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Method for Recording Broadband High Resolution Emission Spectra of Laboratory Lightning Arcs

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Abstract:	Lightning is one of the most common and destructive forces in nature and has long been studied using spectroscopic techniques, first with traditional camera film methods and then digital camera technology, from which several important characteristics have been derived. However, such work has always been limited due to the inherently random and non-repeatable nature of natural lightning events in the field. Recent developments in lightning test facilities now allow the reproducible generation of lightning arcs within controlled laboratory environments, providing a test bed for the development of new sensors and diagnostic techniques to understand lightning mechanisms better. One such technique is a spectroscopic system using digital camera technology capable of identifying the chemical elements with which the lightning arc interacts, with this data then being used to derive further characteristics. In this paper, the spectroscopic system is used to obtain the emission spectrum from a 100 kA peak, 100 µs duration lightning arc generated across a pair of hemispherical tungsten electrodes separated by a small air gap. To maintain a spectral resolution of less than 1nm, several individual spectra were recorded across discrete wavelength ranges, averaged, stitched and corrected to produce a final composite spectrum in the 450 nm (blue light) to 890 nm (near infrared light) range. Characteristic peaks within the data were then compared to an established publicly available database to identify the chemical element interactions. This method is readily applicable to a variety of other light emitting events, such as fast electrical discharges, partial discharges and

	sparking in electrical equipment, apparatus and systems.
Author Comments:	Note for filming: We have a black & white high speed camera available for direct filming of the lightning arc which we can use to provide footage for the final video (typical speed: 100,000 to 200,000 fps). A normal film camera can also be used, but the lightning arc is very fast and a normal camera will sometimes not capture it. Please ask the film crew to contact me for more details.
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Dear Editor,

I am a Research Fellow working in lightning physics at the newly established Morgan-Botti Lightning Laboratory, part of the Advanced High Voltage Research Centre, at Cardiff School of Engineering, Cardiff University. I am writing to you to request consideration of my attached manuscript for publication in the Journal of Visual Experimentation. The manuscript is titled "Method for Recording Broad High Resolution Emission Spectra of Laboratory Lightning arcs" and describes the use of a digital spectrograph system to analyse emitted light from generated lightning arcs within a laboratory environment.

I thank you in advance for your consideration.

Yours sincerely,

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TITLE:
Method for Recording Broadband High Resolution Emission Spectra of Laboratory Lightning Arcs

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SHORT ABSTRACT:
Emission spectroscopy techniques have traditionally been used to analyze inherently random lightning arcs occurring in nature. In this paper, a method developed to obtain the emission spectroscopy from reproducible lightning arcs generated within a laboratory environment is described.

LONG ABSTRACT:
Lightning is one of the most common and destructive forces in nature and has long been studied using spectroscopic techniques, first with traditional camera film methods and then digital camera technology, from which several important characteristics have been derived. However, such work has always been limited due to the inherently random and non-repeatable nature of natural lightning events in the field. Recent developments in lightning test facilities now allow the reproducible generation of lightning arcs within controlled laboratory environments, providing a test bed for the development of new sensors and diagnostic techniques to understand lightning mechanisms better. One such technique is a spectroscopic system using digital camera technology capable of identifying the chemical elements with which the lightning arc interacts, with these data then being used to derive further characteristics. In this paper, the spectroscopic system is used to obtain the emission spectrum from a 100 kA peak, 100 µs duration lightning arc generated across a pair of hemispherical tungsten electrodes separated by a small air gap. To maintain a spectral resolution of less than

1 nm, several individual spectra were recorded across discrete wavelength ranges, averaged, stitched, and corrected to produce a final composite spectrum in the 450 nm (blue light) to 890 nm (near infrared light) range. Characteristic peaks within the data were then compared to an established publicly available database to identify the chemical element interactions. This method is readily applicable to a variety of other light emitting events, such as fast electrical discharges, partial discharges, and sparking in electrical equipment, apparatus, and systems.

INTRODUCTION:

Lightning is one of the most common and destructive forces in nature characterized by a rapid electrical discharge seen as a flash of light and followed by thunder. A typical lightning arc can consist of a voltage of tens of gigavolt and an average current of 30 kA across an arc tens to hundreds of kilometers long all happening within 100 µs. Observation of the light emission spectrum from lightning events have long been used to derive information about their properties. Many techniques were established using traditional film-based camera techniques for the study of natural lightning strikes during the 1960s to 1980s, for example[1-7] and, more recently, modern digital techniques, for example[8-14], have been used to give a more accurate insight into lightning mechanisms. Over time, such work has demonstrated the ability to not only identify chemical element interactions[1,14], but also obtain measurements of temperature[15,16], pressure[5], particle and electron density[5,17], energy[18], resistance, and internal electric field of the arc[8]. However, studies of natural lightning have always been limited by the inherently unpredictable random and non-repeatable nature of lightning events.

In recent years, research has focused on how lightning interacts with the surrounding environment, notably in the aerospace industry to protect aircraft in flight from direct lightning strikes. Several large lightning test facilities have consequently been designed and built to replicate the most destructive elements of a lightning strike, namely the current and delivery time, but at a limited voltage. The Morgan-Botti Lightning Laboratory (MBLL)[19] at Cardiff University can generate four distinct lightning waveforms up to a 200 kA in accordance to the relevant standard[20]. With such a laboratory facility, lightning can be easily reproduced and controlled with a high degree of accuracy and repeatability, providing a test bed for the development of new sensors and diagnostic techniques to understand lightning interactions and mechanisms better[21-23]. One such technique is a recently developed and installed spectroscopic system[14,21] which, like the spectroscopic systems used in natural lightning studies, operates in the Ultraviolet (UV) to Near-Infrared (NIR) range. It is a non-intrusive method which does not interfere with the lightning arc and is largely unaffected by the electromagnetic noise produced during a strike, unlike most electronically based devices.

The spectrograph system was used to observe the spectrum of a typical laboratory generated lightning arc consisting of a 100 kA peak critically damped oscillatory, 100 µs duration, 18/40 µs waveform across an air gap between a pair of 60 mm diameter tungsten electrodes separated by a 14 mm air gap. A typical trace of this lightning arc waveform is shown in **Figure 1**. The electrodes were positioned in an Electromagnetic Impulse (EMI) light-tight chamber so that the only recorded light was from the lightning arc itself, with a small amount of this light being transported via a 100 µm diameter fiber optic, positioned 2 m away and collimated to a 0.12 °

viewing angle giving a spot size of 4.2 mm at the position of the arc, to another EMI chamber containing the spectrograph system, as shown in **Figure 2**. The EMI chambers were used to minimize the adverse effects caused by the lightning event. The fiber optic is terminated at the light-tight optic chassis based on a Czerny-Turner configuration of focal length 30 cm, with the light passing through an adjustable 100 µm slit and onto a 900 ln/mm 550 blaze rotatable grating via three mirrors, onto a 1,024 x 1,024 pixel digital camera, as shown in **Figure 3**. In this case, the optical setup gives a spectral resolution of 0.6 nm across an approximately 140 nm subrange within an approximate full range of 800 nm across UV to NIR wavelengths. The spectral resolution is measured as the ability of the spectrograph to distinguish two close peaks, and the position of the subrange within the full range can be adjusted by rotating the grating. A key component of the system is the choice of diffraction grating which dictates the wavelength range and the spectral resolution, with the former being inversely proportional to the latter. Typically, a broad wavelength range is needed to locate multiple atomic lines whereas a high spectral resolution is needed to measure their position accurately; this cannot be physically achieved with a single grating for this type of spectrograph. Therefore, data from several subranges, with high resolution, are taken at various positions across the UV to NIR range. These data are stepped and glued together to form a composite spectrum.

In practice, due to limitations in the fiber optic light transmission, a spectrum wavelength range of 450 nm to 890 nm was recorded. Starting at 450 nm, light from four independent generated lightning arcs was recorded, background noise was subtracted, and they were then averaged. The wavelength range was then shifted to 550 nm, giving a 40 nm data overlap, with light from another four generated lightning arcs recorded and averaged. This was repeated until 890 nm was reached, and the resulting averaged data were stitched together to create a complete spectrum across the full predefined wavelength range. This process is illustrated in **Figure 4**. Characteristic peaks were then used to identify chemical elements through comparison to an established database[24].

In this paper, the method of optical emission spectroscopy is described. This method is readily applicable to a wide range of other light emitting events with minimal alteration to the experimental setup or spectrograph system settings. Such applications include fast electrical discharges, partial discharges, sparking, and other related phenomena in electrical systems and equipment.

PROTOCOL:

1. Selecting Wavelength Range

1.1. The wavelength range of the lightning to be observed must first be selected. 450 nm to 890 nm was selected.

Note: This will be limited by the laboratory setup, the spectral range as defined by the blazing angle of the grating, and the sensitivity of the camera.

2. Preparing the Electrodes

2.1. Choose a suitable electrode material. A pair of 60 mm diameter hemispherical tungsten electrodes fixed to copper mountings was chosen, as illustrated in **Figure 5**.

Note: Any material with which the lightning arc interacts will emit a spectrum, including the electrode, and it is important to minimize this interference. However, this should be balanced against the ability of the electrode material to withstand repeated lightning strikes with minimal damage during experimentation. For tungsten, many of its emission lines within the chosen wavelength range are only visible between 450 nm and 590 nm and are largely distinguishable from an expected lightning spectra. It is also a very hard material that is commonly used in high voltage and high current experimentation.

2.2. Clean and polish the electrodes to remove any contaminants. Any material with which the lightning arc interacts will emit a spectrum, including that of any contaminants. It is, therefore, important to ensure that the electrodes are contaminant free to ensure no erroneous spectral lines.

2.2.1. Rub the electrode with coarse sandpaper for 5 min, place it into a sonic water bath at room temperature for 10 min, then wipe with a lint free cloth to loosen and remove any contaminants. Always use gloves when handling the electrode to avoid recontamination.

2.2.2. Repeat the above typically ten to fifteen times with decreasing grades of sandpaper, emery cloth, and then polishing cloths until a good polish finish is achieved. Sandpaper and cloth grades of 240 to 8,000 were used.

2.3. Mount the electrodes within the lightning rig establishing a suitable distance between them. Here, the electrodes are mounted within the lightning rig 14 mm apart as shown in **Figure 5**.

Note: Different lightning test facilities have different operational voltages, so the distance between the electrodes should be such that an air breakdown will occur when the lightning impulse generator is triggered.

3. Preparing the Spectrograph

3.1. Place the spectrograph in an independent EMI rated enclosure, as illustrated in **Figure 2**. Ideally, the lightning rig and spectrograph should be housed in separate EMI enclosures.

3.2. Select and install the fiber optic. The chosen fiber was an 8 m long fiber optic and installed between the two EMI chambers.

3.2.1. Chose a fiber optic with good transmission properties within the predefined wavelength range to be observed, *i.e.*, between 450 nm to 890 nm.

3.2.2. Note the transmission efficiency against wavelength data as this will be used for data post-processing. This is often provided by the manufacturer although, ideally, it should be measured using a calibrated lamp.

3.2.3. Connect one end of the fiber optic to the optic chassis in a light-tight arrangement.

3.2.4. Position the other end of the fiber optic to view the lightning arc between the electrodes. Light from a laser sent through the spectrometer in reverse can help with alignment. The fiber optic is positioned at the same height as the center of the electrode gap at 2 m, as shown in **Figure 6**.

3.2.5. Adjust the amount of light reaching the camera if necessary to minimize any saturation. A collimator is used which reduces the fiber optic viewing angle to 0.12 ° resulting in a spot size of 4.2 mm at the position of the lightning arc for a total arc length of 14 mm, reducing the light by approximately one quarter.

Note: The intensity of light reaching the camera can alternatively be adjusted by altering the distance between the light source and fiber optic, by adjusting the slit, or by using a neutral density filter.

3.3. Switch the spectrograph system on and start the associated control software. The digital camera requires around 10 min to reach a temperature of -70 °C.

Note: Some digital cameras require cooling to reduce noise before they become fully operational.

