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# Yield measurements in a self-propelled forage harvester by means of X-rays

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## Abstract

Currently available yield monitoring systems for self-propelled forage harvesters do not meet the requirements. Therefore, X-rays were investigated for this purpose. Two different test rigs have been constructed. The first test rig was employed for static experiments. With it different masses of chaff (grass and maize) and with different moisture contents could be monitored. Also, different distribution patterns of the chaff in the path of rays could be investigated. The results displayed a strong correlation ($R^2$ = 99 %) between the mass and the measured voltage signal. For the moisture content no significant influence could be detected. On the other hand the distribution pattern affects the reading. With the second test rig the mass flow in a spout of a forage harvester was simulated and throughput measurements have been carried out. The calculated coefficient of determination was about 80 %. Finally, the mass of the chaff, which was blow through the spout was determined ($R^2$ = 90 %).

**Keywords: forage harvester, yield measurements, X-rays**

## 1 Introduction

One primary basis of precision farming is local yield monitoring. It delivers information required for site specific planting or fertilizing. Also, it enables the performance of other tasks, like precise adding of preservatives to feed or calculating the accurate costs for harvesting operations carried out by contractors.

For combine harvesters yield measurement systems are available for almost two decades, now. For other harvesting machines, like forage harvesters, suitable systems are still missing. This is mainly caused by a variety of influencing parameters like rough environmental conditions, high chaff velocities and chaff masses and densities (Kormann, 2004).

In the past, different approaches have been chosen for detecting the yield respectively the forage throughput in the forage harvester. Missotten et al. (1997) tried to determine the throughput with an impact plate resting on a force sensor. It was installed at the end of the spout. The results of their tests demonstrated satisfactory accuracies only in part. Another commonly employed method for yield measurements was to determine the distance between the first pair of feed rolls at the header. It was shown that this method is influenced by different chaff compression and the resulting fluctuation of its density (Ehlert, 1999). Demmel (2007) investigated the energy absorption of the cutterhead as factor for the throughput. Also, several influencing parameters, e.g. knife sharpness, interfered with the mass flow measurements.

Investigations with radiometric measurement systems have been carried out in the 1990'ies (Auernhammer et al., 1995; Kormann, 2004). The radiation source was a gamma emitter. The gained accuracies have been higher than with other methods, but due to concerns about a radioactive source on a harvesting machine this system was not accepted. Wild et al. (2003) used a pulse radar system. With it the radiation could easily be turned on and off, but the low penetration depth when investigating very moist chaff was disadvantageous in this test trials.

Therefore, the objective of this project was the development of a mass flow system based on a radiometric measurement device, which allows turning off the radiation and provides a sufficient penetration depth. These requirements are met by X-ray and therefore this technology should be employed.

## 2 Materials and methods

The X-ray attenuation caused by an object is determined by its atomic number, the density and the thickness of the irradiated material. If the transmitted radiation is measured it can be concluded how much mass was in the path of rays.

For examining the usability of an X-ray based system for yield monitoring in a forage harvester two test rigs, one for static and one for dynamic tests, have been developed and constructed. With them influencing factors should be determined and ways for elimination should be investigated, too. Both test rigs consisted of an X-ray tube for generating the radiation and an ionisation chamber for detecting the arriving X-rays. The voltage signal measured at the ionisation chamber presented the amount of ionisation processes along the entire path of radiation respectively the irradiated mass.

### 2.1 Test rig for static measurements

For static measurements the test rig with a X-ray tube, sample container and voltage-generating ionisation chamber was used. In this application a maximum acceleration voltage of 50 kV (X-ray energy of 50 keV) and a current flow value of up to 1 mA was generated. The metal sample chamber could be fed with 11 l of chaff for testing different amounts of grass (freshly cut and ensiled) and maize (due to the lack of fresh material only ensiled) with various distribution patterns. In the test trials, the sample box contained sample sizes between 0.2 kg and 2 kg and sample thickness of up to 105 mm. When the aperture of the X-ray source was opened, the radiation emitted at an angle of β = 35° (Fig. 1).

