Multi-Wavelength Airborne Laser Scanning

Martin Pfennigbauer and Andreas Ullrich
RIEGL Laser Measurement Systems GmbH, Horn, Austria

Since the introduction of airborne laser scanning systems employing echo digitization and full waveform analysis, there has been a continuous improvement of both data acquisition with respect to measurement rate and measurement range, and data processing with respect to classification and surface model extraction. A further direction is the diversification toward more than one laser wavelength: either to optimally cover the designated application (topography, hydrography, or glaciography) by selecting the best-suited wavelength, or to retrieve additional information about the targets, such as, e.g., crop analysis or tree species detection by using several wavelengths in parallel.

1. Introduction

Airborne laser scanning systems employing echo digitization and full waveform analysis became commercially available with the *RIEGL* LMS-Q560 in 2004 (Ullrich 2005, Wagner 2006, Mallet 2009). Since then there has been a continuous improvement in laser scanner hardware and thus data acquisition with respect to measurement rate and measurement range, but also in data processing with respect to classification, surface model extraction, and radiometric measurements (Ullrich, et al., 2007, Wagner 2010). Additionally to full waveform analysis based on digitized and stored echo signals in off-line processing, commercial systems have been introduced by *RIEGL* in 2008, (Pfennigbauer 2010), offering also echo digitization but on-line waveform processing, yielding similar results compared to full waveform analysis with even higher accuracy and precision but with limitations in multi-target resolution.

The primary data provided by airborne laser scanning is a dense and accurate georeferenced point cloud preferably with low noise, i.e., high precision. Data density has continuously increased over the past years from just a few measurements to several tens of measurements per square meter recently, of course trading-off acquisition parameters against project requirements. Techniques such as multiple-time around, i.e., emitting the next laser pulse before the echoes of the last pulse have been received, with proper post-processing in order to resolve the ambiguity raise data density even further, especially from higher altitudes above ground.

In principle, the primary data, the point cloud, is sufficient to derive the traditional data products such as a digital terrain model (DTM), digital surface model (DSM) be applying geometric filters to classify the points into measurements on ground, vegetation, or man-made objects. However, LIDAR systems provide more information per laser shot: at first, several target returns are usually provided when the laser beam hits more than one target, as it is the case when the laser pulse with its finite laser footprint diameter penetrates, e.g., vegetation. Additionally, the amplitude of every return is provided which allows, after some calibration, to estimate the target's laser radar cross section at the laser wavelength (see e.g., Wagner 2010). Especially full waveform systems provide detailed and calibratable information on echo amplitude and thus on radiometric target properties. The additional parameter provided by echo-digitizing systems, i.e., echo pulse width or echo pulse shape deviation, gives valuable information to improve the quality of the classification process in post-processing (Ullrich. et al., 2007). Echo amplitude and subsequently laser radar cross-section information can be seen as the secondary data of a LIDAR system. These values depend on the wavelength of the LIDAR, whereas the wavelength does not show up directly in the primary data (provided the echo signals are above the systems detection threshold).

A diversification toward making use of more than one laser wavelength seems favorable and feasible. Obvious benefits include to optimally cover a designated application (topography, hydrography, or glaciography) by selecting the best-suited wavelength, or to retrieve additional information about the targets, such as, e.g., crop analysis or tree species detection by using several wavelengths in parallel.

We subsequently discuss selection criteria for the wavelength of ALS sensors. We will classify different system approaches for acquiring multi-wavelength ALS data sets, we will provide an assessment and draw conclusions.

2. Wavelength Considerations

2.1. Definition “Multi-Wavelength”

The terms multispectral and hyperspectral are well-defined in the field of imaging, in the past decade also frequently in the field of airborne photogrammetry. However, multispectral – synonymously multi-wavelength – is not to be mixed up with hyperspectral. While the term multispectral refers to sensors operating at a few (at least two) different wavelengths (mostly considerably separated), hyperspectral measurement corresponds to sensors covering a certain wavelength range with a multitude of – usually equally-spaced – channels at a high spectral resolution. Hyperspectral sensors are mostly passive imaging systems; multispectral sensors can be either passive or active. Figure 1 illustrates the different concepts. An example of a multispectral device is a color camera with three distinctive channels at red, green, and blue.