3.4. Select the spectrograph grating. A 900 ln/mm 550 blaze grating was used.

Note: The grating defines the wavelength range and spectral resolution within the spectrograph system used, with a spectral resolution of < 1 nm required for peak identification. The selected grating gives a wavelength range of approximately 140 nm and a resolution of 0.6 nm.

3.5. Calibrate the spectrograph against a known calibration source, such as a Mercury-Argon lamp.

3.5.1. Position the grating in its starting position at the bottom of the preselected wavelength range. Here, the grating was positioned at 450 nm giving a range of 450 nm to 590 nm.

3.5.2. Switch the calibration source on and place it against the open end of the fiber optic.

3.5.3. Adjust the camera exposure via the control software to a suitable time to achieve a good unsaturated signal, such as an exposure of 0.1 s.

3.5.4. Adjust the slit via the control software to sharpen the spectral peaks if required or, in some cases, the position of the detector can also be adjusted to optimize the signal. A slit of 100 µm was used.

Note: The slit should be set to a minimal value to decrease the broadening of the atomic lines due to diffraction of light at the slit, with values up to 20 µm often used. However, a narrow slit will also reduce the signal and a balance may need to be found between light intensity and sharpness of peaks.

3.5.5. Record the spectra of the calibration source and identify the pixel number on the resulting camera image at which the peaks occur.

3.5.6. Plot the position of the pixel number for each peak against the known wavelength of each peak provided with the calibration source and fit a straight line to derive an equation which will allow the conversion of pixels to wavelength. An example of this for three known Mercury atomic lines is illustrated in **Figure 7**.

3.5.7. Apply the calibration to this grating position before moving onto the next. For some spectrograph systems, the conversion of pixel number to wavelength can be applied to the software using a calibration file.

3.5.8. Position the grating for the next subrange and repeat the above steps. Here, the grating was next positioned to 550 nm giving a range of 550 nm to 690 nm resulting in an overlap of 40nm with the previous wavelength range.

Note: The width of the overlap region needs to be sufficient to allow the recognition of trends at the end of the first range and beginning of the second range for the later step and glue process.

3.5.9. Repeat the above steps for all grating positions. This was repeated until 890 nm was reached.

Note: Calibration sources, typically a lamp with known spectral peaks, are usually provided with spectrograph systems and the manufacturer will be able to provide more details on how calibration can be achieved.

3.6. Select spectrograph parameters to record the generated lightning arc.

3.6.1. Adjust the slit further if required.

3.6.2. Set the camera exposure time to ensure that the entire lightning event is captured; consider the trigger time and any delays in any in either the lightning generator or spectrograph when setting this parameter. For the lightning generator at MBLL, an exposure time of 5 s was used.

Note: A longer exposure time will increase noise levels and the likelihood of artifacts, such as cosmic rays, so efforts should be made to keep this to a minimum. However, the time must also be sufficient to account for any uncertainty in the triggering of the generated lightning arc or spectrograph system to ensure the entire event is captured.

3.6.3. Change the spectrograph system mode to receive a trigger from the lightning generator. A 5 V TTL signal was used to trigger the camera 2.5 s before the lightning arc was initiated.

4. Running an Experiment

4.1. Prepare the lightning generator.

4.1.1. Ensure that all lights are off and chambers are closed where relevant to ensure a light-tight environment.

4.1.2. Switch on the lightning generator. Each lightning test facility will have its own protocol for preparing and switching on. At MBLL, the area is cleared of personnel and the relevant safety devices are engaged before the lightning generator can be activated.

4.1.3. Select the relevant lightning waveform and charge to the required peak current. A typical 54 kV, 100 kA peak critically damped oscillatory 100 µs peak 18/40 µs waveform was used.

4.2. Acquire spectra from multiple generated lightning events

4.2.1. Position the spectrograph grating at its start position and take a background image using the same parameters as for the lightning strike. This may be an average of several background images. A 5 s exposure with a 100 µm slit was used at the 450 nm setting.

4.2.2. Ensure the spectrograph system is ready to be triggered to record the spectra with the correct settings. A 5 s exposure with a 100 µm slit was used at the 450 nm setting.

4.2.3. Charge the lightning generator and trigger the lightning event, which will also trigger the spectrograph.

4.2.4. Record the output spectral data.

4.2.5. Check the spectroscopic data for any interference. Spectrographs are occasionally prone to data spikes caused by cosmic radiation or other artifacts caused by non-responsive or dead pixels. Efforts should be made to remove such interference and some spectrographs have software which can do this. An alternative is to disregard the data and repeat the experiment. **Figure 8** shows an example of the difference between data with and without a cosmic radiation spike.

4.2.6. Clean the electrodes of any contamination if required by either wiping down with alcohol or, if contaminated, repeating step 2.2.

4.2.7. Repeat steps 4.2.2 to 4.2.5 until four sets of spectroscopic data for the 450 nm range have been achieved.

4.2.8. Position the spectrograph grating to 550 nm and repeat steps 4.2.1 to 4.2.6 until four sets of spectrograph data for the 550 nm range have been achieved.

Note: The number of repeated steps needs to be sufficient to average out any shot-to-shot variance seen in the generated lightning arc.

4.2.9. Repeat the above until all datasets have been collected to reach the maximum wavelength value of 890 nm, resulting in sixteen sets of spectral data.

4.2.10. If there is significant variation in the spectra of each subrange at the same lightning current generator settings, for example, in the intensity of atomic lines, then the experiments at each stage may have to be repeated more than four times. The purpose of this is to minimize the effect of any one-off anomalies and to average out the shot-to-shot variation from the lightning generator and the lightning free arc.

4.2.11. If there is a difference in spectra at the same lightning current generator settings, then the experimental setup may need to be assessed for contaminants.

5. Post-processing Data

5.1. For the post-processing and analysis of data, select a spreadsheet software application incorporating calculation capabilities. Such software is widely available.

5.2. Subtract the background data acquired in step 4.2.1 from each relevant generated lightning spectra data.

5.2.1. The average of the 450 nm background data is subtracted from each 450 nm generated spectra data, the average of the 550 nm data is subtracted from each 550 nm generated lightning spectra data, and so on. An example of this is shown in **Figure 9**.

5.3. Average each individual set of data for each wavelength range. This is illustrated in **Figure 10** where the four 450 nm datasets are averaged.

5.4. Use the overlapping region to align consecutive spectra data, then average the overlapping region. This is illustrated in **Figure 11** which shows the averaged 450 nm and

550 nm data.

Note: The alignment and averaging of the overlapping region will introduce errors and it may be necessary to carry out a relative intensity calibration for the complete spectrum using, for example, a tungsten ribbon lamp.

5.5. Correct for fiber optic attenuation and quantum efficiency. This is illustrated in **Figure 12**.

Note: A more accurate correction can be achieved by using a calibrated lamp to measure the transmission of light for each subrange. In this case, the correction can be applied before the stitching process.

5.6. Present the final data as either a graphical representation or an intensity plot, as shown in **Figure 13**.

6. Analyzing Data

6.1. Identify the characteristic spectral peaks.

6.1.1. Some spectrograph systems will include software which will automatically identify element peaks. Care should be taken, especially with stitched data, that the peak locations are correct.

6.1.2. Manual peak identification can be done using publicly available databases, such as[24]. Care should be taken to fit the strongest (relative intensity) peaks from the lowest ionization levels first (*i.e.*, I, then II, then III) one element at a time.

6.1.3. Problems in accurately identifying peaks or aligning them may be due to calibration issues or misalignments in the optics. Assess the position of the optics in the optics chassis and repeat step 3.

Note: The high energy of the generated lightning arcs will cause broadening of the atomic emission lines due to the Stark Effect and reliable identification of all lines may not be possible.

REPRESENTATIVE RESULTS:

A representative lightning intensity against wavelength plot for a 100 kA peak critically damped oscillatory 100 µs peak 18/40 µs waveform, across an air gap between a pair of 60 mm diameter tungsten electrodes positioned 14 mm apart, is given in **Figure 14**. These data consist of four sets of four 140 nm averaged data segments stitched together and corrected for background noise, fiber optic attenuation, and the digital camera quantum efficiency. These data have been converted into an intensity plot, as shown in **Figure 15**. Prominent peaks have been manually identified through comparison to an established database, as shown in **Figure**

16.

FIGURE LEGENDS:

Figure 1: Generated lightning arc profile. The recorded trace of a typical 100 kA peak critically damped oscillatory, 100 µs duration, 18/40 µs generated lightning waveform.

Figure 2: Experimental setup. A schematic of the experimental setup (not to scale), where light from a generated lightning arc between two electrodes is transported via a fiber optic to the spectroscopic system, consisting of an optics chassis and digital camera.

Figure 3: Spectrograph setup. A schematic of the spectrograph system (not to scale), where light from the fiber optic is turned into a spectrum, via a grating, which is then recorded by a digital camera.

Figure 4: Collating, processing, and presenting spectral data. An illustration of the steps used to collate, average, stitch, and correct data towards achieving a broad high resolution spectrum.

Figure 5: Electrode configuration. An image of the two 6 mm diameter hemispherical tungsten electrodes fixed to copper mountings positioned 14 mm apart within the lightning rig.

Figure 6: Fiber optic configuration. An image of the fiber optic positioned at the same height and at a distance of 2 m from the mounted electrodes.

Figure 7: Wavelength calibration. (**a**) A table of three known Mercury lines against the pixel number at which they were measured, and (**b**) a plot of each point (crosses) and a straight-line fit (dashed line) giving an equation (inset) allowing pixels to be converted to wavelength. This is done for multiple known atomic lines across the entire wavelength range.

Figure 8: Cosmic ray interference. Spectral data from a 100 kA laboratory generated lightning arc in the 550 nm to 690 nm range showing: (**a**) data with no cosmic ray interference, and (**b**) and (**c**) data with characteristic cosmic ray spikes.

Figure 9: Subtraction of background. Spectral data from a 100 kA laboratory generated lightning arc in the 550 nm to 690 nm range showing: (**a**) averaged background data, (**b**) raw data, and (**c**) data with average background subtracted.

Figure 10: Averaging data. Spectral data from a 100 kA laboratory generated lightning arc in the 550 nm to 690 nm range showing: (**a–d**) individual data, and (**e**) averaged data.

Figure 11: Stitching data. Spectral data from a 100 kA laboratory generated lightning arc showing: (**a**) the 550 nm to 690 nm range, (**b**) the 650 to 790 nm range, and (**c**) the two overlaid datasets with a 650 nm to 690 nm overlap. The overlap region is then averaged.

Figure 12: Correcting data. Plots in the 450 nm to 890 nm wavelength range for (**a**) fiber attenuation, and (**b**) spectrograph camera quantum efficiency provided by respective manufacturers. These are used to correct the stitched spectral data accordingly.

Figure 13: Presenting data. Examples of (**a**) a graphical data plot and (**b**) an intensity plot representing the spectrum of a 100 kA laboratory generated lightning arc in the 550 nm to 790 nm wavelength range.

Figure 14: Typical graphical data. A typical averaged, stitched, and corrected graphical plot in the 450 nm to 890 nm wavelength range for a 100 kA laboratory generated lightning arc.

Figure 15: Typical intensity plot. A typical averaged, stitched, and corrected intensity plot in the 450 nm to 890 nm wavelength range for a 100 kA laboratory generated lightning arc.

Figure 16: Chemical element identification. An illustration of spectral line chemical element identification for first order ionization levels using a publicly available database[24]. Elements in the air (nitrogen, oxygen, argon, helium) and in the electrode (tungsten) have been identified. This spectrum is near-identical to that in reference[14] as it uses the same apparatus to analyze the same type of lightning arc. This figure has been adapted from reference[14].

DISCUSSION:

Spectroscopy is a useful tool for identifying chemical element reactions during both natural and generated lightning strikes. Given a sufficiently accurate and reproducible experimental setup, further analysis on the data can reveal a variety of other lightning properties. It has, for example, been used to verify that the spectra of laboratory generated lightning arcs are spectrally similar to natural lightning and that the addition of other materials into the lightning arc can alter this spectrum significantly[14]. The method can also be used for other light emitting events such as fast electrical discharges, partial discharges, sparking, and other related phenomena in high voltage systems, where the simultaneous identification of multiple atomic lines or elements across a broad spectrum is important.

