Shamrock 193i: The high performance compact spectrograph

The Shamrock 193i is the latest addition to the Andor portfolio of Czerny-Turner spectrographs. It is a shorter focal length Czerny-Turner (CZ) symmetric system with focal length of 193 mm which offers excellent throughput. The optical design has been optimised to ensure excellent spectral resolution even with a shorter focal length configuration. The Shamrock 193i comes with a number of innovative features including active-focusing where the system can be automatically adjusted to ensure optimum focusing performance – for example when changing gratings, switching between ports, or making measurements over extensive wavelength ranges. The system has been designed to lend itself particularly well to modular spectroscopy solutions where a compact, robust, high performance spectrograph is needed to integrate conveniently to larger systems such as those used for microspectroscopy, or those requiring portability.

Introduction:

The Shamrock 193i has been designed with several key requirements in mind at the outset:

- ✓ **Excellent throughput**
- ✓ **Good resolution**
- ✓ **Compact and robust**
- ✓ **Flexibility**
- ✓ **Easy to optimise and use**
- ✓ **Multiple ports**
- ✓ **Versatile for wide range of modular solutions**
- ✓ **Microspectroscopy configurable**
- ✓ **Good cost/performance ratio**

Figure 1: The Shamrock 193i with Newton and iDus cameras.

With these in mind the Shamrock 193i has been based on an optimised image corrected symmetric Czerny-Turner geometry with focal length optics of 193 mm. It has two exit ports, a single entrance port, a high repetition rate shutter and active focusing capability.

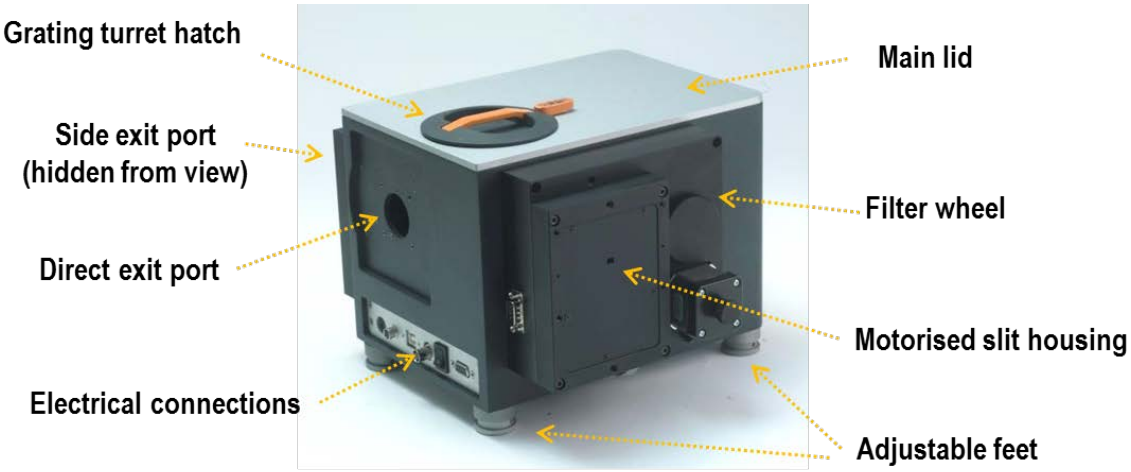

Figure 2: Main external components of the Shamrock 193i.

Key features:

The key features of the Shamrock 193i can be summarised as:

- **High fidelity imaging** – using toroidal optics
- **High Spectral Resolution** – 0.13 nm FWHM with 1200 g/mm grating
- **Czerny-Turner optical design**
- **Active-focusing** – capable of adjusting focus of the system automatically to ensure optimum resolution
- **Pre-calibrated** – 'plug and play' set up
- **Turret** – dual grating, on-axis rotation and interchangeable
- **Easy exchange of grating turrets with RFID tagging**
- **Motorized and Manual slits**
- **High throughput** with F/3.6 optical design
- **Dual exit ports** with easy switching between the two
- **Auto-calibration** – for easy setup
- **Wide range of accessories** – compatible across Shamrock series
- **Multitrack spectroscopy**
- **Versatility** - wide range of configurations and applications
- **High rep. rate shutter** – up to 10 Hz continuous (40Hz – burst)
- **μ-Manager integrated control for microspectroscopy**
- **Scanning capable**
- **Tuneable light source configurable**

Specifications:

A summary of the key performance specifications is given in Table 1. Resolutions and bandpass are quoted here based on a 1200 g/mm grating and a 27.6 mm wide sensor with 13.5 μm pixels – unless otherwise stated [1].

Table 1: The main performance parameters of the Shamrock 193i.

Performance Parameters	Values
Resolution (nm) using 1 mm central band (with 13.5 μm pixel sensor and 10 μm entrance slit)	0.15
Resolution (nm) using FVB (with 13.5 μm pixel sensor, 6.7 mm high and 10 μm entrance slit)	0.21
Resolution (nm) (with 10 μm exit slit)	0.14
Aperture (F/#)	F/3.6
Dispersion (reciprocal linear) (nm/mm) (with 1200 g/mm, 500 nm blaze)	3.53
Bandpass (nm) (with 27.6 mm wide sensor)	98
Accuracy Central λ (nm)	+/- 0.15
Accuracy Side λ (nm)	+/- 0.3
Repeatability (nm)	+/- 0.075
Stray Light (measured at 1 nm from 633 nm laser line)	3.8×10^{-4}
Stray Light (measured at 10 nm from 633 nm laser line)	4.7×10^{-5}
Multitrack capability (on a 6.7 mm high sensor)	~5 tracks

A comparison of these key parameters for the whole Shamrock series is given in Appendix A. This shows how the Shamrock 193i fits in with the Shamrock portfolio. Of particular note is how its performance is relatively close to that of the Shamrock 303i thus showing an enhanced performance for such a compact short focal length system. This is primarily due to the improved optimisation incorporated into the development of the new spectrograph.

Table 2 summarises the main design parameters for the system. It has a focal length of 193 mm, fully automated dual-grating turret, adjustable focusing mirror, and two exit ports.

Table 2: Summary of key design parameters of the Shamrock 193i.

Design Parameters	Values
Optical Design	Czerny-Turner - Toroidal optics
Focal length (mm)	193
Aperture (F/#)	f/3.6
Focal plane size (w x h)	30 x 14
Magnification H x V	1 x 1.1
Motorised slits (S-standard, O-optional)	10 µm - 3 mm (S)
Manual slits (S-standard, O-optional)	10 µm - 3 mm (O)
Slit height options (mm)	4 mm - 14 mm
Grating size W (mm) x H (mm)	50 x 50
Gratings per turret mount	Dual grating - close-to-on-axis RFID tagged
Turret type	Interchangeable
Scanning capable	Yes
Mechanical scan range (nm) (1200 g/mm)	0 - 1400
Shutter Repetition rate (max)	10 Hz - continuous 40 Hz - burst
Shutter Min open/close times	6 ms /6 ms
Shutter lifetime (cycles)	> 1e6

A summary of other features of the system including the body size and weight, optical axis height and software control is given in Table 3. The Shamrock 193i can be operated through either USB 2.0 or I^2C communication protocols.

The actual design of the Shamrock 193i has been based on the traditional Czerny-Turner layout with toroidal optics to enhance the imaging performance by minimisation of the intrinsic aberrations of this type of geometry. Figure 1 shows a picture of the spectrograph with an iDus camera on the main exit port and a Newton on the side exit port. The main external components of the system are shown in figure 2. Figure 3 gives a schematic of the layout of the main components within the system.

Table 3: Other important parameters: dimensions, weight, optical axis and control.

Miscellaneous Features	Values
Spectrograph size	245 mm x 220 mm x 210 mm
Optical axis height	133
Adjustable height with feet	130 - 136 mm (+6 mm increments)
Weight (kg)	7.4
Communications protocol	USB 2.0, I^2C
Software control	Solis/ Solis scanning/ SDK 2.0
Third party software	Micro-Manager

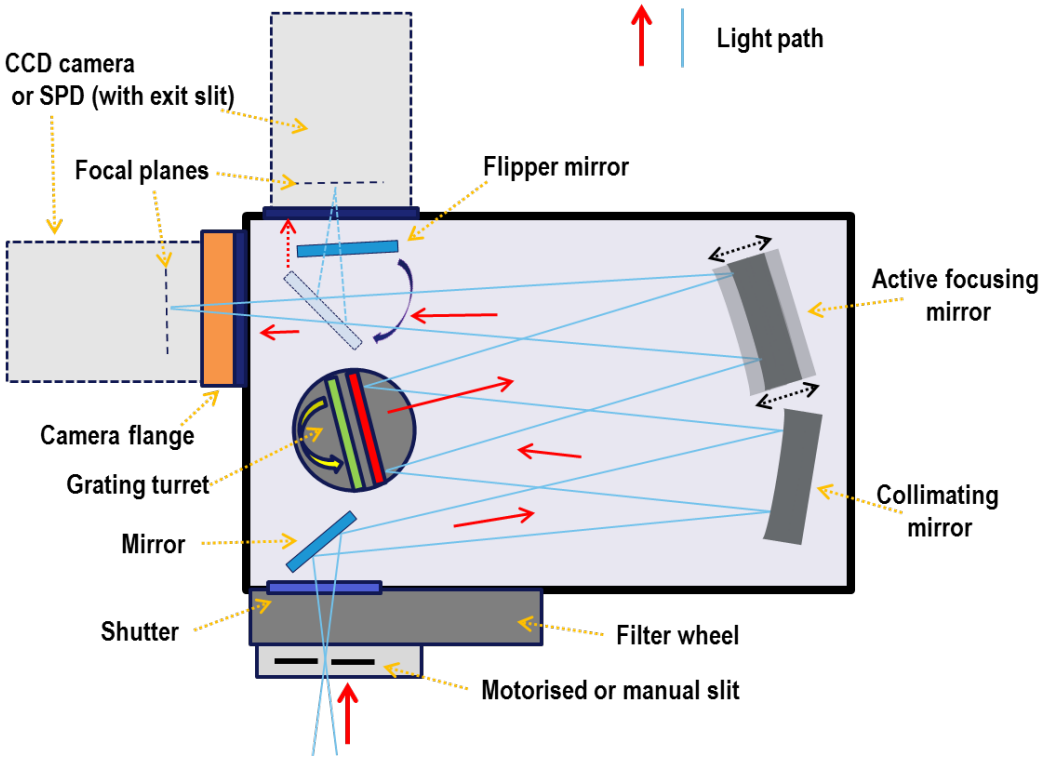

Figure 3: Schematic layout of the main components of the Shamrock 193i.

