Performance evaluation of standard and extended InGaAs detector array spectrometers

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Introduction

Array detectors are proving themselves more and more useful in applied spectroscopy. Spectrometers based on array detectors offer many advantages such as capability to record a full spectrum typically using 128, 256 or 512 pixels, high speed, lack of moving parts, wavelength repeatability and compatibility with fiber optics for flexible process interfacing. Figure 1 presents a schematic of a typical detector array based spectrometer. Array detectors operating in the near infrared region (NIR, 0.75–2.5 μm) are potential for process measurement applications but there is only limited information available on the performance tradeoffs between the various technology options.

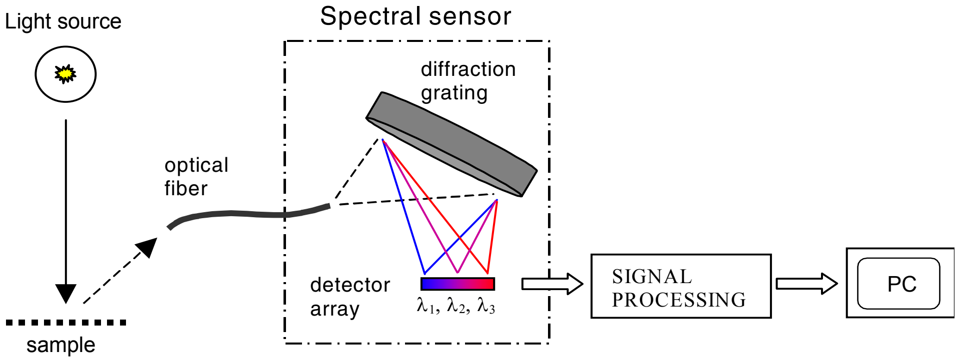

Figure 1. Schematic of a detector array based spectrometer.

VTT Electronics has studied commercial spectrometer units based on PbS (Lead Sulphide), standard InGaAs (Indium Gallium Arsenide) and extended InGaAs array technologies. Main objectives of the evaluation were to determine linearity, instrument noise as well as spectrometer system stability in varying ambient temperature. Commercial spectrometers evaluated were Zeiss MCS 511 NIR,[1] TQA Analyser,[2,3] J&M Tidas[4] and Hamamatsu PMA-11 series C8147-38.[5] The main specifications of the studied systems are presented in Table 1. A typical miniature InGaAs spectrometer is shown in figure 2.

Table 1. Main specifications.

	Zeiss MCS 511 NIR	J&M Tidas	Hamamatsu PMA-11	TQA Analyser
Technology	InGaAs	Extended InGaAs	Extended InGaAs	PbS
Wavelength range	950–1700 nm	1200–2300 nm	1600–2350 nm	1200–2200 nm
No. of pixels	128	256	256	24
Pixel size	50 x 500 µm	50 x 250 µm	50 x 250 µm	1 x 4 mm
Electronics	Integrator	Integrator	Integrator	Amplifier

Figure 2. Typical miniature InGaAs spectrometer (courtesy of Hamamatsu Photonics).

Experimental

All evaluated spectrometers have an A/D converter with 16-bit resolution. Linearity was determined within this dynamic range by simply measuring different illumination levels for a constant integration time. Different illumination levels were realised by using an adjustable blind together with appropriate beam homogenisation. Ando optical power meter was used as a reference instrument, with a germanium probe AQ-2711 or AQ-1971. The measurements were made for a complete system composed of spectrometer optics permanently aligned in front of the detector array. As detected light has wavelength distribution, only pixels that experienced close to full A/D converter scale were selected for the linearity study.

Signal to noise ratio tests were performed using stabilised illumination (Gilway, part no. L519-G, 12 V/20 W) and Spectralon 99 % reflectance standard. Signal levels were optimised by adjusting integration time for each spectrometer. Signal to noise ratios were mathematically averaged in the cases of J&M and Hamamatsu spectrometers and calculated to noise spectra in the absorbance scale. This yields to an effective 100 ms integration time value which corresponds to Zeiss spectrometer's direct integration time of 100 ms. Input of the Zeiss spectrometer had to be neutral density filtered (OD = 2, T = 1 %) to avoid detector saturation.

The tests for stability of dark current were arranged for the InGaAs spectrometers only. The spectrometers were placed inside a weather chamber and pre-programmed temperature cycling was run through. All spectrometers were equipped with internal temperature stabilisation or cooling, which was operational during the tests. Later it was found, that the set value for temperature stabilisation in J&M was set too low. This impaired the stability results obtained for J&M in the study. Operating temperature recommendations notified by the manufacturers were taken into account when temperature cycling was programmed. The spectrometer was operated in a temperature for a two hour period to ensure time for stabilisation, after which a new temperature level was executed. Depending on the spectrometer, the steps were ± 5 … 10 °C each. Three temperature levels were tested and dark current spectra were recorded during the process.

