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Spectrometer Application Report

Exploration of the Sun’s spectrum with LightMachinery spectrometers

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A. Introduction

Over the past few years LightMachinery has developed a novel series of cross-dispersion spectrometers. The LightMachinery family of spectrometers covers the spectral range from 270 nm to 1675 nm (1 nm = 10^{-9} meters, or 10 Angstroms), with resolutions as high as 0.5 picometers (1 pm = 10^{-12} meters, and 0.5 pm resolution is ~500 MHz at 500 nm) in some spectrometers and ~300 nm wavelength coverage in other instruments. Figure 1 shows two typical instruments.

Figure 1: Two spectrometers, each with 6 in rulers for scale. The HN-9332 unit on the right has a resolution of ~30 pm, while the larger HF-8993-0.5 has a resolution of 0.5 pm.

The principles of operation of LightMachinery crossed-dispersion spectrometers are described in [1]. In these spectrometers, a Fabry-Perot type etalon is used to provide a large dispersion (and thus high resolution) in the vertical direction, but only for a limited wavelength range corresponding to the Free Spectral Range, FSR, of the etalon. In the horizontal direction, a diffraction grating separates the overlapping orders of the etalon to allow the entire high-resolution spectrum to be “unwrapped”. The cross-dispersion scheme disperses the incident light in two dimensions prior to capture with a 2D sensor, typically enabling more than 10,000 spectral elements to be captured simultaneously in a single exposure. Thus, when the spectrometer is illuminated by white light, the cross-dispersed spectrum seen by the sensor is a series of near-vertical stripes, as illustrated in Figure 2.

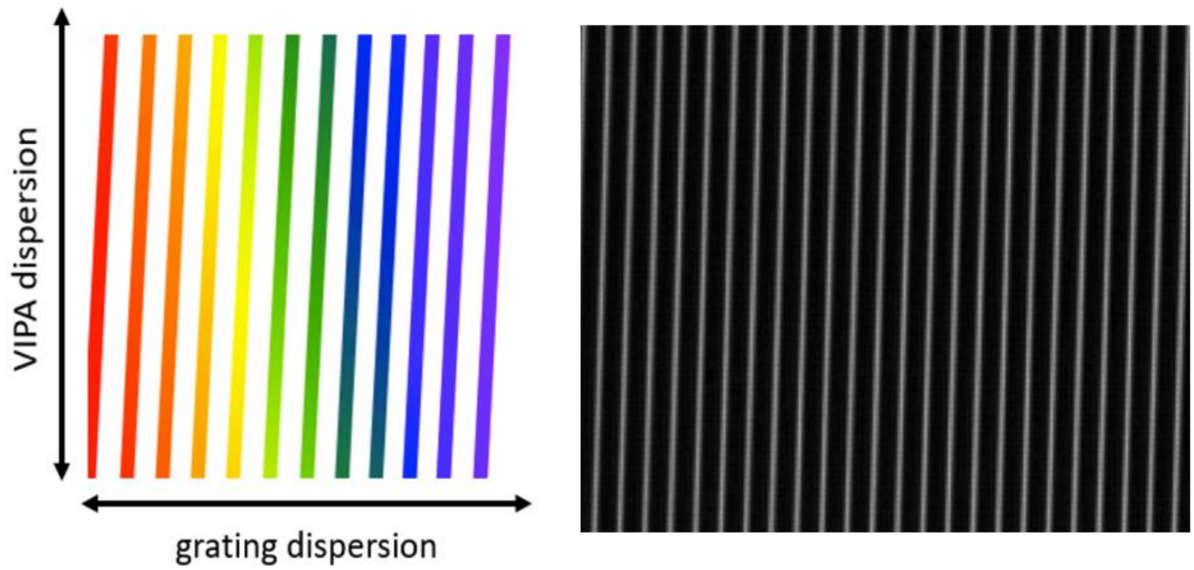

Figure 2: Left: Schematic of the display seen at the spectrometer sensor when the crossed etalon (or VIPA) and grating are illuminated with broadband ("white") light. The vertical stripes are spaced by one etalon FSR in the horizontal direction. In the chart, red represents longer wavelengths; blue shorter wavelengths. A typical screen shot from the sensor is shown on the right. Only a small portion of the full sensor is shown, covering 23 FSRs of the etalon horizontally, and 0.5 FSR vertically.

A particularly interesting and useful white light source is the Sun. Not only is direct sunlight a very intense white light source, but also the existence of thousands of Fraunhofer absorption lines [2-4] throughout the spectrum makes sunlight ideal for calibrating a spectrometer and assessing its performance.

B. The properties of sunlight as a light source for spectrometers

Many sources give very accurate and comprehensive solar spectra [2-4]. Figure 3 illustrates the visible portion of the Sun's spectrum, showing the strong Fraunhofer lines, and an expanded version near 590 nm.