Spectrograph chassis configurations:

There are several options available for chassis configurations depending on whether the side exit port is needed or not, and whether an exit slit or CCD camera is to be mounted on the side exit port. Systems supplied which offer the two exit ports contain an automated flipper mirror for port selection – otherwise this is not included. Models can be supplied with protected silver coated optics for enhanced efficiency in the NIR to SWIR spectral regions. Table 4 summarises the base configurations offered and the corresponding model numbers to use. Note a 'B1' model comes with a manual exit slit mounted on the side exit port (this is not included with the 'B2' model). All models come with a manual slit mounted on the entrance port as standard.

Table 4: Different chassis configurations for the Shamrock 193i.

Model	Direct output port	Side output port	Flipper mirror
SR-193i-A	Camera	-	-
SR-193i-B1	Camera	Manual slit	yes
SR-193i-B2	Camera	Camera	yes
SR-193i-xx-SIL	As per above with silver coated optics (xx corresponds to model code – A, B1 or B2)		

Overview of key features:

1. Dual grating turret – 'close-to-axis' rotation and RFID:

The turret holds two gratings back to back which are aligned to be as close as possible to the common axis of rotation for the turret. So the axis of rotation is close to the central vertical axis through the grating which gives optimal performance over a wide range of grating angles, with the incident collimated beam well centred on the grating for all angles of use. This contrasts with most triple grating turret systems where the gratings are rotating about an off-axis point at the centre of the turret. Grating turrets in the Shamrock 193i are interchangeable. They are supported off two mounting pins and have a kinematic relocation key to ensure correct positioning each time they are mounted in place. A circular access hatch on the lid of the spectrograph allows for access to the gratings when seeking to interchange turrets or tweak grating alignment. A picture of the grating turret is shown in figure 4.

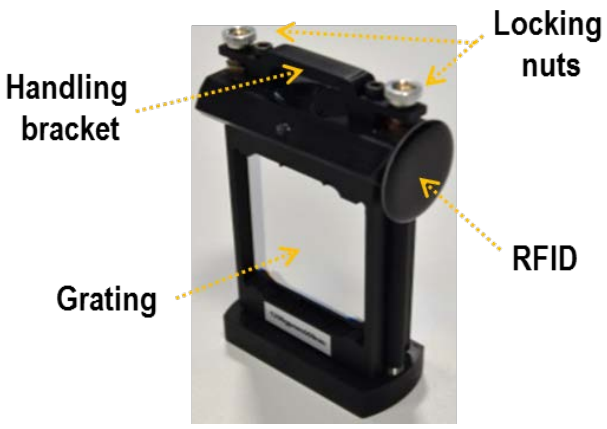

Figure 4: The grating turret and RFID

An added feature of the turret is the **RFID** (Radio Frequency Identification) device which is attached to a position on the top of the turret. The details of the gratings held in a given turret

are pre-programmed into the RFID device at the time of setup. When a turret is being added to the spectrograph a sensor automatically reads the information from the RFID and updates the EEPROM of the spectrograph. This information will include the number of gratings present, their part numbers, line densities, blaze angles, and types of coating. Consequently the interchanging and upgrading of turrets in the system can be done most conveniently without the user having to enter the details manually into the EEPROM each time. Note the RFID is specific to the grating turret – not the individual gratings – so if a new grating is added to a turret the RFID will need to be updated.

2. Active focusing capability:

The Shamrock 193i comes with active focusing capability where focusing within the system is fully automated to ensure optimum resolution and image quality. The main focusing mirror is driven with a stepper motor which is controlled though the SDK and Solis software. This moveable mirror is illustrated in the schematic of figure 3 above. Using a pre-programmed algorithm, the mirror position can be finely adjusted to maintain optimum focus at the output focal plane of the spectrograph. Consequently the system can adapt conveniently to changes in the configuration of the system to ensure the system is always optimised. Control of the focusing can be carried out automatically or manually from the Solis application software.

Situations where this new functionality is of particular benefit include:

- Changing between gratings
- Changing between detectors at the two exit ports
- Changing detectors and/or flanges at a single exit port
- Scanning across a wide wavelength range

The key benefit for all these situations is that small variations in the optical path that may arise are conveniently accounted for without having to manually re-focus the system for each scenario. Figure 5 shows a scan through a range of mirror positions when observing a spectral line profile. The best focus position is generally where the spectral profile has the smallest FWHM, though the optimisation is based on a weighted average across the line profile rather than a simple measurement of the FWHM. The main algorithm for optimisation is applied to a vertically binned segment or track across the plane of the sensor; this can include a fully vertical binned (FVB) spectral profile if so desired.

When a system has been optimised for its different configurations the position values for the mirror are stored in the memory or EEPROM of the spectrograph. For example when switching between exit ports values will be associated with the optimised positioning for

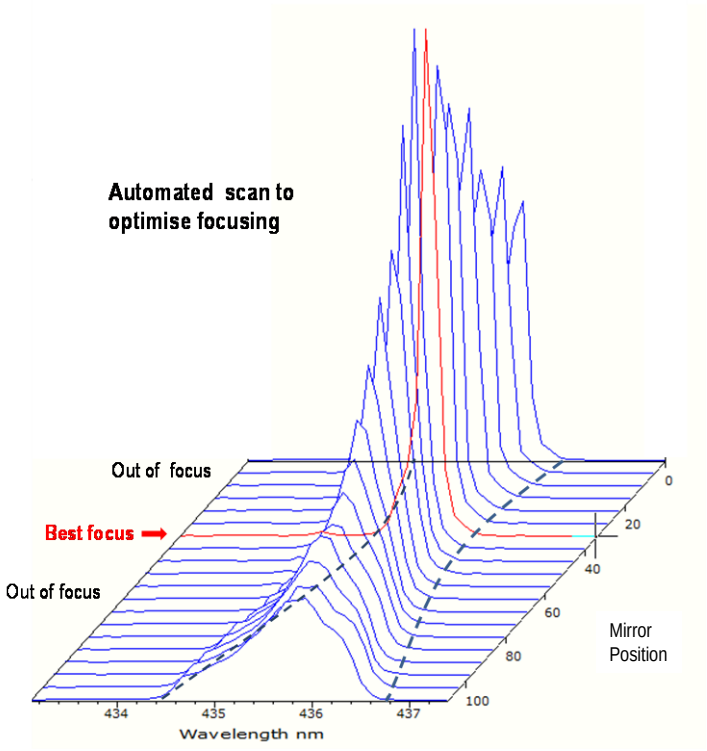

Figure 5: Spectral profiles during active focusing.

each port. This means the software can use these optimised values for each configuration without having to repeat the automated or manual optimisation process. A series of values are generated for each configuration when it is optimised, which are stored and can be used each time that configuration is chosen without having to worry about optimisation each time.

3. Dual exit port configurations:

The system with two exit ports offers a lot of flexibility in terms of possible experimental configurations. These allow for multiple combinations of CCD cameras, single point detectors (SPD), and motorised or manual exit slits.

Cameras are mounted on the direct exit port with a flange whilst those on the side port are mounted directly to the wall of the spectrograph (see figure 3). This means all spectroscopy cameras and slit types can be mounted on the side exit port as well as the direct. However the iXon camera and similar long focal distance systems (including c-mount cameras) can only be mounted on the direct exit port with an appropriate flange.

Motorised and manual slits can be mounted on either port. The single point detectors (SPDs) have been designed to mount on to the exit slit housing. Figure 1 shows an example where an iDus camera is mounted on the direct exit port and a Newton is mounted on the side exit. Figure 6 illustrates other possible combinations.

Figure 6: Different configurations for mounting cameras, slits and SPDs on the exit ports.

The versatility of the system allows for multiple configurations covering a diverse range of applications:

- CCD/ICCD cameras for UV, Visible and NIR spectroscopy
- Single Point Detectors (SPD) for scanning spectroscopy solutions from UV to SWIR
- ICCDs and SPDs for Time Resolved and Lifetime measurements
- Exit slits for monochromator operation as a tuneable light source
- Fibre coupling to deliver output light/signal to another part of experiment

A list of the flanges available for the direct exit port are summarised in table 5. Note the iXon camera (and c-mounted cameras) cannot be mounted on the side exit port.

