BENTHAM

The Light Measurement Company

ISR300 Integrated Spectroradiometer

User Manual

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Contents

1. Introduction

This manual has been written to provide information on the use of the ISR300 integrated spectroradiometer and all standard options pertaining thereto.

2. Overview

The ISR300 is composed of a single TMc300 monochromator with, situated to the base of the unit, a two-channel transimpedance amplifiers/ ADCs to constitute an integrated spectroradiometer.

In the TM300 monochromator, up to three diffraction gratings are mounted on a turret to permit use over a wide spectral range.

For each grating is provided two wavelength calibration parameters; the first is the number of steps from the datum position to the nominal zero order position for that grating (zord), the second is a scaling factor (value near 1) which gives the best wavelength linearity (alpha).

Multiple configurations are accommodated by the addition, at the entrance/ exit ports of each component TMc300, of an additional slit with a computer-controlled selection mirror (SAM) between the two.

The entrance and exit ports are fitted with motorised variable slits.

Figure 1:- ISR300 monochromator

A six- or eight-position order sorting filter wheel is situated behind the entrance port to suppress all but the first diffraction order. Included is a blank disk to act as a shutter.

All control electronics for the monochromator turret, internal filter wheel and SAMs are situated on the underside of the unit.

Mains and the controlling USB connections are made directly to the ISR300.

3. Grating Drive

In the TMc300, is to be found a turret upon which may be mounted up to three diffraction gratings.

The turret is driven through a reduction gear by a stepping motor, used in the micro-stepping mode to yield an angular resolution of 0.00072° per step; 500,000 micro- steps per revolution of the turret.

To the turret drive is fitted a two-stage encoder, allowing the turret to be sent to a fixed datum point (negative limit). On software initialisation, the turret is sent to this position, or “parked”.

The TMc300 does not include any mechanical sine law conversion as is oft the case with grating drives; each step of the stepping motor corresponds to a fixed change in angle and as a result, the wavelength change per step will vary with grating angle.

In common with all gear systems, the grating turret drive in the TMc300 suffers from backlash, a region of inaction immediately after the direction of rotation be changed, albeit reduced by the design of the drive. This is easily overcome by ensuring that the desired location of the turret (wavelength) be at all times approached from the same direction.

To go therefore from a higher to a lower wavelength, the turret should be moved beyond the target location which is then approached in the direction of increasing wavelength.

4. Diffraction Gratings

To the turret of each TMc300 can be mounted up to three diffraction gratings.

The diffraction gratings for the ISR300 are 68x 84mm, provided in a mount for attachment to the turret.

On purchasing a monochromator, all gratings are factory fitted. For those gratings purchased at a later time, further information concerning grating installation is provided in §19.

The following table summarises the maximum recommended range of use in the ISR300 of the most popular diffraction gratings offered by Bentham:-

Between zero nanometres (at which position the grating acts as a mirror) and the minimum cited wavelength, problems may be encountered with re-diffracted light whereby the zero diffraction order is coincident with the diffraction grating, and "re-diffracted".

Above the maximum cited wavelength, the grating is rotated to such an extent that the angle of incidence of light onto the grating shall approach 90°.

Line density (g/mm)	Maximum λ range
2400	200-675 nm
1800	200-900 nm
1200	250-1200 nm
830	500-1800 nm
600	800-2500 nm
400	1- 3 μm
300	1.5-5.5 μm
150	2.4-8.0 μm
100	4.5-16.2 μm
75	6- 21 μm
50	9- 27 μm

Table 1: Grating maximum range of use

5. Order-Sorting Filter Wheel

The governing diffraction equation admits solutions for integer multiples of the wavelength in consideration, thus diffraction orders (see §21.7).

Most spectroradiometry is performed on the first order contribution; it is necessary to avoid measurement of higher diffraction orders for correct measurements.

A six- or eight-position order sorting filter wheel is to be found inside the monochromator entrance port, fitted with order sorting filters suitable for the spectral range of use

Below four hundred nanometres, no filters are required since for the next highest diffraction order, the second, the corresponding wavelength is less than 200nm which is blocked in any case by the atmosphere.

Spectral range	Required OS Filter
<400 m	None
400-700nm	OS400
700-1250nm	OS700
1250-2000nm	OS1250
2000-3600nm	OS2000-
3.6-6 μm	-OS3600
6-10.5 μm	OS6000
10.5-21 μm	OS10500
> 21μm	*please consult*

Table 2: Required order sorting filters

A blank disk in the last position (six or eight) stops light from entering the monochromator during dark current and offset measurements.

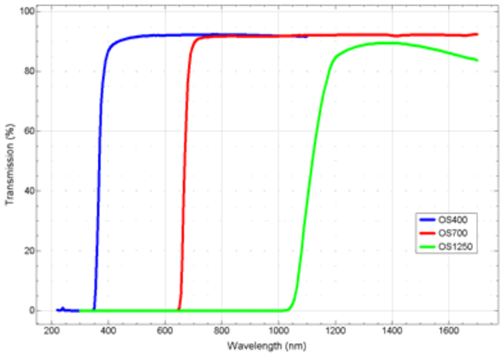


Figure 2:-Typical OS filter transmission

6. Entrance & exit slits

All slits of this system are fitted with motorised variable slits, comprised of stepping motor-driven bi-lateral slits, driven from the internal monochromator electronics and variable from 10μm to 10mm.

The motorised slits are entirely controlled by computer through the USB interface, please see §12.

7. Swing Away Mirrors

Swing away mirrors permit the addition of a supplementary entrance/ exit port to the TMc300, the solenoid based mirror being set to either relay the beam from one slit or to move out of the beam to use the other.

8. Monochromator Bandwidth

The monochromator bandwidth, defined in nm, is the range of wavelengths seen by the detector at one time, and is directly linked to the monochromator slits in use.

This is an important quantity to take into account, particularly when measuring sources have fine spectral features such as line emission- for example the measurement of a source having two spectral lines one nanometre apart with a system bandwidth of five nanometres, will result in the measurement of a single line.

In many instances this is of no concern, since the power measured shall nevertheless be correct.

The effect of monochromator entrance and exit slits on monochromator bandwidth can be viewed in two manners.

In the first instance, the monochromator is an imaging system; the input port is imaged at the exit port; the dimension of the monochromator entrance slit defines the image size at the exit port.