Camera systems are in general passive sensors and rely on sufficient ambient light levels to provide data. Again, in general, the spectral width of the ambient light is considerable larger than the camera’s spectral width of sensitivity. In contrast, airborne LIDAR systems are active systems emitting laser pulses to illuminate targets and detecting echo signals backscattered by the targets. As the weak echo signals have to be discriminated against ambient light, .i.e., so-called background radiation, the LIDAR receivers are “tuned” to the laser wavelength by means of narrow-band filters. Thus, LIDAR systems are considered as narrow-band systems at distinct wavelength determined by the availability of suitable lasers (see further discussion below).

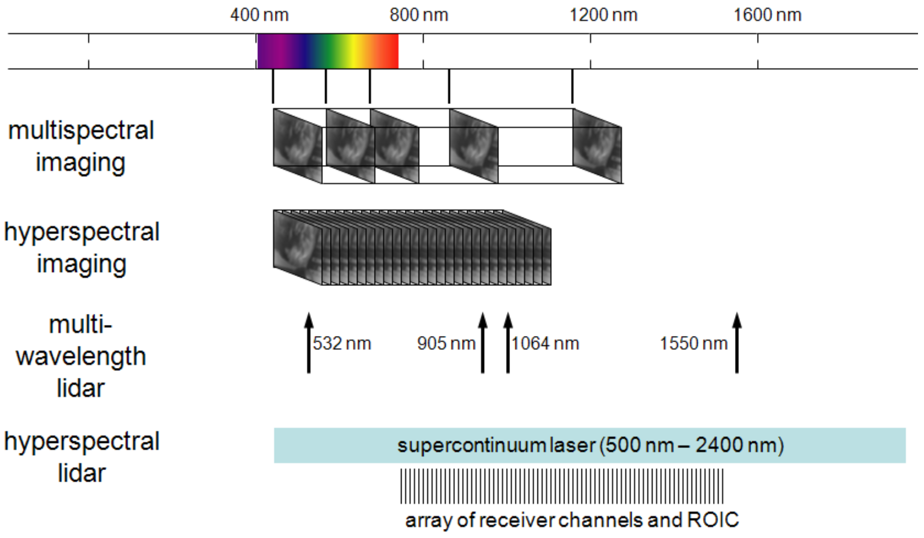

Figure 1: Discrimination of terms multispectral, hyperspectral, multi-wavelength.

There are, however, experimental active hyper-spectral LIDAR setups employing supercontinuum lasers. These are – at least at the moment – of no commercial interest (Chen, et al., 2010) having very limited maximum ranges.

2.2. *Available Laser Wavelengths*

While there are a great variety of laser lines, there are only a couple of wavelengths where lasers powerful enough for airborne laser scanning are available (cf. Figure 2). High-power pulsed diode lasers at 905 nm have been widely used in the past. Today's systems mostly employ diode pumped solid state lasers at 1064 nm or fiber lasers at 1064 nm (based on Ytterbium-doped fibers) or 1550 nm (Erbium-doped fibers).

An additional possibility results from frequency doubling 1064-nm lasers employing nonlinear crystals. This leads to the attractive wavelength of 532 nm, corresponding to bright green. The UV-region can be reached by frequency tripling, however with little commercial impact for lidar systems. There are more fiber laser wavelengths employing active fibers with different dopants: Thulium around 1470 nm, Praseodymium in the 1300 nm region, and Holmium around 2 µm, for which the same applies.

Each wavelength has its advantages and disadvantages, depending on the target reflectance, background radiation, atmospheric transmission, and eye-safety issues.