Table 5: Summary of the various flanges used at the direct exit port.

Flange (apply to direct exit port)	Purpose
MFL-SR2-CCD	Multichannel detector flange for all CCD spectroscopy cameras (Newton, iDus, iVac)
MFL-SR2-IXON	iXon mounting flange
MFL-SR2-IKON-M	iKon-M mounting flange
MFL-SR2-ISTAR-DIRECT	iStar mounting flange on direct exit port
MFL-SR2-ZYLA	Zyla mounting flange

The system has been primarily configured to have exit slits (manual or motorised) on the side exit port. The slit housing mounts directly on to the side of the spectrograph without the need for any intermediate spacer plate or flange. Slits can also be mounted on the direct exit port if need be, but this does require an extra mounting spacer plate. The accessory parts required for the different slit options at both the exit and entrance ports are summarised in table 6.

Table 6: Summary of manual and motorised slits available for the exit and entrance ports.

Flange	Purpose
SR-ASZ-0030	Manual adjustable slit for exit ports
SR-ASZ-0036	Motorised adjustable slit for exit port
SR-ASM-0096	Wide Aperture Slit for exit port
Entrance slit	Manual slit comes as standard part of system
SR-ASZ-0035	Motorised slit for entrance port
SR-ASM-0086	Wide aperture slit for entrance port

4. Shutter:

A very fast shutter has been implemented on the Shamrock 193i. This can run in normal continuous mode at rates up to 10 Hz. There are situations where it is not applicable to use full vertical binning (FVB) of the sensor such as when doing multitrack spectroscopy. In such cases it is important to avoid streaking of one spectral track into another which would result in contaminated data. The use of a shutter prevents cross contamination when reading out the sensor. With the faster rate shutter, multitrack and imaging data can be captured at much faster rates than with the older 2 Hz (max) shutter.

Additionally the shutter can be operated at faster rates up to 40 Hz in what is called a 'burst' mode. After a certain acquisition period of time (4 seconds) the shutter stops for a short period of time (60 seconds) to avoid over-heating of the shutter actuator. During this recovery period a buzzer sounds until it is ready to continue, after which the sound stops and normal operation can be resumed. The shutter details are summarised in table 7.

Note if one is imaging or using multitrack spectroscopy, it is strongly recommended that the system include a shutter. If it is decided to retrofit a shutter at a later date then it can be installed easily in the field by the end-user.

Table 7: Summary of shutter specifications.

Part no	Description	Specifications	
SR2-SHT-9006	Fast shutter for Shamrock 193i	Maximum repetition rate - continuous	10 Hz
SR2-SHT-9006-FIELD	Used if upgrading with shutter in the field	Maximum repetition rate -burst	40 Hz
		Minimum open/close times	6 ms
		Minimum lifetime	>1 million cycles

5. Quick release lid and grating access hatch:

The system has been designed with an easy-to-remove lid which is held in place by four screws. A circular grating access hatch has been added to the main lid to allow for access to the grating turret without opening up the full interior of the spectrograph. This allows for easier exchange of turrets . The lid and access hatch are shown in figure 2. This design minimises the chances of ambient contamination from the surrounding environment getting into the spectrograph.

Accessories:

There is a large range of accessories available to facilitate the diverse types of experimental investigation where the Shamrock 193i may be used [1,2]. This includes:

- A selection of input light coupling accessories – such as filter wheel, fibre optic coupling adapters, fibre optics, microscope coupling components, sample chamber, lens adapters, and F/# matcher,
- A wide range of gratings covering UV, visible, NIR and SWIR, with a choice of coatings of either aluminium or silver (with protective coatings),
- A set of output port accessories for direct detection by CCDs, and SPDs; for connecting to sample chambers; c-mount adapters, and fiber optic coupling adapters to take light elsewhere,
- Microspectroscopy configuration components – such as relay optics, c-mount adapter plates, cage systems, adjustable feet for spectrograph and microscope feet.

It is important to note that all the input port accessories (filter wheel, manual & motorized slits, fibre optic couplers, fibre optics, microscope coupling accessories and sample chamber) are common with the Shamrock 500i and 750 platforms, apart from the new fast shutter. Refer to the spectrograph specification sheet for all the accessories available and their details. A summary of the accessory parts available is included in Appendix B of this tech-note

Details on the specifications and design for the standard optical fibre bundles typically used with the Shamrock 193i can be found in the 'Fibre Optics for Spectroscopy' specification sheet [2].

Software control and interfacing:

Communications with the Shamrock 193i is available through either USB 2.0 or I^2C connectivity. Customer applications can control the spectrograph through Andor SDK development software. A fully integrated spectroscopy solution is available through the Andor SOLIS application software package which fully integrates the control of the camera and spectrograph.

SOLIS offers high and rich functionality for the spectroscopy system of CCD detector and spectrometer. A user-friendly graphical interface (GUI) allows for easy control of the main functions of the system and analysis tools. Figure 7 shows a screenshot of the user interface for SOLIS. A series of icons at the bottom offer intuitive access and control to the main functions, allowing experimental setups to be quickly and conveniently optimised or totally reconfigured within minutes.

The following functions may be controlled through the Solis GUI:

- Selection of grating - ***Motorised Turret***
- Adjustment of entrance port slit width – ***Motorised Slit***
- Selection of shutter options (Open, Closed, Auto or Custom) – ***Shutter* Control**
- Insertion of various types of filters – ***Motorized Filter Wheel***
- Selection of exit port used via flipper mirror – ***Exit Port Selector***
- Adjustment of exit port slit width – ***Motorized Exit Slit***
- Selection of acquisition mode (FVB, Image, Multi-track) – ***Acquisition Mode Selector***
- Wavelength selection on sliding scale – ***Wavelength Selector***

Spectral Calibration:

Automatic and manual spectral calibration options are available through the software which allow for convenient re-calibration of the system. The Shamrock 193i comes pre-calibrated based on the accurate measurement of the key parameters of each individual spectrograph for each grating and using the grating dispersion equation. The key calibration data is stored 'on-board' within the EEPROM of each spectrograph. If cameras are interchanged or adjusted, then the necessary adjustments can be carried out conveniently and quickly to maintain the accuracy of the calibration. The software facilitates the easy interchange of calibration units such as wavelength (nm), wavenumbers (cm^{-1}), and energy units (eV).

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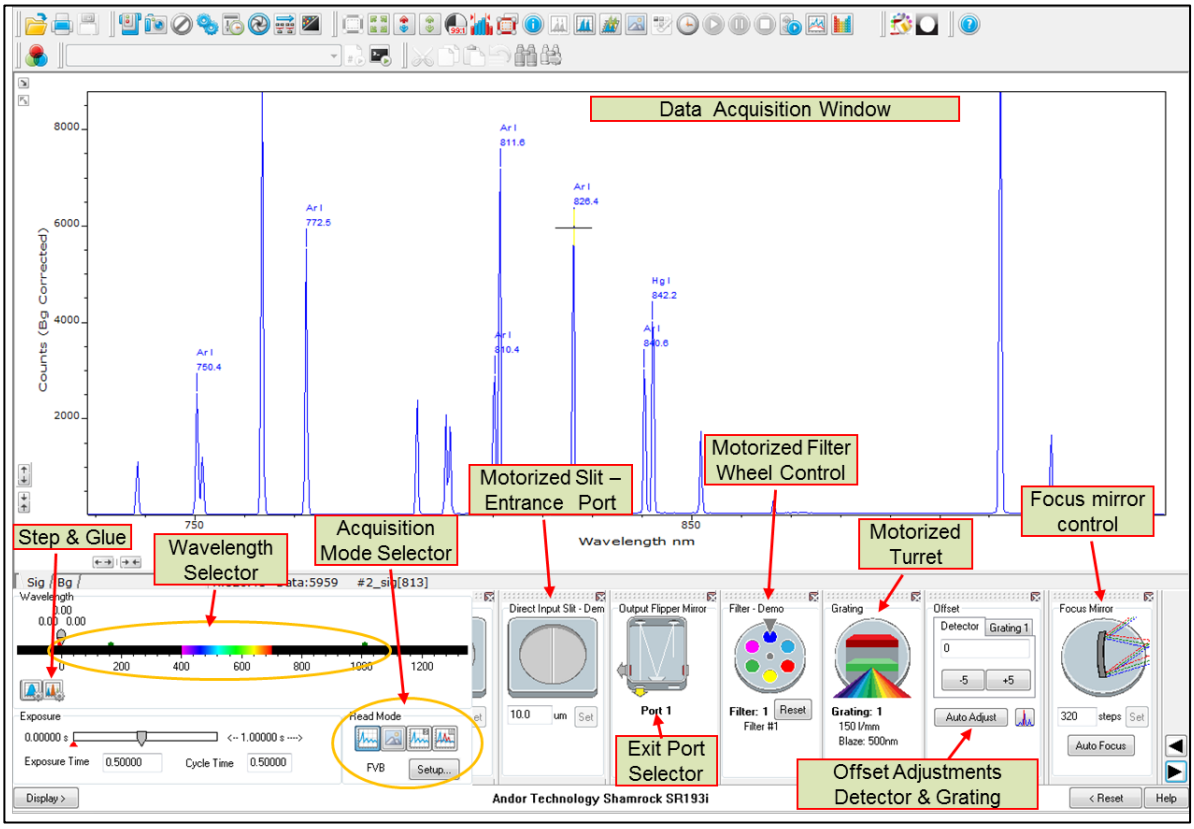

Figure 7: The front end GUI of SOLIS software.

