SZENT ISTVÁN UNIVERSITY

Remote sensing- and spectroscopy-based winter wheat identification procedure

Thesis of Ph.D. work

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CONTENTS

1. INTRODUCTION, OBJECTIVES

Within the frame of my research work I have been studying a special application possibility of remote sensing and spectroscopy in agricultural production.

Multiband remote sensing applications and laboratory spectroscopy are connected by and combined in dual-use portable spectroradiometers. These devices are capable of measuring both in-field and under laboratory conditions.

The aim of the study was defined by two determinative problems: A technical and an economical problem. Latter, originates in biological basis.

The laboratory application of a portable spektroradiométer results in an open-system-type measuring procedure. Quantity of sample, quality and distance of illumination, sensor height and several other parameters can change. As a reference, an external master measurement is needed, from time to time. The protocol affects the reliability and accuracy of measurements. Despite of this, no exact measuring protocol has been defined so far. Measurements, carried out in different laboratories, can differ decisively (Jung, 2009). The generally used measuring procedures are tainted with significant uncertainty factors.

Hungary had been the second biggest sowing-seed exporter of Europe for a long time. The country's role is still decisive but the tendency of sowing-seed production and sowing decreases. The use of certified seed has decreased drastically. Farmers choose other solutions to get by the necessary sowing-seed more and more often. This decision results in deterioration in stability of yield and quality and also threatens the Hungarian wheat production and international market of Hungarian crops. The fundament of quality wheat and food production is certified crop-seed of excellent quality (Bedő és Láng, 2010). One of the most important conditions of breeding and quality crop-seed production is the preservation of varietal purity, the roguing. The collection of off-type plants (other species or varieties) demands focused, skilled and cost-intensive work that – depending on class and purity - has to be performed several times (Izsáki és Lázár, 2004; Elitmag, 2010).

By assembling the reflectance spectroscopy with existing high capacity postharvest seed separator systems operating on the principle of image processing, the final purity of sowing-seed can be improved and controlled. The method can substitute or partly replace the conventional roguing. This can lead to improved sowing-seed quality and reduced seed production costs. Quality seed production is ensured by sowing-seed industry and breeding activity, both depend on the acknowledgement of intellectual property (Bedő és Láng, 2010). Spectral data collected in-field or with airborne acquisition provide identification opportunity to control the origin of wheat varieties and supervise the status of pertaining licence fees. The cost-effective way of certified sowing-seed usage control expanded on large areas can be the fundament of breeding and pedigree maintaining, furthermore of quality seed production. Among the effective and beneficial production system's conditions the balance of breeding and seed production costs, licence fees, certified seed and wheat prices is determinative.

The role of a spectral information-based quality insurance system is complex. Financial background of breeding (licence fee) is ensured, seed production costs decrease, while purity improves. The price of sowing-seed reduces. Farmers sow quality seed, grow quality crop and carry out more beneficial production. Food industry produces quality products.

I studied the reliability of generally used laboratory measuring procedure by using a portable spektroradiometer in the Remote sensing laboratory of the NARIC Institute of Agricultural Engineering. The aim was to develop a new examination procedure that generally reduces the measuring uncertainties of portable spectroradiometers under laboratory conditions. By using a new examination procedure the objective was to build a spectral library suitable for performing crop year and quality independent wheat seed selection. I analysed the possibility of spectral feature-based variety classification, identification of wheat seeds.

In parallel, by applying generally used in-field measuring procedure, the aim was to build a spectral library from crop year and quality independent wheat stand spectra. I analysed the possibility of spectral feature-based variety classification, identification of wheat stands.

Upon my hypothesis:

- An appropriately defined, new examination procedure can improve the reliability of measurements.
- Wheat varieties can be identified based on spectral characteristics.
- Spectral difference between varieties varies as a function of phenophase.

Afore described goals in key points:

- To study the generally used laboratory examination procedure's reliability.
- To development a new examination procedure.
- To build a variety-specific spectral library from winter wheat stands and seeds.
- To develop a spectral library-based variety classification, identification procedure for winter wheat stands and seeds.

2. MATERIAL AND METHOD

In order to achieve the defined goals a small plot production trial, fundamental research, preliminary experiments, new examination and data processing procedure and model development are necessary.

2.1 Generally used examination procedure

Laboratory measurements were carried out in a light-isolated cabinet, situated in the NARIC Institute of Agricultural Engineering, by using an ASD FieldSpec 3 Max portable spektroradiometer. The cabinet excludes all external light and minimizes any unfavourable internal reflexions.

