High Speed Hyperspectral Chemical Imaging

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Hyperspectral imaging (HSI) is emerging from scientific research to an efficient tool for material analysis in industrial quality and process control. This paper compares the performance of two major hyperspectral technologies, push-broom imagers and tunable filters (liquid crystal, acousto-optical, and Fabry-Perot). It is shown that a push-broom imager, which consists of an imaging spectrograph and a 2D detector array, provides three outstanding advantages for high speed HSI. First, all the wavelengths are acquired at exactly the same time, making spectral imaging insensitive to the movement of the sample. Secondly, light throughput in a push-broom imager is 15 to 30 times higher than in tunable filters, resulting in respectively shorter image exposure time (higher image rate) in similar illumination conditions. Thirdly, push-broom imaging only requires line illumination on the sample. We present two high speed near infrared (NIR) hyperspectral application examples, imaging of seeds for chemical uniformity in a few seconds, and imaging full drill core trays (longer than 1 m) for mineral composition in 11 s.

High speed requirements

HSI in the near infrared (NIR) spectral region (700 to 2500 nm) has a huge potential in material analysis and identification in industrial, medical, security and defense applications. One of the main requirements in these applications is doing the analyses in high speed. Fruit sorting for bruises by NIR imaging is a typical example. Spatial resolution of 1 mm or better is required, and target can move at the speed of 1000 mm/s. It leaves an exposure time of 1 ms or less per image. Also many applications where samples are imaged in laboratory or near production line require high speed, like imaging pharmaceutical tablets for chemical uniformity, or screening seeds for chemical composition for breeding purposes. As a third example, a lot of research is being done to apply HSI to diagnosing the human body, like helping the doctor to diagnose a skin area for suspected cancer. Here it is desirable to acquire the hyperspectral image in less than the heart rate period.

Due to the development of higher speed cameras and computers with higher computing power, the only challenge in reaching high speed HSI solutions remains in getting sufficient amount of light onto the sample, and collecting the light reflected or transmitted by the sample efficiently to the camera. Here the light throughput in the optics of the hyperspectral imager comes to play a big role, together with the sensitivity of the camera.

HSI technologies

Push-broom type imagers and various tunable filter imagers are currently most widely applied HSI technologies. Their operating principles are illustrated in Figure 1. A push-broom imager consists of an imaging spectrograph in front of a 2D array detector. It acquires a line image on the target at a time in a way that full spectral data becomes collected for each pixel in the line at exactly the same time. For imaging a target or sample, either the sample or the imager needs to move or be moved. The hyperspectral image (datacube) is built line by line. A tunable filter imager is a staring imager, which acquires an area image at a single waveband at a time. The spectral dimension is acquired by tuning the waveband in time.

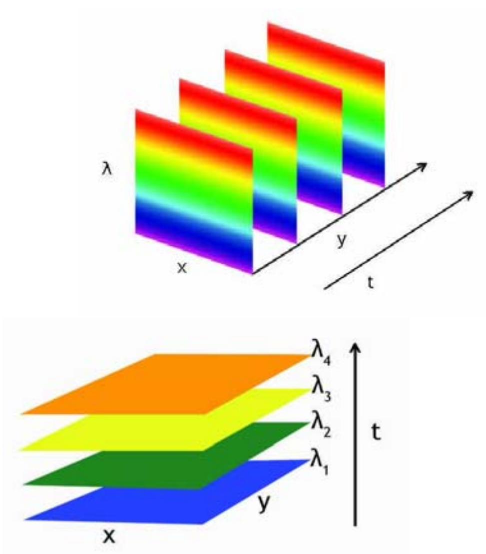

Figure 1. Acquisition of hyperspectral image (datacube) by a push-broom imager (left), and by a tunable filter imager (right).

Inherently, a push-broom imager is a natural choice for on line and other applications where the target or imager itself is moving. A tunable filter imager seems an equally evident choice for imaging stationary samples. The conclusion however is not this simple, because there are considerable differences in the optical characteristics in these technologies, significantly affecting their light collection efficiency and suitability to various uses.

Light collection efficiency in a spectral imager depends on its

- light throughput,

- optical transmission, which is influenced by reflection and absorption losses in optical elements and spectral efficiency in the element which separates the spectral bands, and
- polarization characteristics.

The throughput is determined by the maximum solid angle by which the optics can collect light from the object and transfer it to the detector, multiplied by the area of the light detector. Figure 2 presents principal optical configurations for a push-broom imager and a tunable filter imager. The figure shows a transmissive imaging spectrograph, but the same optical principles apply to an imaging spectrograph with a reflective grating. As an example here, we are taking a look at a NIR hyperspectral imager with spectral resolution of 10 nm and having 320 x 256 pixels of 30x30 microns each (this refers to an InGaAs or a MCT detector array).

