# Next generation echelle spectrometer

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**It has been almost 100 years since the design of the first echelle spectrometer. Over this period the basic design principles have stayed the same. However, 21st century digital cameras, advanced optical component manufacturing, and computer based optical design enable far better performance echelle spectrometers than ever before. Surprisingly, most current echelle spectrometers still do not offer proper light collection efficiency and require a climate-controlled laboratory for stable operation. SPECTRAL Industries offers the first echelle spectrometer that uses the latest developments in camera technology and instrument manufacturing. The result is unmatched performance and robustness at an entirely new price level.**

**Meet IRIS, the next generation echelle spectrometer.**

## Introduction

A typical definition of an echelle spectrometer is a spectrometer that disperses the light in two orthogonal directions using two dispersive elements. Typically, one of these elements is an echelle grating with 50-120 l/mm, but this is not required. An echelle spectrometer is distinguished from other spectrometers by the combination of wide bandwidth (> 500 nm) and high resolution (<< 1 nm). This is achieved by using multiple higher grating diffraction orders from the first dispersive element. The second dispersive element separates the overlapping grating orders in the orthogonal direction, resulting in a ladder ("echelle" in French) type of spectrum projected on a 2D camera as shown in Figure 1.

*Figure 1: Typical echelle image of the IRIS spectrometer*

The combination of a large bandwidth and high resolution is often required in astrophysics applications and optical emission spectroscopy (OES). In this paper, we will focus on OES, since this is a much larger market and Laser Induced Breakdown Spectroscopy (LIBS), a form of OES, is the main application focus of SPECTRAL Industries. The nature of an OES measurement yields the following main requirements for a spectrometer:

- Combination of a large bandwidth and high resolution in order to catch all available peaks and resolve peaks that are close together.
- Gating possibility better than 100 ns.
- Industrial applications: low price and high robustness.

Table 1 shows a tradeoff of the three types of spectrometers commonly used for OES. From this table, it is clear why most industrial applications of OES choose a Czerny-Turner spectrometer. However, most OES applications require between two and six Czerny-Turner spectrometers in order to capture all necessary spectral lines, introducing the issue of synchronization between the individual spectrometers. While one Czerny-Turner spectrometer is affordable, five or six units and sophisticated synchronization electronics makes this a less desirable option.

| | **Pros** | **Cons** |
|---|---|---|
| **echelle** | • Large bandwidth<br>• High resolution<br>• Nanosecond gating possible | • Low optical throughput<br>• High price<br>• Low robustness |
| **Paschen-Runge** | • Large bandwidth<br>• High resolution<br>• High optical throughput<br>• Nanosecond gating possible | • High price<br>• Large volume<br>• Low robustness |
| **Czerny-Turner** | • Low price<br>• High optical throughput<br>• High robustness<br>• Nanosecond gating possible | • Tradeoff between bandwidth and resolution<br>• Often 2-6 units are required to meet the required bandwidth |

*Table 1: Tradeoff between commonly used OES spectrometers*

There is a clear need for a spectrometer that combines all requirements in one instrument. To fulfill this need, SPECTRAL Industries developed the next-generation IRIS echelle spectrometer. The IRIS spectrometer distinguishes itself from other spectrometers because it features all the advantages of an echelle spectrometer, but none of the disadvantages:

- Combination of large bandwidth and high resolution.
- Fast gating (jitter < 10 ns r.m.s.)
- High throughput
- Low price
- High robustness

This paper addresses all of these features.

## Throughput and signal to noise

Low light level applications require a high throughput spectrometer. The detection limits achievable with OES in trace analysis are partly determined by the ability of the spectrometer to efficiently transfer the scarce photons to the detector. The second contributor to the detection limit is the noise of the associated detector.

The optical throughput of a spectrometer is mainly determined by:

- The acceptance NA at the slit: this determines whether the spectrometer is able to capture light from all angles presented at the entrance.
- The slit size: the larger the slit, the more light potentially enters the spectrometer.
- Performance of the coatings and efficiency of the dispersive elements.

The first two points determine the etendue of the spectrometer, which is a direct measure for the throughput of an optical system. The IRIS spectrometer is designed to fully match the numerical aperture of a NA=0.22 multimode optical fiber.

