Hyperspectral Systems: Recent Developments and Low Cost Sensors

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1 Introduction

Each object on Earth has a specific spectral signature in terms of its light emission, absorption or reflection. Therefore in addition to the structural information, spectral measurement can provide significant information relating to classification in remote sensing tasks.

High resolution imaging spectrometry or hyperspectral imaging (HSI) requires sophisticated solutions for both, the detector and it operation as well as for the hardware and mechanics. In particular, the spectrographs with grating or prism are expensive. Detector and grating ensure that the hyperspectral imager can only operate over a limited spectral range. As an example two devices are necessary for visible (VIS), near infrared (NIR) and short wave infrared (SWIR). The co-registration or stable alignment of the two systems is very costly.

If one attempts to avoid this difficulty, for example, by finding other solutions to the spectrograph, significantly cheaper systems can be built. This paper is to deal with such approaches.

Key features essential for a reliable and stable high performance operation are entitled and explained in detail. New developments of detector high resolution line and matrix detector technology in combination with high-sophisticated telescopes are key components for new remote sensing instruments. In case of spectral high resolution systems the ground sampling distance will be in the range of 5 up to 30 m, but the number of spectral bands is more than 100 and spectral resolution is in the range few nanometers.

For these applications the design should be able to keep the required instrument performance high under different environmental, mission and illumination conditions. Another challenge for such instruments is the noise and contrast problem, because of the optics and the design for refractive device. For all of these design aspects it is absolutely necessary to trace all of the performance related parameters especially the signal-to-noise ration (SNR), modulated transfer function (MTF), spectral response function and distortion related parameter (smile, key stone) throughout the whole system chain.

2 OS Heritage in Hyperspectral Instruments

In the Institute of optical sensor systems (OS) a number of hyperspectral instruments or components have been built and in recent years. Some few examples are going to be described in detail.

– **MERTIS** (MErcury Radiometer and Thermal Infrared Spectrometer)

Main scientific goals are observation of the Mercury Surface, Identification of Geo-Minerals spectral imaging of the Surface, observation of the surface temperature and thermal behaviour of the night side and spectral data of the Mercury Surface in a Wave length of $7 - 14$ μm (80 channels).

– **DESIS** (DLR Earth Sensing Imaging Spectrometer)

DESIS is a hyperspectral imager on MUSES platform. MUSES (Multiple User System for Earth Sensing) is a commercial imaging platform on ISS, which was designed in by Teledyne Brown Engineering.
The EnMap FPAis a development for the German VIS/NIR Hyperspectral Mission EnMAP. The CMOS detector is the same as described in Table 1, but is operated in an other regime.

3 Definition of Low Cost

Low cost does not only affect the optical system itself, but in addition to the actual sensor also the Platform up to documentation.

Name	Importance for LC	Weight
Instrument cost	++++	50 %
Accommodation cost	++++	5 %
Test and verification cost	+++	5 %
Documentation cost	++	10 %
In-orbit commissioning phase cost	-	5 %
Mission cost		25 %
Operations	–	
Monitoring	+	
In orbit Calibration	-	

Table 1. Importance for Low cost systems

The claim of LC systems is not to replace the large and expensive systems. However, it is not yet clear how much scientific output is lost through the use of LC systems in comparison to standard systems. LC systems require extremely complex post-processing to make the signal stable or reproducible and needs a deep understanding of the system, the processing and the scientific background.

The LC technology will be able to opens the door for multi systems or systems on systems approaches. In case of LC technology the challenges has to be compensated by novel computing algorithms, which needs of course also more processing time in operations. Table 3 on top shows also the budget split. These numbers based on the experiences of DLR hyperspectral instrument developments.

4 LC-Hyperspectral Systems

LC gives up standard spectrographs, use available optics and electronics. There are basically two options: Snapshot systems and scanning systems. It can be scanned both spatially and spectrally.
As an alternative to the spectrally decomposing systems also interferometers are used. Fourier-transform spectroscopy has some advantages because of its throughput benefit.