***Wide Wavelength Range Spectral Acquisitions – the Step and Glue utility*:**

The software has the ability to take a high resolution spectrum over a wide wavelength range with a pre-programmed '**Step and Glue**' function. This automatically takes a series of spectral segments from which it constructs the final full range spectrum. It is possible to incorporate relative efficiency corrections into spectra with this utility for radiometric measurements. Figure 8 illustrates the use of 'Step and Glue' to capture a wide wavelength range spectrum with high spectral resolution.

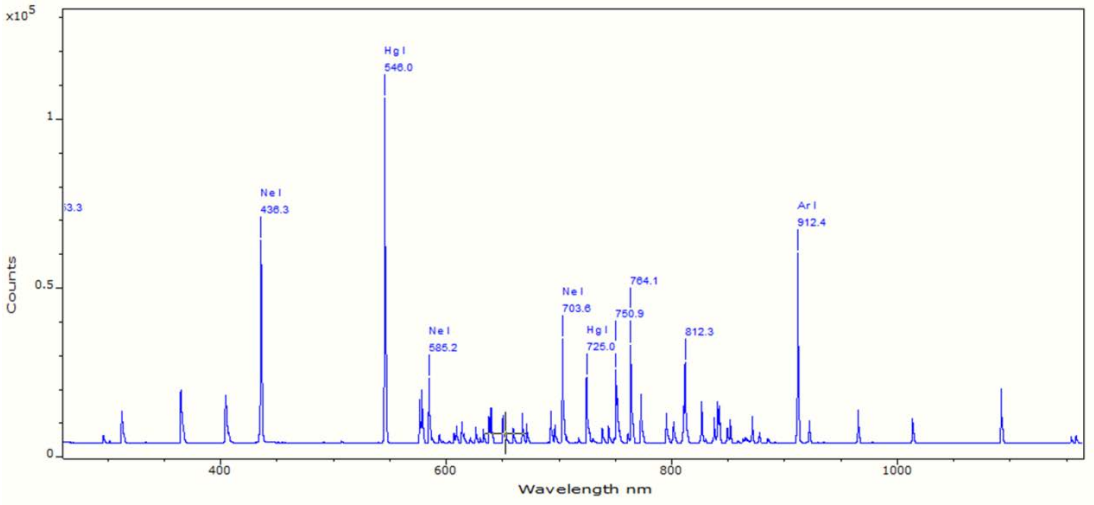

Figure 8: Using Step & Glue feature to capture a wide range spectrum at high resolution.

Analysis tools:

SOLIS comes with a range of tools for analysing acquired spectra. These include **peak identification** and **labelling** of spectral lines as illustrated in figure 9(B). A '**region of interest**' (ROI) tool, as illustrated in figure 9(A), allows for the extraction of characteristic data from spectral profiles and images such as line widths (FWHM), standard deviation, area under profiles and peak intensities.

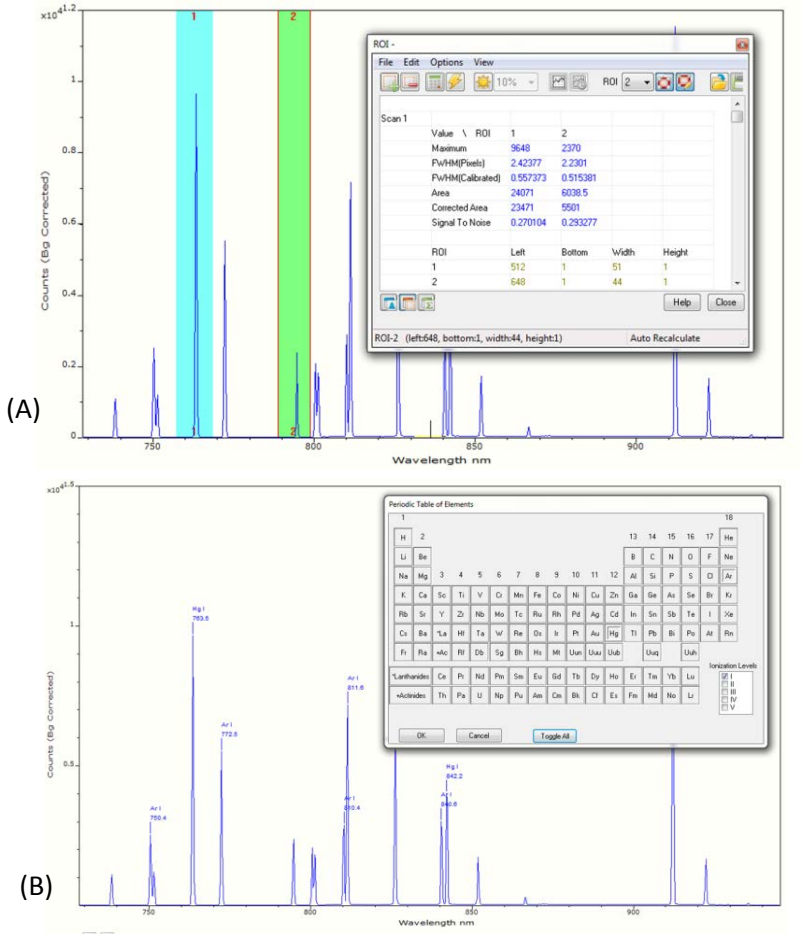

Figure 9: Solis Analysis tools – region of interest (ROI) analysis (FWHM, peak and integrated intensities, standard deviation) is shown in (A), and spectral line identification (using NIST database) is shown in (B).

Imaging performance:

The imaging performance of the Shamrock 193i is illustrated in figure 10, where an image from a test grid on a microscope has been focused on to the entrance port focal plane of the spectrograph and then relayed through the spectrograph on to the detector. The wide aperture slit accessory was used which allows the input aperture to be opened up to a width >14 mm; the grating was set at the zero order position to enable direct imaging. Often a system will be configured with a mirror mounted in one of the grating positions to facilitate high fidelity imaging of the sample. In this example the image was captured on a 27.6 mm x 6.9 mm 'spectroscopy' sensor.

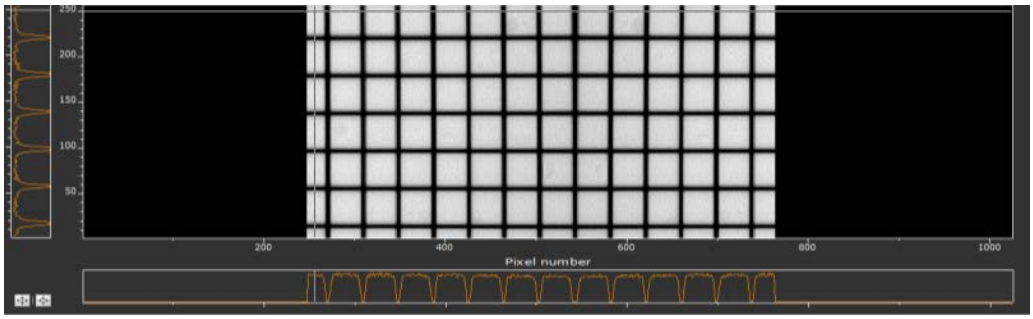

Figure 10: A relayed image of a test grid captured at the exit port of the Shamrock 193i spectrograph.

Multitrack spectroscopy:

Multitrack spectroscopy is possible on the Shamrock 193i with 2D CCD sensors, with the number of tracks possible depending on the height of the sensor used and the imaging performance of the spectrograph. The imaging quality of the Shamrock 193i is very good in comparison to similar short focal length Czerny-Turner designs. Figure 11 shows an image of four spectral tracks captured on a 27.6 mm x 6.9 mm sensor. The fibre bundle used consisted of 4 channels with each channel consisting of 3x 100 μm core fibres arranged in a linear array at the input port of the spectrograph.

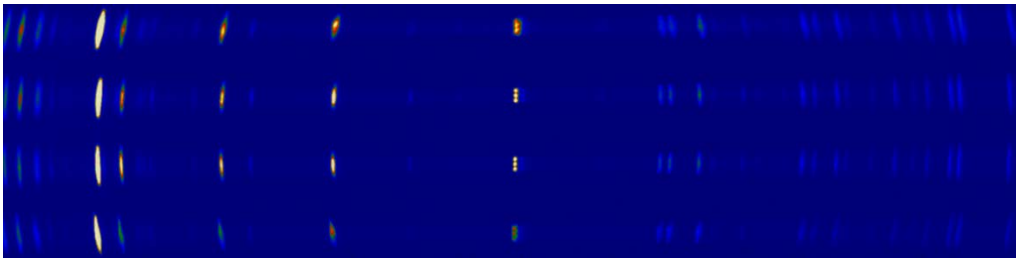

Figure 11: Image of the dispersed multitrack spectra across a 26.7 x 6.5 mm sensor.

Typically 5 spectral tracks can be comfortably accommodated on a sensor height of 6.7 mm. Figure 12 shows multiple spectra captured using multitrack acquisition mode – where each track is defined with a certain number of pixel rows located at the appropriate positions up the sensor, and vertical binning of the pixels is automatically carried out for each spectral track.