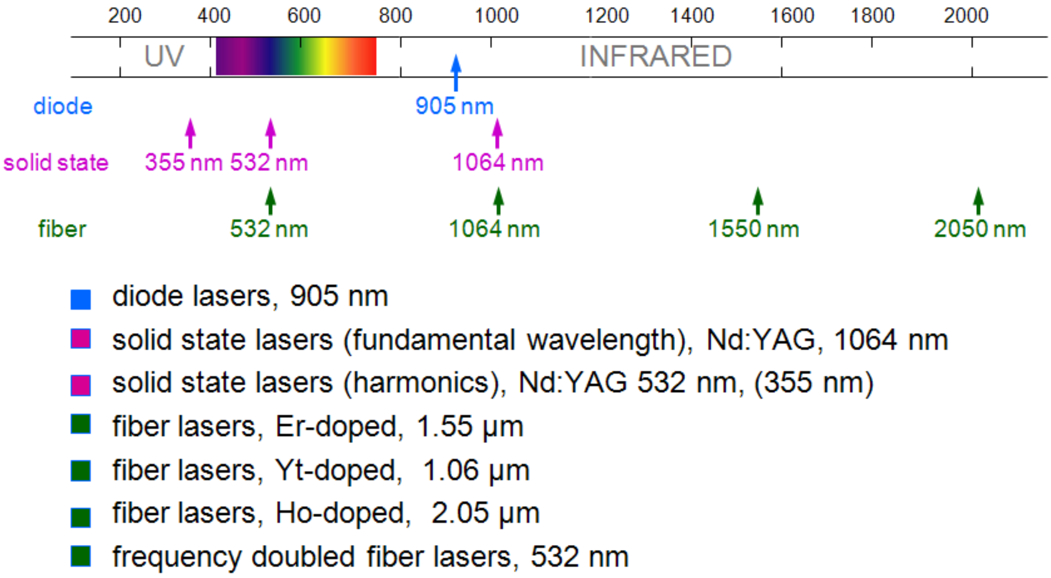

Figure 2: Available laser wavelengths for long range ALS LIDARs.

2.3. *Reflectance, Background Radiation, and Attenuation of the Propagation Medium versus Wavelength*

Besides capturing spatial information alone, airborne laser radar systems also capture amplitude information. While this has been and still is for most systems merely qualitative information about the received echo strength, it may also be used for reflectance determinations. *RIEGL*'s VQ480 directly delivers calibrated amplitude and reflectance reading, and systems providing full waveform information, such as *RIEGL* LMS-Q680i, may be calibrated in post processing by employing reflectance standards or assuming reflectance values for certain targets.

Gaining information on the target's reflectance is important for target classification – by measuring at different wavelengths, even more information like vegetation type, crop ripeness etc. can be obtained.

There are, however, certain targets very unfavorable for certain wavelengths. One example is snow, which gives very low returns at 1550 nm and is very bright at 532 nm (cf. Figure 3). It is interesting though, that vegetation shows a considerably higher reflectance at 1550 nm than at 532 nm. Figure 3 clearly shows that – with respect to reflectance – 1064 nm is a very favorable wavelength (not so with respect to eye safety, cf. the following section).