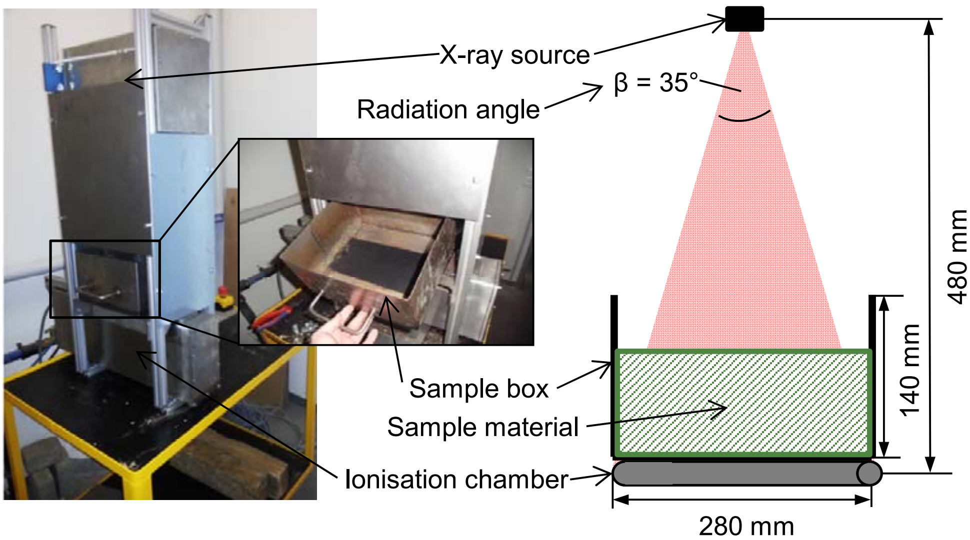


*Figure 1: Test rig and test setup for the static measurements*

The cross section of the sample container was in accordance with the cross section of the spout of a forage harvester. To reduce the X-ray material absorption of the sample container, the floor of the sample container was made out of polyethylene. Thus, the experimental set-up reduced the X-ray voltage minimally.

Similar to the situation in the spout of a forage harvester, where an even chaff distribution is not always present, investigation on various grass and maize chaff distribution patterns were part of the tests. At the same time the mass of the analysed sample material was kept constant. The various distribution patterns of the sample material are displayed in Fig. 2.

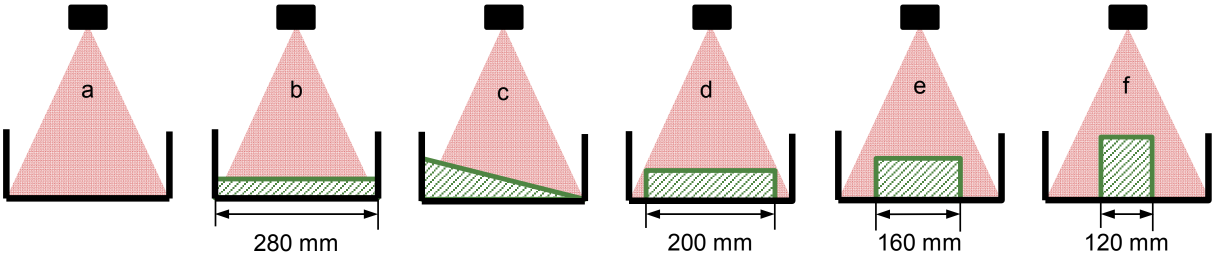


*Figure 2: Investigated distribution patterns of the sample material for static measurements*

In addition, the influence of different moisture contents of the sample material was examined. The moisture content ranged from 25 % to 85 %. It was identified with a NIR spectroscope.

## 2.2 Test rig for dynamic measurements

The main component of the second test rig was a blower, commonly employed for filling a silo. It was powered by the PTO of a tractor with a rotational speed of 600 rpm. At the outlet of the blower a usual spout of a forage harvester was installed. Thus, the mass flow was similar to the mass flow in the spout of a forage harvester (Fig. 3).

