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

**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.

1. **EDITORIAL COMMENTS**

**1.1 General Formatting**

1. If you are re-using figures from a previous publication, you must obtain explicit permission to re-use the figure from the previous publisher (this can be in the form of a letter from an editor or a link to the editorial policies that allows you to re-publish the figure). Please upload the text of the re-print permission (may be copied and pasted from an email/website) as a Word document to the Editorial Manager site in the "Supplemental files (as requested by JoVE)" section. Please also cite the figure appropriately in the figure legend, i.e. "This figure has been modified from [citation]."

*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.*

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

*These have been provided.*

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

*These have been removed.*

**1.2 Protocol**

1. 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.*

1. Line 118 – step 1.1 – label as “note:”

*This has been included.*

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

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

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

*This has been corrected throughout the manuscript.*

1. 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.*

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

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

1. 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.*

1. 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.*

1. 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**

1. Please make sure that your references comply with JoVE instructions for authors. In-text formatting: corresponding reference numbers should appear as superscripts 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**

1. 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**

1. N/A

**2.3 Minor Concerns**

1. N/A
   1. **Additional Comments to Authors**
2. N/A

**3. REVIEWER #2**

**3.1 Manuscript Summary**

1. 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:
   1. **Major Concerns**
2. 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.*

1. 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.*

1. 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.*

1. 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*

1. 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**

1. Replace optic fiber by optical fiber or fiber optic

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

1. Replace spectrographic by spectroscopic

*Spectrographic has been replaced with spectroscopic throughout the manuscript.*

1. 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.*

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

*This has been altered.*

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

*This has been altered.*

1. 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.*

1. 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.*

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

*This has been altered.*

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

*This has been altered.*

1. 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.*

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

*This has been altered.*

1. 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.*

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

*This has been added.*

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

*This has been altered.*

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

*This was addressed in point 14.*

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

*This has been added.*

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

*This has been altered.*

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

*This has been altered.*

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

*This has been included as an alternative option.*

1. 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.*

1. line 176 : spelling

*No spelling error could be found on this line.*

1. 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.*

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

*This has been altered.*

1. 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.*

1. 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.*

1. 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.*

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

*This has been altered.*

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

*The dashed lines have been removed.*

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

*This has been corrected for all graphs.*

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

*This has been altered.*

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

*This has now been removed.*

1. 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**

1. N/A

**4. Reviewer #3**

**4.1 Manuscript Summary**

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

**4.2 Major Concerns**

1. 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.*

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

*This has been altered.*

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

*This has been included*

1. 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 12o was an error and it should have been 0.12o; 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.*

1. 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.*

1. 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.*

1. 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.*

1. 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.*

1. 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*

1. 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.*

1. 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.*

1. 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.*

1. 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.*

1. 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**

1. N/A

**4.4 Additional Comments to Authors**

1. N/A

**5. Reviewer #4**

**5.1 Manuscript Summary**

1. 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**

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

**5.3 Minor Concerns**

1. 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.
2. 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.*

1. 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.*

1. 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.*

1. 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.*

1. 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.*

1. 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.*

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

*This was addressed in point 36.*

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

*This has been included*

1. 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.*

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

*This has been altered.*

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

*This has been altered.*

1. 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.*

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

*This has been included in the materials list.*

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

*This has been included.*

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

*This part of the sentence was removed in point 4.*

1. 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.*

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

*This was addressed in point 50.*

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

*This has been altered.*

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

*This has been added.*

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

*This has been altered.*

**5.4 Additional Comments to Authors**

1. None.