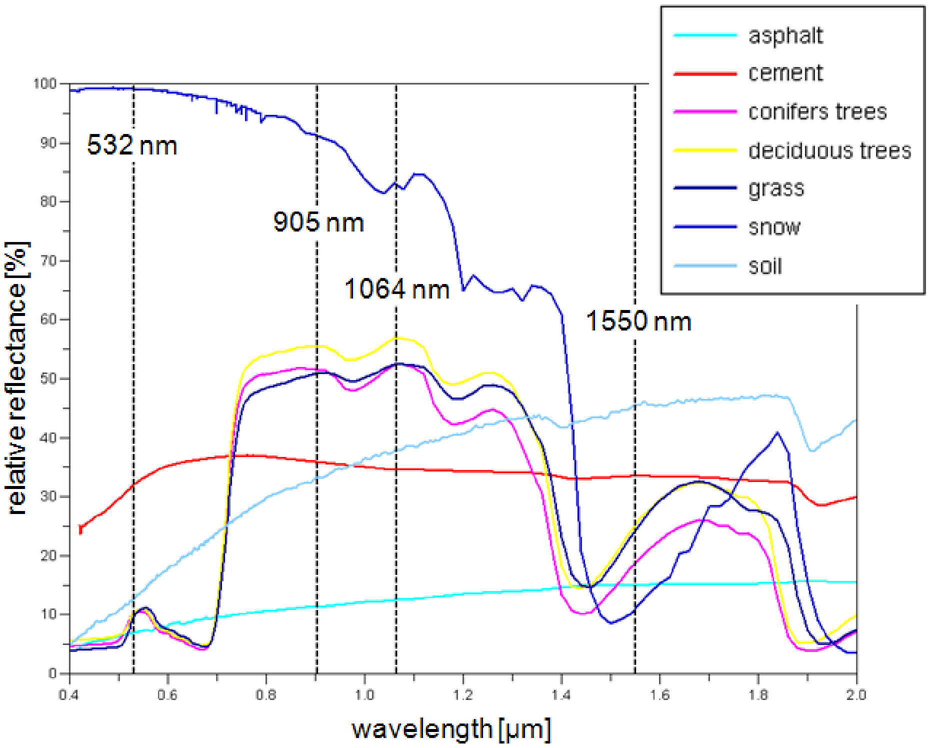

Figure 3: Reflectance vs. wavelength for different materials (based on data courtesy to Baldridge, Hook, Grove, & Rivera, 2008, speclib.jpl.nasa.gov). The dashed vertical lines correspond to laser lines commonly used for laser radar.

When choosing the optimum wavelength, also the spectral irradiance of the sun as shown in Figure 4 has to be taken into account, as a LIDAR has to discriminate the very weak echo return against the background radiation. According to the temperature of the sun's surface of about 5900 K, the solar irradiance has its maximum at about 500 nm. Therefore, systems operating at shorter wavelengths are prone to increased deterioration through sunlight.

Another factor to be considered is the atmospheric transmission. Figure 5 provides the one-way transmission through 20 km atmosphere in a wavelength range from 1 µm to 2.5 µm for different visibility conditions. With respect to this property, 1550 nm is a preferable wavelength, especially under unfavorable atmospheric conditions compared to shorter wavelengths.

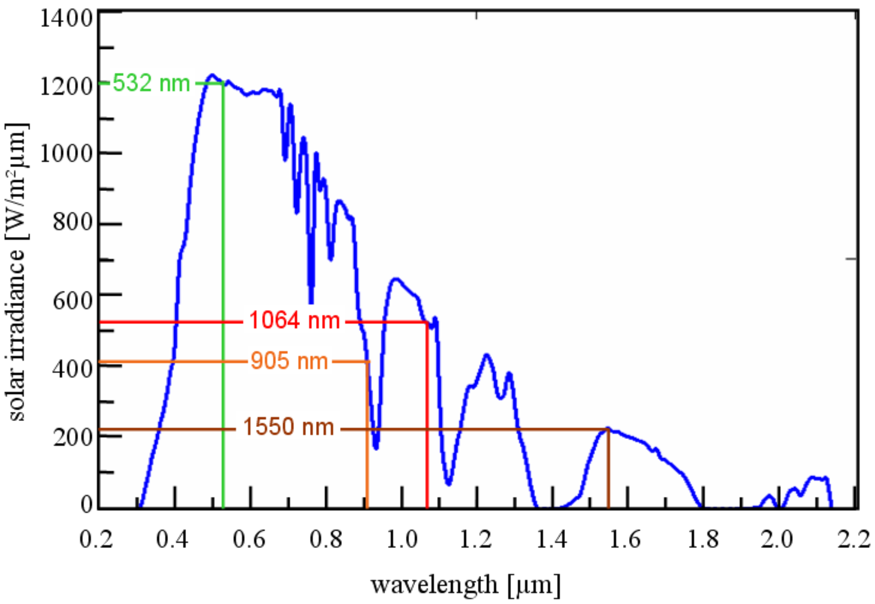

Figure 4: Solar spectral irradiance at zenith sun angle 60° at sea level. Ditches are due to atmospheric absorption (Wolfe 1978).