The most critical step is to ensure the correct parameters are used when setting up the spectrograph, such as the slit, grating, and camera settings, to acquire the best data possible resulting in strong, sharp spectral peaks. Efforts should be made to also ensure that the detector is not saturated when optimizing the signal. The position of the fiber can also be adjusted and/or collimated to improve light intensity, as well as ensuring that any stray light not part of the lightning event is either eliminated or removed as part of the background imaging process. This may take some trial and error. The ability of the lightning generator used to reproduce the same lightning event accurately with minimal variation, or to understand where any variations may come from so that they can be controlled, is important in obtaining reliable and repeatable spectroscopic results.

Alterations can be made to this setup to assess different parts of the electromagnetic spectrum further into the UV and IR bands where imaging technology allows and depending on the type of event being imaged. For example, extending the wavelength range below 450 nm can reveal further atomic and molecular lines, such as emissions from NO and OH radicals. Adjusting the spectrograph grating to give a lower resolution over a broader range may help to identify interesting features, which can then be analyzed using a higher resolution narrower range grating.

The main advantage of this technique is that it is entirely non-intrusive, so it does not require any alteration to the lightning generator. By transporting the light via a fiber optic, the amount of electrical interference from the harsh electromagnetic environment is reduced, which other systems, such as cameras, may experience if not sufficiently shielded. This means that the data from a spectrograph potentially have much lower noise and less interference than other instruments. This specific technique is limited by its lack of time resolution and subsequent lack of further characterization of the lightning arc. For example, high-speed spectrographs do exist which can produce time resolved spectral data leading to temperature and electron density measurements.

It is expected that spectroscopy will become an important tool, alongside other diagnostic instrumentation, in understanding laboratory generated lightning arcs. It will contribute complimentary information on characteristic lightning event signatures and be used to identify the reactive chemical elements within the arc. Further development of this technique may also result in the derivation of additional characteristics.

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The authors have nothing to disclose.

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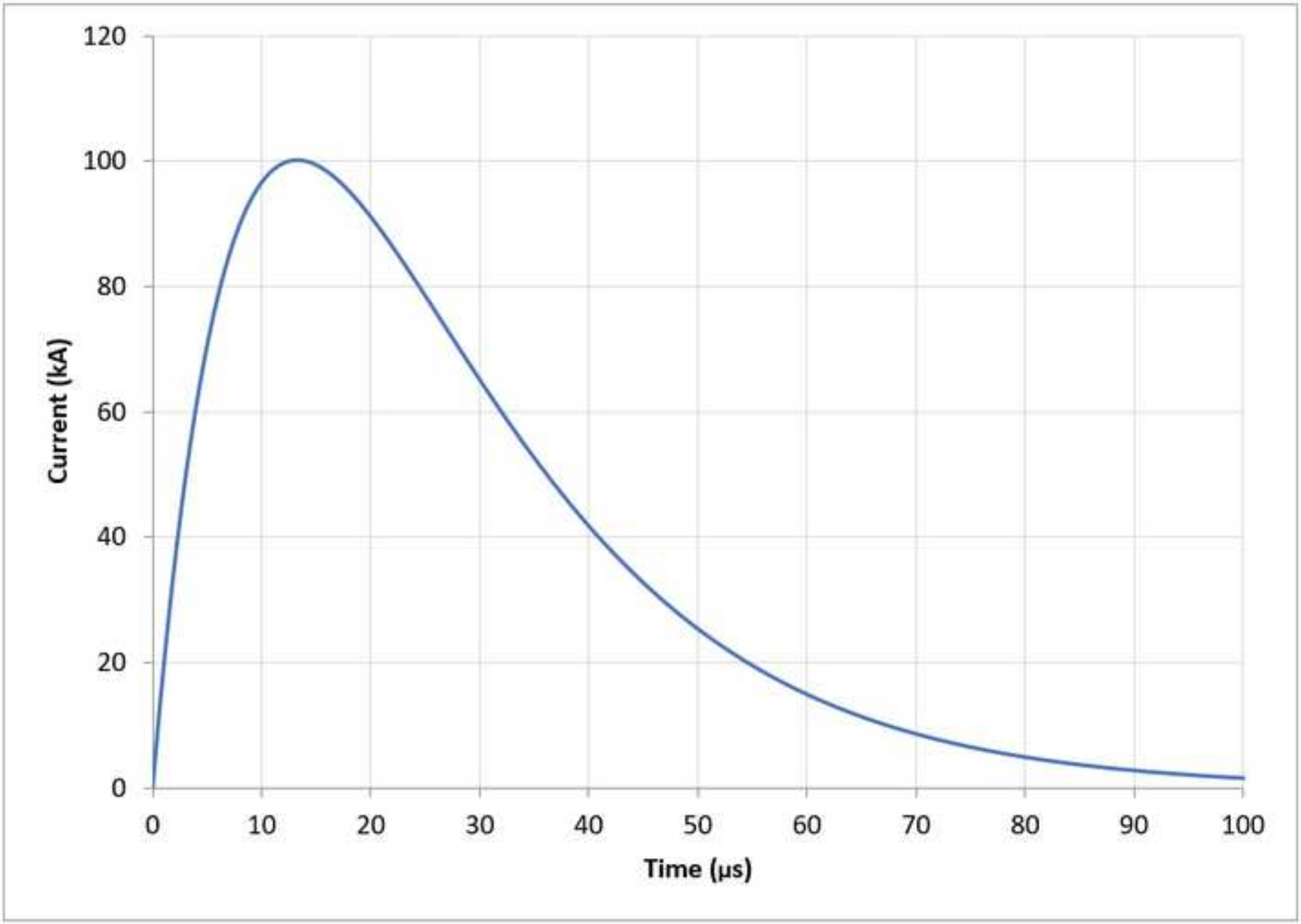

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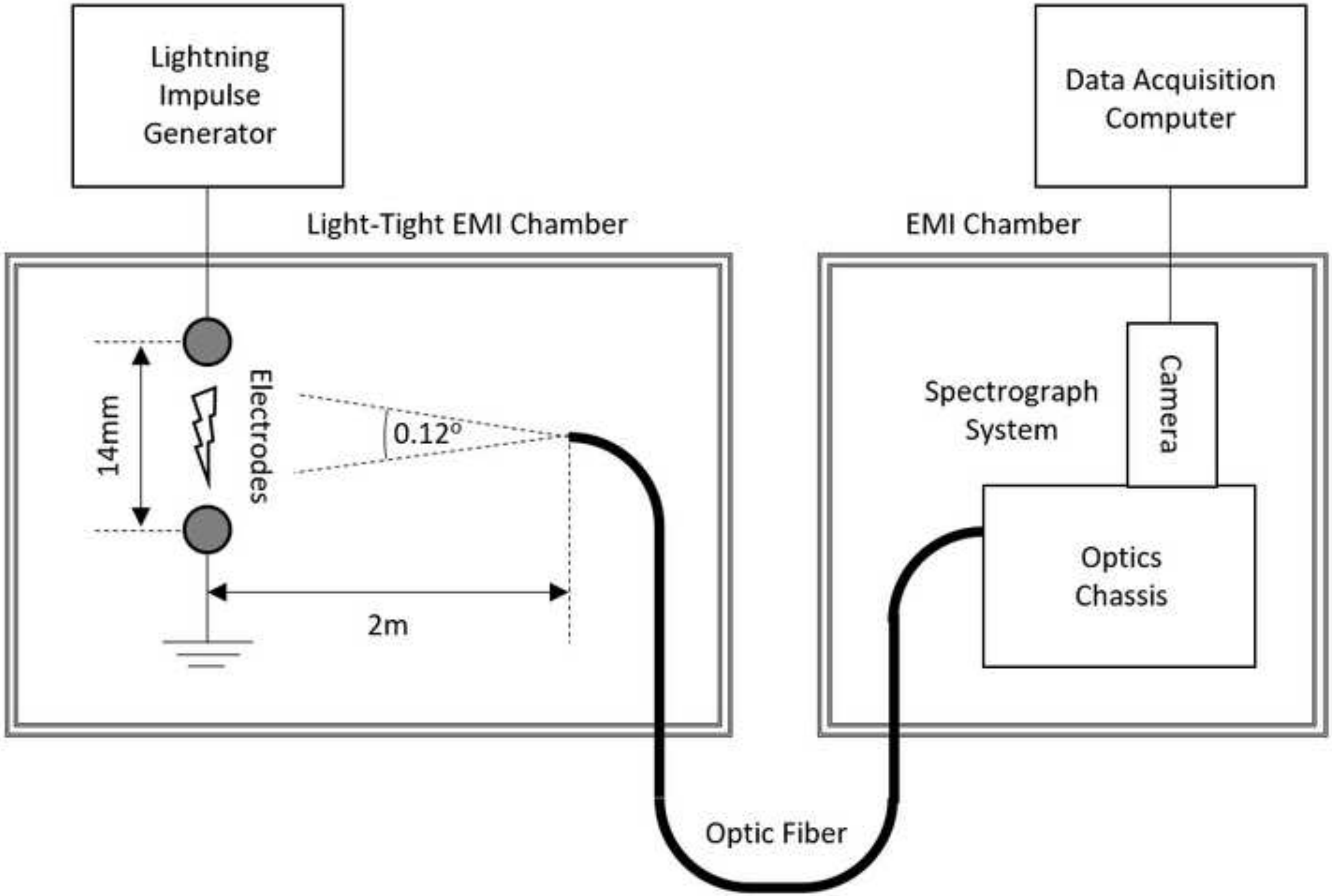

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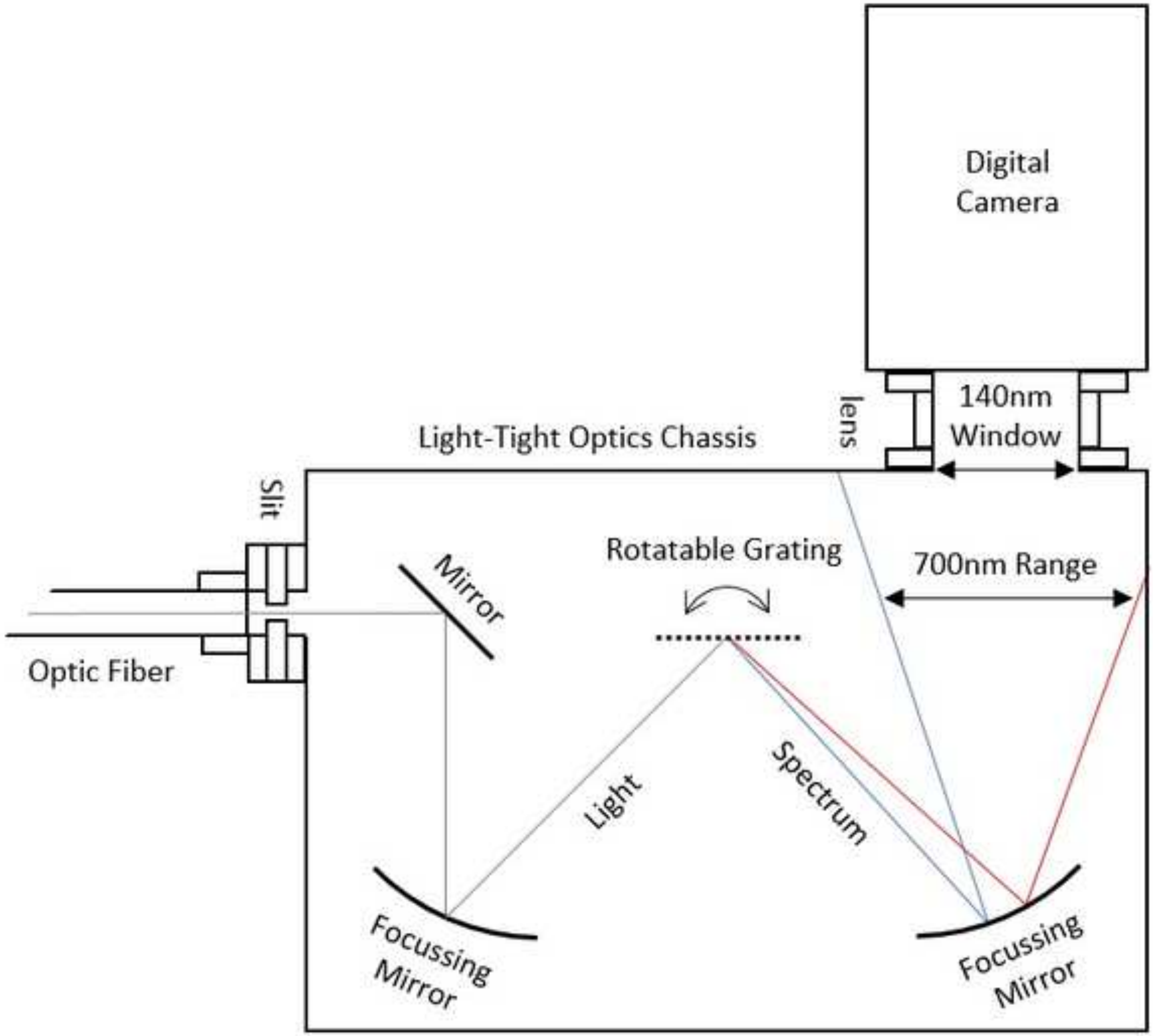