Furthermore, at the exit of the monochromator, since the light incident thereupon is dispersed, on can imagine the wavelength axis running along parallel to the wall of the exit slit, and the size of this slit determines how many wavelengths can be seen at one time.

One can imagine therefore an infinite number of images of the entrance slit, of incrementally differing wavelength, presented parallel to the exit slit; whichever of the two are the largest, defines the bandwidth of the system.

In a double monochromator, a further slit is included, the middle slit (in the case of a system having additive dispersion).

The purpose of this slit is to reduce the amount of stray light going from the first to second monochromators and should at all times be set to at least 20% larger than the largest slit in the system, else tracking problems between the component monochromators shall result.

The slit function of a monochromator provides interesting information with regards the device performance and the system bandwidth.

The slit function may be determined by the measurement of a source of narrow spectral width, such as a laser.

One should perform a measurement at smaller steps than the system bandwidth (for example 0.1nm), over a spectral range of around four times the expected bandwidth, centred on the expected wavelength of the emission line, for example 632.8nm for the HeNe laser.
The full width half maximum (FWHM) of this spectrum provides the bandwidth of the system.

Inspecting the signal at one bandwidth, two bandwidths etc. relative to the peak, provides information of the stray light performance of the system.

If the entrance and exit slits are of the same dimension, the slit function shall have a triangular profile, otherwise, the function shall be flat-topped.

It is worthy to note that care should be made in making this measurement- it is not sufficient to shine a laser in the entrance slit of the monochromator.
This measurement should ideally be performed by filling the entrance slit, for example with the use of an integrating sphere, and illuminating the sphere with the source.

Finally, it follows of course that slit dimension has an impact of the light throughput of the monochromator, and in certain instances where a reduction in signal is required, either the entrance or exit slit is reduced, whilst maintaining the same system bandwidth.

It is preferable that the slit to be reduced be the exit slit to avoid any conflict with the input optic.

The slits of this system are motorised and as such are control by computer.

For information, the following table shows the bandwidth obtained for the monochromator and gratings of this system with a range of slit widths, for the single and double configurations.

It is important to remember that to perform a scan with a step size lower than the bandwidth obtained is satisfactory, on the contrary to step larger than the bandwidth results effectively in the loss of information.

Grating Groove Density (l/mm)		**2400**	**1200**	**600**	**400**	**300**	**150**	**100**	**75**	**50**
Reciprocal Dispersion (nm/mm)		1.35	2.70	5.40	8.11	10.81	21.62	32.42	43.23	64.85
Slit widths (mm)	**Part no. for pair of slits**	**Bandwidth produced (nm)**								
0.05	FS (0.05)	0.07	0.14	0.27	0.41	0.54	1.08	1.62	2.16	3.24
0.1	FS (0.10)	0.14	0.27	0.54	0.81	1.08	2.16	3.24	4.32	6.48
0.2	FS (0.20)	0.27	0.54	1.08	1.62	2.16	4.32	6.48	8.65	12.97
0.37	FS (0.37)	0.50	1.00	2.00	3.00	4.00	8.00	12.00	16.00	23.99
0.4	FS (0.40)	0.54	1.08	2.16	3.24	4.32	8.65	12.97	17.29	25.94
0.5	FS (0.50)	0.68	1.35	2.70	4.05	5.40	10.81	16.21	21.62	32.42
0.56	FS (0.56)	0.76	1.51	3.03	4.54	6.05	12.10	18.16	24.21	36.31
0.74	FS (0.74)	1.00	2.00	4.00	6.00	8.00	16.00	23.99	31.99	47.99
1	FS (1.00)	1.35	2.70	5.40	8.11	10.81	21.62	32.42	43.23	64.85
1.12	FS (1.12)	1.51	3.03	6.05	9.08	12.10	24.21	36.31	48.42	72.63
1.48	FS (1.48)	2.00	4.00	8.00	12.00	16.00	31.99	47.99	63.98	95.97
1.85	FS (1.85)	2.50	5.00	10.00	15.00	19.99	39.99	59.98	79.98	119.97
2	FS (2.00)	2.70	5.40	10.81	16.21	21.62	43.23	64.85	86.46	129.69
2.78	FS (2.78)	3.76	7.51	15.02	22.53	30.05	60.09	90.14	120.18	180.27
3.7	FS (3.70)	5.00	10.00	19.99	29.99	39.99	79.98	119.97	159.96	239.93
4	FS (4.00)	5.40	10.81	21.62	32.42	43.23	86.46	129.69	172.92	259.39
5.56	FS (5.56)	7.51	15.02	30.05	45.07	60.09	120.18	180.27	240.36	360.55
8	FS (8.00)	10.81	21.62	43.23	64.85	86.46	172.92	259.39	345.85	518.77

Table 3: Single configuration bandwidth

9. Wavelength Selection

The first order grating equation for the TMc300 is (for more detailed treatment, see §21):-

$$\lambda = 2d \operatorname{Sin}\theta \operatorname{Cos}\beta$$

Where

λ, wavelength (m)

d = groove spacing of the diffraction grating (m)

θ = grating angle in degrees

β = a fixed angle determined by the design of the monochromator ($\cos\beta$ for the TMc300 = 0.9727)

The grating angle required for wavelength λ is therefore given by:-

$$\theta = \sin^{-1}\left(\frac{\lambda.RD.10^{-6}}{1.9454}\right)$$

Where λ is in nm, RD in grooves per mm.

The ZORD value given for each grating corresponds to the number of motor steps between the datum point and zero angle for that grating (at which point the grating acts as a mirror).

The Alpha value given for each grating is used to modify the calculated grating angle to give the best wavelength accuracy.

The position of the grating for a given wavelength is calculated as the number of motor steps from the datum point.

Position= (θxAlphax(500000/360))+ZORD

This is calculated for the turrets of both component TMc300s.

10. Wavelength Calibration

10.1 Overview

The ISR300 was wavelength calibrated in factory.

It is recommended that the customer periodically check the wavelength calibration, particularly if the device has been transported.

The initial wavelength calibration procedure typically consists of placing a white light source on the monochromator entrance slit and finding the number of micro steps from the park position to the zero order position (ZORD).

At this position, the white light is transmitted through to the exit of the monochromator.

In the case of the ISR300, the first monochromator transmits the white light through the middle slit; the second through the exit slit.

This procedure represents a gross calibration; armed with the ZORD value one can measure a source having known line emission to refine the calibration.