Table 2 compares the IRIS echelle spectrometer to a commonly used Czerny-Turner[1] and a leading commonly used echelle spectrometer[2]. It is clear that the large slit size of the Czerny-Turner is expected to lead to a better light throughput for this type of spectrometer. However, the smaller acceptance angle makes the total theoretical throughput of the Czerny-Turner spectrometer roughly half that of the IRIS echelle. Similarly, the lower acceptance angle of the commonly used "Typical echelle" results in a theoretical throughput of an order of magnitude less than for the IRIS echelle.

| | Acceptance angle (rad) | Slit size ($\mu m^2$) | Etendue ($\mu m^2$.sr) |
|---|---|---|---|
| **IRIS echelle** | 0.22 | 25x100 | 986 |
| **Czerny-Turner** | 0.12 | 50x400 | 411 |
| **Typical echelle** | 0.07 | 50x100 | 80 |

*Table 2: Throughput comparison*

The noise characteristics are equally important for detecting low light levels. Table 3 shows the theoretical noise (dark current + detector read out noise) as reported by the manufacturer of the detectors used in this comparison. Note here that the noise of the ICCD used with the "typical" echelle spectrometer is highly dependent on the intensifier gain. Also, the low noise level is only met when the camera is cooled to -40$^{o}$C, which was indeed done in this study. The latest CMOS technology as used in the IRIS spectrometer exhibits equivalent noise levels at room temperature.

To compare the three spectrometers by their actual performance, identical measurements of a mercury argon calibration lamp were performed with all three, as shown in Figure 2. All measurements were taken with an integration time of 1 ms. Camera gain was set to reach the best signal to noise (S/N) ratio for each system.

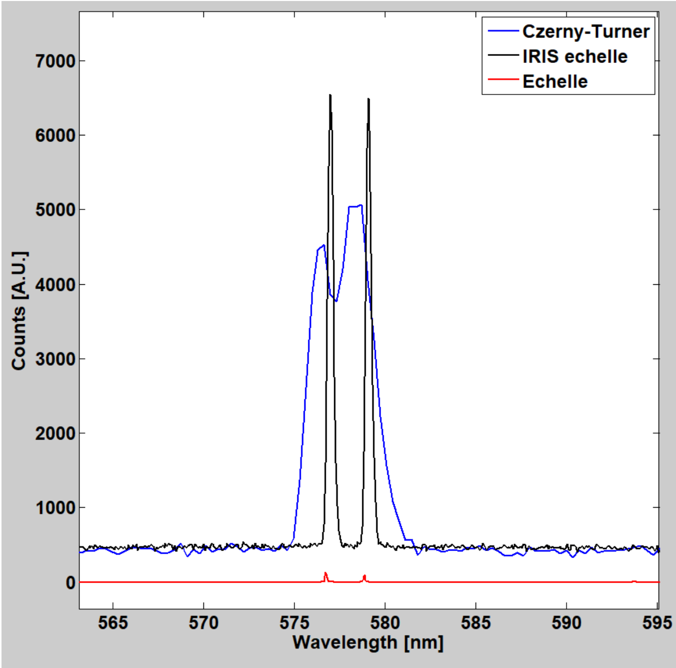


*Figure 2: Spectrometer comparison*

| | Camera noise (e-) | Measured S/N | Normalized S/N |
|---|---|---|---|
| **IRIS echelle** | 7 | 8081 | 1 |
| **Czerny-Turner** | 50 | 1960 | 0.24 |
| **Typical echelle** | 5 | 677 | 0.08 |

*Table 3: S/N comparison*

Figure 2 clearly shows that the light throughput of the IRIS echelle is superior to that of the other spectrometers. If we calculate the S/N ratio as shown in Table 4, the difference is even more evident. The signal is defined as the area under the peak and the noise as the standard deviation of an adjacent part of the spectrum that contains no signal.

## Gating

For more accurate and reproducible OES measurements, signal gating is essential. After a plasma has been created and as it begins to cool, the electrons will decelerate, resulting in broadband Bremsstrahlung emission. This "white" background signal will increase the measurement

[1] For comparison a single spectrometer with a comparable overall bandwidth is used, resulting in a low resolution.

[2] For this study a widely used echelle spectrometer is used in combination with an ICCD.

shot noise, reduce the camera effective dynamic range and introduce peaks that are not associated with atomic emission. Therefore, it is essential that the detector has the ability to start light acquisition at a known time after the laser has fired and that the start of the acquisition can be set with time steps in the order of 100 ns and with << 100 ns accuracy and jitter.