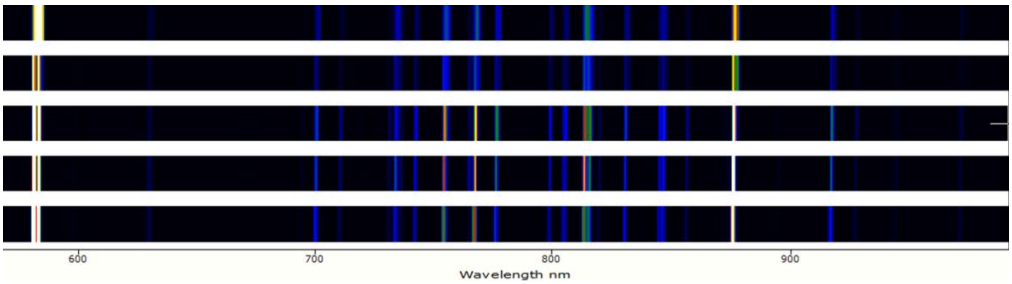

Figure 12: Illustration of multitrack spectroscopy on the Shamrock 193i.

Microspectroscopy Configurations:

The Shamrock 193i design is particularly suitable for modular microspectroscopy configurations [3]. This includes the direct coupling to both inverted and upright microscopes, and the use of indirect coupling via optical fibres. If one uses direct coupling the spectrograph is typically supplied with a wide aperture slit (WAS) which allows access to the full field of view when using the system in imaging mode: the slit is narrowed in again when making the spectroscopic measurements.

A key advantage of direct optical coupling is that the camera on the spectrograph can be used to both capture images of the sample as well as the spectral data. To capture images the system is either configured, i) with a mirror in one of the grating positions on the turret, or ii) one of the gratings is set at its zero-order position (grating acts like a mirror in this position). Imaging mode makes alignment of the sample easier and indexing of the image to the spectral map more straight forward. Both images and spectra can be captured on the one camera and it is easy to switch from imaging mode to spectral through the software interface. A number of typical system arrangements are outlined here.

Case 1: Direct coupling to the side exit port of an upright microscope:

The spectrograph can be coupled directly to the side port of the microscope in a number of configurations:

- Directly coupling the slit housing of the spectrograph to the port of the microscope using a c-mount adapter plate which connects the slit housing to the c-mount adapter of the microscope. This is illustrated in figure 13.

- Coupling via an enclosed purpose built (4F) relay optic. This relay optic has 1:1 magnification and sits between the c-mount port of the microscope and the slit housing of the spectrograph. See figure 14. It is generally used where space restrictions and optical table layout do not allow for the close-coupling as described above.

Figure 13: Direct coupling to side port of inverted microscope.

Figure 14: Direct coupling to side port of inverted microscope using the relay optic accessory.

- Coupling to side port using a cage system. This allows for the greatest flexibility in terms of experimental arrangements. An example of an arrangement using a cage system is illustrated in figure 15.

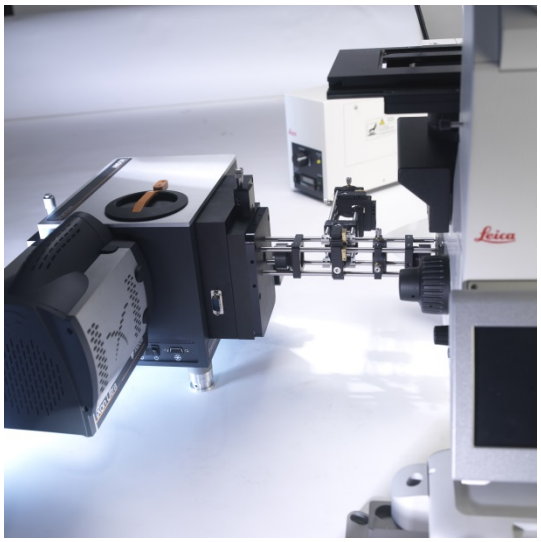

Figure 15: Coupling between spectrograph and microscope using a cage system.

Components for cage systems including the optical parts such as lenses, mirrors, filters, and polarisers, are readily available off-the-shelf from a number of different optical component suppliers [4]. Cage systems can be easily configured and assembled, and offer a very flexible approach to customising any given setup.

Microspectroscopy for Raman and luminescence studies is an application area where the cage system approach is commonly used. The optics within the cage system can be arranged to couple the excitation laser on to the sample via the same exit port as that from which the sample's Raman signal is received for delivery into the spectrograph. This can be achieved with the use of dichroic beam splitters and notch or edge filters mounted within the cage system. For further details on typical arrangements for microspectroscopy systems of this type refer to the technical notes on microspectroscopy [3, 5].

Case 2: Direct coupling to the top port of an upright microscope.

Some approaches include:

- Mounting the spectrograph on an optical table such that the entrance port of the spectrograph is close to the exit port of the microscope and a simple optical arrangement is used to couple the light from the exit port of the microscope to the entrance slit of the spectrograph. This is illustrated in figure 16 where a turning mirror is used to relay the image from the microscope on to the plane of the entrance slits i.e. the plane of the slits corresponds to an image conjugate plane.

- Using a relay cage system to couple the light from the exit port of the scope via a series of optics – lenses and mirrors – on to the entrance slit of the spectrograph. Figure 17 illustrates one such arrangement. This offers more flexibility in terms of options for coupling light into and out of the microscope. In some cases the spectrograph may actually sit beside the microscope at the same level on the same optical table with the use of periscope optics.

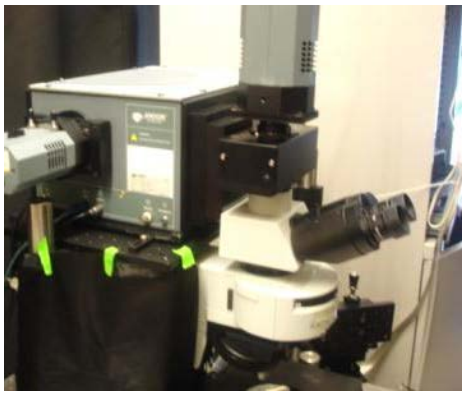

Figure 16: Coupling to upright microscope with a turning mirror accessory.

Figure 17: Coupling to upright microscope using cage system. The Shamrock spectrograph is supported on an optical table to facilitate easier coupling to the output port of the microscope.

Case 3: Indirect coupling using optical fibres.

Indirect coupling may be realised in a number of different ways but generally involves the use of fibre adapter accessories for coupling the optical fibres to the microscope at one end and the spectrograph at the other. Fibres typically used have either the standard SMA or FC terminations. However, some fibre designs use a ferrule termination to facilitate easy coupling to the spectrograph. Other variations of the fibre design are possible.

Single core fibres of a well-defined diameter are typically used including single mode fibres. Fibres with core diameters of 50, 100 and 200 μm are commonly used. The fibre chosen will be largely determined by the application and the requirements of the experiment. For example some users may use the actual core diameter at the end of the fibre as a confocal aperture where they wish to do confocal scanning measurements. Often in this case single mode fibres are used with core diameters of the order of ~10 μm.

Typical configurations are summarised here:

- Coupling one end of the fibre at the output port of the microscope (either inverted or upright) and the other to the input port of the spectrograph. Microscope fibre adapters are readily available off-the-shelf [4]. Refer to the 'Modular Micro-spectroscopy Solutions' specification sheet for more detail on what is available [3].

  There are a number of fibre-coupling adapters available for the Shamrock 193i (reference the accessories section in this note and Appendix B). Adapters can be chosen to either couple the light in without an entrance slit in the optical path or with the entrance slit in place: in the former arrangement the core diameter of the fibre will determine the spectral resolution achievable, whereas in the latter case resolution can be controlled by variation of the slit width. Refer to page 10 of the Shamrock 193i Specification Sheet and/or Appendix B1 here for the different couplers available and their part numbers.

- Coupling the fibre to the output from a relay cage system connected to the microscope. This is a particularly flexible arrangement for a wide range of experimental configurations [5].

Integrated software control of the Microspectroscopy system:

The control of the Shamrock 193i along with CCD camera has been fully integrated with Micro-Manager software to facilitate microspectroscopy. Micro-Manager is a widely used open-source software application which controls the functions of a microscopy system. Its development has been primarily aimed at microscopic imaging applications. Andor has developed the necessary plug-in modules to allow for control of the spectrograph and CCD camera along with the rest of the microscopy system, thus enabling an automated modular microspectroscopy solution all controlled centrally from the Micro-Manager software [6].

The plug-in allows for the capture and display of the spectral data. Figure 18 shows the main Micro-Manager window and how to access the Andor Microspectroscopy plug-in from the 'Plugins' drop-down menu.

