NIR Trends: Penetrating The Haze Of Scattered Light

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In the July column of NIR Trends, we discussed the interaction of electromagnetic waves with materials they encounter, and how the interaction can tell us a great deal about the chemistry and physical makeup of those materials. This is the basis of most forms of spectroscopy. We went on to describe the impact NIR spectroscopy is having on our lives, particularly in biomedical imaging. In that context, light scattering was mentioned as a complication. This column will expand on the topic of light scattering and its impact on imaging with cameras at various wavelengths. Illustrations will compare images taken between visible and the shortwave infrared SWIR in haze, dust and smoky conditions.

If you hold a flashlight or a red laser pointer up to one side of the webbing between fingers in your hand, you will observe a red glow spreading broadly from the point of contact. The blue and green wavelengths of light from the flashlight never make it out of the tissue as the energy from those wavelengths is absorbed. The red light, however, penetrates the tissue, bounces around many times (scatters) and then re-emerges at many angles, appearing as a diffuse glow. Imaging even longer wavelengths of light, in the NIR and SWIR bands, would show less scattering and therefore more penetration, except at the wavelengths of significant water absorption. The absorption eventually grows strong enough to prevent any reemergence of photons. For this reason, optical coherence tomography (OCT) is rarely used in tissue imaging at wavelengths longer than 1.3 microns.

Figure 1: Water vapor scattering all wavelengths produces white glow around sun setting behind ridge.

Daily demonstrations of light scattering effects occur in the atmosphere. The sky is blue because the shorter wavelengths of light (the blue end of the rainbow) are scattered by air molecules, while the longer wavelengths (green, yellow, orange, red) mostly continue on their original path. Without this scattering, the sky would appear black to us on the ground. The distance the light passes through the scattering media is also important: The sun at noon appears white-hot because the path length to our eyes is short, so only a small amount of the blue wavelengths are diverted. It appears yellow when it is lower in the sky due to the much longer path the light travels through the atmosphere (which causes the loss of a much greater amount of blue light). This phenomenon was first identified in liquid solutions by John Tyndall in 1859, but eventually became known as Rayleigh scattering after Lord Rayleigh. His extensive investigations showed that the amount of light scattered is inversely proportional to the fourth power of the wavelength for sufficiently small particles (those that are ten times smaller than the wavelength of the light being studied). He assumed that water vapor or other particles in the sky were responsible for the blue sky scatter, but it was Albert Einstein in 1911 who showed that the blue sky was due to scattering by molecules of O_2 and N_2 in air (for more discussion of this history, see http://math.ucr.edu/home/baez/physics/General/BlueSky/blue_sky.html)

When water vapor and dust are present in the atmosphere, additional effects are observed: The vapor turning the blue sky whitish because most of the visible wavelengths are now being scattered to the ground observer's eyes (*see Figure 1*). Dust makes sunrises or sunsets red as only the longer wavelengths survive the direct journey to our eyes when traveling just above the horizon. As the particles get denser and as their size increases, visible imaging of any distance becomes very difficult. This is illustrated by the visible camera movie shown in *Figure 2*. This movie was taken of the San Francisco Bay Bridge in July 2008, and you can hardly see the bridge, let alone the car traffic on the bridge. Contrast that to the movie taken by the SWIR camera (Goodrich model SU640KTSX), which responds in the 0.9 to 1.7 micron wavelength range. Longer wavelengths penetrate the haze, providing clear detail of the ship traffic, buildings and vegetation on the hills behind the bridge.

Figure 2: Daytime movies in San Francisco Bay. Click on each and note the small boat crossing in front of the large freighter, a white box in the visible, clearly seen in the SWIR.

This case and in others where light interacts with molecules will also exhibit spectral absorbance. That is the phenomenon where the frequency of some photons matches the vibration frequency of the constituent molecules within the drop or particle. The associated wavelengths of light will be absorbed and missing from the reflected light. The brownish coloration of smog is due to the nitrogen dioxide (NO_2) concentrations, which absorb a lot of the blue-green wavelengths. Water vapor and carbon dioxide have many infrared absorbance bands, used with machine vision SWIR cameras to monitor moisture content in agricultural products. In the atmosphere, the wider of the absorbance bands absorb considerable energy from sunlight, contributing to heating of the environment. These bands also define the ends of the major mid-wave and long-wave infrared transmission windows. In the short-wave there is a mixture of absorbance bands and transmission windows, with the latter permitting SWIR imagers to see over long distances with little loss due to either scattering or absorbance.

Figure 5: This aerial video alternates between visible footage to shortwave infrared, both imaging the same forest fire scene. Note how the SWIR imager, captured with Sensors Unlimited's SU640KTSX camera, clearly shows the location of the flames, which the smoke hides from the visible camera. The cameras were integrated into a TASE Duo stabilized gimbal from Cloud Cap Technology (http://www.cloudcaptech.com/gimbal.shtm). The TASE gimbal was mounted on a manned Cessna 172 flown at ranges between 7000 m and 2000 m from the fire hot-spots.

As the particle size grows to a diameter (or cross section) equal to or larger than the wavelength, the scattering is predominately more forward in direction. The drawing in *Figure 4* illustrates the relative natures of the Mie and Rayleigh models of light scattering. The intensity loss also becomes less dependent on wavelength. The relationship is described by the Mie solution of Maxwell's equations for the scattering of electromagnetic radiation by spherical particles, named after Gustav Mie as the first to publish a solution. Though most particles in the atmosphere are not spherical, models based on the Mie solution are useful for explaining their scattering properties and help us understand why the sky becomes white with vapor, then gray as the particles become larger and denser. Eventually the size of fog, dust or smoke particles become large enough to obscure SWIR images. Since the scattering function vs. wavelength now has a weak relationship to wavelength, even the longer wavelengths are easily scattered. The images in *Figure 3* of a car viewed through dust, show that the SWIR camera sees through the lighter dust particles that obscure the visible camera, but not through the larger and heavier particles that stay closer to the ground. The movie in *Figure 5* illustrates the effects of wood smoke on camera visibility as an Unmanned Aerial Vehicle switches between visible and SWIR cameras. Note how the SWIR camera sees through the smoke to the far mountains and clearly sees the active burn site, a location that is completely obscured in the visible image.

So, when having trouble penetrating haze, dust, smoke, or even coats of paint (whose suspended particles in the solvent matrix obscure what's below due to light scattering), try imaging in the SWIR.

For a concise discussion of why the sky is blue, the Blue Ridge Mountains and blue moons, see: http://math.ucr.edu/home/baez/physics/General/BlueSky/blue_sky.html

For a comprehensive discussion of scattering, see this book:
Atmospheric Pollution: History, Science, and Regulation
By Mark Zachary Jacobson
Published by Cambridge University Press, 2002
ISBN 0521010446, 9780521010443 pages
This can be previewed at here.

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