Basically, there are two examination procedures. Contactless measurement with external light source and contact measurement carried out with a sensor-head equipped with internal illumination (Fig. 1). Advantage of latter is more reliable measurements due to independency of atmospheric factors.

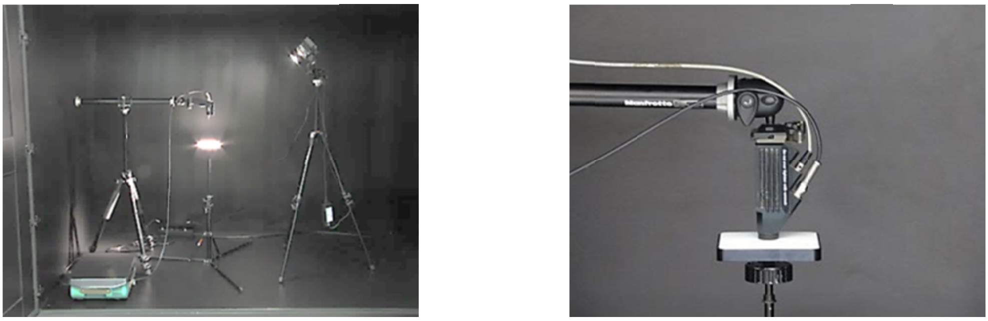

Figure 1: The use of external light source (Pro Lamp) (left), contact measurement using Plant Probe sensor-head (right).

The basis of both in-field and laboratory measurements is the so called white reference measurement that is suggested being repeated every 15 (in-filed), 45 (laboratory) minutes. All reflectance measurements are derived from a reference panel’s calibrated reflectance features.

2.2 Preliminary experiments

To reveal the drawbacks of generally used measuring method I performed a preliminary experiment on grounded soil, cloddish soil, wheat kernel and maize kernel samples. Measurements were performed in repetition on same, undisturbed samples. ‘Uncertainty’ was assessed by calculating and comparing the results’ standard deviation (OMH, 1995). The following uncertainty factors have been identified:

- Lack of standard time between reference and sample measurement
- Lack of constant sensor height (measuring height)
- Dependence of illumination direction

- Lack of standard sample-layer thickness
- Uncertainty of contact measurement

2.3 New examination procedure

In order to validate, minimize and eliminate the factors identified in preliminary experiment I have designed and built a unique sample rotating system. It is capable of rotating the sample over a wide range of RPM. Measuring height can be adjusted precisely. Based on the rotating system I have worked out a new near-contact examination procedure that combines the advantages of external illumination-based and contact measurements, on the other hands it is free from its drawbacks. By using 1 [mm] of measuring height the atmosphere has no effect yet and the measurement is not tainted with uncertainty of taction. This way the sensor-head and white reference panel will not contaminate (Fig. 2).

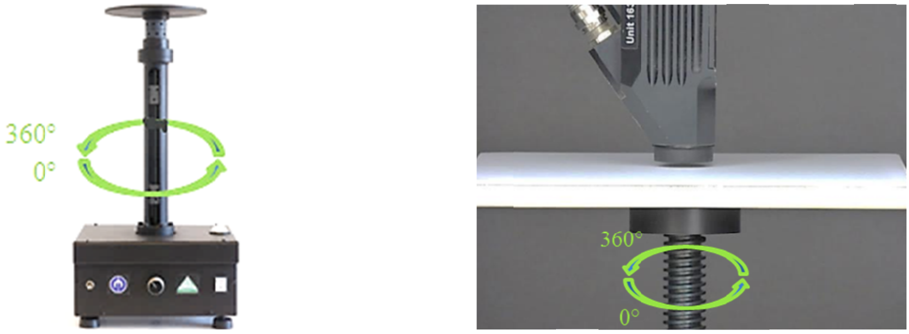

Figure 2: Sample rotating system (left) and near-contact examination procedure improved with rotating (right).

To achieve the best measuring accuracy I have standardized (36 [s]) the time between white reference and sample measurement. White reference is measured prior all measurements. Rotation of the sample during the measurement (12 [s]) is continuous. Efficiency of the procedure is 1 [sample/min.].

2.4 Production trial

In parallel, I performed periodical in-field measurements on the experimental sight of Szent István University, Faculty of Agricultural and Environmental Sciences in Hatvan-Nagygombos region to study the spectral characteristics of winter wheat varieties. Five (Alföld 90, Mv Csárdás, Mv Magdaléna, Mv Suba, Mv Toborzó) winter wheat varieties were evaluated at three different level of nitrogen supply (0, 80, 120 [kg/ha]), in four repetition, in three successive crop year (2010, 2011, 2012). Measurements were carried out in tillering, prior to heading and before harvesting. The spectra collected in tillering phenophase were not processed due to the intense effect of soil.