Results and discussion

Figure 3 presents nonlinearity of photometric scale as a function of normalised reference power for a typical pixel of each spectrometer. Linearity of Zeiss and TQA spectrometers was very good, typically 0.2 and 0.5 percent, correspondingly. The extended InGaAs spectrometers were found to have more nonlinear characteristics. Typical results for J&M ranged from 2 to 6 percent, depending on pixel in question and operating mode. It was possible to operate J&M Tidas in both standard and sensitive modes. Operating modes are implemented by switching between integrator capacitances of a different size. Standard mode was found to be more linear than the sensitive mode. The nonlinearity measured for Hamamatsu was around 3.5 percent peak-to-peak, with a characteristic shape for all pixels. The nonlinearity of the test setup was minimised by design, but is not known. The result measured for Zeiss is likely to be affected by the setup nonlinearity, but the results with higher nonlinearity for the other spectrometers are expected to be reliable.

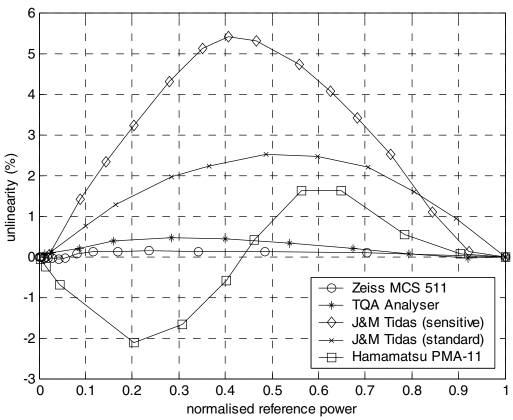

Figure 3. Nonlinearity of photometric scale – extended InGaAs is significantly nonlinear, sensitive and standard modes are different.

Figure 4 presents measured noise in digital numbers (DN) based on signal to noise tests for the three spectrometers. The optimum integration times chosen were 100, 3 and 10 ms for Zeiss, J&M and Hamamatsu, respectively. Hamamatsu can be seen to have the lowest noise using these measurement parameters. The same measurement data was used to calculate noise in the absorbance scale for equivalent integration time of 100 ms, based on averaging 33 and 10 scans for J&M and Hamamatsu, respectively. Averaging reduced noise according to expectations for J&M, from about 30 DN to 7 DN, whereas the noise of Hamamatsu was only reduced from about 8 DN to 6 DN. This characteristic of Hamamatsu may be due to significant 1/f-type noise content in the measured signals. As shown in figure 5, all tested InGaAs spectrometers reached low instrument noise values in their operating wavelength scale, when appropriate integration time and sufficient illumination was used in diffuse reflectance measurements. It is worth to remember, however, that the illumination used for J&M and Hamamatsu was 100 timed higher than for the Zeiss spectrometer, as discussed earlier.

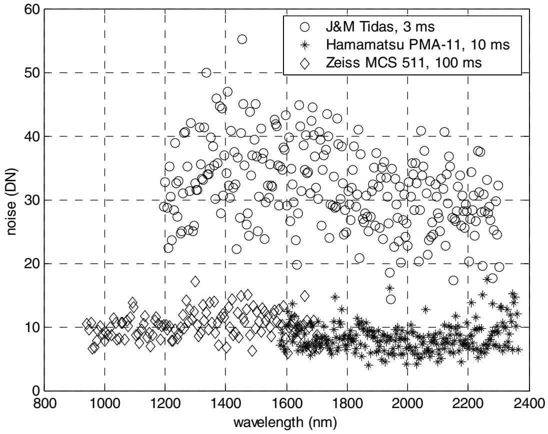

Figure 4. Noise in units of digital number (DN) for spectrometer specific integration time.