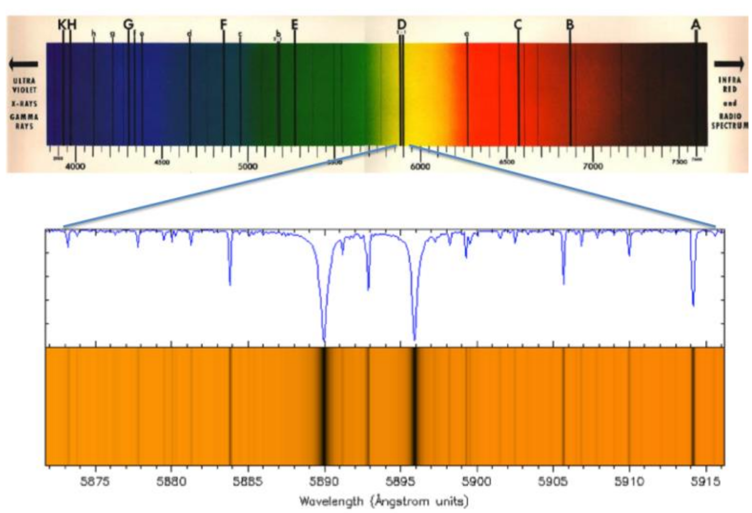

Figure 3: The upper spectrum shows the strong Fraunhofer lines superimposed on the white light spectrum of the Sun. The labeled absorption lines are identified in [2]. The expanded view of the sodium D-lines is taken from [3].

Note the two closely spaced absorption lines in the yellow portion of the spectrum. These are the sodium D-lines, and result from the absorption of yellow light by sodium in the Sun's outer atmosphere. It is worth noting that [4] provides accurate, high-resolution spectra of sunlight from the UV to well into the infrared. In summary, sunlight is an ideal light source for demonstrating the capabilities of spectrometers and for calibration of spectrometers. The next section will describe how to couple sunlight into a spectrometer.

C. Coupling sunlight into a spectrometer, and tracking the Sun

The simplest method of displaying the solar spectrum on a LightMachinery spectrometer is to couple direct sunlight into an optical fiber that is connected to the input port of the spectrometer. Some versions of LightMachinery spectrometers have sufficient throughput and sensitivity that a solar spectrum can be recorded by aiming the fiber end roughly in the direction of the Sun. For the majority of the spectrometers, a lens should be used to collect sunlight, and the input end of the fiber positioned at the focus of the lens. There are two drawbacks to this simple conceptual experiment. First, it is not a trivial matter to aim the lens at the Sun while positioning the fiber input at the focus. Second, the daily rotation of the earth ensures that the Sun's image at the focus will move one complete disc diameter in ~3 minutes, requiring a re-alignment every couple of minutes. Both these problems can be overcome by using a commercial fiber collimator [5] to couple sunlight into a fiber. If the collimator is mounted on a stable tripod it can be aimed at the Sun and can manually track the Sun's movement across the sky. A more elegant method is to purchase an inexpensive solar telescope (two examples are given in [6] and [7]), which will automatically track the Sun across the sky. LightMachinery will supply an eyepiece adaptor, upon request, to couple the solar image into a fiber. Figure 4 shows sample telescopes and collimator.

Figure 4: The upper part of this Figure shows two solar telescopes that automatically track the Sun across the sky. Either one can be purchased for ~$500 [6,7]. The lower part of the Figure shows an eyepiece adaptor to couple light from the telescope into a fiber, and a commercial fiber collimator [5] that can be mounted on a tripod for manual tracking of the Sun.

D. Examining the Solar Spectrum with LightMachinery Spectrometers.

Once sunlight is coupled into the spectrometer, a stripe image is recorded on the camera sensor as shown in Figure 5. The stripes are similar to those shown in Figure 2, but the additional dark regions in the white stripes correspond to solar absorption lines. In these narrow wavelength regions the light intensity from the Sun is reduced by absorption in either the outer layers of the Sun’s atmosphere (Fraunhofer lines) or by absorption in the earth’s atmosphere (telluric lines caused by gases such as oxygen and water vapour). Each stripe is separated by one FSR of the etalon or VIPA.