2.5 In-field measurement of wheat stand

Concerning the continuously varying environmental conditions the generally used in-field procedure's accuracy is acceptable.

Measuring height was set to 80 [cm] above the average height of wheat (Fig. 3). In case of using 25° field of view it means approx. 0,5 [m^2] pixel size (~300 wheat ears). I recorded 5 spectra on each plot, 1 [spectrum/position], 20 [spectra/treatment].

Figure 3: In-field measurement

2.6 Laboratory measurement of seed

For seed evaluation I used my new near-contact examination method improved with sample rotating system (Fig. 4). Cleaned seed samples were measured at equilibrium moisture content (14 [%]), without putting back the same sample. I recorded 5 spectra from each sample, 1 [spectrum/position], 20 [spectra/treatment]. The volume of the sample holder is ~ 50 [cm^3] (1600-1700 kernels).

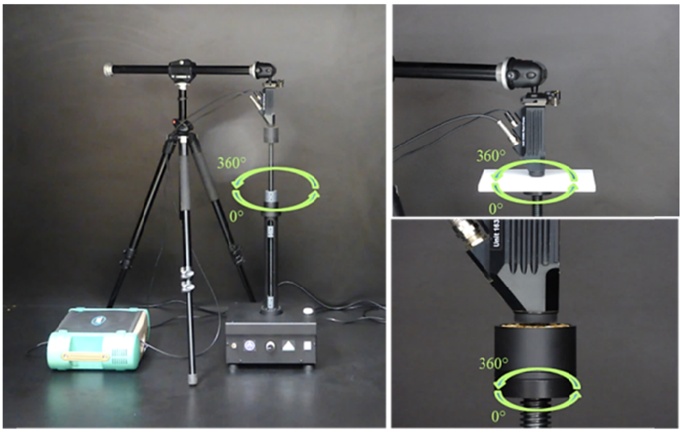

Figure 4: Laboratory examination of seed

2.7 Spectrum processing

I used ViewSpec Pro software to sort and check the spectra. Data processing was carried out at the external Agricultural Engineering Department of Szent István University, Faculty of Mechanical Engineering with Matlab 2010a (Matworks) compatible PLS_Toolbox (Eigenvector research Incorporated) application. For data processing I used the adequate order of selected mathematical and statistical procedures used in chemometrics combined with supervised classification. Among the supervised classification techniques I selected the PLS DA (Partial-Least-Square-Discriminant-Analysis) classification method.

As raw data shows no characteristic absorption peaks or other specific features - that would make possible the identification of wheat varieties - statistical evaluation is necessary. During the spectrum analysis not simply the changes in reflectance values on certain wavelengths but the relation of these values and the function features of curve are also informative.

2.7.1 Pre-processing of spectra

Certain transformations facilitate the statistical comparison of results (for ex.: normalizing, scaling, logarithmic transformation). These are the conditions of uniform data management. Other transformations emphasize the useful information for the classification model while reducing noise.

2.7.2 Classification

The recorded spectral information is extensive. A unique spectrum contains 2151 variables. These are reflectance values recorded on each band, in case of all varieties and treatments. The number of variables has to be reduced. The aim is to identify or create such variables which correlate the best with the characteristics of varieties. Features of a variety cannot be quantified.

Similarly to principle component analysis the PLS regression is a data compressing method. However, during the regression, it considers the characteristics of both independent (spectra) and dependent variables (variety class). It generates statistical correlation between the two variables by creating latent variables.

Treatments were evaluated in groups composed upon variety and crop year. During calibration the model received known classes. During validation it received unknown classes from independent crop year. The number of latent variables was determined upon highest described variance and lowest calibration classification error.

3. RESULTS

Preliminary test results, unique measuring procedure, in-field and laboratory measurement results are presented in the following.

3.1 New laboratory examination procedure

By calculating the standard deviation of reflectance values on each wavelength band one can receive the deviation curve of spectra. These are discrete points (2151 unique points). With the generally used procedure in case of grounded soil, cloddish soil, wheat and maize kernels samples the following deviation spectra were received (Fig. 5).

