV imaging, one must use quartz optics. While it is true that quartz optics have advantages over glass, they are expensive and are often not required for near-UV imaging in the 330 to 400 nm band, especially for imaging between 360 and 400 nm. Certain glass-based color video lenses work quite well and are less expensive. These low-cost glass lenses have about a 50 percent transmission in the near-UV band, which is 1 f-stop, and produce decent quality images. By using fast lenses, one can easily gain back the one stop.

Near-UV imaging applications

The applications for UV imaging can be broken down into three main categories of phenomenology: absorption effects, scattering effects and the imaging of UV light sources.

Most near-UV imaging applications exploit the fact that near-UV light tends to be absorbed more readily than visible or near-infrared light. The higher energy of near-UV photons results in more direct interactions of the photons with electrons in materials. This can lead to stronger absorption relative to visible and near-IR light. Indeed, one of the first things one notes when observing

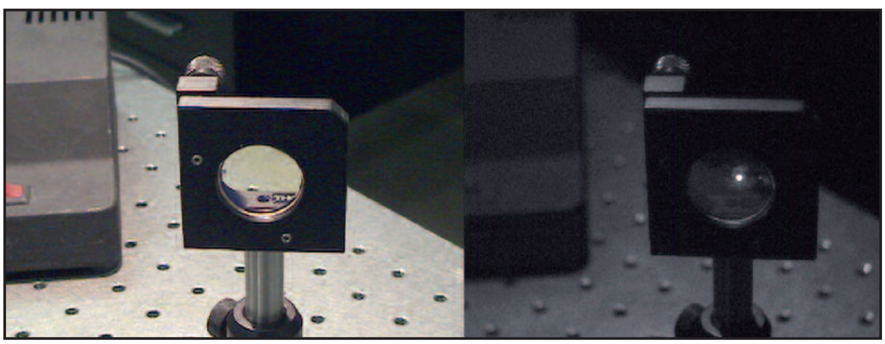

Figure 5. *Left image, color; right image, near-UV.*

everyday objects in the UV band is how dark things look. This higher absorption also means that one tends to see the outermost layers of objects that may be slightly translucent at longer wavelengths. For many materials — especially organic materials — the shorter the wavelength of incident light, the stronger the absorption and the shallower the depth of penetration.

The absorption effect can lead to the detection of thin layers of visibly-transparent substances on a substrate and their surface texture (Figure 2). The teeth shown in Figure 3 are real, but the left incisor has been repaired with a composite resin. The resin is strongly absorbing in the near-UV band, and the absorption effect gets stronger as the wavelength gets shorter. Normal tooth material is inorganic, and tends to reflect near-UV readily due to Fresnel reflection at the interface between air and the microcrystals of hydroxyapatite, the mineral that constitutes tooth enamel.

Wave scattering effects

Another class of applications exploits the short wavelength of near-UV light and the reflection of light off surfaces. Lightwaves tend to scatter off of surface features that are comparable in size to or larger than a wavelength of the light. This means when illuminating a surface with near-UV light and imaging the reflection with a near-UV camera, there will tend to be stronger scattering off of surface anomalies such as scratches and digs than what one observes with a visible-light camera. A piece of metal polished with steel wool will have a dull finish when examined by eye. In the near-IR band the same piece often will appear to be a perfect mirror. The scratches in the surface are smaller than a wavelength of infrared light, but larger than a wavelength of visible light (~0.5 μ). This same effect works in reverse for shorter wavelengths. A piece of smooth plastic, like a CD jewel case, may appear very polished to the eye. When the same surface is viewed with a near-UV imaging system, numerous small scratches appear, as shown in Figure 4.

Ultraviolet light sources

A third class of applications is the imaging of UV sources. In many applications where UV light is used, it is not necessary to directly image the UV light source. For example, in Figure 5, the lens in the lens holder is transmitting an ultraviolet laser beam, a frequency-tripled YAG laser operating at 355 nm. The operator can verify the presence of UV light in the system by placing a standard business card in the optical path. The UV light makes the card stock glow, since it has been treated with fluorescent optical brighteners. But in this particular instance, the lens has been burned by excessive laser intensities. The burn mark acts as a diffuser, bleeding laser energy in all directions. A UV camera system can see that effect in a way that would be impossible to reproduce with a fluorescent card. □