For detectors compatible with an echelle spectrometer, only high-end scientific (expensive) cameras with an intensifier (ICCD or ICMOS) currently exhibit this performance. Now, SPECTRAL Industries is introducing a revolutionary new approach to achieve sub-100 ns gating. Our patented feedback loop scheme in combination with sophisticated software algorithms enables us to reduce the inherent 10 µs jitter of a standard machine vision CMOS camera to < 10 ns r.m.s.. Using a standard pulse delay generator (PDG) yields full control over the desired delay time between plasma initiation and signal acquisition for gated LIBS applications.

To demonstrate the performance of the detector gating, we have performed LIBS measurements on a water jet containing 2 g/l (0.2 %) sodium. LIBS on liquids is known for rapid temporal dynamics, so this is an ideal test case to illustrate the gating capabilities of the IRIS spectrometer. The results of the experiments are shown in Figure 3. Different delay settings between the laser and camera acquisition were used. This figure shows raw measurement data of 10 summed single-shot measurements for each delay setting, to average out fluctuations in the water jet position.

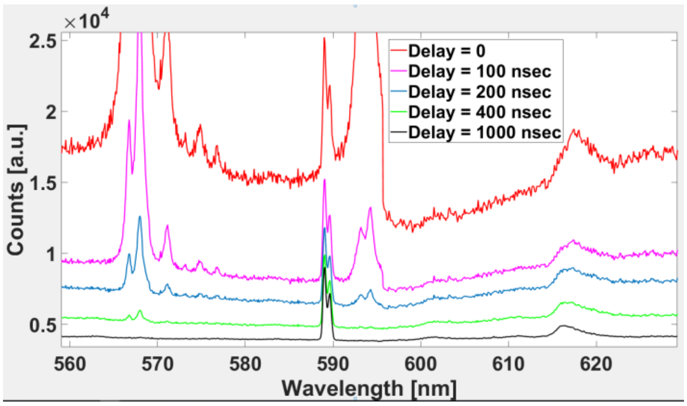

*Figure 3: LIBS measurements on a running water jet*

The measurements show that by increasing the delay between the laser excitation and the camera acquisition from zero to 1 µs (1000 ns) the background signal decreases until only the sodium doublet remains. These results demonstrate that the IRIS spectrometer has excellent gating performance for high-end LIBS applications.

To show the stability of the gating we performed a sequence of LIBS measurements on a flat steel sample. Figure 4 shows the raw counts of the peak height of an arbitrary iron emission line. Every measurement point is a single shot measurement including all noise factors of the entire LIBS system, like the signal shot noise, laser power fluctuations, electronics noise and camera noise. The standard deviation (STD) of the noise is 306 counts which corresponds to 7.6%. Fourier analysis shows that there is no sign of any systematic features in the noise pattern.

The STD of the signal scales nicely with the square root of the number of measurements if one aggregates multiple measurements. Already after summing 40 individual measurements the STD drops below 1%. The detector is shot noise limited. As this type of signal related noise is inevitable by nature, this is the optimum one can achieve for an optical system like this.

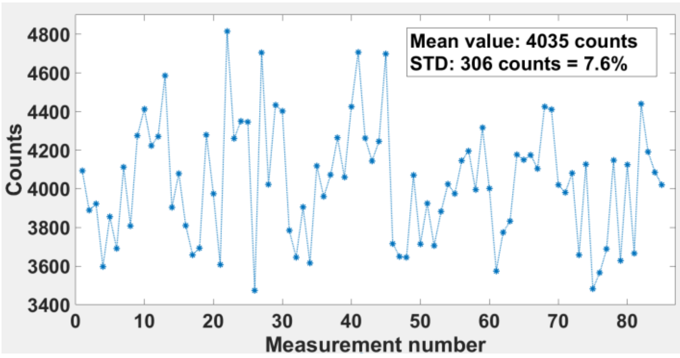

*Figure 4: Sequence of 85 single shot LIBS measurements. Counts are the peak hight of an iron peak measured on a flat steel sample.*

## UV performance

Standard CCD and CMOS cameras have no response below 350 nm. Therefore, users often choose more expensive back-illuminated cameras or intensifier plates to be able to measure down to 180 nm for OES applications. Unfortunately, the choice of affordable deep-UV compatible cameras is very small. For this reason, SPECTRAL Industries has applied a UV phosphorescence coating on a machine vision CMOS camera chip. This coating has a fluorescence decay time of a few nanoseconds so the influence on camera gating is negligible.