The attenuation of the laser signals in water is of crucial importance in hydrography applications and can be depicted from Figure 6. The minimum absorption coefficient and thus the minimum attenuation occurs around 450 nm. For a depth of 10 m, a green laser pulse at 532 nm will only be attenuated by about 4 dB, whereas a 1064 nm pulse is almost completely absorbed after only 10 cm of depth and a 1550 nm pulse after only about 1 mm. In addition to absorption, laser pulses also suffer refraction and – most problematic for hydrographic laser scanners – severe scattering.

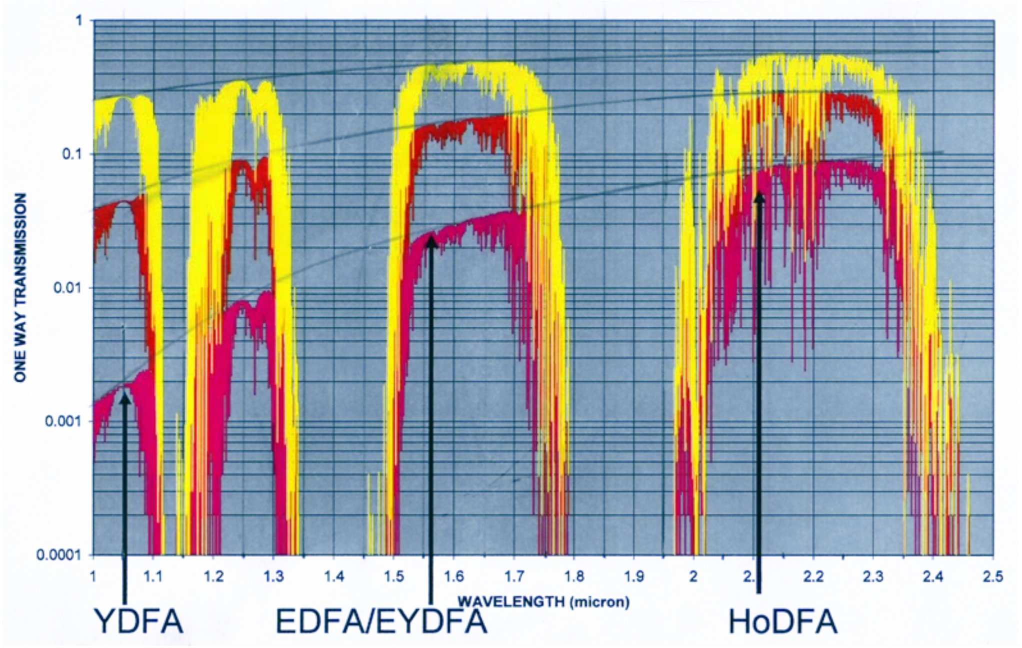

Figure 5: One-way horizontal transmission over 20 km atmosphere vs. wavelength for visibility ranges of 5 km (magenta), 10 km (red), and 23 km (yellow) (Samson & Toruellas, 2007).