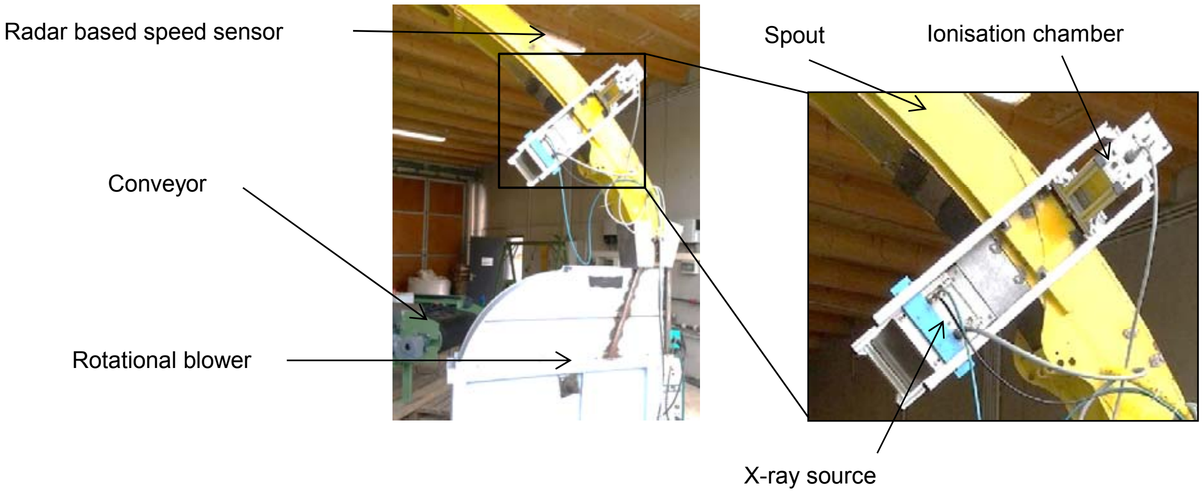


*Figure 3: Test rig for the dynamic throughput measurements*

For feeding the blower with chaff, a conveyor belt of 5.80 m length and 1.30 m width was used. The blower forwarded the chaff into a container with a moving floor. The container rested on a scale so the total mass of blown chaff could be determined. From there the chaff was transferred to the conveyor belt. Therefore, a closed loop was established.

About 2 m above the rotor of the blower the X-ray source and the detector unit were attached at the spout. For controlling the speed of the chaff a radar based speed sensor was located next to the X-ray device.

For simulating various mass flows through the blower different amounts of chaff have been placed on the conveyor belt and the belt was employed with several velocities. The mass of chaff differed between 10 kg and 50 kg per trial, which corresponded to a mass flow range of 5 kg/s to 18 kg/s. The sampling rate of the measurements was 1000 Hz for gaining detailed information about the voltage signal and the chaff speed. In addition, a low-pass filter of 10 Hz suppressed undesirable higher-frequency signals. Afterwards, a weighting of the voltage signals with the speed data was performed to achieve comparable, speed depending detector signals.

## 3 Results and discussions

### 3.1 Static measurements

Initially, the static tests should confirm in accordance with the theoretical background the exponential correlation between the absorbing material and the X-ray signal. Also, the measurements should obtain knowledge about the behaviour of radiation when penetrating grass and maize samples with particular attention to chaff mass, chaff distribution as well as chaff dry matter content.

The voltage signal caused by the ionisation processes decreased exponentially when increasing the mass which corresponds with the thickness of the sample in the sample box (Fig. 4).

