Laser reflection method for vegetation monitoring at eye-safe sensing wavelengths in the NIR spectral band

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Abstract. The paper analyses capabilities of a laser reflection method for remote vegetation monitoring at eye-safe sensing wavelengths in the NIR spectral band and provides a statistical simulation of correct detection and false alarm probabilities to solve the tasks of vegetation monitoring. Shows that at the wavelengths of 1.54 and 2.03 μm, for example, the laser reflection method of sensing allows us to detect vegetation under adverse conditions with a probability of correct detection close to one and a probability of false alarm ~ second decimal places. The laser reflection method using two sensing wavelengths in the NIR spectral band can be accepted as a basis of the vegetation monitoring method using a high-flying aircraft.

1. Introduction
Remote vegetation monitoring is one of advanced applications in laser sensing. Adverse external conditions (drought, bogging-up, freezing), plant diseases, plant pests, environment pollution, etc. make a natural course of plants growth impossible. Therefore, monitoring system engineering to provide sensing of vegetation cover is of relevance.

For remote vegetation monitoring a laser-induced fluorescence\(^1\%-6\) method is efficient. However, for most of the fluorescence lidars a remote sensing range is 100 - 150 m, at most. Low height sensing leads to a small swath on ground and a low capability of this method.

Methods based on the spectral analysis of vegetation-reflected radiation allow monitoring from a high-flying aircraft, thereby scanning a large ground swath.

The spectral analysis methods of vegetation-reflected radiation are, currently, passive \(^7\%-9\). To estimate vegetation health (from an aircraft or a satellite) are used special complex parameters called vegetation indices\(^10\%-12\). The use of vegetation indices is based on the differences in vegetation reflectivity in the visible (VIS) and near infrared (NIR) spectral bands.

However, the passive optical sensing systems in the VIS and NIR spectral bands have a shortcoming. Monitoring is possible only in daylight hours, and there is a heavy reliance on the optical state of the atmosphere.

The advanced option of an optical device, which allows vegetation monitoring from a high-flying aircraft (scanning a large ground swath) no matter the time of day, is the laser system, which uses the reflection method to monitor vegetation health in the NIR spectral band.

The paper conducts a capability analysis of the laser reflection method for vegetation cover monitoring, which uses two eye-safe sensing wavelengths in the NIR spectral band.
2. Problem description

Laser radiation used for remote sensing is always a potential hazard to eyes. However, this hazard can be minimized.

Radiation in the NIR and UV spectral bands with the wavelengths above 1.4 $\mu$m and above 0.18 – 0.38 $\mu$m, respectively, affects the anterior ocular media and is safer than radiation in 0.38 – 1.4 $\mu$m spectral band, which acts on amphiblastroses.

However, the UV spectral band is not really useful for sensing the vegetation condition.

First, a spatial swath of the aircraft depends on its flight altitude. The higher is the flight, the larger is the swath and the more is the monitoring system capacity. An ozone layer, available at 15 – 30 km heights in the earth atmosphere, strongly absorbs UV radiation thereby making the use of the NIR spectral band more preferable (at least, for high-flying aircrafts).

Second, the UV spectral band with the wavelengths of 0.18 – 0.38 $\mu$m is less eye-safe than the NIR spectral band with the wavelengths over 1.4 $\mu$m.

Today, there are available spectra libraries with data on reflection coefficients of various kinds of plants (for instance,\(^1\)). Figure 1\(^1\) illustrates examples of vegetation reflection spectra, in particular the inherent reflection spectra of spurge leaves (lat. *Euphorbia*) in July (curve 1) and October (curve 2).

It is seen from Fig.1 that under normal conditions for development, the live green plants (curve 1) have fairly well defined local maximum in the reflection spectrum in the green spectral band (0.52 – 0.58 $\mu$m). In the NIR spectral band (at the wavelengths longer than 0.75 $\mu$m) a reflection coefficient of the live green plants under normal development conditions reaches a maximum value.

![Figure 1. Spurge leaves reflection spectrum.](image)

With changing growth season (curve 2) or under adverse development conditions there is a change in the reflection spectrum of plants: a local maximum in the spectral band within 0.52 – 0.58 $\mu$m becomes smooth (or disappears) while with transition to the NIR band a maximum “drop” in the reflection coefficient becomes less.

A reflection spectrum variation of plants under adverse conditions is a physical basis for an optical method for vegetation monitoring.

Variations in the vegetation reflection spectra with changing season growth or under adverse conditions for plant development in the NIR (above 1.4 $\mu$m) spectral bands are not so obvious.

Based on the spectral library data about reflection coefficients of various kinds of plants the paper provides statistical simulation of correct detection and false alarm probabilities to detect vegetation under adverse conditions for plant development (with the abnormal reflection spectra inappropriate to the season growth) according to reflection coefficients from dual spectrum measurements at two wavelengths in the NIR spectral band.
3. Statistical simulation of correct detection and false alarm probability for detecting vegetation under adverse conditions

In statistical simulation the spectral library data are used. A ratio R of the plant reflection coefficients at the wavelengths of 1.54 and 2.03 μm is taken as an information index (the plant under normal or adverse conditions). These wavelengths were chosen because of high atmospheric transmittance (figure 2) and available radiation sources suitable for laser sensing.

![Figure 2. Atmospheric transmittance versus wavelength for a zenith path from sea level to space.](image)

Figure 3 shows values of the information index R, which is equal to the ratio of the reflection coefficients at the wavelengths of 1.54 and 2.03 μm for the plants from the created database (based on the spectral library). The Y - direction shows a calculated R ratio of the plant reflection coefficients at the wavelengths of 1.54 and 2.03 μm for a number of plants, and the X - direction shows the i number of the plant reflection spectrum in created database (Figure 3).