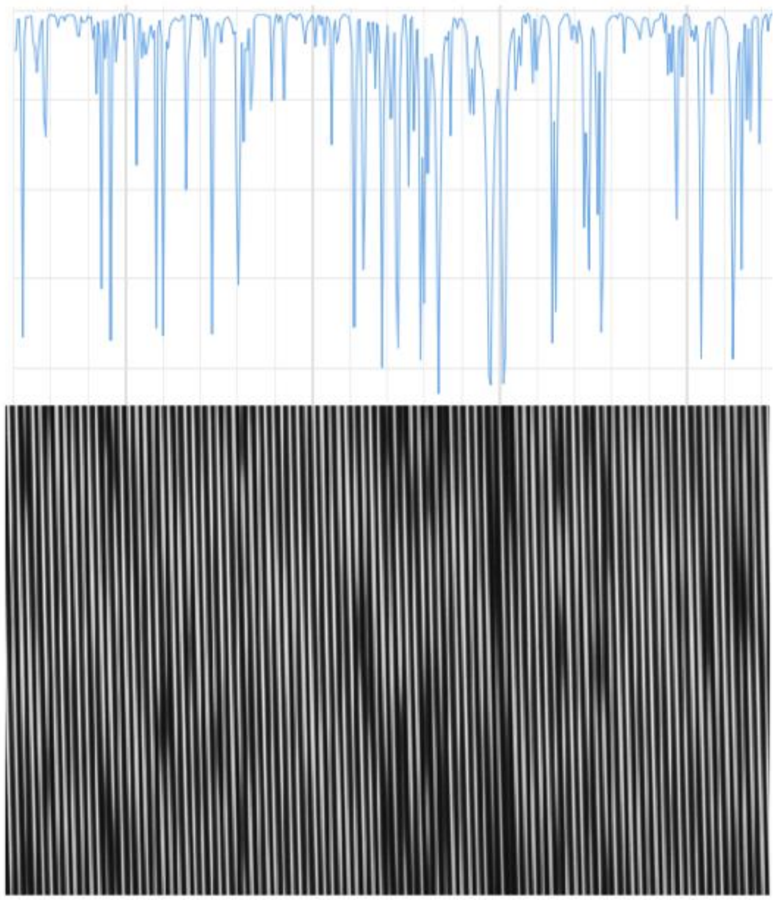

Figure 5: A comparison of the solar spectrum from [4] with the sensor image recorded near 526 nm. The sensor display is a grey-scale image with white pixels corresponding to higher intensities. The solar spectrum has been scaled in the X-direction to agree with the known stripe spacing in the image. The wavelength range is ~524 to 528.5 nm, covering 90 stripes.

As the etalon FSR is very accurately determined by the manufacturing process, it is relatively simple to compare the solar spectrum from the literature with the raw sensor image. If the approximate spectral region is known (from the grating angle, for example), there is no need for an accurate calibration. Such a comparison is shown in Figure 5. (The sensor image has been flipped by 180 degrees in the horizontal direction to match the wavelength display from [4]).

Careful examination of the sensor image in Figure 5 reveals that some absorption features repeat at the top and bottom of the image. As described in [1], the portion of the image shown represents >1 etalon order in the Y-direction, hence the repeating features. All LightMachinery spectrometers ship with SpectraLoK software that is designed to “stitch” together the successive stripes and display the resultant spectrum, a process described as “unwrapping”. (The “unwrapping” process takes account of the non-linear dispersion in the vertical direction caused by the etalon). Figure 6 shows the unwrapped solar spectrum for an interesting region near 518 nm, as directly displayed by the SpectraLoK software.

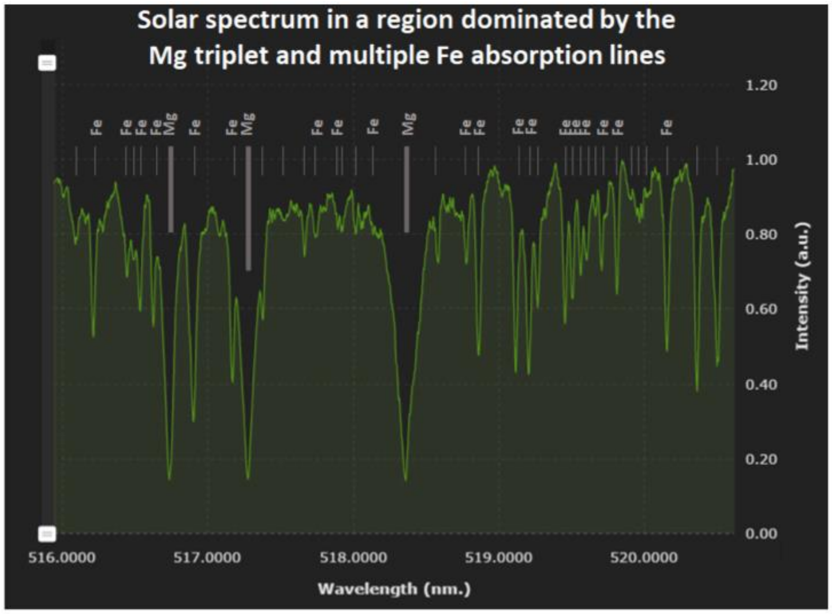

Figure 6: Solar spectrum recorded by the HN-9332 spectrometer in the region near 518 nm displaying the Mg triplet absorption in the Sun's outer layers. (In addition to the Mg and Fe lines indicated, there are also some Ni absorption lines in this region of the solar spectrum [8]).

In addition to directly displaying the spectra, the SpectraLoK software enables the data to be exported for further analysis and for comparison with reference spectra. Figure 7 shows comparison graphs using data downloaded by SpectraLoK (red data) and a reference spectrum [4] (blue data).