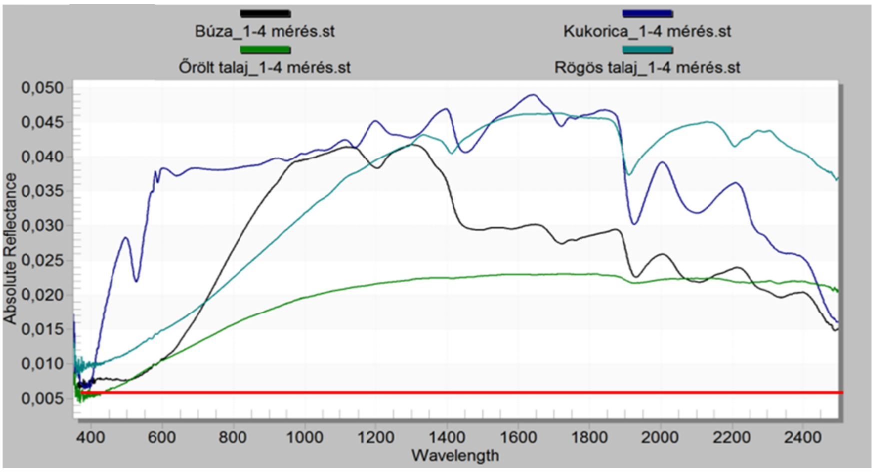

Figure 5: Obtainable deviation with general procedure

By using the new examination procedure the deviation dropped below the red line. The results of repeated measurement are presented below (Fig. 6).

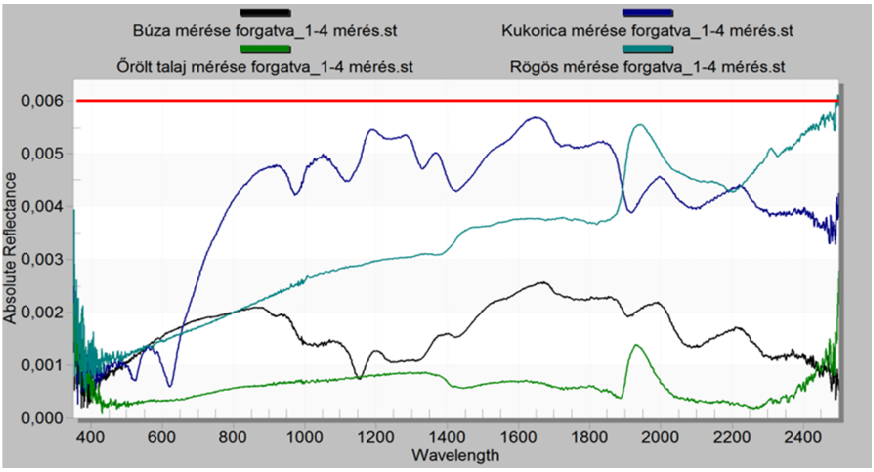

Figure 6: Obtainable deviation with the new examination procedure

3.2 In-field measurements of wheat stand

Classification in various phenophases was performed by using the data of different crop years. Results are presented in the dissertation, in detail. Best results of validation are presented in the followings.

3.2.1 In-field measurements prior to heading

In case of calibrating the model on one crop year's data the classification (prior to heading) was successful. Based on calibration files of 2010 crop year the overall accuracy was 97,66 [%]. Amendment of calibration samples can further increase the efficiency of model. Classification results are summarized (Table 1). Statistical distribution of data is illustrated (Fig. 7).

Table 1: Results of validation: samples from 2012 (horizontally), classification of independent samples based on the calibration dataset of 2011 crop year (vertically)

Confusion Table (Val)					
	Alföld 90	Mv Csárdás	Mv Magdaléna	Mv Suba	Mv Toborzó
Predicted as Alföld 90	60	0	7	0	0
Predicted as Mv Csárdás	0	60	0	0	0
Predicted as Mv Magdaléna	0	0	53	0	0
Predicted as Mv Suba	0	0	0	60	0
Predicted as Mv Toborzó	0	0	0	0	60