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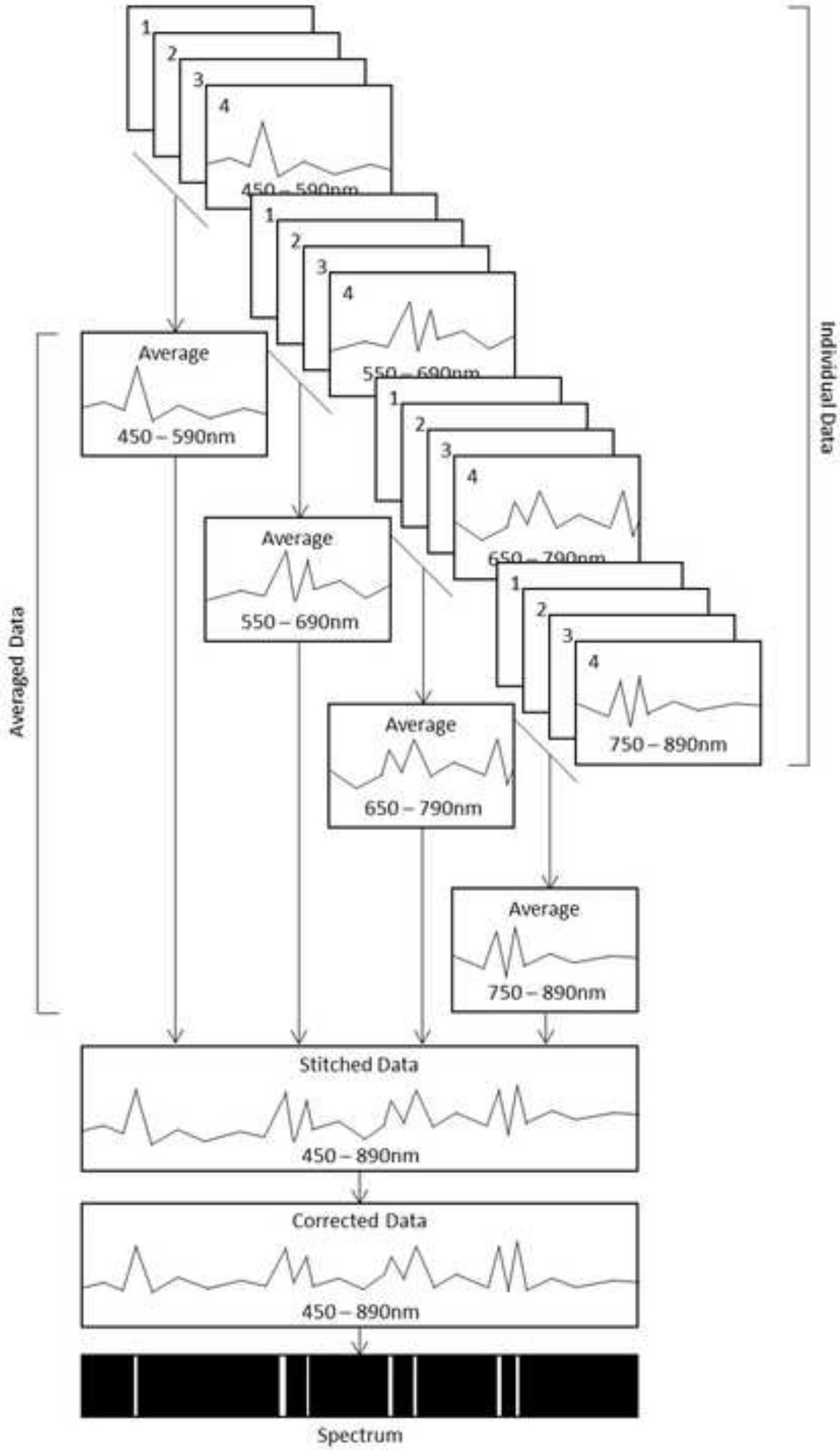

Figure 5

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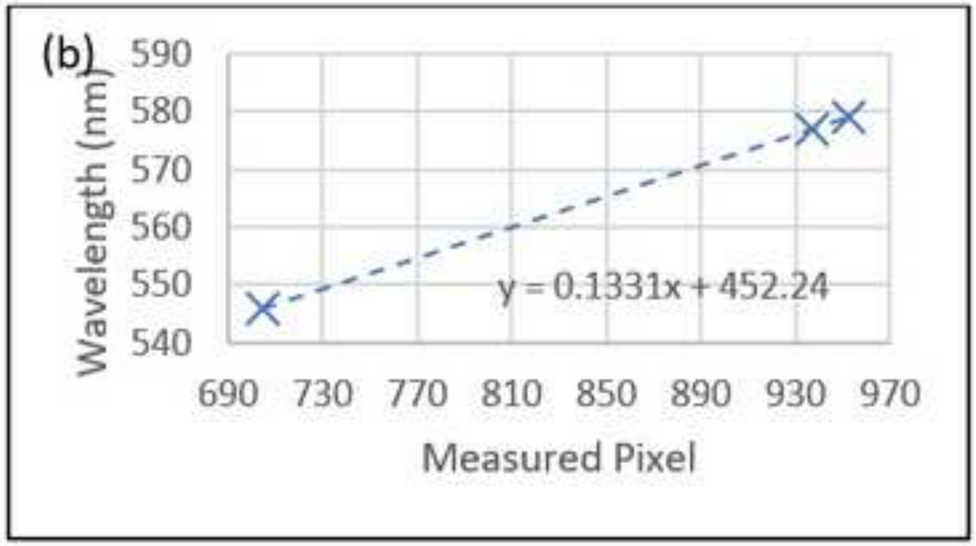
(a)

Mercury Atomic Lines	
Wavelength (nm)	Measured Pixel
546.07	705
576.96	937
579.07	953



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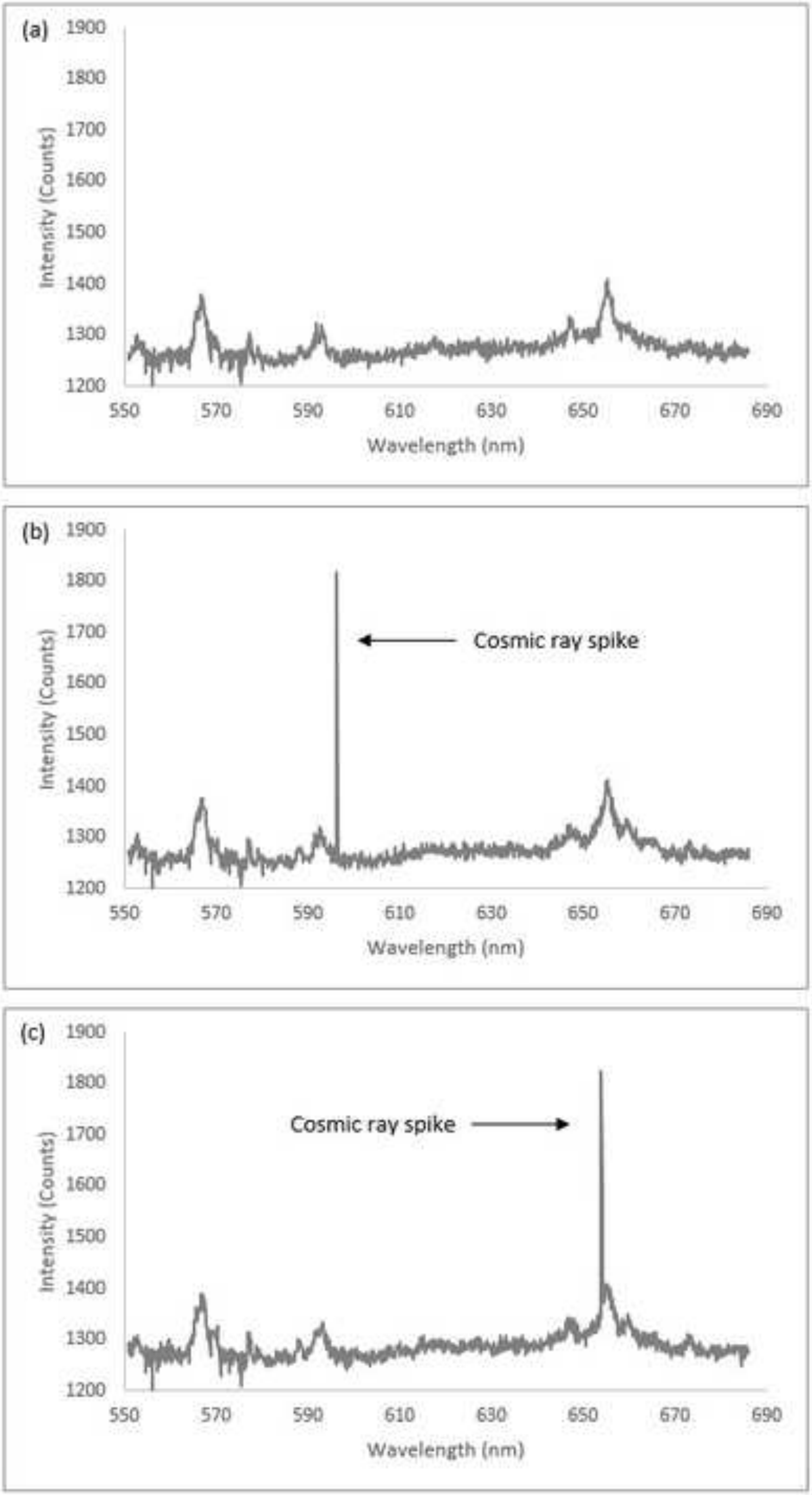