To this end a mercury lamp is typically employed, which emits a number of spectral lines in the region 250-700nm, whose position never changes.

In practice, higher diffraction orders are useful when performing wavelength calibration to provide a larger number of reference points. It is of course important to ensure that whilst observing the higher order lines, the order sorting filters of the monochromator are de-activated. This is done by setting the insertion wavelength of the non-required filters to 0nm (in Benwin+, instruments menu/ filter wheel).

The following summarises a number of the useful mercury lines. Those marked in red are particularly strong lines, leading therefore to higher orders with a measurable contribution.

1st Order	2nd Order	3rd Order	4th Order	5th Order	6th Order	7th Order
184.91						
194.17						
226.22						
237.83						
248.2						
253.65	507.3	760.95	1014.6	1268.25	1521.9	1775.55
265.2						
280.35						
289.36						
296.73						
302.15						
312.57	625.14	937.71	1250.28	1562.85		
313.17						
334.15						
365.02	730.04	1095.06	1460.08	1825.1		
365.44						
366.33						
404.66	809.32	1213.98	1618.64			
407.78						
434.75						
435.84	871.68	1307.52	1743.36			
491.6						
496.03						
546.07	1092.14	1638.21				
576.96						
579.07						
690.7						
1013.98						

Table 5: Principle Hg emission lines

10.2 Spectral Measurements

Spectral measurements are performed, the positions of these lines checked and the calibration factors, alpha and zord changed to bring the monochromator into calibration.

It is recommended that the customer does not change alpha however.

Where the Hg lines are too low in wavelength, the zord value should be increased and vice versa.

As a guide, for 2400g/mm in the double configuration, 100steps corresponds to ~1nm, and 50 steps in the single configuration. The dispersion of the 1200g/mm grating is half this, etc.

Measurements in step of 0.1nm (with the slits in manual bandwidth mode) should be made of the regions around the Hg lines, and either the peak values or FWHM central wavelength taken as the position of the line.

Be aware of the slits presently in use in the system. Having for example 5nm slits and looking at the lines around 365nm, one will effectively see several lines which can distort the result and wrongly show lack of calibration.

In the case of infrared gratings where there is no useful emission of the Hg source, gratings are set up with the zero-order position, setting the monochromator to zero nanometres and ensuring the white light is transmitted through the exit slit.

Where a mercury lamp is not available, overhead fluorescent lamps are often of use since they contain mercury gas.

Because of the glass envelope of the lamp no light is emitted below 350nm.

Where a system contains SAMs, the calibration procedure should be repeated in all ports.

10.3 ISR300 Calibration

The calibration of the ISR300 should be performed with the smallest slits width intended to be used, with the motorised slits operated in manual bandwidth mode.

Measurements should be made of a mercury source and the ZORD value modified to bring the device into calibration.

The calibration should be checked with the smallest slits intended to be used in measurement.

11. Grating Installation

11. 1 Fitting

Where a grating is purchased at a later date, it should be carefully installed by the customer using the following instructions as a guide.

Do not touch the gratings or mirrors. If the grating is touched by accident, trying to clean it can only do more harm

- Remove the lid of the monochromator
- Using the control computer, rotate the turret to give access to the free grating location
- Note that the grating has two attachment points, upper and lower
- Attach the grating positioned in the correct orientation and vertical
- Note the grating is asymmetric about the attachment points; the small area should be to the side of the order sorting filter

11.2 Setting Up

Note that the upper attachment point of the grating is slotted. The angular position of the grating is checked by ensuring that the image does not move in the vertical plane as the grating is scanned.

This is easily checked by placing a white light source at the entrance slit and using the computer to rotate the grating, at the same time ensuring that either the image at the exit port or the diffracted light on the walls of the monochromator do not change in height.

If this is not the case, reset the angular position of the grating until this is so.

11.3 Wavelength Calibration

Follow the wavelength calibration as detailed in §11.

12. Detection electronics

12.1 Components

The ISR300 houses a trans-impedance amplifier/ integrating ADC.

BNC current amplifier inputs are labelled channels 1 and 2.

12.2 487 DC Current Amplifier

The 487 is used as the main amplifier in dc systems employing photodiode or photomultiplier detectors. At low frequencies such devices give their best performance when connected to this type of virtual ground input.

The input effectively has zero input impedance and hence no voltage is generated across the device as a result of the photocurrent.

This short circuit operation enhances linearity of detectors and reduces the effect of cable capacitance.

The output of the current amplifier goes directly to the ADC. The output of the current amplifier is 0-10V per range.

There exists effectively two such amplifiers in this system, number one containing inputs one and two; number two, inputs three and four.

12.3 ADC

The ADC uses a continuously running voltage to frequency converter to produce a pulse train whose frequency is proportional to the instantaneous input voltage. The pulses are accumulated in a counter.

At fixed intervals, 100ms, the contents of the counter is transferred to an output buffer and the counter reset to zero. The total number of pulses accumulated by the counter in any counting period represents the true average of the signal during that counting period.

If the accumulated pulses from a number of counting periods are added and normalised then a true average over a longer period is obtained.

The ADC has two other special features which enhance its usefulness in light measurements systems.
Firstly, the input to the ADC is offset giving the unit a small negative range. This ensures that negative going noise peaks, occurring in near zero signals, are correctly averaged while retaining most of the available resolution for positive going signals.

Secondly, the ADC provides information to the computer indicating that a transient overload has occurred at some point during the conversion period. This information is essential if accurate measurements are to be made on pulsed light sources such as CRT monitors.

The ADC provides 2000 counts per volt and has a maximum of 20000 counts.

Due to the quantum nature of light and the way in which optical detectors work, signals in light measurement systems are always accompanied by electrical noise. The limit of low light level detection is often imposed by the ability of the measuring system to distinguish between the signal to be measured and the associated electrical noise.

In most cases, where the noise is truly random, the signal to noise ratio can be improved by averaging. For a signal accompanied by random noise the signal to noise ratio will increase in proportion to $1/\sqrt{T}$ where T is the averaging period.

With dc systems the maximum period which can be used for averaging is limited by so called dc drifts (i.e. low frequency noise. The noise power in fact increases continuously as zero Hz is approached).

The ADC therefore behaves as a digital averager with the averaging period programmable in 100ms increments.

For dc systems the averaging period can be fixed for a particular experimental set-up or can be varied depending on the signal level to give a substantially constant signal to noise ratio for all signal levels.