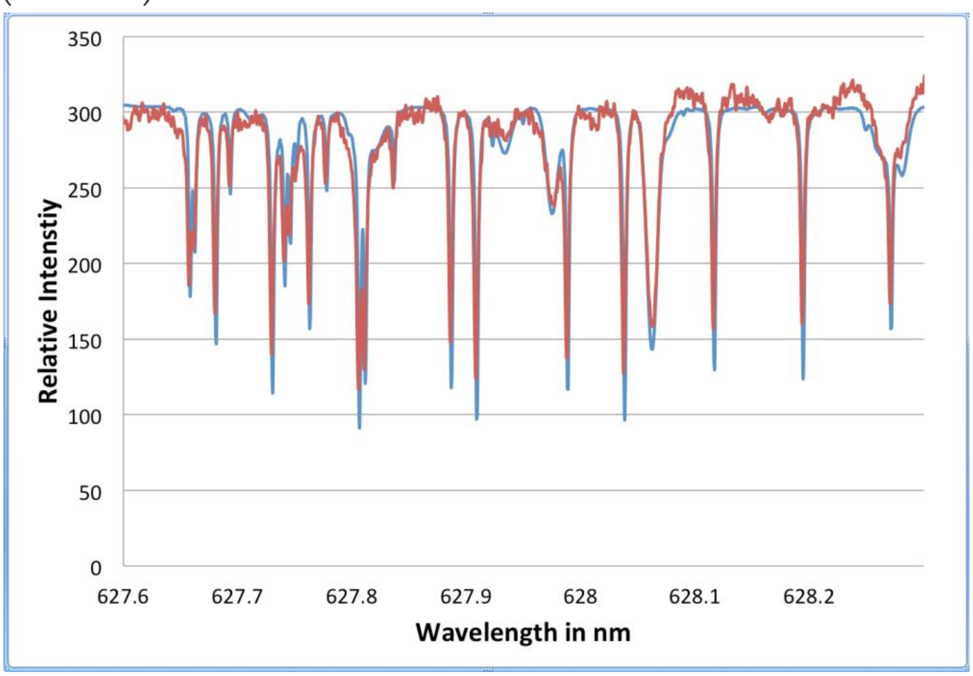

Figure 7: Comparison of a solar spectrum recorded with a LightMachinery HF-8989-2e spectrometer (red data), and a reference spectrum (blue data) from [4]. The region displayed is ~ 1nm wide, centered around 628 nm.

Figure 7 illustrates the spectral density of the absorption lines, the quality of the high-resolution solar spectra available online, and the utility of the online data for comparisons with experimental spectra.

E. Fun with the Sun

E-1. Coverage of ~300 nm in a single exposure

As the solar spectrum covers the range from the UV to the IR, and includes spectral absorption lines created as light travels through both the Sun's outer atmosphere and through the atmosphere of earth, there is a vast array of possibilities for "fun" spectrometer experiments and demonstrations (many of the examples in this paper were inspired by [9]). This section includes a few examples of the possible experiments. To set the stage, Figure 8 shows a solar spectrum taken with a HN-9332 spectrometer. This spectrometer can record almost the entire visible range of wavelengths with a single exposure.