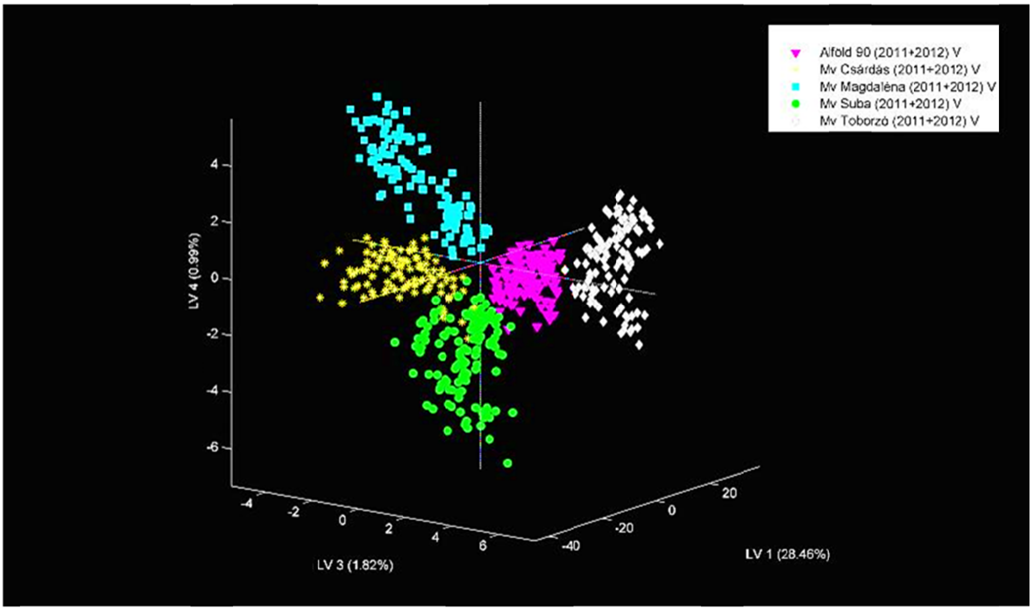

Figure 7: Distribution of wheat varieties (2011, 2012) in a 3D space defined by LV1-2-3 (Alföld 90-magenta, Mv Csárdás-yellow, Mv Magdaléna- turquoise, Mv Suba-green, Mv Toborzó-white).

3.2.2 In-field measurements before harvesting

The classification (before harvest) was already successful even when only one crop year was used as calibration data. Based on calibration files of 2010 crop year the model identified spectra of 2012 crop year with 100 [%] overall accuracy. Based on calibration files of 2011 crop year the model identified spectra of 2012 crop year with 96,33 [%] overall accuracy. Best results were achieved when spectra of 2010 and 2012 crop years were used as calibration dataset. The overall accuracy of the model was 100 [%]. Amendment of calibration dataset or rather increasing the number of crop years definitely increased the model's efficiency. Classification results are summarized in table (Table 2). Statistical distribution of samples is presented in Figure 8.

Table 2: Results of validation: samples from 2012 crop year (horizontally), classification of independent samples based on the calibration dataset of 2010 and 2011 crop years (vertically)

Confusion Table (Val)					
	Alföld 90	Mv Csárdás	Mv Magdaléna	Mv Suba	Mv Toborzó
Predicted as Alföld 90	60	0	0	0	0
Predicted as Mv Csárdás	0	60	0	0	0
Predicted as Mv Magdaléna	0	0	60	0	0
Predicted as Mv Suba	0	0	0	60	0
Predicted as Mv Toborzó	0	0	0	0	60

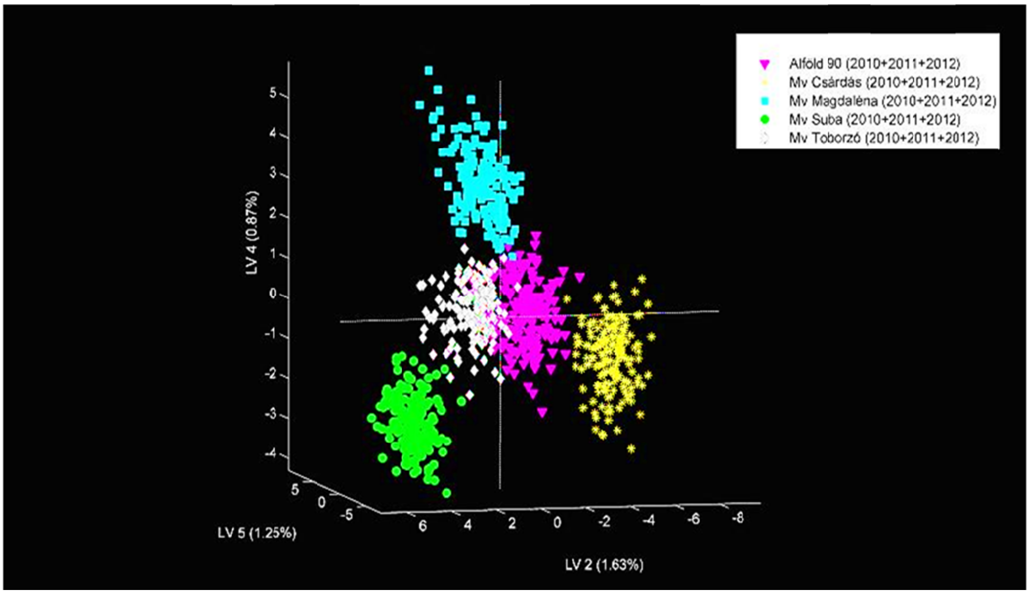

Figure 8: Distribution of wheat varieties (2010, 2011, 2012) in a 3D space defined by LV2-4-5 (Alföld 90-magenta, Mv Csárdás-yellow, Mv Magdaléna-turquoise, Mv Suba-green, Mv Toborzó-white).