Software schemes have been used where the averaging period is determined by looking at the variance between successive readings or, more simply, by linking the averaging period to the sensitivity range of the amplifier so that averaging period increases as the sensitivity required increases.

This last approach is very useful in solar UV measurements where in a typical spectral scan from 280nm to 400nm the signal level changes by ~10^6.

Similarly, measurements which have included a transient noise pulse such as that produced by Cherenkov events in the window of a photomultiplier, can be recognised and repeated if required.

13. Setting mains voltage

The ISR300 is fitted with a switch mode power supply.

Fuses are fitted dependant on location.
Fuses are:-

110 V- 1260mA anti- surge
220/240V – 630mA anti- surge

14. Software Control

14.1 Introduction

The ISR300 may be controlled, as part of a Bentham spectroradiometer system, with Benwin+ or by customer written applications based on the Bentham Instruments SDK.

For further details of control with the SDK, please consult the SDK manual.

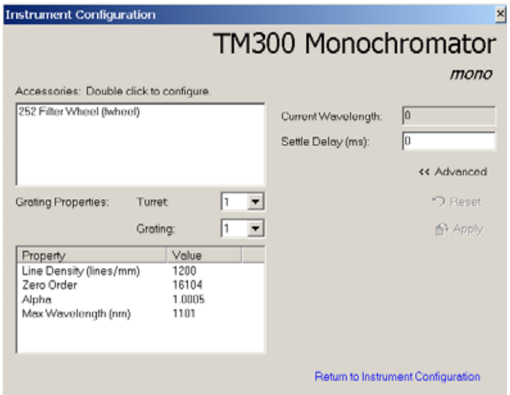
For an overview of the instrument settings in Benwin+ please see the following. For use of the software to perform spectral measurements, please consult the Benwin+ manual.

14.2 Monochromator

The properties of the ISR300 monochromator are obtained in the following menu item:-

Instruments/ Monochromator

Selecting Advanced>> gives access to the grating properties: line density, zord, alpha and maximum wavelength.



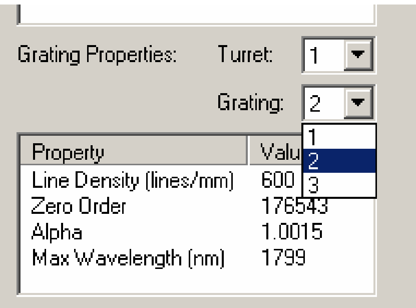
Accessories: Double click to configure.
252 Filter Wheel (fwheel)

Current Wavelength: 0
Settle Delay (ms): 0

Grating Properties: Turret: 1
Grating: 1

Property	Value
Line Density (lines/mm)	1200
Zero Order	16104
Alpha	1.0005
Max Wavelength (nm)	1101

The pull down arrow permits toggling between gratings and turrets.



Grating Properties: Turret: 1
Grating: 2

Property	Valu
Line Density (lines/mm)	600
Zero Order	176543
Alpha	1.0015
Max Wavelength (nm)	1799

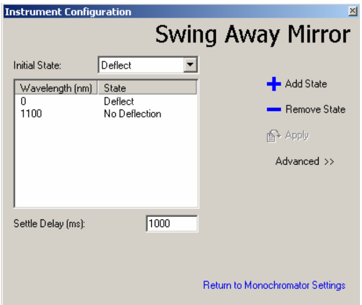
The zord and alpha parameters for each grating are obtained from the calibration certificate.

The max wavelength is the selection criterion from one to another grating. This should not exceed that recommended in table 1, but can be changed to optimise signal, for example where one grating loses efficiency another might gain (taking into account both change in efficiency and change in bandwidth as one migrates to another grating).

The settle delay can be set to 0ms.

14.3 Swing Away Mirror (SAM)

Accessed via a link in the monochromator page is the SAM page, named according to their positions.



Initial State: Deflect

Wavelength (nm)	State
0	Deflect
1100	No Deflection

Settle Delay (ms): 1000

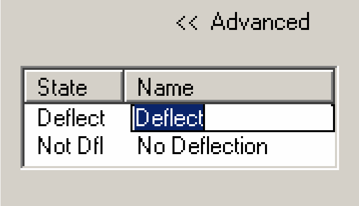
Here, one might add (“+”) a number of states (or remove by highlighting and hitting “–“).

Define states by the wavelength of insertion (inclusive), and the SAM state.

SAM states are as follows:-

•Deflect- deviate light from current path
•No deflection- move out of beam

In advanced>> can be named the two SAM states for easier setting up.



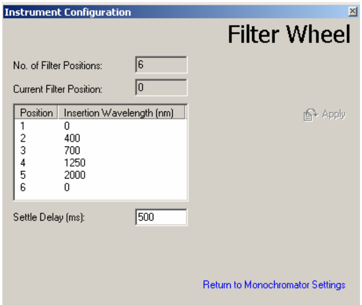
State	Name
Deflect	Deflect
Not Dfl	No Deflection

Settle delay of 1000ms is sufficient.

14.4 Filter Wheel

The properties of the filter wheel are obtained in the following menu item:-

Instruments/ Filter wheel



No. of Filter Positions: 6
Current Filter Position: 0

Position	Insertion Wavelength (nm)
1	0
2	400
3	700
4	1250
5	2000
6	0

Settle Delay (ms): 500

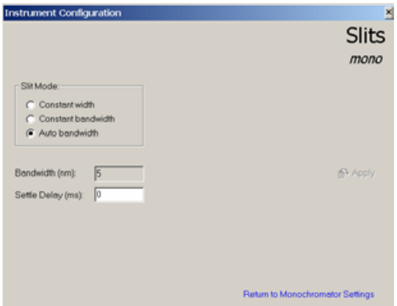
The insertion wavelength relevant to the filter in a given position should be input. The order need not be ascending.

A settle delay of 1000ms is sufficient.

14.5 Motorised slits

The properties of the motorised slits are obtained in the following menu item:-

Instruments/ Motorised slits



Slit Mode:
○ Constant width
○ Constant bandwidth
● Auto bandwidth

Bandwidth (nm): 5
Settle Delay (ms): 0

There are three available modes of operation:-

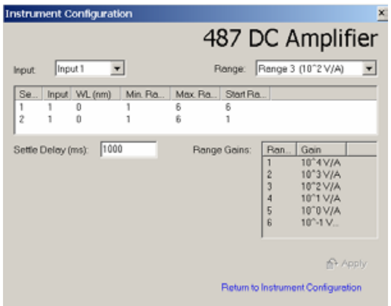
- *constant width*- input required dimension
- *constant bandwidth*- input required bandwidth
- *auto*- sets the bandwidth to the step size defined in the scan setup page

It should be noted that having calibrated a system in auto mode at a given step size, to change the step size would invalidate the calibration.