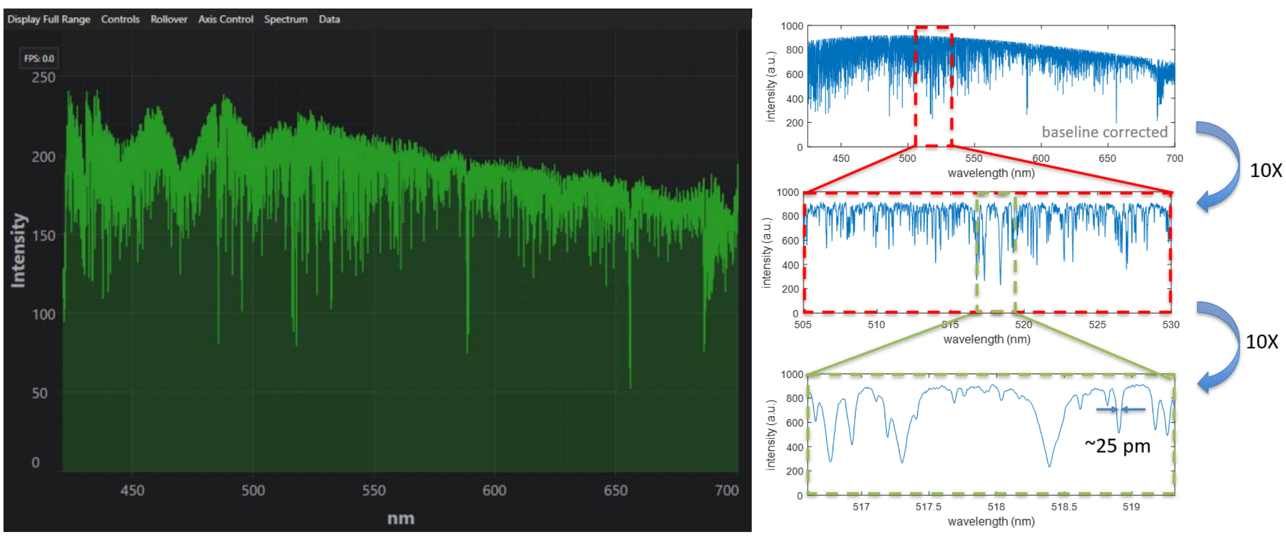

Figure 8 – Demonstrating the wide wavelength coverage of the HN-9332 spectrometer by recording the visible region of the solar spectrum with a single exposure of only 0.7 seconds. The left portion of the Figure shows the entire 425-700 nm wavelength range as displayed directly by the SpectraLoK software. The number of pixels on the computer screen, rather than the resolution limit of the spectrometer, limits the accurate representation of the multitude of absorption lines. The right part of the Figure shows successively expanded regions around the magnesium triplet near 517 nm.

The instrument resolution of the HN-9332 spectrometer is best expressed in frequency units – ~20 GHz across the wavelength coverage of the instrument. This corresponds to a resolution of ~15 pm at 425 nm, ~20 pm at 550 nm, and ~30 pm at 700 nm. Thus the data displayed in Figure 8 is equivalent to >10,000 resolution points, all recorded in a single exposure of less than one second. The broad wavelength coverage of the HN-9332 instrument enables quick "survey" spectra to be taken throughout the visible region of the spectrum. However, some of the Fraunhofer lines (and most of the telluric lines) are narrower than the HN-9332 instrument resolution. Detailed examination of the interesting regions of the solar spectrum requires switching to spectrometers with higher resolution, such as those from the HF-8989 family.

E-2. High Resolution Solar Spectra

Figure 9 shows a particularly interesting region of the solar spectrum. This region around 689 nm is dominated by telluric absorption in the earth's atmospheric caused by oxygen. Individual absorption lines in both the R-branch and the P-branch of the oxygen band can be clearly seen, and the stronger absorption lines demonstrate ~100% absorption at the line-center.

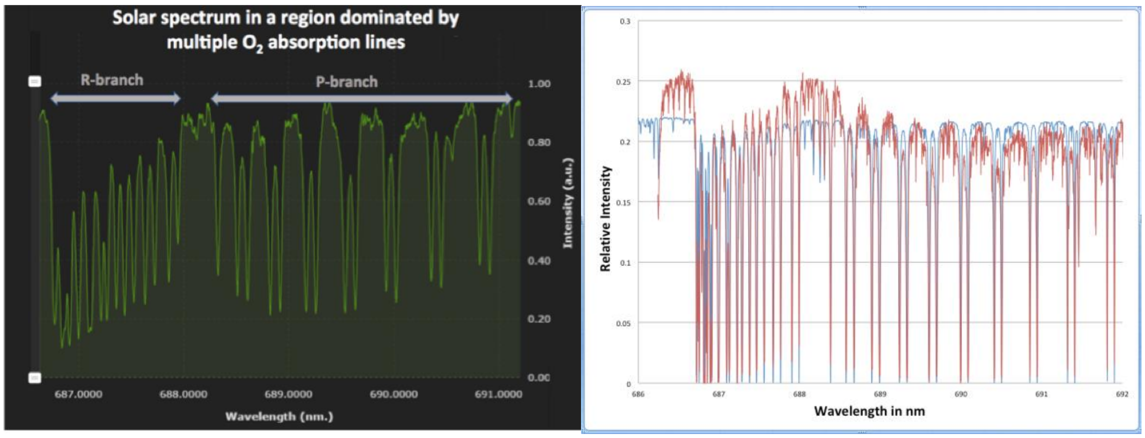

Figure 9: Telluric oxygen band in the 689 nm region of the solar spectrum. The screenshot on the left was recorded with a HN-9332 instrument (resolution ~30 pm). The experimental data (red) on the right was recorded with an HF-8989-3 spectrometer with a resolution of ~1 pm, and this experimental data is compared with a spectrum from [4] (blue).

In general, the telluric oxygen lines have significantly narrower linewidths than the Fraunhofer lines, and hence are sometimes used to determine the instrumental linewidths of the spectrometers recording the solar spectrum. A recent (2014) paper by Fathivavsari et. al. [10] describes the use of two telluric oxygen lines near 629 nm to compare the intrument profiles of two different spectrometers used to record spectral atlases of the Sun. We have used a LightMachinery HF-8989-3 spectrometer to record the same two oxygen lines in Figure 10.