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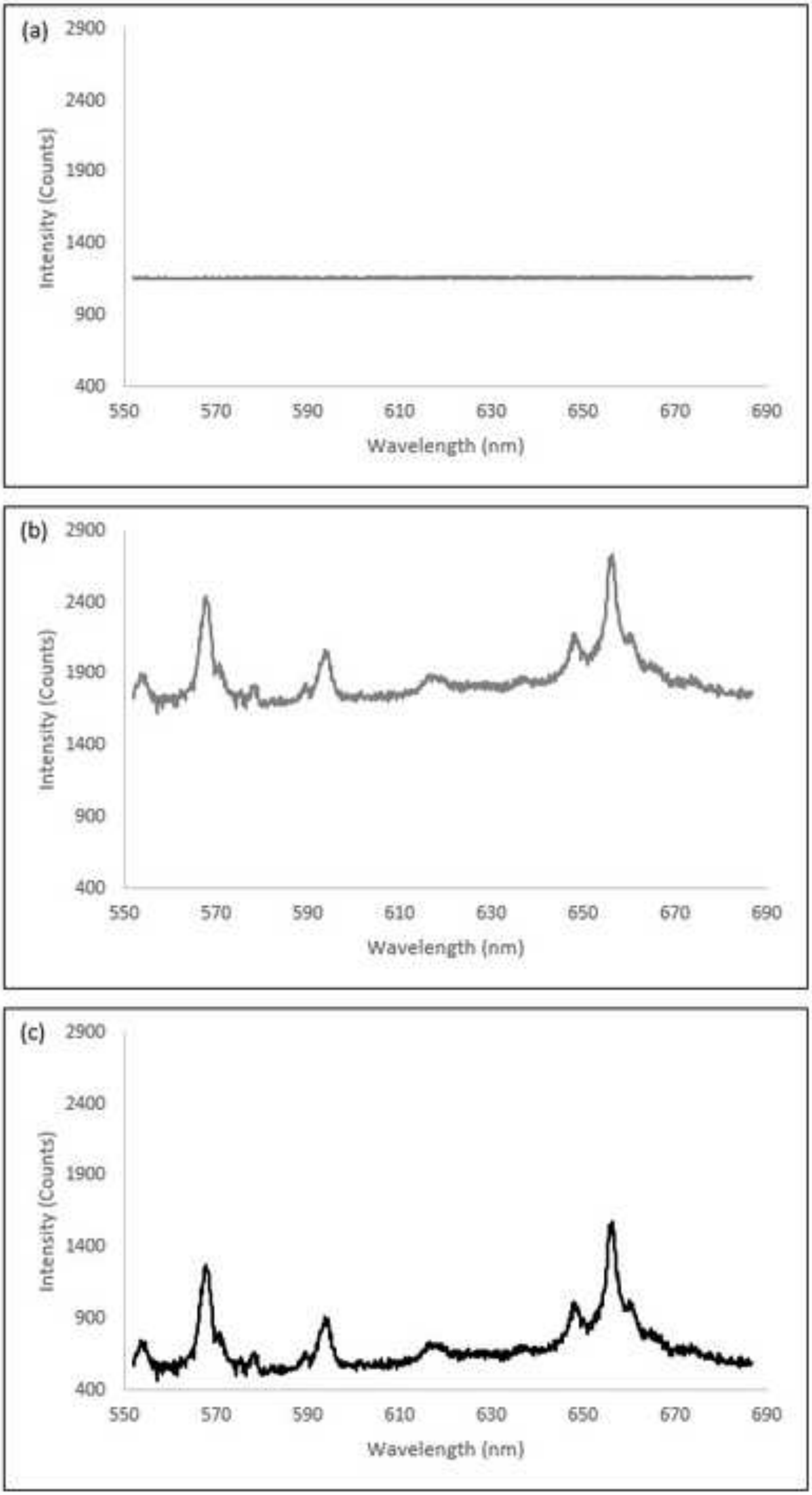

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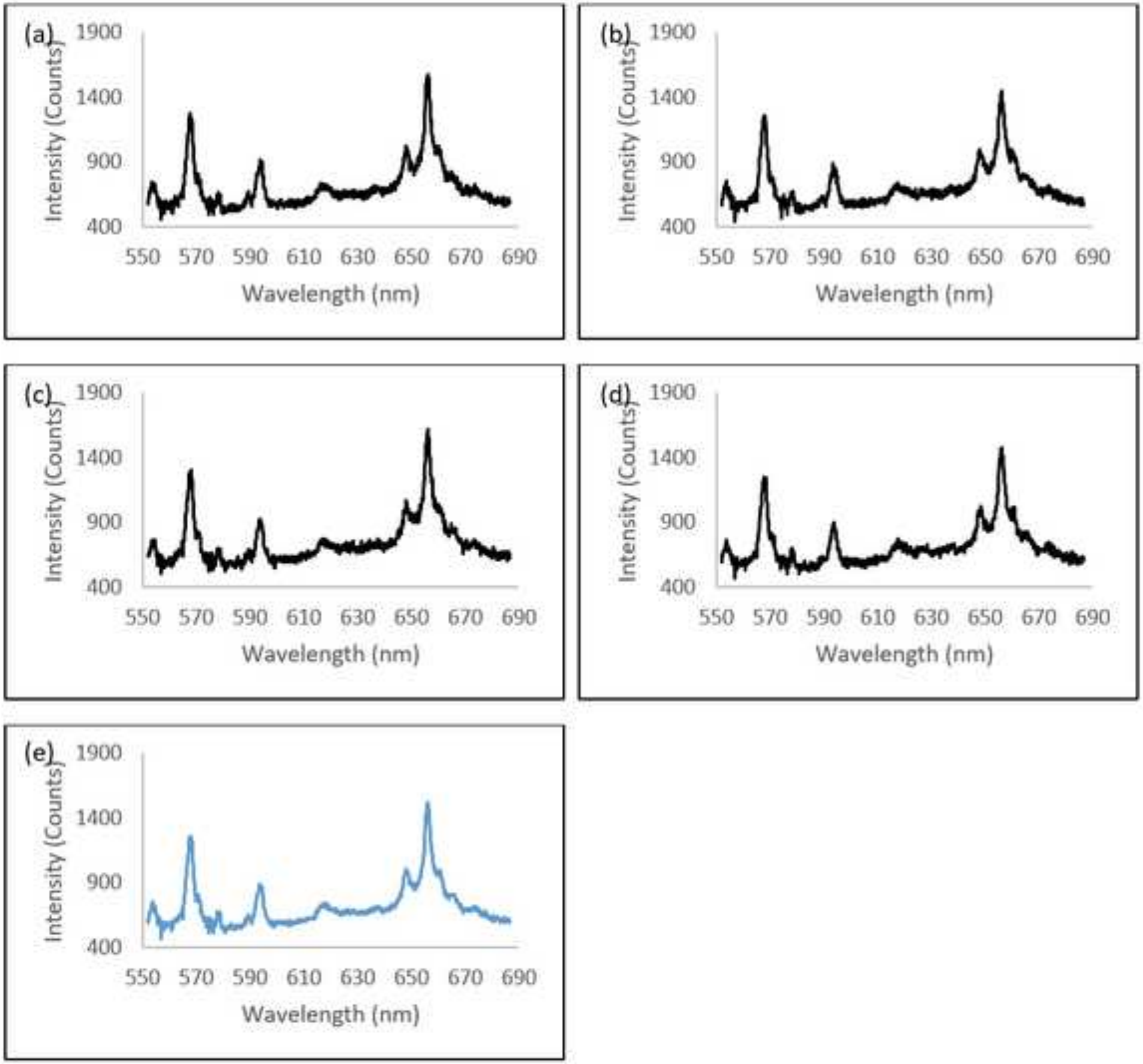

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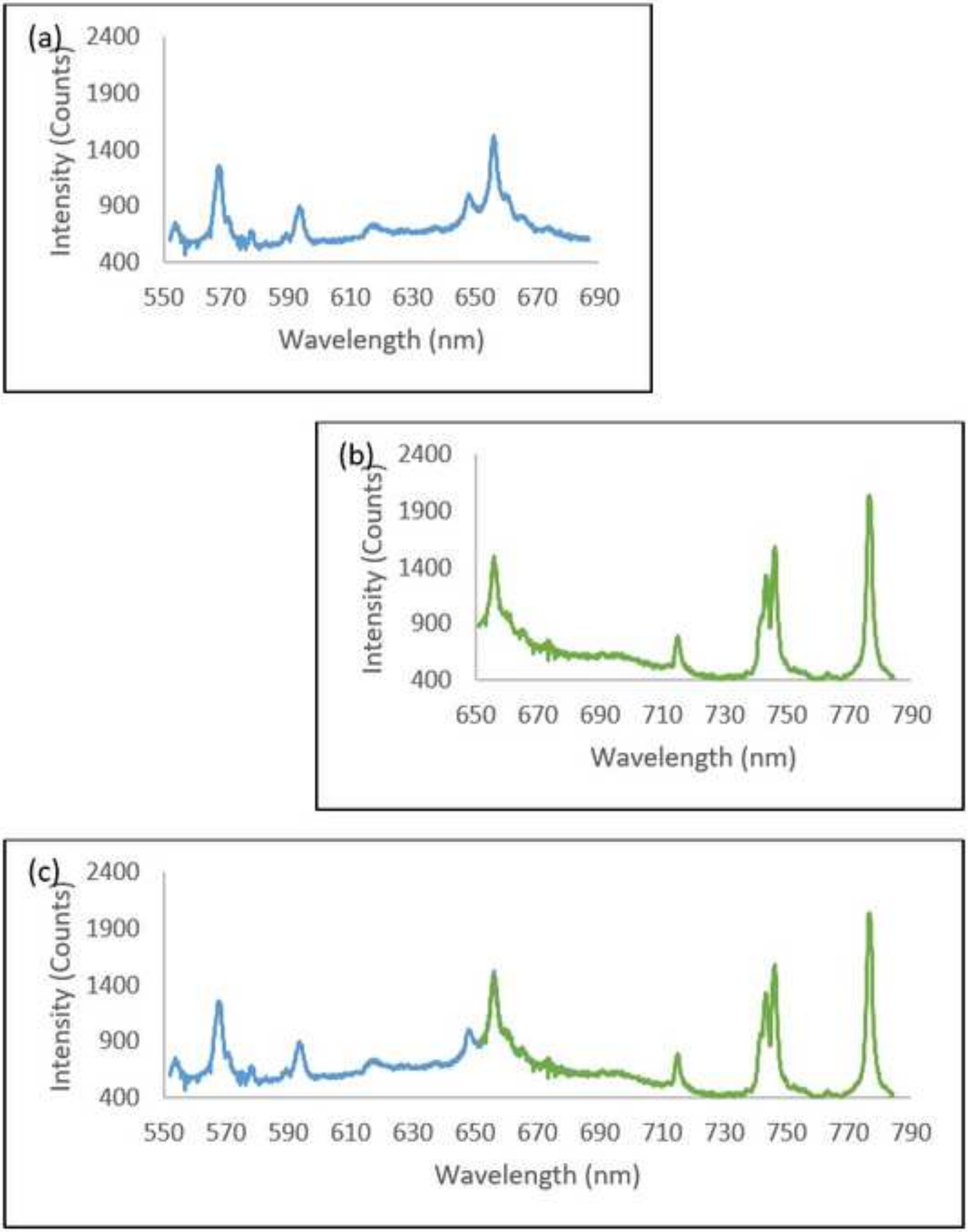