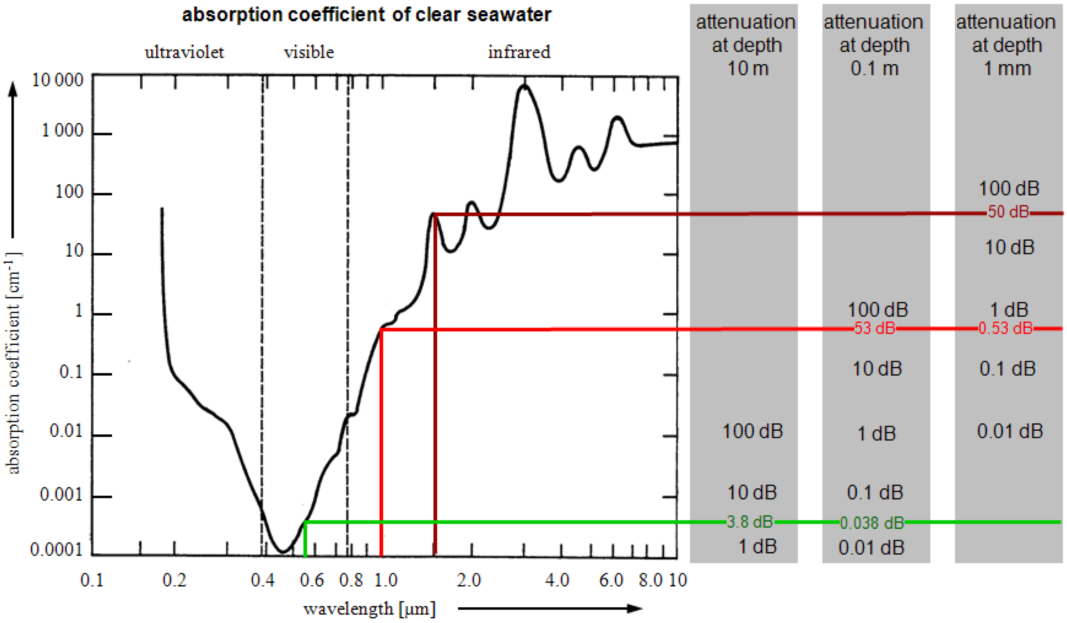

Figure 6: Absorption coefficient of clear seawater vs. wavelength. On the right hand side, the attenuation at certain depths for typical wavelengths is compared. (Ewing 1965)

2.4. *Laser Safety versus Wavelength*

Laser radiation has the potential to be harmful due to the fact that it can be collimated to narrow beams with nearly planar wave fronts and low divergence. Hence, even at large distances, power densities can be produced which might affect the human skin or eye where the interaction may be based on photochemical or thermal effects. IEC standard 60825-1 deals with classification of laser products and determines how laser products have to be designed and handled. The US-based standard 21 CFR 1040.10 uses similar measurement rules and limits but has different nomenclature with respect to the actual laser classes. Its impact has decreased in the recent years because since 2001 US authorities also accept classification according to IEC standard (CDRH, 2001).

As the human eye has evolved to capture light and to focus it onto the retina very efficiently around the peak of the solar irradiance, i.e. from 400 nm to 700 nm, it is also most sensitive to laser radiation in that wavelength region, as reflected by the most restrictive limits of the laser safety standard in the same wavelength range. This range of low *accessible emission limits* (given in W or J) or *maximum permissible exposure* (given in J/m^2 or J/m^2) extends, however, from 700 nm up to 1400 nm where light hitting the eye – although not visible – might again be focused by the eye's lens or may at least transmit to the retina. Below 400 nm and above 1400 nm laser safety issues are relaxed since corresponding laser light is not able to penetrate human tissue and only interaction at the surface of the cornea or skin has to be taken into account. These statements are reflected by the curves provided in Figure 7: While the lowest value for the MPE is in the visible range, it slowly increases in the near IR and reaches its maximum value around 1550 nm.