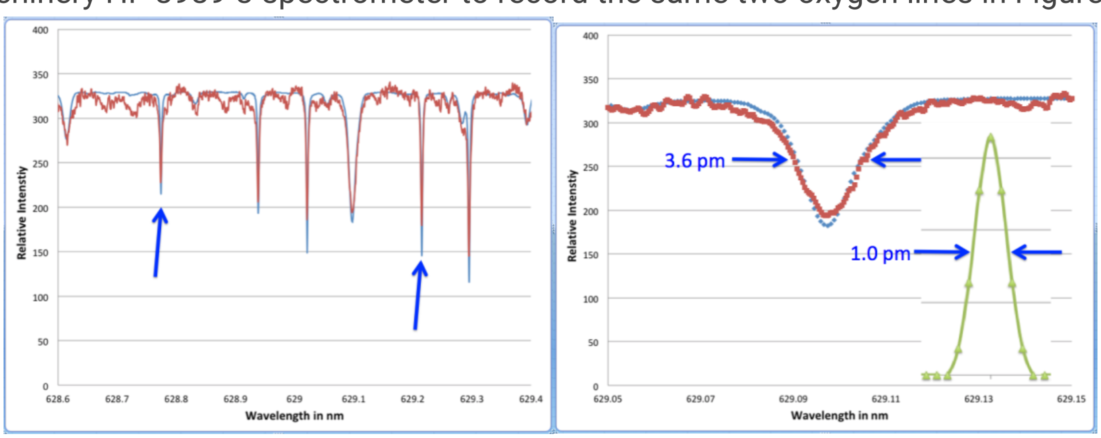

Figure 10: On the left is a high-resolution solar spectrum taken with a HF-8989-3 spectrometer in the 629 nm region. The two oxygen lines used in [10] to compare instruments profiles are identified with arrows. (Experimental data shown in red and compared with a reference spectrum from [4] in blue). The right side shows expanded views of the oxygen line at

629.216 nm, together with an inset showing the spectrum of a red He-Ne laser (essentially a single frequency source at 632.816 nm) recorded with the same instrument resolution.

Fathivavsari et. al. [10] used a large grating spectrometer (30 cm diameter mirrors with focal lengths of 3 m, and a 16 cm wide grating), but measured a FWHM of 8.9 pm for the oxygen line at 629.216 nm. Their results were compared with the measurements made on the massive FT spectrometer at Kitt Peak [11], which measured a FWHM of 3.1 pm for the same oxygen line. The much smaller HF-8989-3 spectrometer measures FWHM of 3.6 pm for this line. Both the HF-8989 and the Kitt Peak spectrometers demonstrate little instrumental broadening of the oxygen lines. (The instrument resolution of the HF-8989-3 is 1.0 pm, as demonstrated by the He-Ne spectrum, while the instrument resolution of the 1m path-difference Kitt Peak FTS is ~0.2 pm).

E-3. Atmospheric investigations.

The telluric oxygen lines can also be used to demonstrate the change in the solar spectrum as the pathlength of the sunlight through the earth's atmosphere varies, as shown in Figure 11.

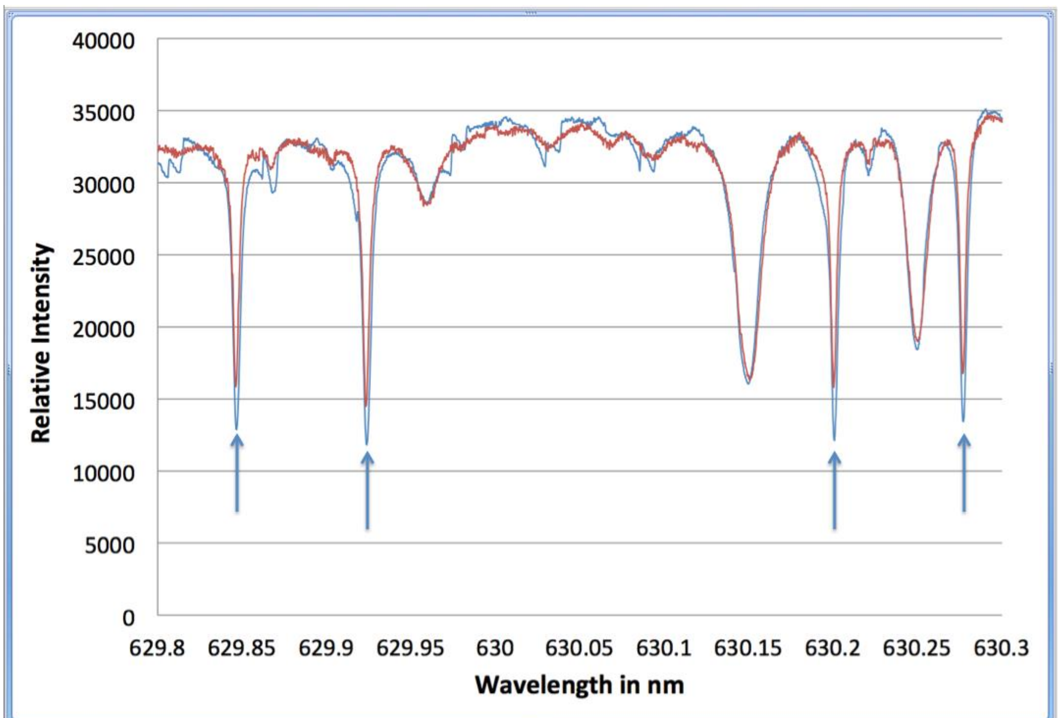

Figure 11: Effect of change in the pathlength through the earth's atmosphere on the solar spectra taken near 630 nm. This region contains both narrow telluric oxygen lines, and wider Fe solar lines. The red spectrum was recorded near noon, while the blue spectrum was recorded later in the afternoon. The additional oxygen absorption caused by a longer path through the earth's atmosphere can be clearly seen in the four oxygen lines marked by arrows.