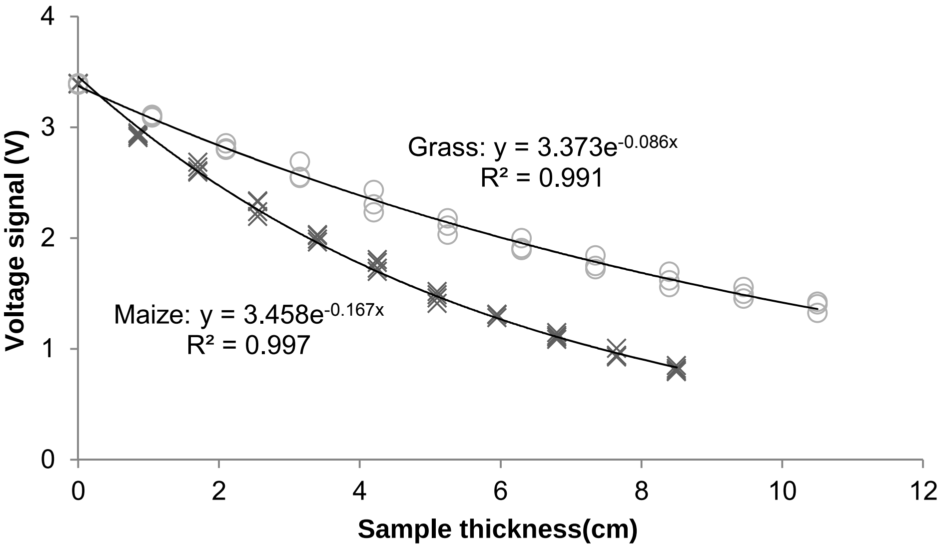


*Figure 4: Correlation between sample thickness and detected voltage signal (n = 3)*

For both tested materials a coefficient of determination of more than 99 % could be calculated. For grass it was 0.991, for maize 0.997. A comparison between fresh und ensiled grass displayed no significant different in the voltage signals. The moisture content of all material was in about the same range (~ 65 %).

The linear attenuation coefficient is calculated by $\alpha_g$ = 0.086 $cm^{-1}$ for grass chaff and $\alpha_m$ = 0.167 $cm^{-1}$ for maize chaff. The voltage signal decrease is stronger for maize chaff than for grass chaff. This is due to the higher density and therefore due to more mass for a certain sample thickness.

Varying the distribution pattern of the chaff in the sample box results in significant differences in the detected voltage signals (Fig. 5).

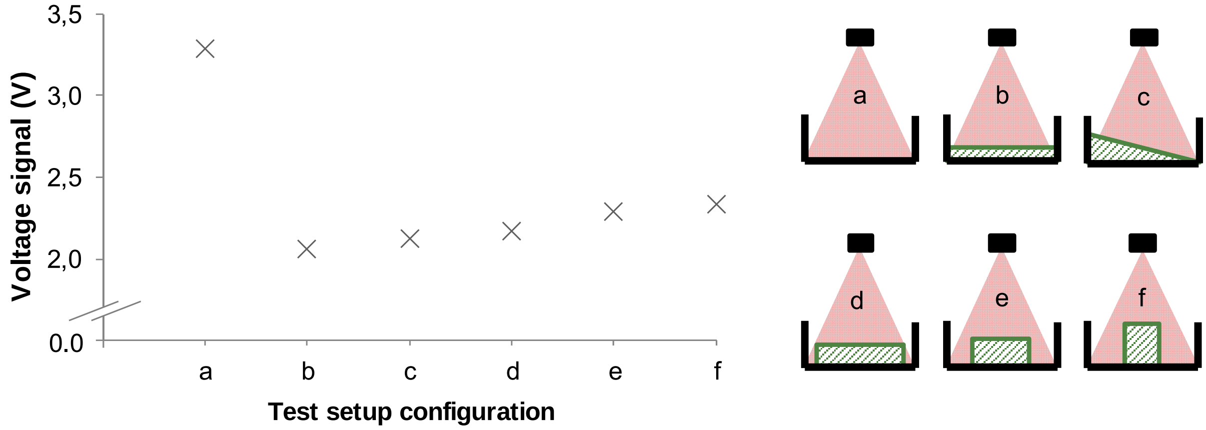


*Figure 5: Correlation between distribution pattern and voltage signal*

For configurations “b” to “f” the same amout of chaff was used. From configuration “d” towards “f” the thickness of the chaff increases as well as the area of the floor of the sample container, which is not covered with chaff. Again, the results displayed the exponetial correlation between the thickness of the chaff and the attenuation or voltage signal.