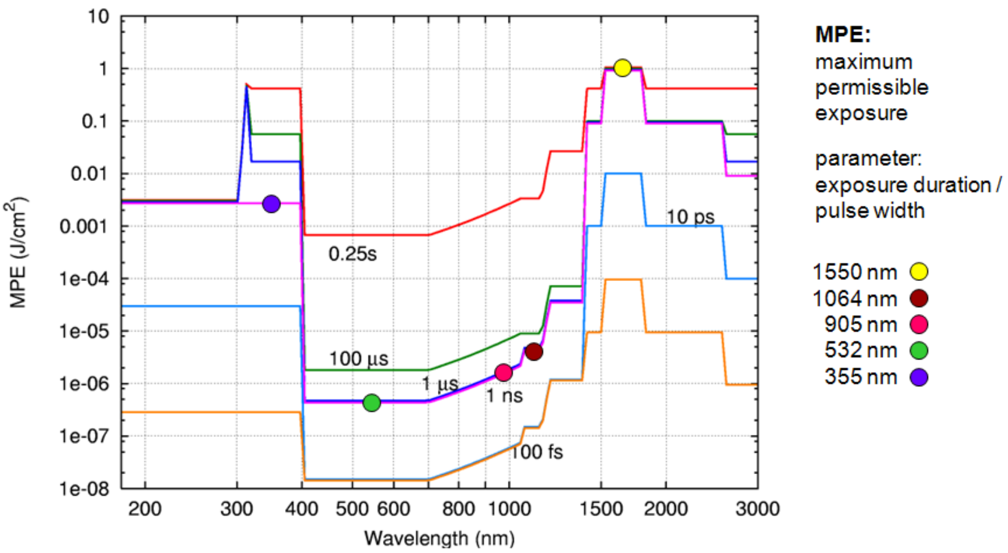

Figure 7: Maximum permissible exposure (MPE) vs. wavelength for different pulse lengths (Wikipedia, 2011).

With this in mind, and also taking into account the logarithmic vertical scale in Figure 7, it is clear that 1064 nm or even 532 nm are by far more critical than 1550 nm.

For any laser product having a laser class other than 1 (this applies for more or less any of the high-end long range airborne laser scanners available today), a kind of safety range, the NOHD (nominal ocular hazardous distance) and the eNOHD (extended nominal ocular hazardous distance) have to be determined and stated for the user's information. At this distance from the laser product, the exposure drops below the MPE value (NOHD refers to the unaided/naked eye while eNOHD relates to the case when the potential observer might use binoculars). Even a Class 4 laser instrument seen from far away (beyond eNOHD), does not impose a hazard but is still Class 4. The operator of such a system is responsible for taking all necessary measures to ensure that no potential observer is harmed by the laser radiation.

For practical purposes this now means that for every airborne laser scanner there is an operational zone between the eNOHD (since observers wearing binoculars can never safely be excluded), determining the lower limit for the flight altitude, and the maximum measurement range. Since the eNOHD may be as large as 500 m, this is not always easily achieved, especially in hilly areas. The relation of NOHD, eNOHD, and maximum measurement ranges for different *RIEGL* ALS instruments is presented in Figure 8.