A settle delay of 100ms is sufficient.

14.6 Current Amplifier

The properties page of each DC pre-amplifier is as follows:-



Input: Input 1
Range: Range 3 (10^2 V/A)

Se...	Input	WL (nm)	Min. Ra...	Max. Ra...	Start Ra...
1	1	0	1	6	6
2	1	0	1	6	1

Settle Delay (ms): 1000

Range Gains:

Ran...	Gain
1	10^4 V/A
2	10^3 V/A
3	10^2 V/A
4	10^1 V/A
5	10^0 V/A
6	10^-1 V...

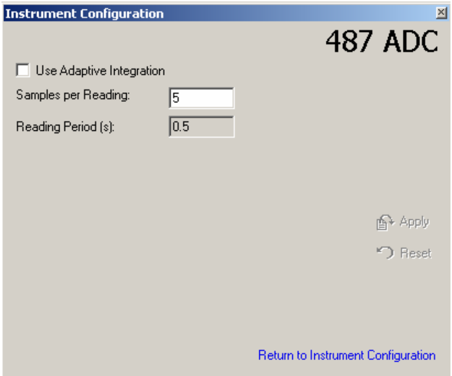
There are two setups, for which the properties may be defined. In multiple detector setups, the start wavelength of the second setup should be defined.

It is recommended to use all ranges 1 (min) to 6 (max). Set the start range as the max range.

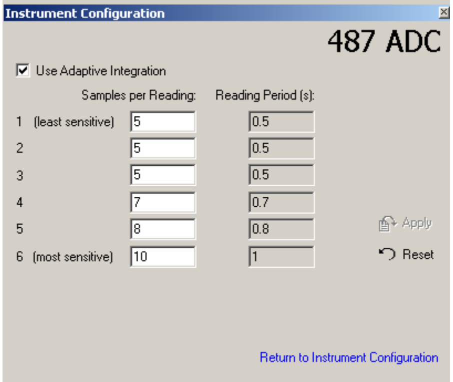
A settle delay of 1000ms is sufficient.

14.7 Analogue Digital Converter

The 487 ADC integrates over 100ms periods. One can choose how many of these periods shall be taken to determine the reading at each wavelength.



☐ Use Adaptive Integration
Samples per Reading: 5
Reading Period (s): 0.5



☑ Use Adaptive Integration

	Samples per Reading:	Reading Period (s):
1 (least sensitive)	5	0.5
2	5	0.5
3	5	0.5
4	7	0.7
5	8	0.8
6 (most sensitive)	10	1

A good number to use for reasonable signal is 5 averages.

One may also select adaptive integration which permits varying the number of averages taken as a function of the gain range of the current amplifier, fewer averages in the low gain ranges and more in the higher gain ranges to smooth out noise.

14.8 Changeover Wavelengths

It is important to note the mode of use of the changeover wavelengths in Benwin+, notably that the gratings behave in a manner different to all other items.

The specified changeover wavelength for a grating is the maximum wavelength of use, and is inclusive.

The changeover points of all other devices are defined as the start point of the new state, and are also inclusive.

Gratings should change therefore at x-0.1 nm, whilst all other elements at x nm.

It is important to synchronise such changes as those of SAMs, detectors and amplifier inputs in use.

It is also of use to make a number of changes at one particular wavelength rather than having a series of changes throughout a scan.

14.9 Configuration Files Syntax

Please consult the Benwin+ manual for further information concerning configuration file syntax.

15. System Specifications

The specifications of the ISR300 are as follows:-

XXX

16. Precautions

The following is a list of specific precautions aimed to preserve for good use this system.

•Do not touch gratings nor optics

•Do not subject monochromator to violent physical shock- this may invalidate wavelength calibration

•Do not use over-long screws when mounting items to entrance slit for fear of damaging bi-lateral slits

•Do not let the slits bear any heavy objects

17. Monochromator Operation

17.1 Introduction

The term monochrome and its variants come to us from the Greek words *mono* “single” and *chroma* “colour”.

No light source is truly monochromatic; no light source emits light of a single wavelength, all sources containing contributions from a finite range of wavelengths, termed its spectrum.

It is often of interest to decompose a source into its component wavelengths, for the purpose of determining the spectral distribution (UV, visible, infrared etc), or to employ that source as a means of testing samples under “monochromatic” stimulation.

In either case, a means of wavelength dispersion is required.

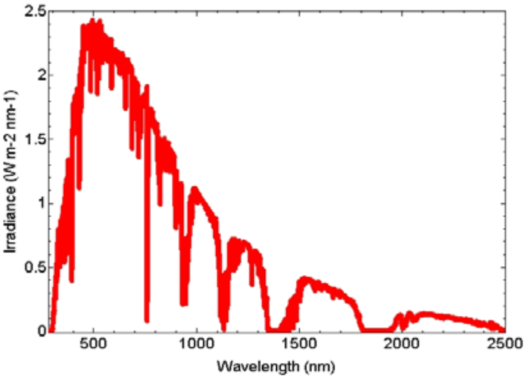


Figure 9:- Solar spectrum- from ultra violet to infrared

17.2 Light dispersion

The image of the dispersion of light can be little better conjured up than that of a rainbow.

Though not an entire description of the processes in play, the apparently “white” light from the sun, on travelling through the droplet is refracted, or bent from its path. The amount light is refracted depends upon its wavelength; blue light on one extreme of the visible spectrum is refracted more than the rest of the visible spectrum, through to red light on the other extreme, resulting in a rainbow.

In effect the sun contains wavelength components from the UV to the infra red (heat radiation), not visible to the human eye, but nevertheless part of the solar spectrum.

17.3 Light Dispersion Mechanisms

In terms of scientific instrumentation for use in the laboratory or field, the following are the principal manners of either determining the spectrum of a source.

Of the described techniques, only the reflection diffraction grating can be used over wide spectral range in a practical application, providing potentially very high spectral resolution.
It is this technique that is employed in all Bentham monochromators.