3.3 Laboratory measurements of seed samples

Similarly to in-field measurements, evaluation steps of the relation of crop years and the flow diagram of classification procedure for seed examination are presented in the dissertation, in detail. Best results of the validation and its graphical illustration are presented in the followings.

In case of seed examination effective classification was achieved even by using the data of one crop year as calibration dataset. Based on calibration files of 2010 crop year the model identified spectra of 2012 with 95,66 [%] overall accuracy. Based on calibration files of 2011 crop year the model identified spectra of 2012 with 93 [%] overall accuracy. Like previously, best results were achieved when spectra of 2010 and 2011 crop years were used together as calibration dataset. In this case the overall accuracy of model was 96,66 [%]. The worst result occurred in case of Mv Csárdás with 91,66 [%] accuracy. The amendment of calibration dataset by increasing the number of crop years obviously increased the efficiency of model. Classification results are summarized in confusion table (Table 3). Statistical distribution of samples is presented in Figure 9.

Table 3: Results of validation: samples from 2012 crop year (horizontally), classification of independent samples based on the calibration dataset of 2010 and 2011 crop years (vertically)

Confusion Table (Val)					
	Alföld 90	Mv Csárdás	Mv Magdaléna	Mv Suba	Mv Toborzó
Predicted as Alföld 90	58	0	1	0	0
Predicted as Mv Csárdás	0	55	0	0	0
Predicted as Mv Magdaléna	1	0	59	0	1
Predicted as Mv Suba	0	2	0	59	0
Predicted as Mv Toborzó	1	3	0	1	59

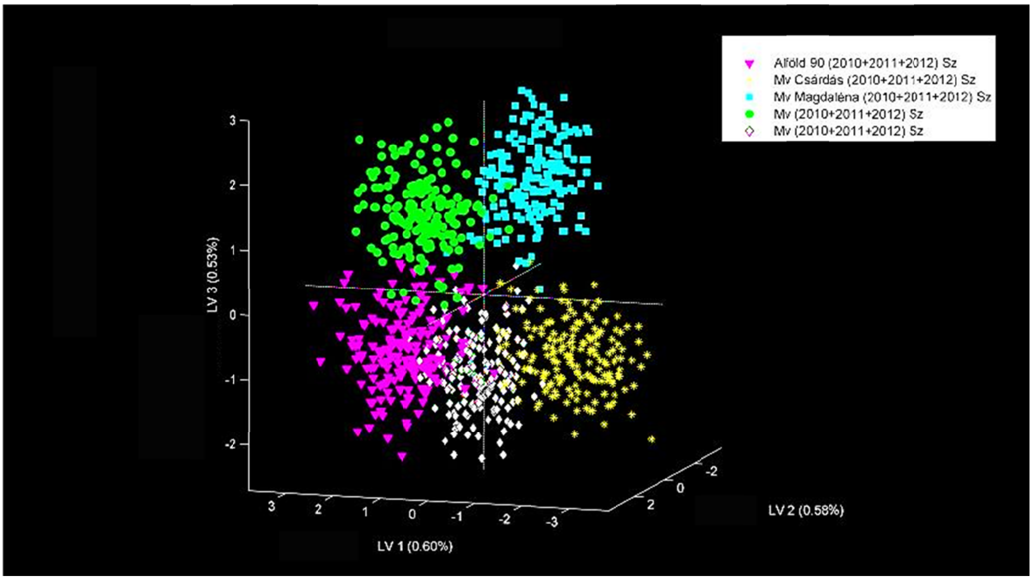

Figure 9: Distribution of wheat varieties (2010, 2011, 2012) in a 3D space defined by LV1-2-3 (Alföld 90-magenta, Mv Csárdás-yellow, Mv Magdaléna-turquoise, Mv Suba-green, Mv Toborzó-white).

3.4 Variation of discriminative features of wheat as a function of time

In case of different phenophases or samples the five selected latent variable described significantly different levels of variance. Highest level of variance of results was described in case of wheat stands prior to heading, 20,46 [%]. In case of seed samples this number went down to 0,82 [%] which means two orders of magnitude. Results of 2010 crop year are summarized in Table 4.