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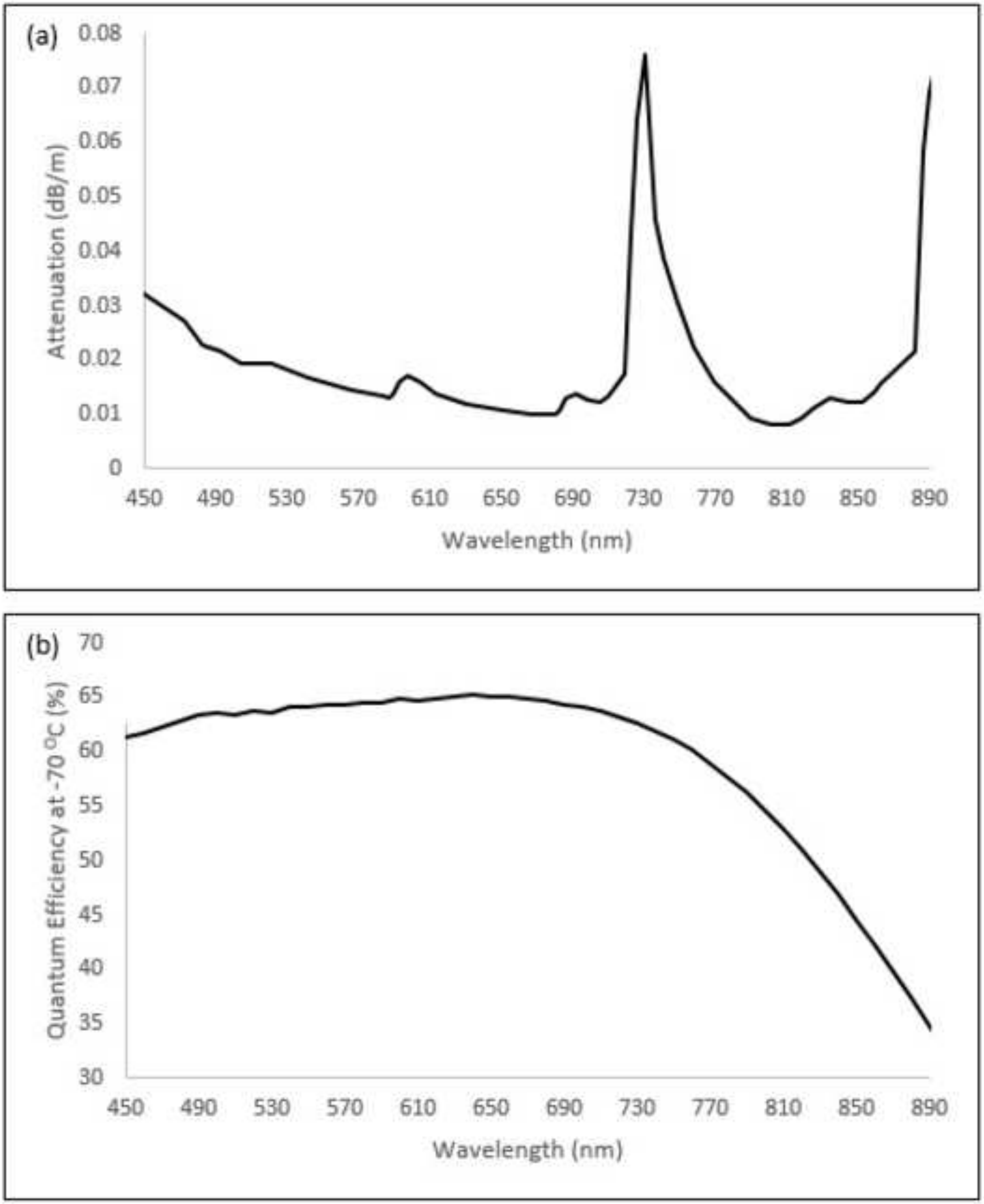

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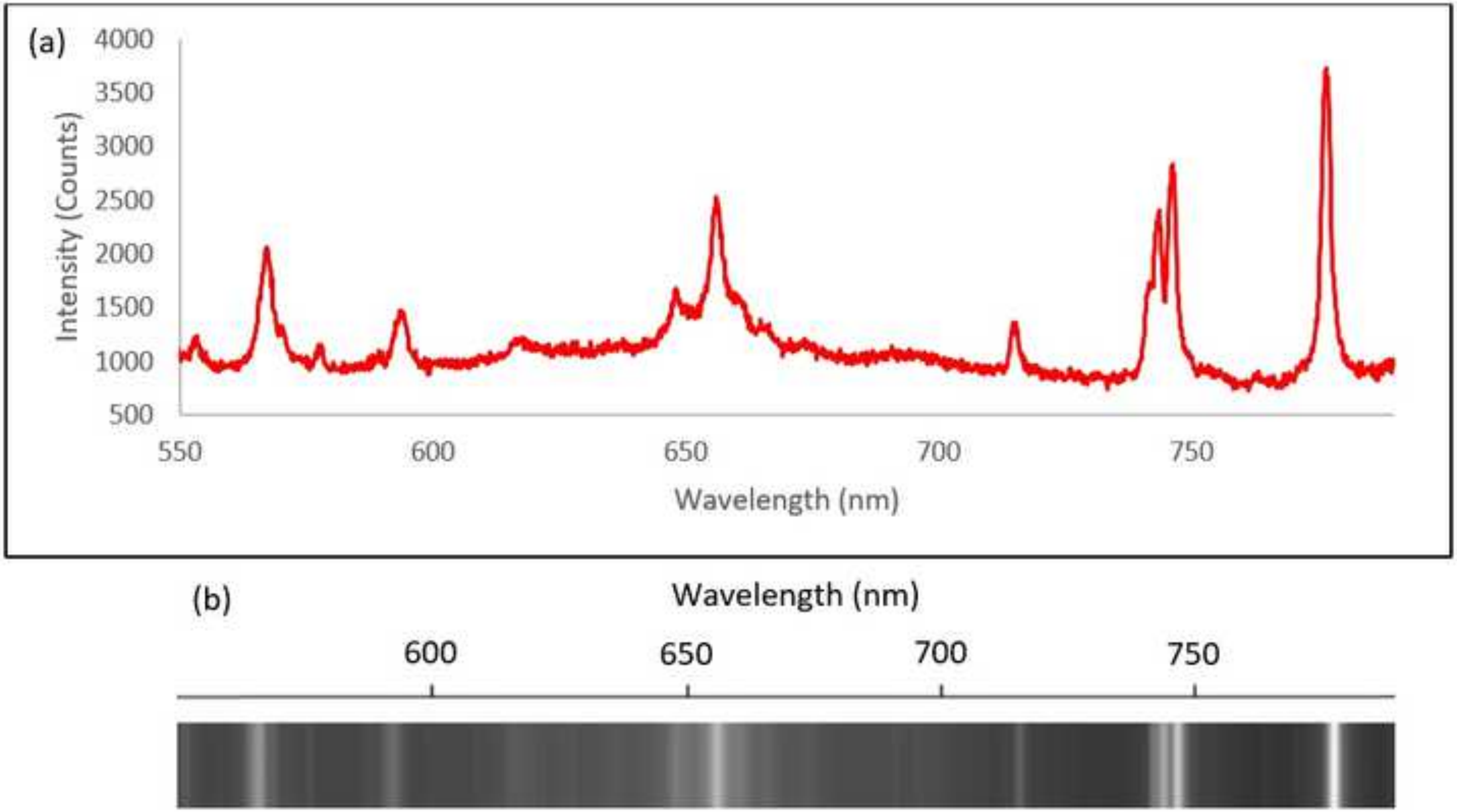

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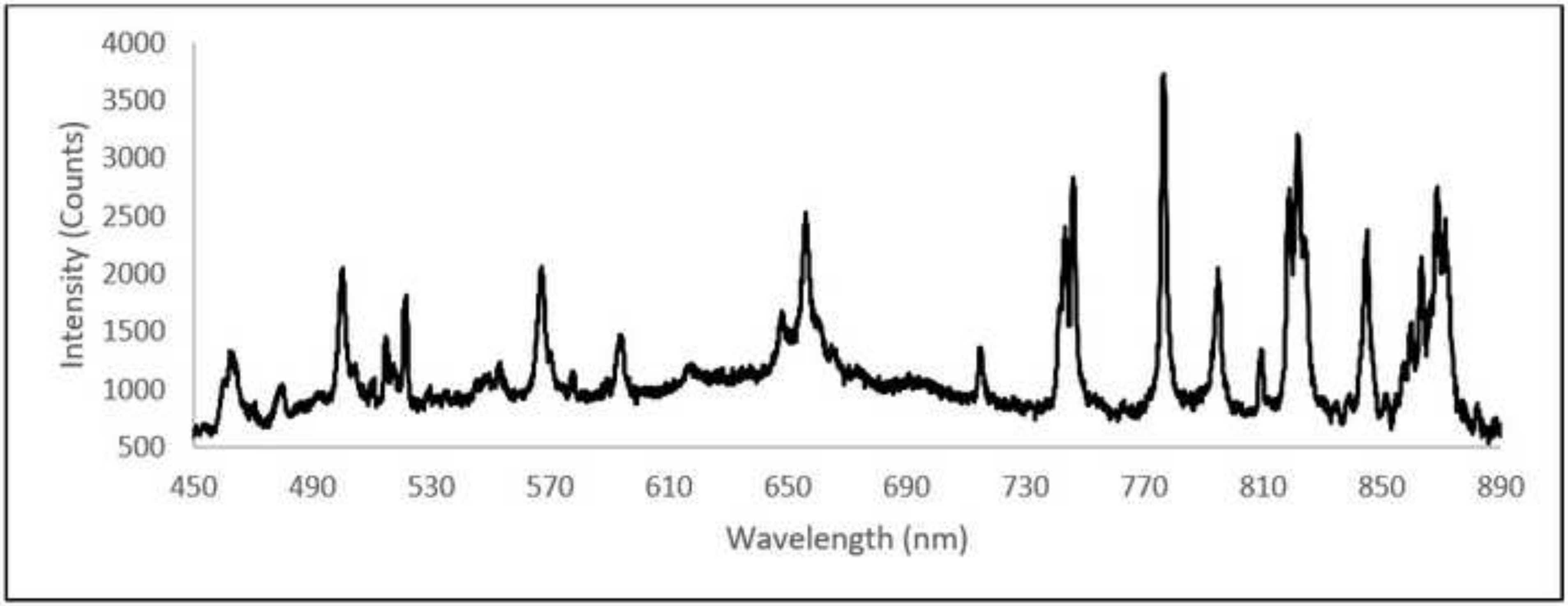

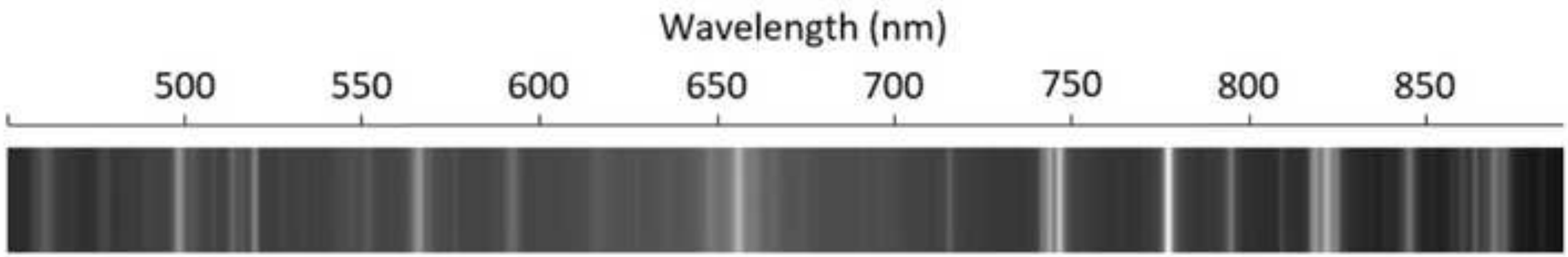
Wavelength (nm)
500
550
600
650
700
750
800
850

Figure 16

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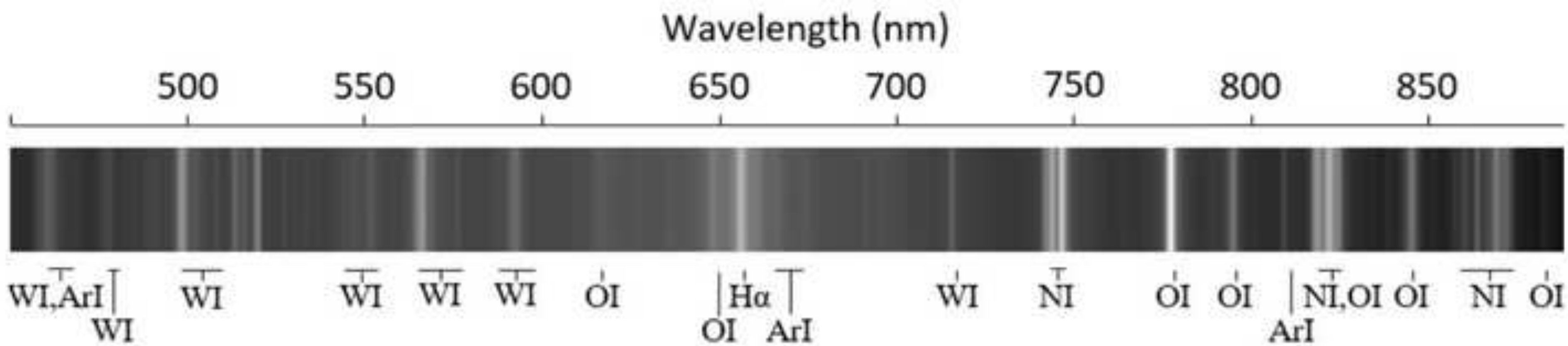

Name of Material/ Equipment	Company	Catalog Number
Lightning Generator, including EMI shielded chambers, lightning rig and associated control and safety systems	Cardiff University	N/A
60mm diameter tungsten electrodes with copper mountings	Unknown	N/A
Spectrograph, including chassis, camera, optic fibre and control software	Andor	Chassis: SR-303i-B-SIL Camera: DU420A-BU2 Optic Fibre: 249309 SR-OPT-8018-9RX Software: Solis v4.25
Mercury argon calibration source	Ocean Optics	HG-1
Anaylsis software	Microsoft	Excel 2016

Comments/Description

Designed, developed and constructed by Cardiff University

Available from any specialist electrode / high voltage equipment manufacturer

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Author(s): D. MITCHARD, D. CLARK, D. CARR, C. STONE, A. HADDAD

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Response to Reviewer Comments

The authors would like to thank the editors and reviewers for their extensive analysis of our paper and the valuable comments to improve its quality. We have revised the paper accordingly and our response to each specific point is given below.

