Doppler effect based hyperspectral imaging

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Abstract

There are multiple solutions for hyperspectral imaging, all of them include either grating or filters and therefore lose spatial resolution (2D patterns) or time resolution (1D patterns or line scan or push broom). In this paper, we present a method for hyperspectral imaging that does not require either gratings or multiple filters and that maintains the full 2D resolution of the sensor and arbitrary small wavelength resolution is possible. However, the camera may become heavy.

1. Review of hyperspectral imaging

In traditional hyperspectral imaging, the image is split into its narrow band components and each of them is imaged by a series of pixels. If the splitting is made as the sensor's plane by extended Bayer patterns with, say, 5x5 pixels, then 25 wavelength bands can be identified at the expense of a loss of resolution of 25 compared to a monochrome sensor.

Another approach is similar to line scan imaging. Each line of the sensor is covered by a different filter so that each line operates as a one band line scan sensor. By moving the camera over the target or, more usually for remote sensing, when moving the object (the earth) in front of the sensor, each band will see the object in sequence and therefore there is no loss of resolution. However, as the required number of frames is equal to the number of bands, the resolution in time is reduced. This is the mostly used hyperspectral imaging approach.

2. The Doppler-Fizeau effect

When a source emitting a wave of wavelength λ_s is fixed and the detector moves towards the source at a speed of v, then the detector perceives a wavelength of

$$\lambda_o = \lambda_s \frac{c+v}{c}$$

where c is the velocity of the wave in the medium. The speed is measured negatively towards the source as the distance reduces.

This is the traditional Doppler-Fizeau effect encountered everyday when hearing sirens with a relative displacement to the observer.

3. The Doppler effect with light

As light travels at a very high speed of approximately 3.10^8 m/s in vacuum, and slightly less in air, the Doppler effect can only be measured if the speed of the detector is very high. At such high speeds, we can no longer use the usual classical Doppler-Fizeau theory and we have to make use of special relativity.

In special relativity, the time depends on the observer and there is a time dilation given by

$$t_0=\frac{t}{\gamma}$$

where γ is the relativistic Lorentz factor given by

$$\gamma=\frac{1}{\sqrt{1-\beta^2}}$$

where $\beta=v/c$ is the fraction of the speed of light at which the receiver moves towards the source.

With this approach, one can demonstrate that the relativistic Doppler formula is

$$\lambda_o=\lambda_s\sqrt{\frac{1+\beta}{1-\beta}}=\sqrt{\frac{c+v}{c-v}} \quad .$$

The speed must be considered negatively when the detector moves towards the source because the distance decreases.

At figure 1, the observed wavelength is plotted versus the detector's speed for three source wavelengths of 500nm, 700nm and 900nm.

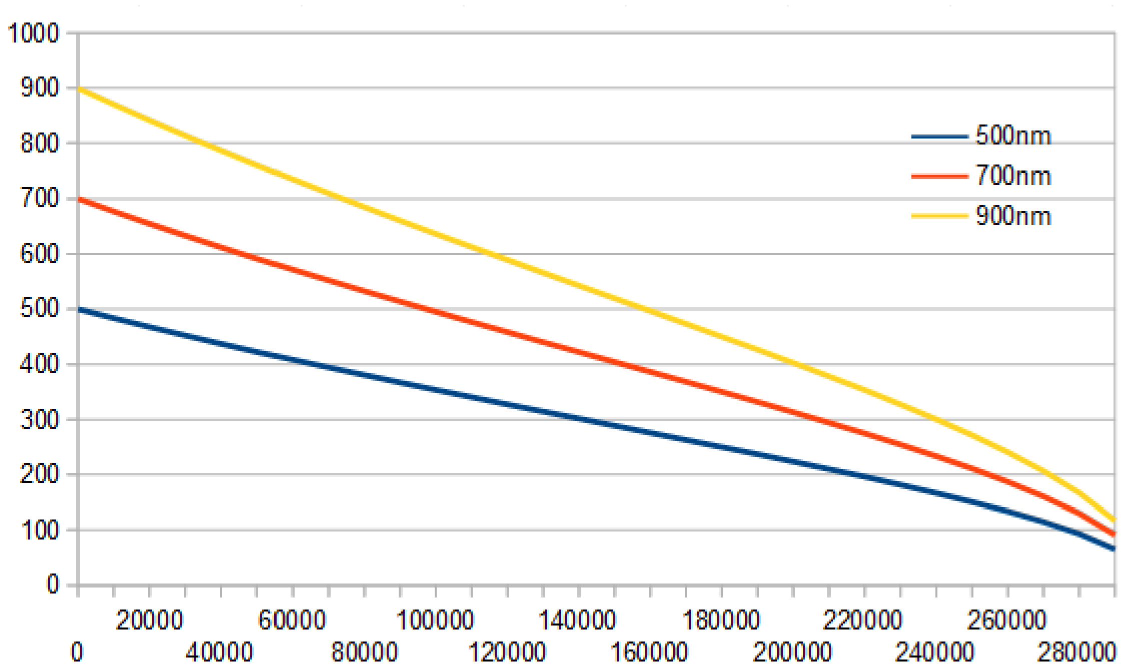

Figure 1: observed wavelength for a 500nm, 700nm or 900nm light source wavelength versus the speed of the detector towards the source in km/s.

4. The method

A 2D image sensor is covered close to the pixels by a glass coated with a narrow band filter of 5nm FWHM or less with a central band at a low wavelength, say 100nm.

At rest, the device sees a full 2D image at full frame rate of the source but only for its 100nm +/- 2.5nm components.

As the sensor is accelerated towards the source, the Doppler effect shifts the source wavelength down so that successive wavelength above 100nm will become visible through the narrow band window. When the speed of 290000km/s is reached, the sensor sees the 900nm component of the source in the window.

This method can image the bands from 100nm to 900nm. If the image sensor does not operate at 100nm, then another band will be observed. With a filter at 400nm, the band of 400nm to 700nm is observed with a speed of only 145000 km/s.

The resolution of the system is only limited by the frame rate of the sensor and the rate of acceleration. If the frame rate is high enough and the acceleration rate is small enough then the difference between two consecutive images can be used to increase the spectral resolution beyond the bandwidth of the narrow band filter.

A high acceleration rate is required in order to reduce the total traveled distance by the detector. A higher speed sensor (high frame rate) can allow for higher acceleration rates.

However, the system may apparently become very heavy as the apparent mass of the sensor will apparently increase by a factor of γ . The apparent mass of a 1kg camera becomes over 5kg at 290000km/s.

As the distance between the sensor and the object is progressively reduced, the relative size of the object increases and therefore the field of view must be adjusted accordingly so that the relative size of the object does not change. Therefore a zoom lens with the zoom directly controlled by the speed of the sensor is used. The lens requires a structure that can withstand the high acceleration rate.

The data communicated by the sensor is also Doppler shifted. Therefore, to avoid communication issues, all images are stored locally and processed only when the sensor returns. The operation is therefore not real time.

5. Conclusions

This papers presents a new, but practically unusable method to perform high performance hyperspectral imaging and is published as an April fool's joke.

Bibliography

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[2] Relativistic Doppler effect, Wikipedia.
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