The numbers 1 - 24 are green plants, broad-leaved or needle-leaved trees in normal conditions: 1, 2, 22 – aspen leaves, fresh leaves from tree, 3 – oak, fresh leaf, 4 – Russian olive, fresh leaves, 5 – blue spruce, 6 – Engelmann spruce, 7 – fir tree, 8 – juniper bush, 9 - 15 – spurge, green leaves from different areas, 16 – lodge-pole pine, green needles, 17 – walnut, green healthy leaves, 18, 19 - lawn grass, 20 – willow, fresh leaves from tree, 21 – maple, fresh leaves from tree, 23 - pine, green needles, 24 – conifer and meadow); the numbers 25-38 – dead plants, fall period (25 – sage brush, dead leaves, 26, 37, 38 – dried grass, 27 – oak leaf dried, 28, 29, 34 - spurge with flame-colored leaves, fall period, 30 – lodge-pole pine, dried green needles, 31 – lodge-pole pine, dried brown needles, 32 – dried long brown grass, 33, 36 - willow, dried leaves, 35 – dried tumble-weed).

![Figure 3. Information indices values for 1.54 and 2.03 μm wavelengths.](image)
Figure 3 shows that values of the information index $R$ (for the wavelengths of 1.54 and 2.03 $\mu$m) for green plants under normal condition ($i$ values from 1 to 23) are mostly more than those for dead plants, fall period, etc. ($i$ values from 24 to 35).

The similar values of the information index $R$ for the wavelengths of 0.66 and 0.85 $\mu$m (as an analogue for the passive optical system) are shown in Fig. 4.

Figure 4 illustrates that the information index $R$ values (for the wavelengths of 0.66 and 0.85 $\mu$m in the visible spectral band) for green plants under normal conditions are mostly less than those for dead plants, fall period, etc.

Generally, in choosing the 0.66 and 0.85 $\mu$m sensing wavelengths a situation with detecting vegetation sites under adverse development conditions a varies (and may be even slightly worse) from that of in case of choosing the eye-safe sensing wavelengths of 1.54 and 2.03 $\mu$m in near infrared spectral band.

To estimate a correct detection probability (the probability of attributing the plants under adverse development conditions just to this category of plants) and a false alarm probability (the probability of attributing the plants in normal condition to those that are under adverse conditions for plant development), when choosing the laser sensing wavelengths of 0.66; 0.85 $\mu$m and 1.54 $\mu$m; 2.03 $\mu$m, we have performed mathematical simulation.

For the wavelengths of 1.54 and 2.03 $\mu$m, decision on plant detection under adverse conditions for plant development was made if the following condition was fulfilled: the information index $R$ is less than a threshold value for the wavelengths of 1.54 and 2.03 $\mu$m.

For the wavelengths of 0.66 and 0.85 $\mu$m, decision on plant detection under adverse conditions for plant development was made if the following condition was fulfilled: the information index $R$ exceeds a threshold value for the wavelengths of 0.66 and 0.85 $\mu$m.

The results of mathematical simulation, given below in Section 4, were obtained at the following threshold values of the information index: 1.99 for 1.54 and 2.03 $\mu$m sensing wavelengths and 0.17 for 0.66 and 0.85 $\mu$m sensing wavelengths.

4. Statistical simulation results
In mathematical simulation measurement noise was thought to be Gaussian random variable with zero-mean value and relative mean square deviation $\delta=1–10\%$. The statistical simulation used $10^5$ noise samples.

The statistical simulation results of the correct detection probability $P_d$ and the false alarm probability $P_a$ are given in Table 1 (for the sensing wavelengths of 1.54 and 2.03 $\mu$m), in Table 2 (for the sensing wavelengths of 0.66 and 0.85 $\mu$m).
Table 1. Correct detection probability and false alarm probability for 1.54 and 2.03 μm.

| δ (%) | Pd   | Pa   |
|-------|------|------|
| 1     | 1    | 0.04 |
| 3     | 0.99 | 0.047|
| 5     | 0.97 | 0.049|
| 10    | 0.96 | 0.089|

Table 2. Correct detection probability and false alarm probability for 0.66 and 0.85 μm.

| δ (%) | Pd   | Pa   |
|-------|------|------|
| 1     | 0.93 | 0.04 |
| 3     | 0.92 | 0.043|
| 5     | 0.91 | 0.056|
| 10    | 0.88 | 0.087|

The results (tables 1,2) show that at two eye-safe sensing wavelengths in the NIR spectral band the laser reflection method allows highly reliable detection of vegetation sites under adverse conditions with correct detection probability close to one and false alarm probability ~ second decimal places.

Thus, the analysis of an information index R for the eye-safe sensing wavelengths in the NIR spectral band (for example, 1.54 and 2.03 μm) can be accepted as a basis of the laser method for vegetation monitoring under adverse conditions from a high-flying aircraft.

5. Conclusion

The statistical simulation of correct detection and false alarm probabilities to monitor vegetation sites under adverse conditions has been conducted as a result of laser sensing at two eye-safe sensing wavelengths in the NIR spectral band. It is shown that the laser method allows us to detect vegetation under adverse conditions with correct detection probability close to one and false alarm probability ~ second decimal places. The laser reflection method, using two sensing wavelengths in the NIR spectral band, can be accepted as a basis of the method for vegetation monitoring from a high-flying aircraft.

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