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   Figure 16 presents an identical spectrum and atomic line identification to that of Figure 4(a) in [14] as it uses the same apparatus to analyze the same type of lightning arc. The publisher of [14] has confirmed that written permission is not required for this but that a credit line should be included in the caption, and this has now been done. A copy of the email correspondence has been uploaded under 'supplemental files'. No other figures have been published elsewhere.

2. Please provide email address of all co-authors on line 10.

   These have been provided.

3. Remove the figures from main text [.docx]. keep the text of figure legends only.

   These have been removed.

1.2 Protocol

4. Since you planning to show the arc generator between 450 – 890 nm, write your protocol steps with more specifics and details rather than writing "in this work…" for every step.

   This has been altered throughout the manuscript.

5. Line 118 – step 1.1 – label as "note:"

   This has been included.

6. Line 134 – what is the water bath temperature?

   The bath was at room temperature and this has now been included.

7. Line 141 and rest of the protocol – the notes should not have step numbers

   This has been corrected throughout the manuscript.

8. Line 191 – how is the calibration done? Please provide the screen shots of the software and highlight which buttons are clicked

Following the comment of Reviewer #2 in point 18 that details of spectrograph calibration are often left out, I have elaborated on the method used to illustrate how camera pixels are converted to wavelength using the identification of known spectral peaks from a calibration source. Alterations have been made to sections 3.5.5 to 3.5.7 and an additional figure, Figure 7, has been included to reflect this. We feel that this would offer a better explanation of the process rather than screenshots of the software used, which is not very clear.

9. Line 199 – where do you specify the set the exposure time?

   This was done via the control software, and has been included.

10. Line 202 – how do you adjust the slit? Manually or remotely via the software

    This was done via the control software, and has been included.

11. Line 212 – what was the interval between successive gratings? 100 nm? How was this decided?

    There was only one grating which produces a subrange of 140nm, as outlined in section 3.4.1. This grating is first positioned at its starting position of 450nm, giving a range of 450nm to 590nm, as outlined in section 3.5.1. Once the spectra in this range has been recorded, the grating is rotated to the next position of 550nm, giving a range of 550nm to 690nm with a 40nm overlap with the previous range, as outlined in section 3.5.8. The width of the overlap is arbitrary but needs to be sufficient to allow feature recognition for the step and stitch process. The above sections have all been altered to clarify this process.

12. Line 289 – which software is used for processing and analyzing the data? – add to table of materials and leave a note in main text

    The processing and analysis software used was Microsoft Excel 2016, although any equivalent spreadsheet software with calculation capabilities will suffice. This has been added to the table of materials and a new point, point 5.1, has been included to describe this.

1.3 References

13. Please make sure that your references comply with JoVE instructions for authors. In-text formatting: corresponding reference numbers should appear as <u>superscripts</u> after the appropriate statement(s) in the text of the manuscript.

    This has been corrected throughout the manuscript

2. REVIEWER #1

2.1 Manuscript Summary

14. First, the electrode material is tungsten. Emission lines of tungsten atoms in the visible and near infrared band are too much, which impacts on the final spectrum greatly. Such as the existing calibration line in the manuscript, the spectral line approximately coincident in the infrared band and natural lightning, but the visible band are basically tungsten atomic lines, which is different from the natural lightning. Second, the time distinguishability is too low, thus the quantitative analyses on temperature, electron density have little significance.

    Any material used for the electrode will inevitably contribute to the spectrum of a generated lightning arc. Tungsten was chosen because, although it does have numerous emission lines, almost all of these are only visible between 450nm and 590nm of the chosen wavelength range and are mostly distinguishable from the expected lightning emission lines; this is further discussed and illustrated in [14]. However, an additional factor in choosing tungsten is its hardness, meaning that it can withstand repeated lightning strikes with minimal damage during experimentation. This was accidentally omitted in the paper but has now been included. Ultimately, there is a *balance between the spectral interference an electrode may produce and its ability to survive the experiment. This has been further elaborated in the note following section 2.1.*

The drawback of this technique in comparison to high-speed spectroscopy, where the latter can characterize further lightning arc properties, such as temperature and electron density, has been emphasized in the fourth paragraph of the 'Discussion' section.

2.2 Major Concerns

15. N/A

2.3 Minor Concerns

16. N/A

2.4 Additional Comments to Authors

17. N/A

3. REVIEWER #2

3.1 Manuscript Summary

18. This paper presents a method for recording broad high resolution spectra of electrical arc generated in lightning laboratory. A generator injects 100 kA during 100µs in a spark gap consisting of 2 tungsten hemisphere according to the aeronautics standards. The authors emphasize that in the field of lightning aircraft protection, optical emission spectroscopy (OES) should provide useful data regarding lightning constraint. The aim of this paper is not to describe the simulated lightning; in fact the chosen geometry is inspired by the standards but is specific to this study. The aim is to describe their OES method for broadband spectra acquisition. A detailed description of a commercial apparatus suitable for this application is given as well as the different steps needed to acquire a full reconstruct spectrum. Similar techniques are used in this field and in others such as arc welding, circuit breaker, or plasma torch and are well described in papers/books but no video for this specific application exist to the best of my knowledge and moreover, details on the calibration method are often missing. This is the reason why this paper should be accepted with some major concerns in the following sections:

3.2 Major Concerns

19. If the aim is lines identification then a wavelength calibration is sufficient but if a step and glue is used, then a relative intensity calibration is needed using a tungsten ribon lamp for example. If not, the error in the overlapping area may be too high because the algorithm does more than an average, it does a linear correction between the two spectra. In the paper the intensity calibration is done after the step and glue, but it should be done before and not with data from the manufacturers but using a real calibration lamp. this is the only way to take into account the complete acquisition chain transmission (lens, fiber, spectrometer and camera).

The additional errors in the overlapping region and the requirement for a relative intensity calibration have been discussed in a note following section 5.4. The option to carry out a calibration of the optics and camera is discussed in a note following section 5.5.

20. The stitching method does not always work and a discussion about potential error in the overlapping area should be added.

This has been addressed in point 19.

21. In the case of a 100 kA pulsed arc discharge that reaches temperature of 30 kK, the atomic lines are strongly broadened by stark effect. The identification may become impossible even with good resolution. A note on this issue should be added in section 6 : Analyzing data

A note on this has been added following section 6.1.

22. The entry slit is set to 100 µm, this value is high. Whenever possible, a user should set the entry slit to the minimum in order to decrease the broadening of the lines due to the diffraction of this slit. Lines identification is easier with thin lines, an entrance slit of 20 µm or less is often used even if this reduced the signal. Those aspects should be discussed.

A note of this has been included following section 3.5.4

23. The proposed method is spatially and temporally integrated even if the proposed apparatus consist of a fiber bundle allowing to measure 5 points in space. The trigger is also an issue because it forces the exposure time to 5s in order to catch the discharge. This 5s exposure time induce noise and increase the probability of cosmic rays. Those points are somewhat discuss in the paper but it would be interesting to have more information in the discussion section as well as potential solutions.

The 5 s exposure time is due to uncertainties in the triggering of the lightning generator. The importance of keeping this to a minimum has been discussed in a note following 3.6.2.

3.3 Minor Concerns

24. Replace optic fiber by optical fiber or fiber optic

Optic fiber has been replaced with fiber optic throughout the manuscript.

25. Replace spectrographic by spectroscopic

Spectrographic has been replaced with spectroscopic throughout the manuscript.

26. line 49 : A reference would be useful if possible

Such lightning parameters greatly vary depending on numerous atmospheric and geographical conditions, as well as an inherent randomness. Although the parameters stated are widely quoted within this field, there is no single reference source which measures or defines this and it is often stated unreferenced unless, for example, the study specifically relates to the measurement of one such parameter or an industrial standard is being defined. If the reviewer could suggest a suitable reference, we will be happy to include it.

27. line 72 : "it is a non-intrusive method" instead of "passive"

This has been altered.

28. line 73 : "is largely unaffected by the"

This has been altered.

29. line 80 to 88 : The apparatus is not sufficiently detailed, for example the resolution of the camera and the blazing of the grating should be added

The camera resolution and grating blaze has now been included.

30. line 84 to 85 : The spectrometer is based on a czerny-turner configuration which is well-known. It is probably easier to mention this configuration and the diffraction instead of trying to explain it.

A reference to the Czerny-Turner configuration has been included, although the brief description and figure 2 remain for those who may be unfamiliar with the layout.

31. line 90 : add "of diffraction grating" and remove the part with the prism and the rainbow color.

    This has been altered.

32. line 94 : replace "narrow wavelength ranges" to "subrange" as it is used before

    This has been altered.

33. line 94 : "this cannot be physically achieved with a single grating", but an echelle spectrometer may solved this problem ?

    "...for this type of spectrograph" has been added to clarify this.

34. line 96 : replace "stitched" by "step and glue"

    This has been altered.

35. line 98 : The UV limitations is due to physical limitations or spectral response ? And based on the material references, the camera is UV as well as the optical fiber, which parts is cutting the UV ? This may be of interest to the readers.

    The UV cut-off was in the optic fiber, and this has been confirmed using a calibrated light source. The transmission rapidly drops off for < 450nm, and the start of this is visible in figure 12(b). This has been clarified in the text.

36. line 106 : Add reference [24] here.

    This has been added.

37. line 108 : optical emission spectroscopy is more suited than method of spectrographic measurement.

    This has been altered.

38. line 124 : Is there a criteria for choosing suitable electrodes ?

    This was addressed in point 14.

39. line 125 : a reference to figure [4] may be added

    This has been added.

40. line 134 : Replace "course" by "coarse"

    This has been altered.

41. line 141 : 2.2.3 could be added to 2.2 for clarity

    This has been altered.

42. line 165 : For transmission efficiency, a real calibration is needed using a calibrated lamp

    This has been included as an alternative option.

43. line 170 : An alignment laser should be used for the alignment. One solution is to have this laser go through the spectrometer in reverse. The presented spectrometer has entry option for this.

    This has been included.

44. line 176 : spelling

No spelling error could be found on this line.

45. line 191 : "calibrate the wavelength of the spectrograph ...", Also i think it is a mercury argon lamp and not a laser. Those calibration lamp are low-pressure gas discharge and not laser diode or laser.

'Laser' and 'low powered laser' have been replaced with 'lamp' throughout the manuscript.

46. line 250 : Maybe replace "spectrographic" data with "spectra" ?

This has been altered.