Figure 5 shows the difference in response between an uncoated chip (black) and UV coated chip (red). The structure in the signal is from each of the various orders of the echelle. Note that the apparent lamp output drops quickly below 250 nm unless a purging gas is applied. Experiments with a purged spectrometer showed that e.g. the 193.09 nm carbon line in steel can be detected using the IRIS spectrometer. Figure 5 illustrates substantial performance improvement for the coated chip above 190 nm.

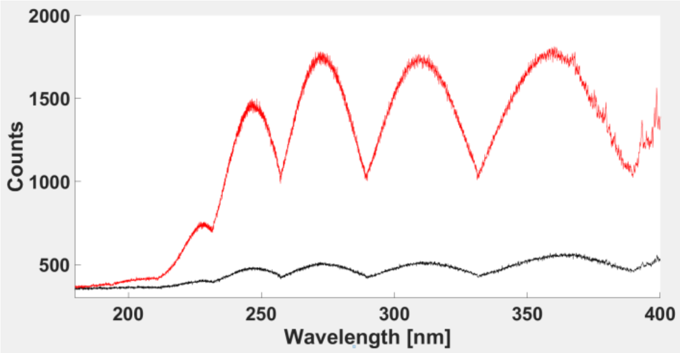


*Figure 5: CMOS response with UV coating (red) and without coating (black)*

## Robustness

For industrial applications, it is essential that equipment can operate under a wide range of environmental conditions, enduring temperature changes and mechanical shocks. The IRIS spectrometer was designed by a team that was involved in the equipment development for the ExoMars mission of ESA. Figure 6 shows the temperature dependence of signal from the IRIS spectrometer, illustrating robustness. The resulting spectral shift is <5 pm/K. The IRIS spectrometer has also undergone shock and vibration tests and always maintains its calibration after shipment to the customer.

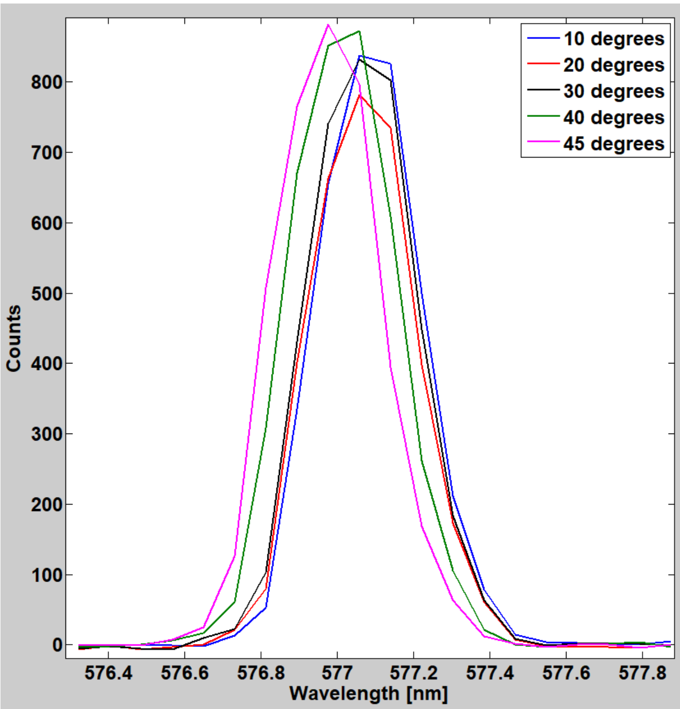


*Figure 6: IRIS temperature stability*

## ICCD versus CMOS

Above we have shown the performance of the IRIS spectrometer with a CMOS camera compared to an echelle spectrometer using an ICCD. However, it is also of interest to directly compare the IRIS advanced CMOS camera to an ICCD. For this comparison, an IRIS spectrometer was equipped with either the CMOS, or a commonly used ICCD camera. The same calibration light source was used and the gain settings for both cameras were tuned to have the brightest spectral line at 60% of the pixel saturation value.