Henceforth shall be presented the theory and operation of such a device.

Mechanism	***Dispersion Process***	***Pros***	***Cons***
Prism	Refraction	-Simple -Inexpensive	-Prism material absorbs light -Non-linear dispersion
Reflection diffraction grating	Diffraction	-Can be optimised	-Linear dispersion -Complex process -Delicate optics -Expensive -Delicate optics
Transmission diffraction grating	Diffraction	-Relatively simple	-Linear dispersion -Complex process -Delicate optics -Expensive -Grating material absorbs light
Band Pass Filter	Band pass filters	-Simple -Relatively inexpensive (in visible-NIR only)	-Low spectral resolution -Low throughput

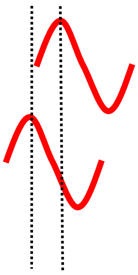
17.4 Wave Interference

Light can be considered as having a wave-like nature. When two such waves are brought into proximity, they interact, the resultant wave depending on the amplitudes, frequencies and relative phases of the two waves. In the context of diffraction gratings, it is sufficient to consider the case of the superposition of two waves of equal frequency (and therefore wavelength). The resultant wave is simply the sum of the two.

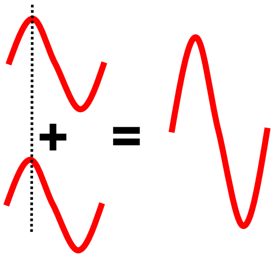
With a phase difference of zero or a whole number of wavelengths, constructive interference obtains, ie mλ where m is an integer.

With a phase difference of half a wavelength, they interfere destructively, ie mλ/2 where m is an whole number

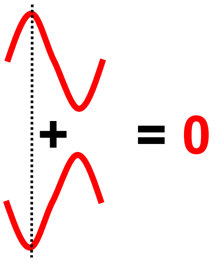
Between these two conditions varying degrees of interference result.



Phase difference



Constructive Interference

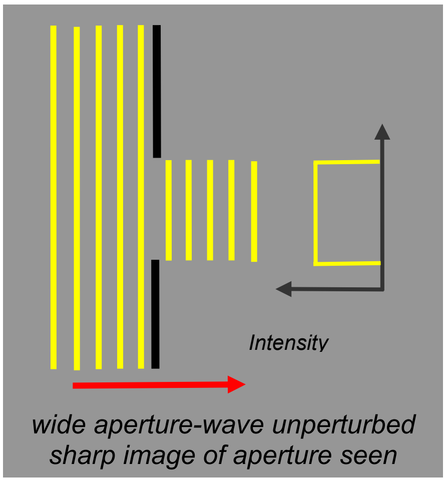


Destructive Interference

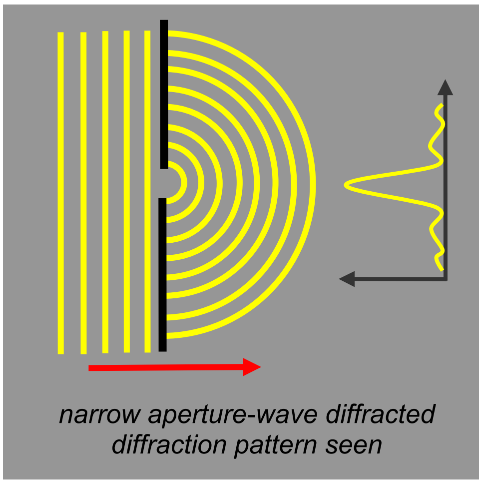
Figure 10:-Wave interference

17.5 Theory of diffraction

Diffraction describes a variety of processes which obtain when waves, such as light, approaches an obstacle of dimension of the order of their wavelength, and is characterised by the apparent bending of the waves around the object, such as is demonstrated across.



wide aperture-wave unperturbed sharp image of aperture seen



narrow aperture-wave diffracted diffraction pattern seen

Figure 11:-Single slit diffraction

What is transmitted in the one case is a sharp image of the aperture, and in the other a diffracted image of the aperture (seen , whereby most of the light is transmitted on axis, but at wider angles, because of interference effects, a diffraction pattern obtains.

Whilst this example demonstrates the principle in transmission, the same applies were the aperture replaced by a reflecting surface; would be reflected in the case of a narrow mirror light would be reflected in all directions.

Note that in the case of reflection, specular reflection obtains, where the peak in intensity is transmitted in the same angle as the angle of incidence.

This is termed single slit diffraction.

17.6 Reflection Diffraction Grating

A reflection diffraction grating is a surface which, on the microscopic scale, is made up of a large number of rectangular grooves of width comparable to the wavelength of light to be considered. Bentham uses gratings with a “groove density” from 75- 2400 grooves per millimetre.

On shining light upon this surface, diffraction at each of the grooves obtains; each groove acting as a (coherent) source of light, emitting a cylindrical wave.

The coherence of these cylindrical waves is an important aspect since any phase difference between adjacent grooves is due solely to geometry and not from the source.

It is the interference of the light from these numerous sources that is of interest.

Diffraction can be visualised by the following, whereby light of wavelength λ is incident at an angle α to the normal of a diffraction grating of groove spacing, d. Light is diffracted along angles β_m into a number, m, of diffraction orders.

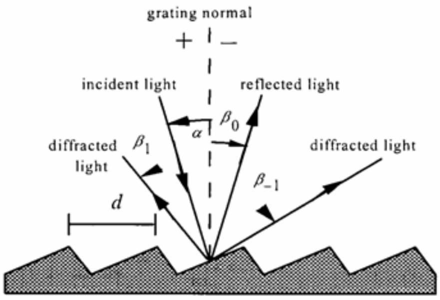


Figure 12:- Plane reflection grating diffraction

It is the interference between the waves diffracted from each groove the provides wavelength discrimination as a function of angle.

A sign convention exists for the definition of angles and orders. In general angles are measured from the grating normal to the incident wavefront.

Should diffraction occur on the opposite side of the grating normal, then negative angles are used.

This view can be simplified to the following, where one can consider two adjacent grooves separated by a distance, d.