47. line 259 : the sentence "the same settings as for the background image above" should appear in paragraph 4.2.1 for clarity

As section 4.2.1 describes the settings for the background image, moving this sentence would not make sense. However, 4.2.2 has been clarified anyway.

48. section 4.2.5 : Among interference, a damage pixel is also an issue worth mentioning. the effect is similar to the cosmic rays.

This section has been re-written to include this.

49. section 4.2.9 : the variation is a variation of total lines intensity between spectra or a variation of lines intensity ratio ? It is not clear.

This has been clarified.

50. line 286 : "if there is a difference"

This has been altered.

51. figure 2 : There is no legend for the dash and straight lines

The dashed lines have been removed.

52. figure 6,7,8,9,11,12 : "Intensity"

This has been corrected for all graphs.

53. line 473 : replace "passive" by "non intrusive"

This has been altered.

54. line 474 : "placing a measuring device in-line with the arc" is not clear

This has now been removed.

55. Referencing : The referencing is adequate. However, the reference [4] is difficult to obtain.

The reference is accessible via DOI but is not open access and may not be available in all academic libraries unless the relevant fee is paid. However, it remains relevant as the second part of reference [3].

3.4 Additional Comments to Authors

56. N/A

4. Reviewer #3

4.1 Manuscript Summary

57. The authors describe a standard procedure for optical emission spectroscopy in thermal arcs applied to lightning arcs.

4.2 Major Concerns

58. Technically there are a number of major concerns. There is information missing and wrong facts are given. Scientifically, I doubt that you can see Ar I lines in the spectral range slightly above 500 nm. There must be really good reasons to identify argon in spectra of free burning arcs in ambient air. The lines you can see there should be from Cu I, from which I conclude that you probably do not have a pure tungsten electrode but a copper-tungsten electrode. Or you have some arc attachment close to the copper fixture. Line identification is not as easy, e.g. around 500 nm there are W I and N II lines as well, which are hard to discriminate. Furthermore, from the spectra it is clear that the spectral lines are strongly broadened (around 5 nm FWHM). This means a fiber optic compact spectrometer ranging from 200 to 1000 nm and a spectral resolution of about 1.5 nm should give you exactly the same information with much less effort.

    Figure 5 illustrates that the electrode consists of tungsten hemispheres attached to copper mounts. The geometry is designed to guarantee an arc between the centers of these hemispheres and, although the arc may wander, it is very unlikely to reach the copper and we have not seen this happen in any of our experiments to date. However, we accept that copper may exist in the system, as well as other elements. As the paper focusses on the method of acquiring spectra, rather than identification of atomic lines, for Figure 16, we have removed the Argon identifier in this region but not replaced it with a copper identifier.

    The broadening of the spectra and how this may be improved has been addressed in points 21 and 22.

59. Title: The term "broadband spectra" should be used, because "broad spectra" may be interpreted as broad spectral feature.

    This has been altered.

60. Line 81: The diameter of the fiber should be given.

    This has been included

61. Line 82: The given angle of 12° is very close to the half angle of the cone of light that can enter a fiber with a typical numerical aperture of 0.22. So, what is the effect of the collimator? Usually a collimator is used to focus a parallel beam of light into the focal point of the lens where the fiber is placed. One should give the spot size at the arc position that is imaged to the fiber core.

    The value of 12^o was an error and it should have been 0.12^o; this has now been corrected throughout the text and on Figure 2. The spot-size at the position of the arc has a diameter of 4.2mm, covering around a quarter of the total 14mm arc length. This has also been included at this point in the text and further described in the note following section 3.2.3.

62. Line 85: I guess they are not using a self-made spectrometer. It should be standard to give the manufacturer and the type of the spectrograph. From the figure it is clear that it is a spectrometer in Czerny-Turner configuration. However, the focal length should be given as well. If one really wants to describe the internal function of a Czerny-Turner spectrometer one should spend some more words. The manufacturer and model of camera must be named as well.

    The spectrometer was not self-made and details of the manufacturer, including the optics chassis, camera, optic fiber and software, are included in the material list. The focal length was 30cm and *this has now been included in the third paragraph of the 'Introduction'. This point regarding the Czerny-Turner configuration was addressed in point 30.*

63. Line 87: What do the authors mean with spectral resolution of 0.2 nm? How did they measure the instrumental profile? Are they talking about full width at half maximum or half width at half maximum? Should be standard in a spectrocopy paper.

    The spectral resolution was 0.6 nm and not 0.2 nm as originally stated, and this has now been altered. The term 'spectral resolution' was used to refer to the ability of the spectrograph to distinguish two close peaks as seen in any spectrum taken with the system. This was measured at 0.6 nm, i.e., the spectrograph can distinguish two individual peaks which are 0.6 nm apart. This has been clarified in the text.

64. Line 94: Broadband spectra with high resolution are possible with one grating. If one really needs a high spectral resolution one could think about an Echelle spectrometer.

    This was addressed in point 30.

65. Line 118-120: These are basics of spectroscopy. The spectral range that is mentioned here is determined by the blazing angle of the grating. Of course, the camera should be sensitive in this spectral range as well. That's not really clear in the manuscript.

    This has been clarified in the note following section 1.

66. Line 176: There are much more convenient ways to reduce the radiation intensity than choosing a collimator. At first the slit width could be reduced. 100 micrometer slit width are quite a lot for a spectrograph. See also line 218.

    This has been addressed in point 22, and has now been included

67. Line 191: I'm absolutely sure that the authors did not use a Mercury-Argon-Laser for wavelength calibration. Usually mercury-argon low pressure discharge lamps are used also known as penray lamps.

    This has been addressed in point 45.

68. Line 269: It's a long time ago that I have seen a cosmic spike on my camera. Most probably this can happen with intensified CCDs if the gain is too high.

    The manufacture of the spectrograph has confirmed that the system may occasionally experience interference from cosmic rays and that the data presented in this paper is typical of a cosmic ray spike. A 'cosmic ray filter' is included with their software to remove such artifacts if necessary.

69. Line 282: Which kind of errors do the authors consider to be removed by averaging some shots? Free burning arcs are known to have a shot to shot varation. I doubt that one can significantly increase the signal-to-noise ratio by this means.

    The purpose of average the data is to minimize the effect of one-off anomalies and average out the shot-to-shot variation. This has now been included.

70. Line 332: The digital camera quantum efficiency is not the only parameter which affects the spectral sensitivity of the spectroscopic system, e.g. the grating itself will have an effect as well. Usually spectral segements do not fit smooth to each other. One option is to scale spectra to fit the previous overlapping region, which might introduce an additional uncertainty.

    This has been addressed in point 19.

71. Line 453: This method is already applied in the spectroscopy of thermal arcs. But it is only usefull if there are broad(!) spectral features which can not be covered by a single spectral segment.

The technique is useful for the simultaneous identification of multiple atomic lines or elements across a broad spectrum (as certain atomic lines are only visible in distinct parts of the spectrum). This is further discussed by Reviewer 4 in point 77 and has been altered in the text accordingly.

4.3 Minor Concerns

72. N/A

4.4 Additional Comments to Authors

73. N/A

5. Reviewer #4

5.1 Manuscript Summary

74. The experiment described herein enumerates a procedure for obtaining moderate-resolution emission spectra of high-voltage, high-current atmospheric discharges similar to naturally-occurring lightning. In this reviewer's assessment, there are three key components of this work: geometry and physical parameters (i.e., voltage) of the discharge, configuration of the spectrometer, and finally processing and analysis of data. These were all included and discussed.

5.2 Major Concerns

75. This reviewer has no major concerns regarding the content of this manuscript.

5.3 Minor Concerns

76. It may be appropriate to add some more details pertaining to this particular experiment in the protocol provided. Specific instances (and reasons therefore) will be included below.

77. Much of the physical chemistry occurring during a lightning event can be observed in emission between the VUV/air limit (~200 nm) and 450 nm (i.e., emission from NO and OH radical). Increasing the bandwidth of the spectrometer to include the UV/violet end of the spectrum could be useful for additional atomic and molecular identification and analysis. This is mentioned briefly as an addition to this technique, but some more discussion would be appropriate.

This has been included under the Discussion section.

78. Could neutral density filters be used rather than a collimator? These are slightly simpler to use and should attenuate evenly across this wavelength range.

This has been included.

79. This reviewer does not disagree with the authors claiming that they could be observing signals indicative of cosmic rays in their spectra, however, I am not entirely convinced that these signals are not a result of electrical interference. Some additional discussion would be appropriate.

This was addressed in points 48 and 68.

80. In general, gridlines are rarely included in figures of these types. This reviewer would recommend plotting these data without gridlines to increase clarity. This is, however, a matter of aesthetics.

The gridlines have been removed from all relevant figures.

81. Lines 77-78: An oscilloscope trace or figure of the voltage waveform used to generate the lightning is warranted.

This has been included as a new figure, Figure 1.

82. Line 92: "Typically, a large..." this reviewer would argue that a large wavelength range is not needed for spectral assignment-- the NIST ASD is very precise and should work well across a small bandwidth. I suppose this is a semantics argument; what do the authors mean by "large wavelength range?"

    This has been clarified.

83. Line 106: a reference to the database used is warranted here.

    This was addressed in point 36.

84. Steps 2.2.1-2.2.2: grit ratings of sandpaper should be included.

    This has been included

85. Should the polishing steps (2.2.1-2.2.2) be repeated before every discharge? If so, this should be stated explicitly.

    The cleaning/polishing of the electrode was only performed once at the beginning of the experiment. However, the electrode may need to be cleaned with alcohol between shots or, if contaminated, step 2.2 may need to be repeated. This is now included in step 4.2.6.

86. Line 155: recommend replace "locate" with "place" or other synonym.

    This has been altered.

87. Line 176: recommend replace "with" with "which"

    This has been altered.

88. Step 3.4: the description of the grating is inadequate. The manufacturer and blaze wavelength (if appropriate) should be included.

    The grating was provided by the manufacturer of the spectrograph system, as listed in the materials table. Further details of the grating were addressed in point 29.

89. Step 3.5: more information about the mercury-argon laser (manufacturer, etc.) should be included.

    This has been included in the materials list.

90. Step 3.5.4: the detector position can also be adjusted to optimize the signal, depending on the detector used.

    This has been included.

91. Line 224: recommend replace "this" with "these".

    This part of the sentence was removed in point 4.

92. Step 4.2.7: four repeats seems arbitrary... would it not be better to increase the number of spectra?

    A note has been included on this following point 4.2.7.

93. Line 286: recommend replace " If the" with "If there".

    This was addressed in point 50.

94. Line 296: recommend replace "one." with "on."

This has been altered.

95. Lines 457-459: recommend adding a clarifying statement that saturating the detector is not desired when optimizing signal.

    This has been added.

96. Line 477: recommend replace "has" with "have".

    This has been altered.

5.4 Additional Comments to Authors

97. None.

Method for Recording Broadband High Resolution Emission Spectra of Laboratory Lightning arcs

Response to Reviewer Comments

The authors would like to thank the editor for their comments. We have revised the paper accordingly as listed below.

1. EDITORIAL COMMENTS

1.1 Editor modified the formatting of the manuscript and adjusted spacing of the protocol section. Please read the entire manuscript carefully and make changes if required. Do not change the formatting.

The hyperlinks have been removed from lines 12 to 14 and they do not work with track changes, and the capitalisation needed to be removed from one email address. Line 51 to 52 have been clarified. Otherwise the manuscript is fine.

2.2 Editor added track changes to the word document of your manuscript, attached to this email. Please approve/revise all track changes; however, do not accept the changes so that we can confirm the changes you made.

This has been done

2.3 The length of the highlighted text in the current version exceeds JoVE's 2.75 page limit. We suggest that you remove highlighting from steps 5 [post-processing data] and 6 [analyzing data] to focus on the method. Remember that the non-highlighted protocol steps will remain in the manuscript and therefore will still be available to the reader.

The highlighted text has been revised, with lines 217 to 223, 232 to 335, 269 to 272, 336 to 351, and 375 to 377 having highlighting removed.

Figure 16 re-print permission

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Supplemental File

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