It is possible to identify telluric lines by their sensitivity to pathlength through the atmosphere, and when comparing solar spectra from different websites, it is often apparent that the spectra were taken with significantly different pathlengths through the earth's atmosphere.

In general, a comparison of the experimental solar spectra with the reference solar spectra [4] makes it very easy to confirm the calibration of most spectrometers. However, in some spectral regions, there may not be an exact correspondence between the experimental absorption lines and the lines shown in [4]. For example, in the wavelength region near 800 nm, extra absorption lines can appear in the experimental spectra, as shown in Figure 12.

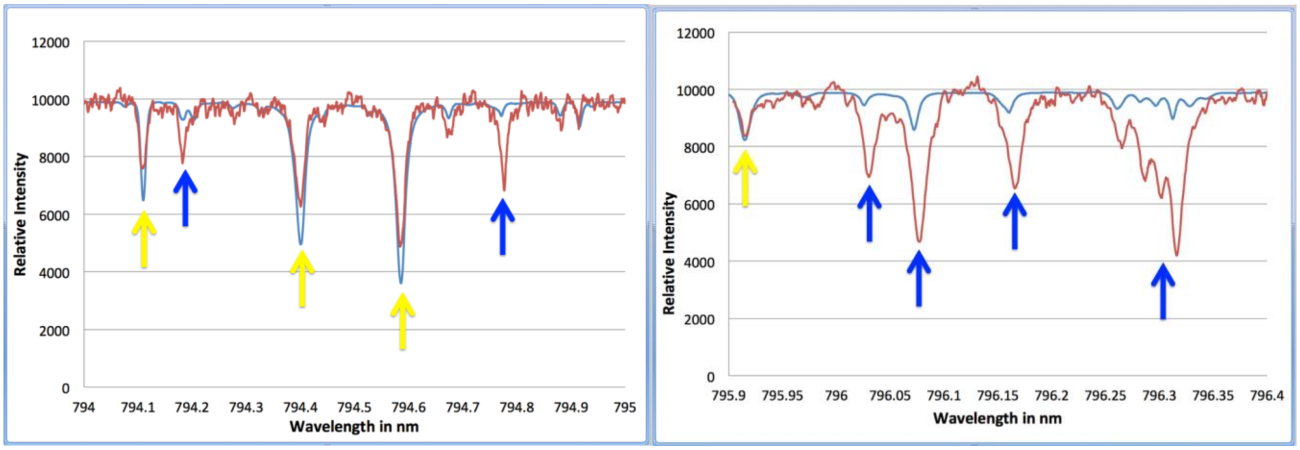

Figure 12: Demonstration of the effects of humidity on solar spectra by comparing spectra from [4] (blue) with spectra taken in Ottawa on a humid summer's day using a HF-8995-1 spectrometer (red). In the left chart, it is easy to recognize the 3 Fraunhofer lines marked with yellow lines. From [8] the remaining two lines (marked with blue arrows) can be identified as atmospheric water vapour lines. The right chart shows a nearby wavelength region where water vapour lines dominate the spectra. Clearly the spectra from [4] were recorded at a location with much less water vapour in the atmosphere.

It is interesting to note that recording the spectrum of the Sun not only tells us details about the conditions in the Sun's outer atmosphere, but also provides information about the earth's atmospere above the spectrometer.

E-4. Measuring Doppler shifts caused by the Sun's rotation

The close proximity of solar absorption lines and telluric oxygen lines in some regions of the solar spectrum can be exploited to determine the rotational velocity of the Sun (and hence the distance between the earth and the Sun) by measuring the Doppler shift of the solar lines relative to the fixed oxygen lines. The only equipment required is the solar telescope and the HF spectrometer. As the Sun is rotating relative to the earth, one limb of the Sun's disc is moving towards the earth, while the other limb is receding. Consequently, the light from one side of the Sun's disc is red-shifted by the Doppler effect, while the light from the other side is blue-shifted. These shifts can be observed as shifts in the wavelength of the solar lines relative to the telluric oxygen lines (the oxygen lines result from absorption in the earth's atmosphere, which is not moving relative to the telescope). Full details of this experiment are described in [9], and the key measurement is shown in Figure 13.