Table 4: Comparison of variance level described by latent variables used in the model in case of two wheat stand phenophases and in case of seeds.

	In-field measurements prior to heading (described variance in X [%])	In-field measurements before harvesting (described variance in X [%])	Laboratory measurements of seed (described variance in X [%])
LV 1	20,46	8,52	0,82
LV 2	2,17	3,23	0,76
LV 3	1,82	1,90	0,73
LV 4	0,99	1,50	0,71
LV 5	1,64	1,86	0,63

Higher percentage of described variance resulted in more effective classification. Scale of the variance defined in percentage is actually the expression of variety-specific spectral feature hidden in the sample dataset. In a certain dataset the scale of expression is the existing spectral difference detected among varieties.

4. NEW SCIENTIFIC RESULTS

The new scientific results on the area of laboratory spectroscopy and spectrum-based winter wheat classification achieved during my research work are the followings:

1. Sample rotation-based near-contact procedure

I have worked out a new examination procedure to minimize (dependence of illumination direction), in certain cases, to eliminate (uncertainty of taction, changing of measuring height, sample layer thickness) factors responsible for the measuring uncertainty.

I have proven the existence of uncertainty factors occurring during an open-system-type laboratory measurement. I have proven that uncertainty can be reduced by standardizing the time between white reference and sample measurements. Using a self-manufactured modular laboratory equipment I have justified the role of uncertainty factors originated in changing measuring height, illumination direction and sample layer thickness. I have also justified the possibility of minimizing and eliminating them. By using the new equipment I have worked out a near-contact procedure which ensures contactless measurement but still excludes the atmospheric effect. Contactless measurement excludes surficial disturbance of sample, contamination and damage of sensor and reference surface. Combining the procedure with sample rotation I have minimized the effect of illumination direction. Compared to the generally used measuring method the standard deviation of new procedure is smaller by one order of magnitude. That means wheat seed samples can be measured with one order of magnitude better accuracy. The procedure can be generally used in open-system-type laboratory measurements.

2. Variety identification of wheat stands

I have proven the possibility of winter wheat varieties' spectral segregation prior to heading phenophase. I have justified that using my spectral library as calibration dataset my spectrum transformation and model developing procedure is capable of identifying wheat varieties upon in-field measurements. By modifying the procedure I have extended and validated the model on pre-harvest wheat stands. I have proven the possibility of winter wheat variety classification/identification based on in-field measurements carried out before harvest.

I have proven that classification/identification procedure is not sensitive for various nitrogen supply and crop years. However, evaluation of sight-specific characteristics of varieties is recommended on other production sights.

3. Spectral seed identification procedure

I have extended and validated the procedure on seed samples. By using the combination of the new laboratory examination and data processing procedure I have proven the possibility of crop year independent identification of wheat variety upon seed samples.

With a seed-specific spectrum transformation procedure I have developed a model that effectively identifies wheat varieties upon seed samples. The procedure works on clear seed samples, at uniform moisture content under laboratory conditions. Identification works even with samples from different crop years.

I have proven that classification/identification procedure is not sensitive for various nitrogen supply and crop years. However, evaluation of sight-specific characteristics of varieties is recommended on other production sights.

4. Variation of discriminative features of wheat as a function of time

I have proven that spectral difference amongst wheat varieties depends on the phenophase of wheat. I have justified that the biggest spectral difference is during photosynthetically active period of wheat stand while the slightest different among varieties is in form of kernels.

I have demonstrated that manifestation of variety-specific spectral characteristics used for identification is more defined in case of entire wheat plant (prior to heading) than in case of seed (wheat kernels). In case of seed samples the manifestation of varietal features or rather its detectability – despite of stable laboratory conditions – is two orders of magnitude smaller than in wheat stands, studied with in-field measurement method.

5. CONCLUSIONS AND SUGGESTIONS

Practical importance of results in spectroscopy

The general examination procedure is tainted with significant uncertainties. By minimizing, or rather eliminating uncertainty factors the measuring accuracy can be greatly improved.

Through the use of standard measuring-time-based and rotation-improved procedure the standard deviation of measurements decreases with one order of magnitude. The procedure minimizes the effect of atmosphere and dependence of illumination direction, furthermore eliminates the uncertainty originated in physical taction. It also improves reliability even in cases where external illumination or increased sensor height are used. It provides precise and repeatable and constant sensor height even if the white reference panel's and sample holder's heights differ. It is highly recommended to evaluate the transmittance of sample materials prior to measurements. This affects the optimal thickness of sample layer. Depth of the sample holder must be selected accordingly.