| | CMOS | ICCD |
|---|---|---|
| **Integration time** | 1 millisecond | 1 millisecond |
| **Gain setting** | 9 out of 40 | 100 out of 250 |
| **Max peak height** | 2,186 out of 4,096 counts | 38,486 out of 65,536 counts |
| **STD of the dark noise** | 0.14 counts | 1.49 counts |
| **Dynamic range** | 4096/0.14 = 30,000 | 65536/1.49 = 44,000 |
| **S/N** | 15,614 | 25,829 |

*Table 5: Comparison between ICCD and IRIS CMOS*

The results of the camera comparison are shown in Table 5. Although the ICCD is 16-bit and the CMOS only 12-bit, the dynamic range of both cameras is comparable. The larger full well capacity of the ICCD is partly compensated for by the lower noise level of the CMOS. The resulting S/N shows that the ICCD has a better performance than the CMOS. This in contrast to the measurement results shown in **Fout! Verwijzingsbron niet gevonden.** that also include the spectrometer performance. Taking into account the price difference of more than one order of magnitude, the difference in performance is surprisingly small.

## IRIS next generation echelle spectrometer

Spectral Industries' IRIS spectrometer has the specifications shown in Table 6.

| | |
|---|---|
| Spectral range | 180 - 800 nm (incl. purging option) |
| Resolution (FWHM) | 0.1 - 0.45 nm (@ 180-800 nm, for 25 µm wide slit) |
| F-number | f/2 |
| Slit size | 25 x 100 $\mu m^2$ (also available: 10 x 100 $\mu m^2$ and 50 x 100 $\mu m^2$) |
| Wavelength stability | <5 pm/K |
| Size | 220 x 195 x 80 $mm^3$ (incl. camera) |
| Weight | 3 kg (incl. camera) |
| Camera | CMOS detector (deep-UV enhanced) |

*Table 6: IRIS spectrometer specifications*

For LIBS users, SPECTRAL Industries offers a complete LIBS setup, comprising:

- Our IRIS UV spectrometer
- A nanosecond pulsed laser
- A PDG for gated LIBS measurements
- Laser focusing and signal collection optics
- Automated 3-axis translation stages for sample scanning
- Software for hardware management and performing and processing measurements

Software and hardware interfacing the IRIS spectrometer with an ICCD camera is possible for scientific users who prefer to upgrade their existing LIBS setup. Note that most ICCD intensifiers will introduce a blur resulting in a decreased spectral resolution.

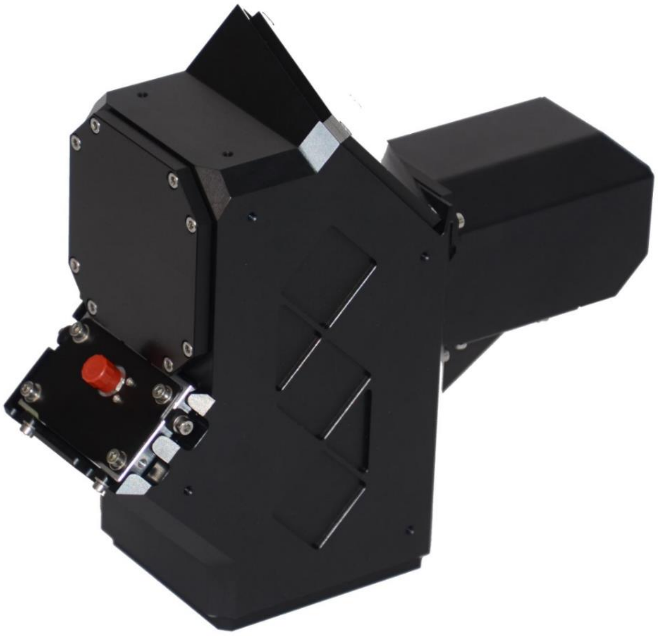

*Figure 7: Picture of the IRIS spectrometer*

## Conclusions

In this white paper, we have shown the performance of the next generation SPECTRAL Industries IRIS spectrometer. It features:

- Combination of a large bandwidth and high spectral resolution. Ideal for OES applications, but also for astronomy and (time-resolved) fluorescence.
- Gating below 100 ns is possible with a patented feedback loop scheme in combination with sophisticated software algorithms.
- High optical throughput, combined with a low noise detector, results in an unmatched S/N ratio.
- High robustness is achieved through design for a space environment.
- Low price level due to a combination of design choices and the use of a machine vision CMOS camera