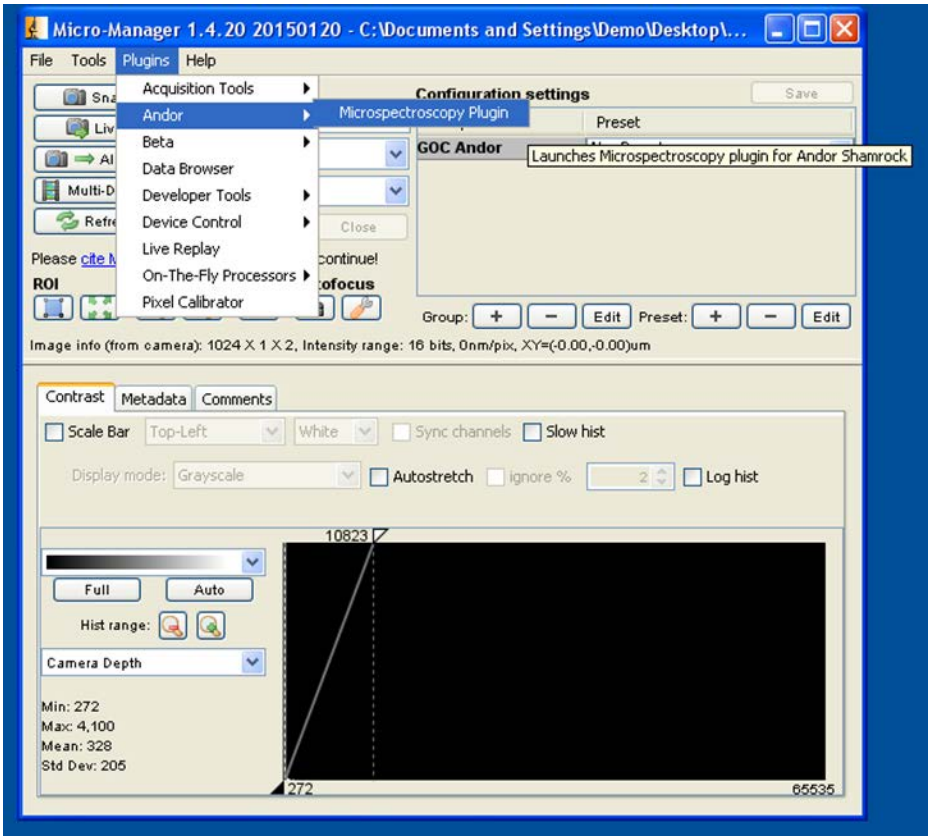

Figure 18: Main Micro-Manager window and accessing the Andor plug-in.

This launches the Shamrock 193i data acquisition screen which is shown in figure 19. The system can be readily configured to capture a series of raw spectral data to facilitate 2D chemical mapping of samples. Adding the spectroscopic capability to an existing microscopy system should be relatively easy for those already familiar with the Micro-Manager software. Figure 20 shows a screenshot of the 'Device Property Browser' window. The control and/or acquisition parameters of the various components within the system can be set through the table displayed in this window. For the spectrograph this will include the wavelength region of interest (grating position), the grating to be used, and the relevant offsets and dispersion coefficients to ensure accurate spectral calibration of the system.

There are other approaches as regards software control where users are developing their own custom applications. Using Labview along with Andor SDK for the spectrograph and camera is proving to be a popular approach to configuring and integrating an automated microspectroscopy system.

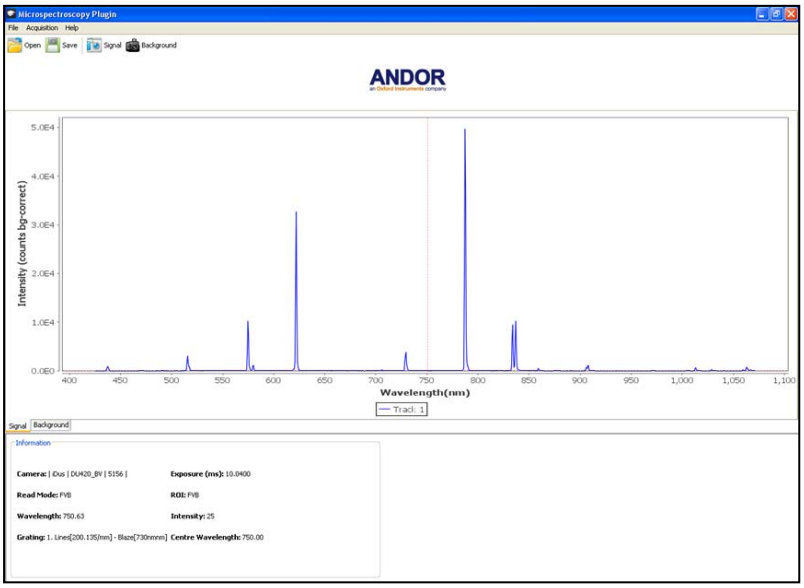

Figure 19: The spectroscopy 'acquisition screen' of the Andor plug-in showing an acquired background-corrected spectrum and relevant information on the acquisition settings.

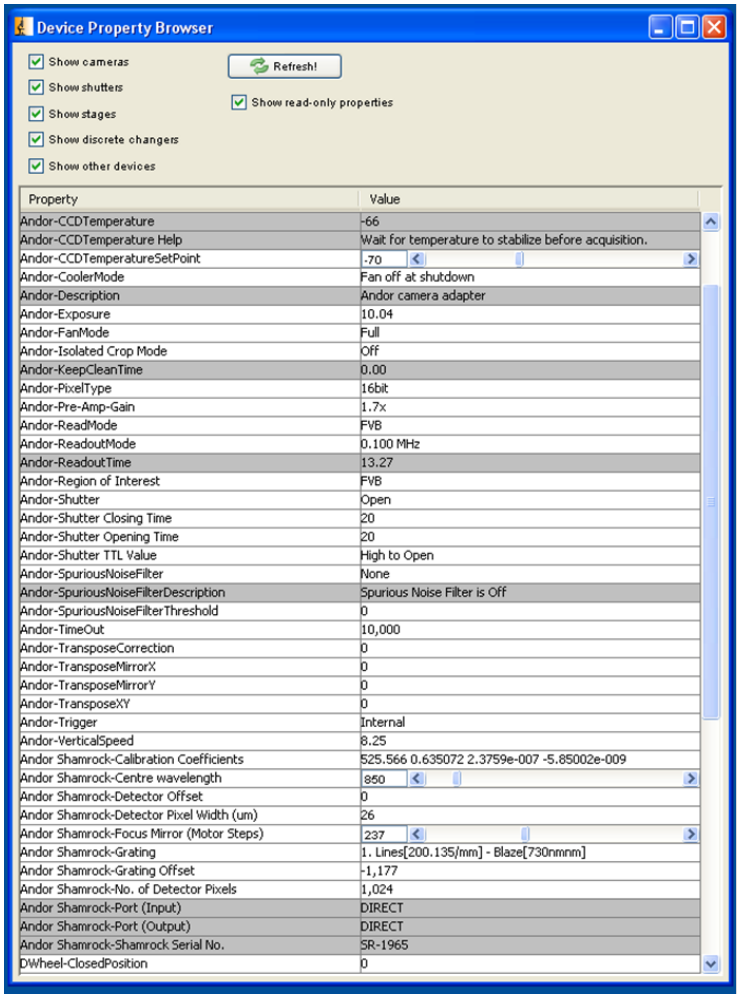

Figure 20: The 'Device Property Browser' in Micro-Manager where the spectroscopy acquisition settings can be accessed. The settings for all the other components in the system such as xy and z stages, light sources, objectives, filters etc are accessed and altered through this browser as well.

Tuneable light source and Scanning configurations:

The Shamrock 193i has been designed with flexibility and versatility in mind. It can be easily configured as a tuneable light source. Typically the system is operated in monochromator mode with an exit slit to control the bandpass of the exiting 'monochromatic light'. Control can be provided with scanning software or the spectrograph SDK. Light is delivered with appropriate coupling optics from a broad band source such as a halogen lamp or arc lamp into the entrance port of the monochromator. The monochromatic light from the exit port may be coupled directly via a free-optical bench to where it is needed or may be coupled into optical fibres or light guides. The fibre adapter accessories mentioned earlier are used in the latter case (see appendix B1), and bolt directly on to the exit slit housing.

The Shamrock 193i may be operated with full scanning capability, thus allowing it to be used in monochromator mode with single point detectors (SPD). An exit slit is mounted at the side exit port to which is attached the SPD, such as a photomultiplier tube (PMT), InGaAs detector or MCT detector. In this mode and with these sensors, the spectrograph can be used well into the IR region – up to wavelengths of ~30 μm.

Areas of Application:

Two of the key strengths of this spectrograph are its flexibility and its performance for such a short focal length compact system. Consequently it lends itself to a wide range of applications, and experimental configurations, among which are listed:

- Raman
- Fluorescence
- Photoluminescence
- Transmission, Absorption, Reflection (TAR)
- Plasma studies
- Plasmonics
- Cathodeluminescence
- Thermoluminescence
- Microspectroscopy

Case studies of work by various researchers can be accessed on the Andor website at ***www. andor.com***.

References:

[1] Shamrock 193i specification sheet
[2] Specification sheet for 'Fibre Optics for Spectroscopy'
[3] Specification sheet for 'Modular Micro-spectroscopy Solutions'
[4] Some examples of suppliers of general optical components: Thorlabs - *www.thorlabs.com*, Edmund Optics - *www.edmundoptics.eu*, LINOS - *www.qioptiq.com.*
[5] Technical note on 'Modular Solutions for Microspectroscopy'
[6] Technical note on 'Micro-Manager: Integrating solutions for microspectroscopy'

APPENDICES

Appendix A: Comparison of the key parameter for the Shamrock family of spectrographs.