The maximum light collection angle in imaging optics is determined by its F-number. High quality fore objective lenses and imaging spectrographs are working with an F-number of F/2, resulting in the total collection angle of 28 degrees, and solid angle of 0.19 sr. In an imaging system, the light detection element is a pixel. Multiplying the solid angle by the pixel area, we get the light collection efficiency of 17 $\times 10^{-11}$ m^2sr for a high performance push-broom hyperspectral imager.

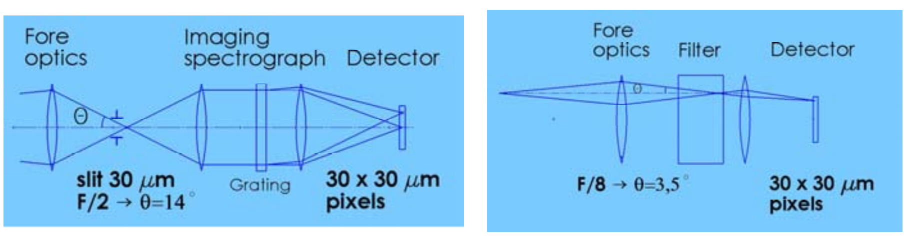

Figure 2. Basic optical configurations in a push-broom imager (left), and in a tunable filter imager (right).

In all tunable filter technologies, the maximum incident angle has to be kept much lower (corresponding to higher F-number). For the 10 nm resolution in a liquid crystal tunable filter (LCTF), the total incident angle has to be limited to ca. 7 degrees (corresponds to F/8). NIR LCTFs are currently available in the size of 20 mm in diameter. It is larger than the detector, and thus the optics from the filter to the detector can have a demagnification of ca. 1 to 0.67. This increases the total incident angle on the detector to 10.5 degrees, giving a solid angle of 0.026 sr. Multiplying this by the pixel area, we have the light collection efficiency of 2.4 $\times 10^{-11}$ m^2sr.

Acousto-optical filters (AOTF) have the same or even tighter limitation to the incident angle as LCTFs, and their active areas are not larger than 10 mm in diameter in current technology. Accordingly, this results in even lower light collection efficiency in order of 1 $\times 10^{-11}$ m^2sr.

Fabry-Perot type tunable filters with large areas are available, but we leave them out from this consideration because of their narrow tunable spectral range.

This analysis shows considerable differences in the light collection efficiency of the technologies, as summarized by the relative figures in Table 1. The technologies differ also in terms of polarization and spectral transmission, the biggest difference being in polarization behavior. A transmissive spectrograph is nearly independent of polarization. In a reflective spectrograph, polarization effects depend on the configuration, and can be from a small influence up to 50% with randomly polarized incident light. All the tunable filters require linearly polarized incident light in order to work properly, and have a linear polarizer in the input. It results in 50% light loss with randomly polarized incoming light.

Other factors affecting the optical transmission are fairly similar in the technologies. Losses caused by surface reflections and material absorptions are in the order of 10 to 20% in all technologies. Spectral efficiency (diffraction efficiency) in a transmission grating is from 70% in the centre down to 35-40% at the ends of the spectral range from 1000 to 2500 nm. In a reflective grating, the efficiency is slightly lower, and its dependence on polarization is higher. A LCTF provides spectral efficiency in the range of 40 to 80 % for linearly polarized light. An AOTF has more uniform spectral efficiency in the range of 70 to 80% (for linearly polarized light), but its spectral resolution suffers from sidebands. Table 1 summarizes the optical performance figures for the various technologies. It also compares a few other parameters which are outside the scope of this paper, but will be significant criteria when selecting the technology for real life uses.

Summarizing the analyses done above, we conclude that LCTFs require typically 15 times and AOTFs even 30 times more light, or by the same order of magnitude longer exposure times per image in similar illumination conditions than push-broom imagers.

	Pushbroom		**Tunable filter**	
	Transm.	**Reflective**	**LCTF**	**AOTF**
Spectral range/resol.	**970-2500/10**	**1000-2500/10**	**1200-2450/10**	**900-1500/10**
Light collection effic. (relat.)	**1**	**1**	**0.14**	**0.06**
Transmission (spectral efficiency, surface reflections, absorption)	**35-65%**	**15-60%**	**30-75%**	**70-85%**
Polarization loss	**No**	**Small to 50%**	**50%**	**50%**
Total light throughput (relat.)	**1**	**0.5 - 1**	**0.07**	**0.03**
Image quality	**G**	**G**	**G**	**M - G**
Stray light	**G**	**G**	**G**	**M**
Temp stability	**E**	**E - G**	**P**	**P**
Cost	**1**	**1.5-2**	**2-3**	**2-3**

E = excellent, G = good, M = medium, P = poor

Table 1. Comparison of typical performance figures in push-broom and tunable filter hyperspectral imagers.

Illumination

Requirements for illumination are intrinsically very different in a push-broom and a tunable filter system, the first requiring line illumination and the second one a full square area illumination. Generating uniform illumination over an area is much more challenging than over a line. Also, focusing the light energy along a line will easily provide 30 times higher intensity with the same total light source power than illuminating a square area. It can result in 30 times shorter exposure time, and 30 times higher image rate in a push-broom system. On the other hand, if the speed is not the primary requirement, a push-broom system can work at 30 times lower light power and heat load on the sample. It may become a very essential benefit with biological and medical samples.