The influence of the moisture content of the chaff is not very distinctive (Fig. 6).

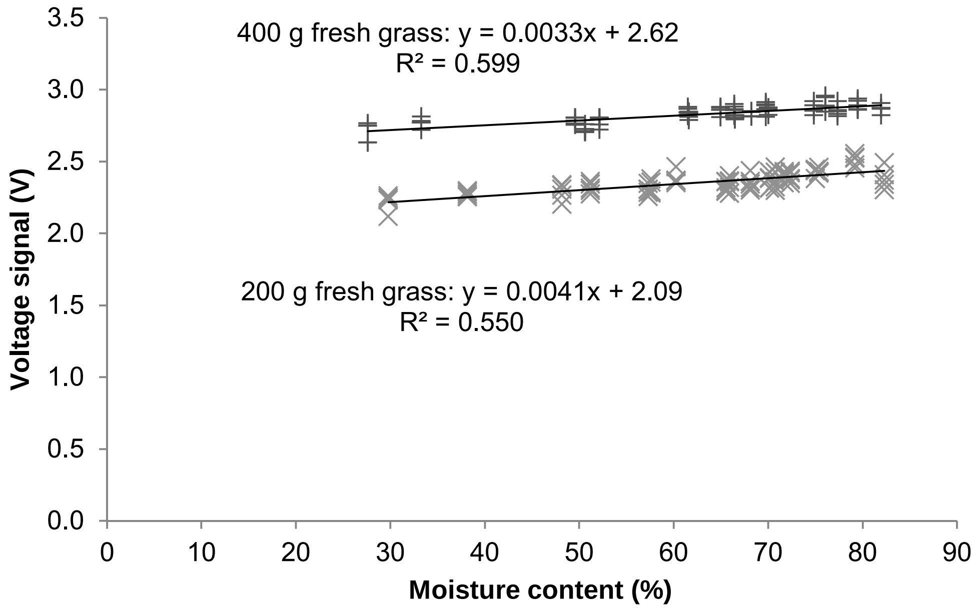


*Figure 6: Correlation between the moisture content of fresh grass and detected voltage signal*

The detected maximum coefficient of determination reaches approximately 60 % only. The difference in the voltage signals between the samples with the lowest moisture content and the samples with the highest moisture content is merely about 5 %.

## 3.2 Dynamic measurements

The second test rig was employed to detect the correlation between the throughput and the measured voltage signal. In order to develop a transfer function, the speed of the chaff in the spout had to be taken into consideration by the transfer function, too. The following transfer function is based on 45 trials, which have been carried out with grass chaff (moisture content about 64 %). Statistical tests revealed that an exponential function provides the best fit (Fig. 7).