Parameters	Shamrock 163(i)	Shamrock 193i	Shamrock 303i	Shamrock 500i	Shamrock 750
Resolution (nm) (with 13.5 μm pixel sensor and 10 μm entrance slit) 1 mm central band	0.17	0.15	0.1	0.07	0.04
Resolution (nm) (with 13.5 μm pixel sensor and 10 mm entrance slit) FVB of 6.7 mm high sensor	0.25	0.21	0.16	0.11	0.07
Resolution (nm) using 2400 g/mm grating (with 13.5 μm pixel sensor) FVB	0.13	0.12	0.08	0.06	0.04
Resolution (nm) (with 26 μm pixel sensor) FVB	0.35	0.19	0.15	0.1	0.06
Resolution (nm) (with 10 μm exit slit)	X	0.14	X	0.05	0.03
Aperture (F/#)	f/3.6	f/3.6	f/4	f/6.5	f/9.8
Dispersion (reciprocal linear) (nm/mm) (1200 g/mm, 500 nm blaze)	4.43	3.53	2.6	1.7	1.1
Bandpass (nm) (27.6 mm wide sensor)	120	98	65	39	26
Accuracy Central λ (nm)	+/- 0.25	+/- 0.15	+/- 0.04	*+/- 0.026*	*+/- 0.026*
Accuracy Side λ (nm)	+/- 0.25	+/- 0.3	+/- 0.08	*+/- 0.026*	*+/- 0.026*
Repeatability (nm)	+/- 0.05	+/-0.075	+/- 0.004	*+/- 0.015*	*+/- 0.015*
Stray Light (measured at 1 nm from 633 nm laser line)	X	$3.8x10^{-4}$	$6.1x10^{-4}$	$1.1x10^{-4}$	$1.1x10^{-4}$
Stray Light (measured at 10 nm from 633 nm laser line)	X	$4.7x10^{-5}$	$2.2x10^{-5}$	$2.6x10^{-5}$	$2.5x10^{-5}$
Multitrack capability (on a 6.7 mm high sensor)	<3	~5 tracks	~6 tracks	~10 tracks	~10 tracks

Appendix B1: Summary of the product codes and descriptions for all general accessories with the Shamrock 193i.

Part no	Description
ACC-SR-ASZ-0056	Shamrock sample chamber, lens & feet
ACC-FC-DIRECT-APT	FC fibre upgrade kit for direct entry (no slit) XY adjuster
ACC-FC-SLIT-APT	FC fibre upgrade kit for entry through slit XY adjuster
ACC-FCAPC-DIRECT-APT	FC/APC fibre upgrade kit for direct entry (no slit) XY adjuster
ACC-FERRULE-SLIT-APT	Ferrule fibre upgrade kit for entry through slit XY adjuster
ACC-SMA-DIRECT-APT	SMA fibre upgrade kit for direct entry (no slit) XY adjuster
ACC-SMA-SLIT-APT	SMA fibre upgrade kit for entry through slit XY adjuster
ACC-SR-ASM-8003	Fixed SMA fibre adapter (no slit)
ELC-05323	Cable I2C TO BNC for shutter triggering
SR-ASM-0002	Shamrock 1.5" Oriel accessories adapter
SR-ASM-0010	Shamrock mot. slit cover plate aperture 6Wx8H
SR-ASM-0011	Shamrock mot. slit cover plate aperture 6Wx14H
SR-ASM-0013	Shamrock Nikon lens F-mount input adapter
SR-ASM-0014	Shamrock pen ray lamp mount
SR-ASM-0015	Shamrock mot. slit cover plate aperture Ø15
SR-ASM-0016	Shamrock mot. slit cover plate aperture 6Wx4H
SR-ASM-0017	Shamrock mot. slit cover plate aperture 6Wx6H
SR-ASM-0021	Shamrock C-mount adapter (on slits)
SR-ASM-0025	SR manual slit cover plate aperture 6Wx4H
SR-ASM-0026	SR manual slit cover plate aperture 6Wx6H
SR-ASM-0027	SR manual slit cover plate aperture 6Wx8H
SR-ASM-0028	SR manual slit cover plate aperture 6Wx10H
SR-ASM-0029	SR manual slit cover plate aperture 6Wx14H
SR-ASM-0038	F-Matcher - suitable for Shamrock 193i - with ferrule input
SR-ASM-0041	Shamrock F-matcher SMA fibre adapter
SR-ASM-0064	Shamrock F-matcher FC fibre adapter
SR-ASM-0065	Shamrock Thorlabs/Linos Cage adapter
SR-ASM-0067	SR manual slit cover aperture Ø15mm
SR-ASM-8001	Shamrock fixed fibre ferrule adapter
SR-ASM-8006	Shamrock X-adjust fibre optic ferrule adapter
SR-ASM-8011	Shamrock fixed FC fibre adapter
SR-ASM-8029	Shamrock Ø11 mm fibre light guide adapter
SR-ASM-8040	Shamrock gas purge plug
SR-ASM-8052	Shamrock XY-adjust SMA adapter
SR-ASM-8053	Shamrock XY-adjust FC adapt, NO slit
SR-ASM-8054	Shamrock XY-adjust SMA adapt, NO slit
SR-ASM-8055	Shamrock XY-adjust FC/APC adapt, NO slit
SR-ASM-8056	Shamrock XY-adjust FC adapter
SR-ASM-8057	Shamrock XY-adjust ferrule adapter, NO slit
SR-ASM-8069	Shamrock XY-adjust Ferrule adapter
SR-ASZ-0030	Shamrock manual slit assembly - output port
SR-ASZ-0031	Shamrock manual slit assembly - input port
SR-ASZ-0035	Shamrock motorised slit - side input port
SR-ASZ-0036	Shamrock motorised slit - side output port
SR2-ASM-0098	Shamrock 193i 7 mm extension feet (set of 4)
SR2-ASZ-7007	Shamrock 193i 6-position motorised filter wheel
SR2-SHT-9006	Shamrock 193i entrance shutter
SR2-SHT-9006-FIELD	Shamrock 193i entrance shutter (installation in the field)
SR-ASZ-0086	Shamrock 193i wide-aperture entrance slit for side input port
SR-ASZ-0079	Shamrock optical extender/relay optic

Appendix B2: Summary of camera flanges available with the Shamrock 193i.

Part no	Description
MFL-SR2-CCD	Shamrock 193i mounting flange for iDus, Newton, iStar and iVac, direct output port
MFL-SR2-IXON	Shamrock 193i mounting flange for iXon3 (exc. iXon 3 888) and iXon Ultra, direct output port
MFL-SR2-IKON-M	Shamrock 193i mounting flange for iKon M, direct output port
MFL-SR2-ZYLA	Shamrock 193i mounting flange for Zyla, direct output port
MFL-SR2-ISTAR-DIRECT	Shamrock 193i mounting flange for iStar, direct output port
MFL-SR2-ISTAR-SIDE	Shamrock 193i mounting support bracket for iStar, side output port
MFL-SR2-NEO	Shamrock 193i mounting flange for NEO, direct output port

Appendix B3: Summary of the standard optical fibre bundles available with the Shamrock 193i

Part no	Description
SR-OPT-8002	1 leg fibre bundle 100 um cores - VIS/NIR - SMA-Ferrule 2m
SR-OPT-8007	2 leg fibre bundle 100 um cores - VIS/NIR - SMA-Ferrule 2m
SR-OPT-8008	4 leg fibre bundle 100 um cores - VIS/NIR - SMA-Ferrule 2m
SR-OPT-8009	5 leg fibre bundle 100 um cores - VIS/NIR - SMA-Ferrule 2m
SR-OPT-8013	3 leg fibre bundle 100 um cores - VIS/NIR - SMA-Ferrule 2m
SR-OPT-8014	1 leg fibre bundle 100 um cores - UV/VIS - SMA-Ferrule 2m
SR-OPT-8015	2 leg fibre bundle 100 um cores - UV/VIS - SMA-Ferrule 2m
SR-OPT-8016	3 leg fibre bundle 100 um cores - UV/VIS - SMA-Ferrule 2m
SR-OPT-8017	4 leg fibre bundle 100 um cores - UV/VIS - SMA-Ferrule 2m
SR-OPT-8018	5 leg fibre bundle 100 um cores - UV/VIS - SMA-Ferrule 2m
SR-OPT-8019	1 leg fibre bundle 200 um cores - VIS/NIR - SMA-Ferrule 2m
SR-OPT-8020	2 leg fibre bundle 200 um cores - VIS/NIR - SMA-Ferrule 2m
SR-OPT-8021	3 leg fibre bundle 200 um cores - VIS/NIR - SMA-Ferrule 2m
SR-OPT-8022	4 leg fibre bundle 200 um cores - VIS/NIR - SMA-Ferrule 2m
SR-OPT-8024	1 leg fibre bundle 200 um cores - UV/VIS - SMA-Ferrule 2m
SR-OPT-8025	2 leg fibre bundle 200 um cores - UV/VIS - SMA-Ferrule 2m
SR-OPT-8026	3 leg fibre bundle 200 um cores - UV/VIS - SMA-Ferrule 2m
SR-OPT-8027	4 leg fibre bundle 200 um cores - UV/VIS - SMA-Ferrule 2m
SR-OPT-8039	1 leg fibre single 100 um core - VIS/NIR - SMA-SMA 2m

Appendix B4: Summary of standard gratings available for Shamrock 193i.