Collecting and focusing light from discrete lamp(s) across a line in a way that the illumination is uniform, constant within a reasonable depth range (to tolerate variations in sample height) and as diffuse as possible (illuminates the target surface from range of directions) is technically far from trivial, and solutions have not been commercially available. In order to fully utilize the line imaging benefit, Specim has developed an innovative and inexpensive line imaging solution, which can be equally well adapted to high speed desktop sample scanners and on line systems.

Summary and application examples

Combining the results from both the light collection efficiency and illumination efficiency, we come to the very significant conclusion that push-broom type HSI is capable of working at 450 to 900 times shorter exposure time, and equally higher image rates. This means that push-broom HSI is a feasible solution not only for on line applications, but also for sample imaging. Moving the sample in a push-broom setup is easily accomplished by a linear stage, which are available at low cost and can be integrated with the image acquisition system for automatic operation. Push-broom imaging makes it possible the collect a full hyperspectral image (datacube) on a sample in a few seconds, meaning that the operator does not need to wait during imaging, and the heat load on the sample from the light source is minimized.

Figures 3 and 4 present two hyperspectral images acquired on samples by a push-broom imager. The first image is three-band visualization from a datacube acquired on a seed with resolution of 75 x 75 ☐m. The size of the datacube is 320(horizontal) x 230(vertical) x 256(spectral) pixels. It was built by acquiring 230 line images across the seed while the seed was moving on a small linear stage under the imager and illumination. Each line included 320 pixels with spectral information in 256 contiguous bands from 1000 to 2500 nm. The full image (datacube) was scanned in only 2.3 seconds by using a push-broom imager acquiring 100 line images per second. This demonstrates a chemical imaging and analysis solution with very high capacity and throughput, and which can be applied to many other applications, like inspection of chemical non-uniformity in pharmaceutical tablets.

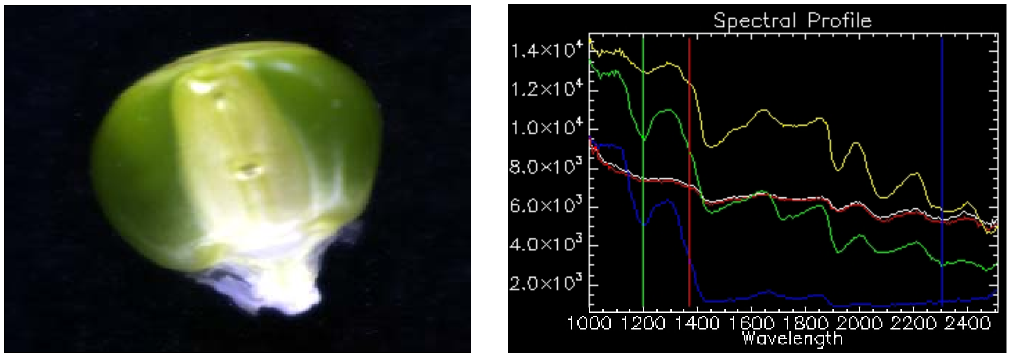

Figure 3. Hyperspectral image of a seed, visualized as a three band image (left),and reflectance spectra in 1000-2500 nm picked from various locations on the seed (right).

Figure 4 is a classified hyperspectral image on drill core samples in a core tray. The tray is 40 cm wide and 132 cm long. The image was acquired in less than 11 seconds with the resolution of 1.3 x 1.3 mm, and makes a datacube of 320(across) x 1050(along) x 256(spectral) pixels.

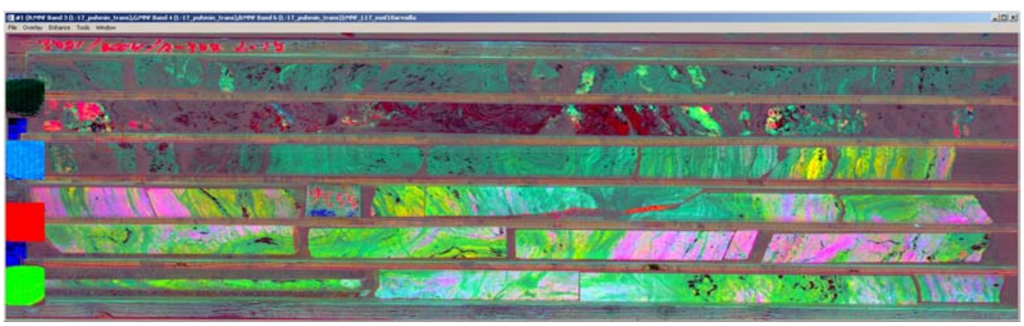

Figure 4. Hyperspectral image of drill cores, classified to identify various minerals in the cores.