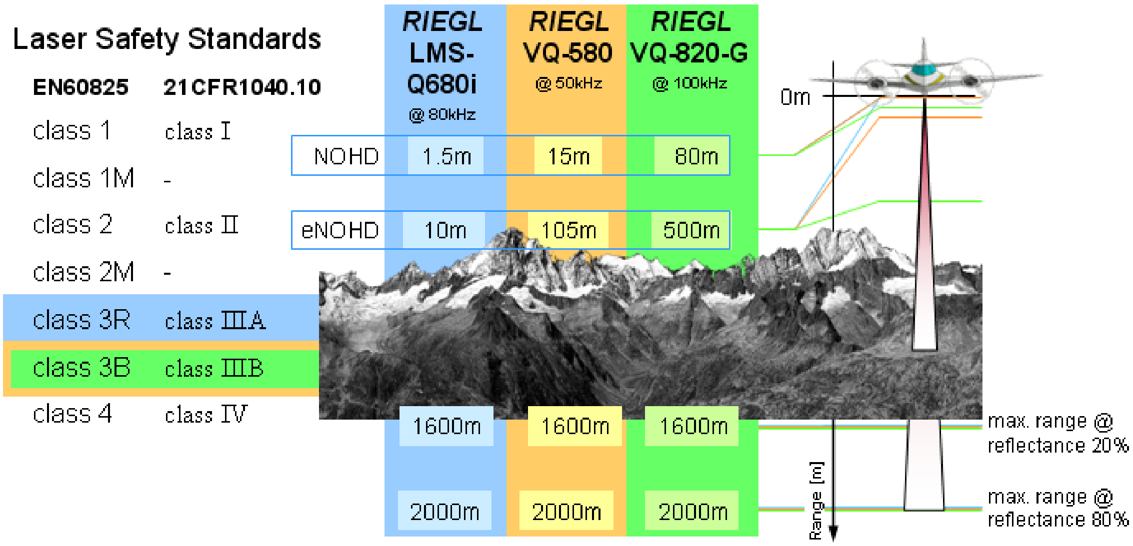

Figure 8: NOHD, eNOHD, and maximum measurement ranges for different *RIEGL* instruments. *RIEGL* LMS-Q680i, *RIEGL* VQ-580, and *RIEGL* VQ-820-G utilizing laser wavelengths of 1550 nm, 1064 nm, and 532 nm, respectively. (*RIEGL* 2011)

3. Classification of Multi-wavelength ALS Data and Systems

Multi-wavelength airborne laser scanning means to capture spatial (location) and waveform data / amplitude / reflectance information of dedicated target areas with laser scanners operating at different wavelengths. While ideally the spatial information should be independent of the wavelengths, the added value of multi-spectral laser scanning lies in the wavelength-dependence of the target's reflectance.

Due to this, multi-wavelength airborne laser scanning systems a) may provide data on targets in areas which cannot be measured at one single wavelengths because of the reflectance at that first wavelength is too low but might be bright at other wavelengths, and may gain b) additional information about the target reflectance properties by evaluating the laser cross-section of each target at different wavelengths. While the reflectance at only one wavelength may not be sufficient to identify a certain target, reflectance values at several wavelengths certainly improves target classification. Problems in normalizing the reflectance value common to single-wavelength systems may be overcome by multi-wavelength systems / data.

Different classes of multi-wavelength airborne laser scanning systems and/or ALS data can be identified:

- Different time – different location: Scanning of target area with at least two laser scanners operating at different wavelengths during separate flights. This solution is straight forward and comparatively easy to be achieved. Laser scanners may be mounted on different platforms or on the same platform and are exchanged between flights. However, target properties might change in between the measurement times and local differences in target properties might lead to misinterpretations when assuming homogenous situations. Another obvious disadvantage is the increased requirement of flight time or aircrafts.
- Nearly the same time – different location: Joint scanning of target area with at least two laser scanners operating at different wavelengths mounted on the same airborne platform. This solution is much more convenient for the operator but still deprives synchronization and – due to different measurement spot distribution at least caused by aircraft movement – spatial coherence.

- Same time – same location: Scanning of target area with at least two coaxial laser beams at different wavelengths. This technically most demanding solution would be optimum with respect to interpretability of the measurement results.

4. Conclusions

As discussed above, target reflectance of some targets of interest in ALS, e.g., snow and ice, varies significantly with the wavelength. The same applies for the NOHD and eNOHD . A very wide field of applications is preferably covered with “eye-safe” systems at 1550 nm ranging from low altitude, high density corridor mapping with helicopter-borne platforms, to large area acquisitions with medium-point-density requirements from medium to high altitudes above ground. No laser safety measures have to been taken by the operator in all modes of operation. However, for data acquisition dedicated to e.g. glaciology the “non-eye-safe” wavelength of about 1 µm seems preferable. And for hydrography, only the 532 nm are usable.

For research and some scientific applications taking data at the same time at different wavelength seems promising, but for the wide field of commercial ALS data acquisition no actual market can be identified for the time being.

From a stand point of flexibility and cost effectiveness, the best approach is having a single platform with an inertial/GNSS measurement unit, optionally equipped with a camera (RGB, with/without infrared channel, and/or hyperspectral), and a high performance general-purpose eye-safe state-of-the-art laser scanner based on echo digitization and full-waveform analysis or online waveform processing. This system offers all the additional secondary data for deriving radiometric target data and data for quality-improved classification. For specific projects, the laser scanner can be substituted by one at a different wavelength or supplemented by a second laser scanner. Again, making use of echo digitization enables radiometric measurements at the second wavelength and thus the utmost information from a single data acquisition campaign is retrieved.

5. References

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