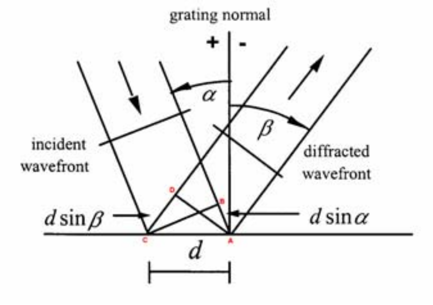


Figure 13:- Path difference between neighbouring rays

The geometrical path difference, Δ, between the path of the incident wavefront between A and B and the diffracted wavefront between C and D is

$$\Delta = AB + CD = d \sin \alpha + d \sin \beta \text{.....1}$$

Now, for constructive interference to obtain, adjacent rays must differ by integer number of wavelengths. This leads to the grating equation.

$$m\lambda = d(\sin\alpha + \sin\beta) \text{ .... } 2$$

or

$$Gm\lambda = \sin\alpha + \sin\beta \text{ .... .3}$$

where G is the groove density, G= 1/d.

For a given incidence angle α, there shall therefore be a set of discrete angles for which constructive interference shall be observed. At all other angles, there will be some measure of destructive interference.

Here m is the diffraction order and is an integer.

Since the absolute value of the sine function cannot exceed unity, then:-

$$| m\lambda / d | < 2 \text{ .... .4}$$

For a particular wavelength the above gives the possible diffraction orders present.

Specular reflection (α =β) always exists, this is the m=0, zero order position, where the grating simply acts as a mirror and the component wavelengths of the incident wavefront are not separated.

In Bentham monochromators, the grating is rotated as a function of wavelength, about a pivot coincident with the central ruling, to scan through wavelengths. The direction of the incident and diffracted light remains therefore unchanged.

In this case, one refers to the angular deviation, 2K, between the incidence and diffraction directions, defined as:-

$$2K = a - \beta = \text{constant} \qquad 5$$

Further defined is the scan angle, φ, measured from grating normal to the dissector of the beams

$$2\varphi = a + \beta \text{.................6}$$

Now, substituting, the grating equation becomes:-

$$m\lambda = 2d \cos K \sin\varphi \text{ ....7}$$

For a given monochromator K is a constant, therefore one can determine select a wavelength by determining the required grating angle.

17.7 Diffraction orders

As noted above, the grating equation may be satisfied at a given angle by a number of wavelengths of different diffraction orders.

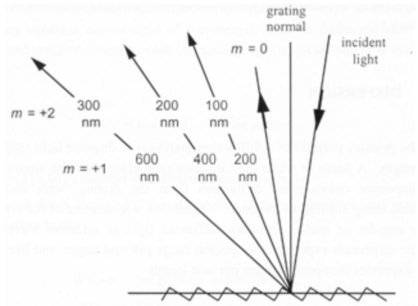


Figure 14:- Existence of diffraction orders

This can lead to problems when attempting to measure light in a given diffraction order, when the detection system is capable of sensing the wavelength in the next diffraction order etc.

Order sorting is therefore required, and consists of the filtering of the monochromator input with long pass filters where higher diffraction orders might be present.

This also leads to on explanation for measurement in first order. The wavelength of light that diffracts along the direction of λ_1 in order m+1, is $\lambda_1+\Delta\lambda$, where

$$\lambda_1 + \Delta\lambda = \frac{m+1}{m}\lambda_1 \ldots\ldots\ldots\ldots 8$$

Hence we define the free spectral range, the range of wavelengths over which overlapping of adjacent orders does not occur,

$$F_\lambda = \Delta\lambda = \frac{\lambda_1}{m} \ldots\ldots\ldots\ldots 9$$

17.8 Diffraction grating production

Gratings found in monochromators are replicas based on master gratings.

Master diffraction gratings are produced by one of two means:-

-Holographic exposure then chemical etch of grooves
-Mechanical ruling of grooves

In the holographic technique a substrate is covered with a photoresist material whose properties change under light stimulation. Exposure to an interference pattern defines the grating outlay, chemical etching is then employed to selectively etch the substrate as a function of the photoresist.

This method produces almost sinusoidal grooves, but of very high surface quality.

The mechanical technique involves the mechanical inscribing, using a diamond tip in a “ruling engine” to define grooves on a metal substrate, a lengthy and difficult process.

This method yields very good, triangular grooves, resulting in gratings of very high efficiency. However, surface defects may have an impact in certain cases by introducing stray light into the monochromator.

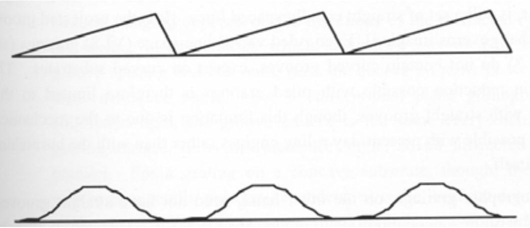


Figure 15:- Groove shape obtained using ruling (upper) and holographic techniques

Replica gratings are resin casting of master gratings, on a glass substrate, which are then coated by a suitable metallic coating for the spectral range of use, such as aluminium.

Diffraction gratings may be produced on flat (plane) or non-flat (for example concave) substrates.

17.9 Diffraction grating efficiency

The efficiency of a grating is defined as the power of monochromatic light diffracted into a given order relative to that light incident.

In order to increase the efficiency of a grating at a given wavelength, the angle of the grooves is designed such that the specular reflection from the grating surface lies in the same direction as that wavelength in question.

This procedure is called blazing, the peak wavelength being the blaze wavelength.

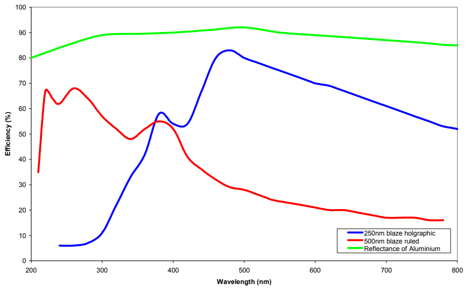


Figure 16:- Example grating efficiency curves

The consideration of grating efficiency becomes more complicated when one considers polarised incident light, and in particular the case of TM polarised light in which case the electric field vector is perpendicular to the grooves, giving rise to anomalies, or abrupt changes in the grating efficiency curve.

17.10 Czerny-Turner Monochromator

The Czerny-Turner configuration, as employed in Bentham monochromators, uses a plane diffraction grating.