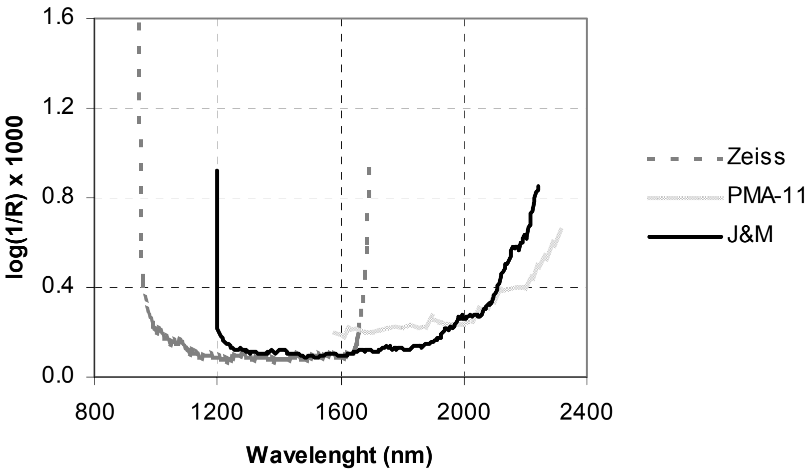

Figure 5. Instrument noise comparison in diffuse reflectance measurements, scans were averaged to equalise integration time to 100 ms.

Figure 6 illustrates dark signal instability of the InGaAs spectrometers based on the measurements in the stability test. The results for J&M are not included, due to problems in the test, as discussed earlier. The data shown was recorded in temperature chamber in two temperatures: +25 °C and +15 °C. The results were calculated to dark signal change in digital numbers per 1 °C and repeated for all pixels corresponding to the wavelength scale of the spectrometer. The changes recorded for Zeiss are very small, but the direction of the change was found to be different for even and odd pixels.[6] The tested extended InGaAs spectrometer (Hamamatsu) seem to have more significant dark signal drift with temperature. The dark signal change recorded seems to vary across the length of the spectrum, which may be due to spatial differences in cooling and thermal stabilisation across the detector array. As figure 6 only presents dark signal change it is also interesting to know its effect on signal when instrument operates in optimal conditions. Figure 7 presents dark signal change in proportion to signal measured with same integration time for both spectrometers. Results show that error in signal is very small for Zeiss spectrometer but the extended InGaAs spectrometer require more frequent dark referencing if ambient temperature is not stable.

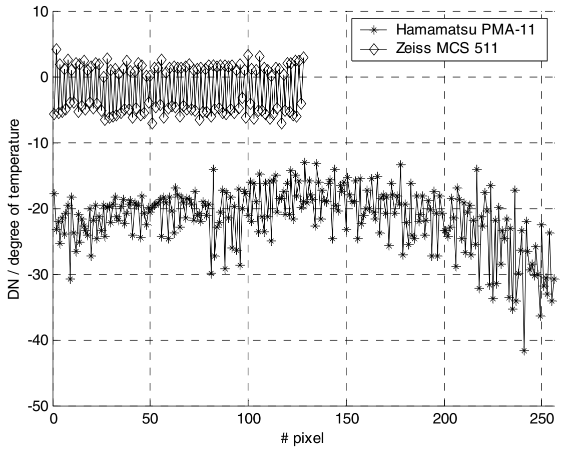

Figure 6. Temperature sensitivity of dark current in temperature chamber, in digital number (DN) per degree Celsius.

Conclusions

Performance testing was arranged for commercial NIR spectrometers based on competing detector array technologies. The tested spectrometers were based on standard InGaAs, extended InGaAs and PbS detector materials. The evaluations made covered linearity of photometric scale, noise characteristics and stability of dark current against fluctuations in ambient temperature. The results obtained for a standard InGaAs spectrometer presented low instrument noise and satisfactory linearity and dark signal stability. The extended InGaAs spectrometers were found to have higher signal nonlinearity ranging from 2 to 6 % and significant dark signal drift due to changes in ambient temperature. Furthermore, extended InGaAs spectrometers require higher level of sample illumination, approximately x100, before they reach ideal signal to noise characteristics. The results of evaluation have produced valuable knowledge and experience, which will be useful in future R&D work for applying these spectrometers in various process monitoring applications.

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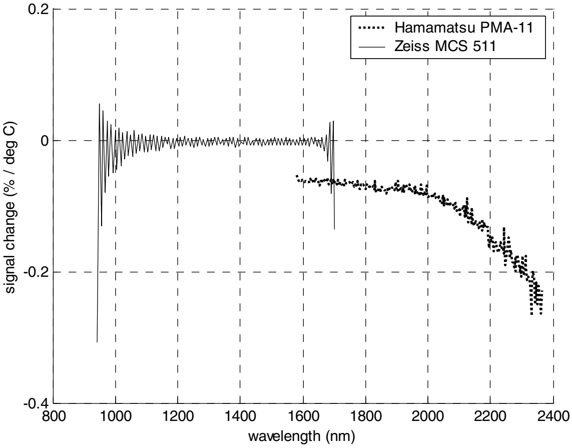

Figure 7. Frequent dark referencing is necessary for extended InGaAs to avoid signal errors: signal error in temperature chamber, in % per degree Celsius.

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