Part no	Description
SR-ASM-8083	Shamrock 193i additional grating turret (gratings NOT included)
SR2-GRT-0150-0300	Shamrock 193i ruled grating, 150 l/mm, 300 nm blaze, aluminium + MgF2 coating
SR2-GRT-0150-0500	Shamrock 193i ruled grating, 150 l/mm, 500 nm blaze, aluminium + MgF2 coating
SR2-GRT-0150-0500SIL	Shamrock 193i ruled grating, 150 l/mm, 500 nm blaze, protected silver coating
SR2-GRT-0150-0800	Shamrock 193i ruled grating, 150 l/mm, 800 nm blaze, aluminium + MgF2 coating
SR2-GRT-0150-0800SIL	Shamrock 193i ruled grating, 150 l/mm, 800 nm blaze, protected silver coating
SR2-GRT-0150-1250	Shamrock 193i ruled grating, 150 l/mm, 1250 nm blaze, aluminium + MgF2 coating
SR2-GRT-0150-1250SIL	Shamrock 193i ruled grating, 150 l/mm, 1250 nm blaze, protected silver coating
SR2-GRT-0150-2000	Shamrock 193i ruled grating, 150 l/mm, 2000 nm blaze, aluminium + MgF2 coating
SR2-GRT-0150-2000SIL	Shamrock 193i ruled grating, 150 l/mm, 2000 nm blaze, protected silver coating
SR2-GRT-0200-0730	Shamrock 193i ruled grating, 200 l/mm, 730 nm blaze, aluminium + MgF2 coating
SR2-GRT-0258-0315	Shamrock 193i ruled grating, 258 l/mm, 315 nm blaze, aluminium + MgF2 coating
SR2-GRT-0300-0300	Shamrock 193i ruled grating, 300 l/mm, 300 nm blaze, aluminium + MgF2 coating
SR2-GRT-0300-0500	Shamrock 193i ruled grating, 300 l/mm, 500 nm blaze, aluminium + MgF2 coating
SR2-GRT-0300-0500SIL	Shamrock 193i ruled grating, 300 l/mm, 500 nm blaze, protected silver coating
SR2-GRT-0300-0760	Shamrock 193i ruled grating, 300 l/mm, 760 nm blaze, aluminium + MgF2 coating
SR2-GRT-0300-0760SIL	Shamrock 193i ruled grating, 300 l/mm, 760 nm blaze, protected silver coating
SR2-GRT-0300-0860	Shamrock 193i ruled grating, 300 l/mm, 860 nm blaze, aluminium + MgF2 coating
SR2-GRT-0300-0860SIL	Shamrock 193i ruled grating, 300 l/mm, 860 nm blaze, protected silver coating
SR2-GRT-0300-1000	Shamrock 193i ruled grating, 300 l/mm, 1000 nm blaze, aluminium + MgF2 coating
SR2-GRT-0300-1000SIL	Shamrock 193i ruled grating, 300 l/mm, 1000 nm blaze, protected silver coating
SR2-GRT-0300-1200	Shamrock 193i ruled grating, 300 l/mm, 1200 nm blaze, aluminium + MgF2 coating
SR2-GRT-0300-1200SIL	Shamrock 193i ruled grating, 300 l/mm, 1200 nm blaze, protected silver coating
SR2-GRT-0300-1700	Shamrock 193i ruled grating, 300 l/mm, 1700 nm blaze, aluminium + MgF2 coating
SR2-GRT-0300-1700SIL	Shamrock 193i ruled grating, 300 l/mm, 1700 nm blaze, protected silver coating
SR2-GRT-0600-0300	Shamrock 193i ruled grating, 600 l/mm, 300 nm blaze, aluminium + MgF2 coating
SR2-GRT-0600-0500	Shamrock 193i ruled grating, 600 l/mm, 500 nm blaze, aluminium + MgF2 coating
SR2-GRT-0600-0500SIL	Shamrock 193i ruled grating, 600 l/mm, 500 nm blaze, protected silver coating
SR2-GRT-0600-0650	Shamrock 193i ruled grating, 600 l/mm, 650 nm blaze, aluminium + MgF2 coating
SR2-GRT-0600-0650SIL	Shamrock 193i ruled grating, 600 l/mm, 650 nm blaze, protected silver coating
SR2-GRT-0600-0750	Shamrock 193i ruled grating, 600 l/mm, 750 nm blaze, aluminium + MgF2 coating
SR2-GRT-0600-0750SIL	Shamrock 193i ruled grating, 600 l/mm, 750 nm blaze, protected silver coating
SR2-GRT-0600-0800	Shamrock 193i ruled grating, 600 l/mm, 800 nm blaze, aluminium + MgF2 coating
SR2-GRT-0600-0800SIL	Shamrock 3193i03i ruled grating, 600 l/mm, 800 nm blaze, protected silver coating
SR2-GRT-0600-1000	Shamrock 193i ruled grating, 600 l/mm, 1000 nm blaze, aluminium + MgF2 coating
SR2-GRT-0600-1000SIL	Shamrock 193i ruled grating, 600 l/mm, 1000 nm blaze, protected silver coating
SR2-GRT-0600-1200	Shamrock 193i ruled grating, 600 l/mm, 1200 nm blaze, aluminium + MgF2 coating
SR2-GRT-0600-1200SIL	Shamrock 193i ruled grating, 600 l/mm, 1200 nm blaze, protected silver coating
SR2-GRT-0600-1600	Shamrock 193i ruled grating, 600 l/mm, 1600 nm blaze, aluminium + MgF2 coating
SR2-GRT-0600-1600SIL	Shamrock 193i ruled grating, 600 l/mm, 1600 nm blaze, protected silver coating
SR2-GRT-0600-1900	Shamrock 193i ruled grating, 600 l/mm, 1900 nm blaze, aluminium + MgF2 coating
SR2-GRT-0600-1900SIL	Shamrock 193i ruled grating, 600 l/mm, 1900 nm blaze, protected silver coating
SR2-GRT-0830-0820	Shamrock 193i ruled grating, 830.8 l/mm, 820 nm blaze, aluminium + MgF2 coating
SR2-GRT-0830-0820SIL	Shamrock 193i ruled grating, 830.8 l/mm, 820 nm blaze, protected silver coating

SR2-GRT-1200-0300	Shamrock 193i ruled grating, 1200 l/mm, 300 nm blaze, aluminium + MgF2 coating
SR2-GRT-1200-0500	Shamrock 193i ruled grating, 1200 l/mm, 500 nm blaze, aluminium + MgF2 coating
SR2-GRT-1200-0500SIL	Shamrock 193i ruled grating, 1200 l/mm, 500 nm blaze, protected silver coating
SR2-GRT-1200-0600	Shamrock 193i ruled grating, 1200 l/mm, 600 nm blaze, aluminium + MgF2 coating
SR2-GRT-1200-0600SIL	Shamrock 193i ruled grating, 1200 l/mm, 600 nm blaze, protected silver coating
SR2-GRT-1200-0750	Shamrock 193i ruled grating, 1200 l/mm, 750 nm blaze, aluminium + MgF2 coating
SR2-GRT-1200-0750SIL	Shamrock 193i ruled grating, 1200 l/mm, 750 nm blaze, protected silver coating
SR2-GRT-1200-0850	Shamrock 193i ruled grating, 1200 l/mm, 850 nm blaze, aluminium + MgF2 coating
SR2-GRT-1200-0850SIL	Shamrock 193i ruled grating, 1200 l/mm, 850 nm blaze, protected silver coating
SR2-GRT-1200-1000	Shamrock 193i ruled grating, 1200 l/mm, 1000 nm blaze, aluminium + MgF2 coating
SR2-GRT-1200-1000SIL	Shamrock 193i ruled grating, 1200 l/mm, 1000 nm blaze, protected silver coating
SR2-GRT-1200-EH	Shamrock 193i holographic grating, 1200 l/mm, optimised 500 - 1600 nm, 500 nm peak, Al + MgF2 coating
SR2-GRT-1800-DH	Shamrock 193i holographic grating, 1800 l/mm, optimised 200 - 650 nm, 265 nm peak, Al + MgF2 coating
SR2-GRT-1800-FH	Shamrock 193i holographic grating, 1800 l/mm, optimised 220 - 1080 nm, 480 nm peak, Al + MgF2 coating
SR2-GRT-2400-0300	Shamrock 193i ruled grating, 2400 l/mm, 300 nm blaze, aluminium + MgF2 coating
SR2-GRT-2400-BH	Shamrock 193i holographic grating, 2400 l/mm, optimised 200 - 700 nm, 275 nm peak, Al + MgF2 coating
SR2-GRT-2400-GH	Shamrock 193i holographic grating, 2400 l/mm, optimised 250 - 800 nm, 400 nm peak, Al + MgF2 coating
SR2-GRT-MR-AL+MGF2	Shamrock 193i flat mirror for grating turret, Al+MgF2 coating
SR2-GRT-MR-SILVER	Shamrock 193i flat mirror for grating turret, silver protected coating

Appendix B5: Summary of scanning accessories available.

Part no	Description
ACC-SR-ASM-0042	MCT single point detector + LN2 Dewar
ACC-SR-ASM-0043	InSb single point detector + LN2 Dewar
ACC-SR-ASM-0044	InGaAs 1.9 um single point detect +TE cooler
ACC-SR-ASM-0045	PbS 2.9 um single point detect + amplifier
ACC-SR-ASM-0046	Si photodiode single point detector, UV+
ACC-SR-ASM-0047	PMT R928 single point detector, uncooled
ACC-SR-ASM-0048	PMT R1527P SPD, uncooled. Photon Counting
ACC-SR-ASM-0066	PMT R928P SPD, uncooled. Photon Counting
ACC-SR-ASZ-0053	PMT High Voltage power supply, 0-1.5kV
ACC-SR-ASZ-0054	PMT photon counting unit for PMT tubes
ACC-SR-ASZ-0055	Data acquisition unit for scanning SPDs
ACC-SRS-SR540	Chopper SRS SR540 compatible with SR830
ACC-SRS-SR830	Lock-in amplifier SRS SR830