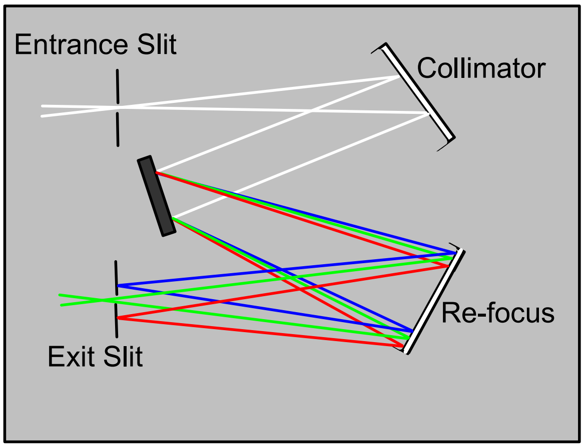


Figure 18:- Czerny-Turner configuration

In order to control the location of diffracted light, the grating should be illuminated by collimated light.

Incident light, diverging from an entrance slit is collimated by a first concave mirror. After diffraction from the grating, light is focussed to an exit slit by a second concave mirror.

As a function of wavelength therefore, the grating is rotated to scan through a spectral range.

17.11 Stepping motor drives

It has been seen that in fixed angle monochromators, it is of question to move the diffraction grating through a range of angles in a repeatable manner. To this end, stepping motors are employed.

A stepper motor is a type of electric motor that moves in increments, or steps, rather than turning smoothly as a conventional motor does. The size of the increment is measured in degrees and can vary depending on the application. Typical increments are 0.9 or 1.8 degrees, with 400 or 200 increments thus representing a full circle. The speed of the motor is determined by the time delay between each incremental movement.

Inside the device, sets of coils produce magnetic fields that interact with the fields of permanent magnets. The coils are switched on and off in a specific sequence to cause the motor shaft to turn through the desired angle. The motor can operate in either direction.

When a current is passed through the coils of a stepper motor, the rotor shaft turns to a certain position and then stays there unless or until different coils are energized. Unlike a conventional motor, the stepper motor resists external torque applied to the shaft once the shaft has come to rest with current applied. This resistance is called holding torque.

Stepping motors, combined with gear systems or sine-bar mechanisms are used to provide high precision and highly repeatable monochromators.

17.12 Double monochromators

When using a single monochromator such as that shown in figure 17, it is possible that light, entering from the entrance slit, be scattered off the walls and structures constituting the monochromator, reach the exit slit. Therefore, at a given wavelength, λ, an artificially high signal is measured.

This is termed stray light and is of concern where low light level measurements are performed where there exists a significant light component at other wavelengths.

Classical examples are measurements of UV sources and high optical density filter transmission.

Consider for example the measurement of a quartz halogen lamp, a lamp often used as calibration standard.

The following figure demonstrates the effect of scattered light in measuring the lamp UV output where there exists a significant amount of visible light.

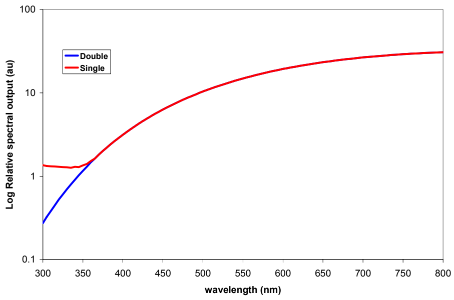


Figure 18:- Measurement of QH lamp with single and double monochromators

A double monochromator situates a second single monochromator at the exit of the first.

Entering the first monochromator is all the light from the source to be measured; entering the second monochromator is the wavelength selected and a level of stray light, which one desires to reduce.

In the second monochromator, the desired wavelength re-selected; at the exit slit one finds that the level of the stray light has reduced to the square of the case of the single, for example a factor 10^4 down in a single, a factor 10^8 down in a double.

There are two possible configurations of double monochromator; with additive or subtractive dispersion.

With additive dispersion, the first monochromator is followed by a device of similar type. The band of light transmitted from the first to second is further dispersed, resulting in twice the dispersion of a single system; for a given required bandwidth therefore, the monochromator slits may be doubled in size with respect to a single monochromator, which increases the system throughput.

With subtractive dispersion, the second monochromator is operated in an inverse manner to the first in such a manner that at the exit slit there exists no net dispersion. At the exit of the first monochromator, the light to be transmitted to the second monochromator is dispersed across the slit; at the exit of the second monochromator this dispersion does not exist and all the wavelengths are combined.

The dispersion of a subtractive double monochromator therefore is the same as that of a single monochromator.

The subtractive configuration is often employed in such systems as primary transfer standard where the uncertainty of dispersion across the detector slit is unacceptable (yet for most applications of no real consequence).

A further important point is that of the slits of the double monochromator. With additive dispersion, it is the entrance and exit slits which define the system bandwidth, the middle slit between the two monochromators being employed to reduce the stray light being transmitted to the second element. The middle slit should be at least twenty percent larger than the largest slit of the system to prevent tracking problems (beating) between the two component monochromators.

With subtractive dispersion, it is the entrance and middle slits which define the system bandwidth; the exit slit is employed to reduce the system stray light and again should be at least twenty percent larger than the largest slit of the system.

Product Guarantee

BENTHAM INSTRUMENTS warrants each instrument to be free of defects in material and workmanship for a period of **one** year after shipment to the original purchaser. Liability under this warranty is limited to repairing or adjusting any instrument returned to the factory for that purpose.

The warranty of this instrument is void if the instrument has been modified other than in accordance with written instructions from BENTHAM, or if defect or failure is judged by BENTHAM to be caused by abnormal conditions of operation, storage or transportation.

This warranty is subject to verification by BENTHAM, that a defect or failure exists, and to compliance by the original purchaser with the following instructions:

1. Before returning the instrument, notify BENTHAM with full details of the problem; including model number and serial number of the instrument involved.

2. After receiving the above information, BENTHAM will give you shipping instructions or service instructions. After receipt of Shipping instructions, ship the instrument “carriage paid” to BENTHAM. Full liability for damage during shipment is borne by the purchaser. It is recommended that instruments shipped to us be fully insured and packed surrounded by at least 2 inches of shock-absorbing material. Specific transit packaging as used in monochromators etc. must be installed.

BENTHAM reserves the right to make changes in design at any time without incurring any obligation to install same on units previously purchased.

This warranty is expressly in lieu of all other obligations or liabilities on the part of BENTHAM, and BENTHAM neither assumes, nor authorises any other person to assume for it, any liability in connection with the sales of BENTHAM’S products.

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