Practical importance of results in wheat production

In-field measuring protocol and my new examination procedure proved to be adequate to build the appropriate spectral libraries. Spectrum transformation procedure and PLS DA models effectively identify wheat varieties.

A reliable system that can identify wheat stands and capable of classifying/identifying wheat kernels can establish new basis of sowing-seed production and royalty system. The generalization of the procedure for other grown varieties with in-field or airborne remote sensing and spectral examination of wheat kernels and building of spectral libraries can be started in the three years of DUS evaluation. In this case a new variety has a spectral library of three years already at the beginning of conventional growing. Measurements are to be performed on the experimental fields of variety testing stations at characteristic nutrient supply levels (0, 80, 120 [kgN/ha]). Thus, the sight-specific features of varieties will reveal and being built into the spectral libraries.

Integration of airborne remote sensing to the royalty system can establish the basis of a national advisory system. Information obtained from regular monitoring can be used for effective yield estimation, plant protection forecast and to study the wheat varieties' sight specific (and nutrient specific) efficiency.

Airborne remote sensing can be a cost-effective tool of data supply on large areas in an integrated advisory system. Through the continuation of the research classification/identification can be extended gradually to other cultivated plants.

6. SUMMARY

Within the frame of dissertation I studied the procedure of open-system-type spectral measurement by using an ASD FieldSpec3 MAX spectroradiometer.

As a result of testing the generally used laboratory procedure I have defined several uncertainty factors. Uncertainty can be significantly reduced with an advanced procedure. The solution, instead of contact measurements, is the near-contact measuring procedure. In order to reduce the uncertainty factors and to develop a near-contact procedure a new laboratory equipment was introduced.

I have designed a modular sample rotating system with high load capacity. Resulting from adjustable RPM the system is capable of supporting various measuring devices and procedures. It provides opportunity to to develop new examination procedures. I have performed a unique methodological development. By applying an improved near-contact examination procedure and using a rotating system I have minimized the atmospheric effect and direction-dependent illumination factor and excluded uncertainty that has been originated in taction. The new examination procedure has significantly increased the repeatability of measurements.

In the meantime, I was working at adapting remote sensing in winter wheat production system. Upon my hypothesis, in-field and airborne remote sensing provides opportunity to identify varieties. This would provide a solution to control the certified sowing-seed usage on large areas, in economic way. Seed identification can become the future of postharvest separation system based sowing-seed production. Better tracking and control could be the fundament of plant selection, maintaining variety pedigree and quality seed production.

On the experimental production sight of Szent István University, Faculty of Agriculture and Environmental Sciences I examined five wheat varieties at three different level of nutrient supply, in 2010, 2011, 2012 cropyears. In-field measurements were carried out prior to heading and before harvesting. Harvested yield was sampled and measured under laboratory circumstances.

By using my own examination procedure spectral libraries were built and PLS DA model was used. Results were validated on independent datasets of different crop years. The possibility of variety classification has been proven in. Augmentation of calibration datasets has increased the efficiency of classification. I have performed a successful classification/identification – independent from crop year and nutrient supply - based on variety-specific spectral signatures.

It is recommended to extend the models onto airborne hyperspectral images and test the procedure on other wheat varieties and field lands.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Articles in foreign language:

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3. Szőke CS., Virág I. , **Szalay D. K.**, Bónis P., Fenyvesi L., Marton L. C., Neményi M. (2012): Investigation of Fusarium ear rot symptoms on maize (Zea mays L.) using a spectroradiometer. Journal of Agricultural Sciences, Debrecen 50: pp. 50-53.
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5. **Салаи К. Д.** (2013): Использование прогрессивных научных методов измерений и сбора информации в цовременном цельцком хозяйстве (Advanced evaluation methods and information management in modern agriculture). Series of Agricultural Sciences 2013, 2 (14), Almaty, NAS RK, pp. 44-51.

Articles in Hungarian language:

6. Deákvári J., Kovács L., **Szalay D. K.**, Tolner I. T., Csorba Á., Milics G., Virág I., Balla I., Kardeván P., Fenyvesi L. (2011): Parlagfű-detektálás hiperspektrális távérzékelési eszközökkel. Mezőgazdasági Technika LII. évfoly. 2011. március, 2-5. o.
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8. **Szalay K. D.**, Bellus Z., Deákvári J., Csorba Á., Polyák D., Tarnawa Á., Jolánkai M., Fenyvesi L. (2013): Gabonafélék fertőzöttségének vizsgálata spektroszkópiával. Mezőgazdasági Technika, LIV évf. 9. szám, 2-5. o.