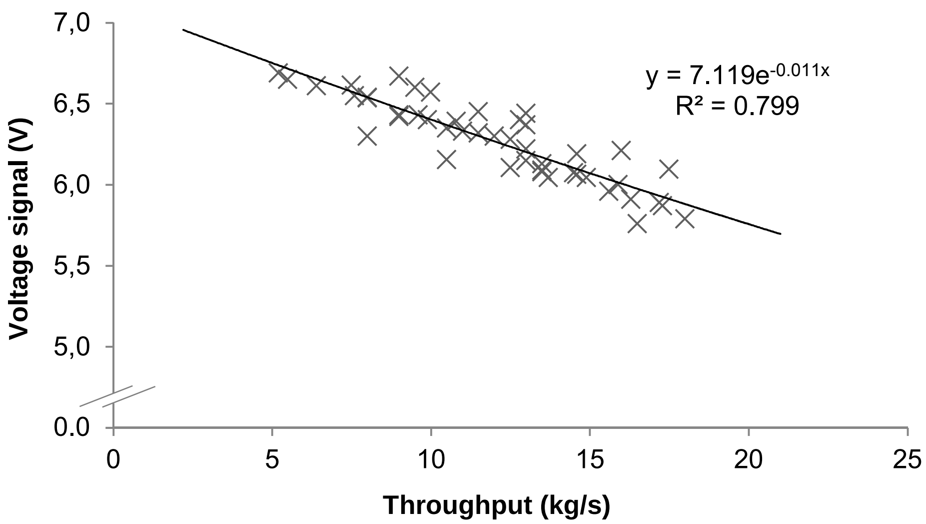


*Figure 7: Transfer function calculated by integrated voltage signal decrease and throughput*

The accuracy is not as high as for the static tests. The coefficient of determination gains about 80 % only.

Next, the transfer function was used to calculate the mass of the chaff which was blown through the spout and compared with the actual mass (Fig. 8).

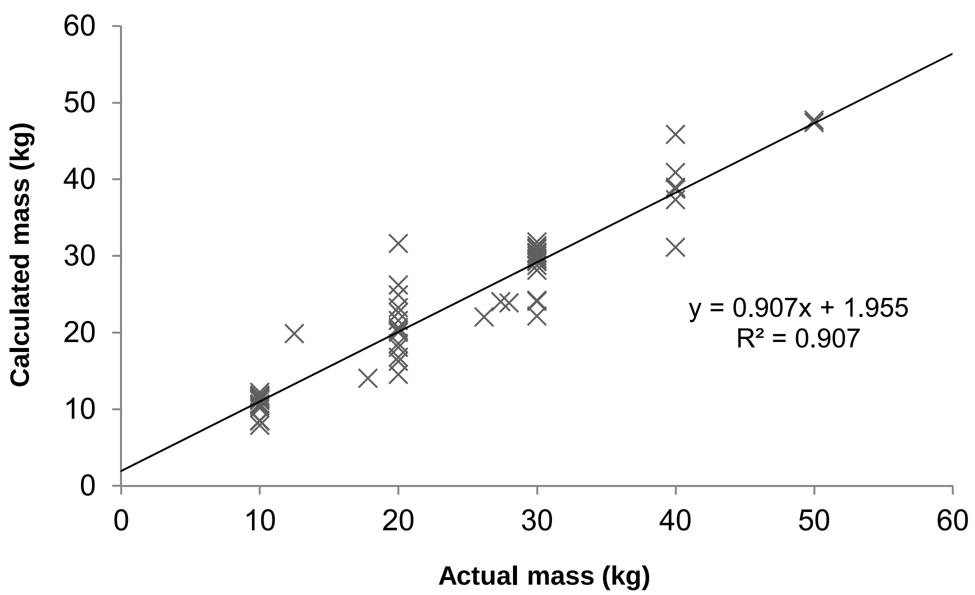


*Figure 8: Correlation between actual and calculated chaff mass (n = 45; grass)*

A coefficient of determination of approximately 91 % could be determined for this comparison. The accuracy is not as high as desired, e.g. for 20 kg actual mass the calculated mass spreads from about 13 kg to 32 kg.

## 4 Conclusions

The results of the static and dynamic tests showed that an X-ray based system has a high potential for mass flow or yield measurements in a forage harvester. With the static experiments, the distinct relationship between the mass and the voltage signals became obvious. Also, parameters which are influencing the measurements appeared. Probably, there are other influencing parameters which have not been determined yet. This might be one cause for the unsatisfactory results of the dynamic tests. But there are other reasons for the low accuracy. The transfer function needs further development. Also, the number of trials has to be increased and material with different structure has to be investigated. Afterwards, the system has to be configured for running on a forage harvester. The conditions on this harvesting machine are much more severe than on the test rig. Finally, tests have to be carried out in the field.

## 5 References


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