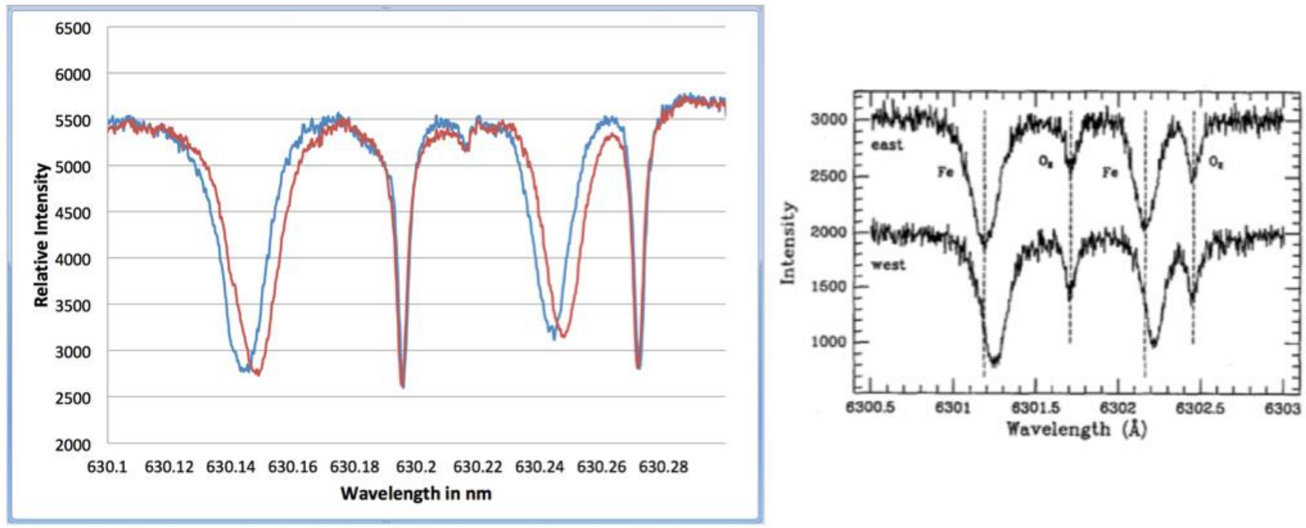

Figure 13: A measurement of the Doppler shift of two Fraunhofer Fe lines (relative to the unshifted oxygen telluric lines) caused by the Sun's rotation. In the left chart, the red and blue lines are experimental data taken with an HF-8989-3 spectrometer as the image of the Sun's disc was moved across the input fiber to the spectrometer (from near one edge to near the other). The exposure time for each experimental spectra was <1 second. The figure on the right side is taken from [9], and shows a similar measurement made with a SPEX 1704 1-m grating spectrometer.

As the maximum Doppler shift from limb to limb of the Sun's disc is only ~8 pm [9,12], the full instrument resolution of the HF-8989-3 (~1 pm) is required to make an accurate measurement. However, the very rapid acquisition rate of the LightMachinery spectrometers is also extremely beneficial for this type of measurement. Rather than set up a complex imaging system to display the portion of the Sun's disc that was coupled into the spectrometer fiber, we simply set the SpectraLoK software to record a new spectrum every 100 milliseconds while scanning the telescope from one limb to the other. The fast display of the live spectra enabled us to find the telescope positions with significant Doppler shifts, and to record longer-exposure spectra with better signal-to-noise ratios at these positions. (Note that the Fe lines in Figure 13 are separated by ~5 pm, as these spectra were not taken at the extremities of the Sun's disc).

F. Conclusions

Sunlight is an intense, yet inexpensive, source of light that comes with thousands of "built-in" calibration features. This paper has illustrated some of the interesting experiments and observations that can be carried out using sunlight as the illumination source, and these experiments were made possible by the high resolution and wide spectral coverage of the LightMachinery family of spectrometers. Many more such experiments are possible in spectral regions from the UV to far into the IR. Have fun trying them out!

References

[1] - https://lightmachinery.com/media/1857/hyperfine-principles-of-operation.pdf

[2] - https://mark4sun.jpl.nasa.gov/report/UT_seminar_Solar_Spectrum_Toon.pdf

[3] - http://fermi.jhuapl.edu/liege/s08_0364.html

[4] - http://bass2000.obspm.fr/solar_spect.php?lang=en The data shown in the interactive chart on this website can be downloaded for further analysis. Links on this site describe the instruments and techniques used to record the solar spectra. Extensive processing was carried out to normalize the solar background intensity, and multiple scans were taken over long periods of time to minimize noise. In the visible region of the spectrum, it appears that the grating spectrometer had a resolution of ~0.6 pm.

[5] – https://www.thorlabs.com/navigation.cfm?guide_id=27 This link describes a large variety of collimators.

[6] – https://www.ioptron.com/product-p/8806.htm

[7] - https://maisonastronomie.ca/en/product/solarquest-skywatcher/

[8] - http://bass2000.obspm.fr/download/solar_spect.pdf

[9] – Stephen J. Ratcliff et. al., "High-resolution spectroscopy in the undergraduate physics laboratory", Am. J. Phys. **60** (7), July 1992, pp 645-649.

[10] - https://arxiv.org/pdf/1407.5727.pdf

[11] - https://www.noao.edu/image_gallery/html/im0449.html

[12] - http://www.astrosurf.com/spectrohelio/spectre_solaire-en.php