4.1 Snapshot Systems

Snapshot means that the entire dataset is obtained during a single detector integration period. An overview can be found in the review paper from Hagen, [4]. Snapshot systems can split the incident beam and mapped onto a 2D matrix (snapshot tiled). Alternatively, the spectral splitting is carried out directly on the matrix (snapshot mosaic). Model is the RGB Bayer matrix. Instead of 2×2 macro-pixel a 3×3 or 4×4 macro-pixel may be used. Company IMEC (Belgium) offers such sensors ([5]).
32 bands snapshot tiled spectral imager solution:

- For snapshot, IMEC has designed an imager with 32 spectral bands having 256x256pixels spatial resolution each (30-60 data-cubes/s)

16 bands snapshot mosaic spectral imager solution:

- IMEC did process one spectral filter ‘per-pixel’ on a full mosaic of 4x4 = 16 spectral band cameras integrated on one single chip.

4.2 Spectral Scanning or Tunable Filter

A review about tunable filter can be found in (Gat, [3]). Tunable filter are mechanically or electrically adjustable filter, e.g.

- Filter wheel,
- Fabry-Perot etalon (FPE),
- Liquid-crystal tunable filter (LCTF),
- Acousto-optic tunable filter (AOTF). (see for example the Altius Mission, Dekemper, [1])

Switching times for the different filter types range from $1s$ for the filter wheel, to $50ms$ to $500ms$ for the LCTF and mechanically tuned Fabry-Perot. AOTF response is from $10\mu s$ to $50\mu s$.
As an example for a LCTF the VariSpec ([8]) should be mentioned.

4.3 Fourier Transform Spectrometer

The Fourier transform spectroscopy (FTS) based on the creation of interference between two coherent optical beams. The variation of the optical path difference (OPD) will be realized by moving and static mirrors (Michelson interferometer). Interferometer has some advantages:

- FTS does not separate energy into individual frequencies. Each point in the interferogram contains information from each wavelength of light being measured.
- The instrument does not limit the amount of light reaching the detector using a slit.
- Spectral calibration is based on laser sources.

For snapshot imaging interferometry, all optical path differences within the interferogram for all spatial locations within the scene must be measured simultaneously. A snapshot imaging interferometer that realizes this in a Multiple-Image Fourier Transform Spectrometer (MFTS), was first proposed from (Hirai, 1997).
It is possible to replace movable mirror by a static using birefringent polarization interferometer (BPI). An example is propose by Kudenov [7], the Snapshot Hyperspectral Imaging Fourier Transform (SHIFT) Spectrometer.

5 Scanning Hyperspectral Systems

Pushbroom Spectrometer
The input aperture is a long slit whose image is dispersed across a 2-D detector array, so that all points along a line in the scene are sampled simultaneously. To fill out the spatial dimension orthogonal to the slit, the scene is scanned across the entrance aperture. An ideal scanning device analogue to push broom scanner is a 2D-detector with variable spectral filters in flight direction. Example is the sensor from IMEC (see [6]).
New types of a scanning hyperspectral instrument based on a Fourier-transform spectrometer (FTS) have been developed in recent years. This camera does not need any moving parts.

6 New detector developments

Through a rapid detector development, there are many new approaches in all spectral regions. In visible and NIR spectral range, CMOS detectors have established. In addition to a high sensitivity and low power consumption it can also be reach a good signal to noise ratio. Another advantage is the direct integration of digital signal processing directly on the chip. Further opportunities of CMOS-detectors are:

- On Pixel data Processing

- Analog Processing inside the Silicon layer
- Information extraction on Detector
- Detector control via Nano-Technology
- Combination Position & Information

New MCT detector technologies allows signal detection in a very broad range from UV to SWIR. In [2] the new CHROMA detector was presented.
SLS (strained-layer super-lattice) Technology will open the door for a verity of hyperspectral instruments. Is a "hot" or uncooled technology. The detector can be tuned for different application.

7 Calibration and Performance Verification

Static, snapshot and scanning hyperspectral systems are available in the whole spectral range. It is necessary to clarify the conditions under which they can be used in space.
Following radiometric performance parameter are measured and derived for system verification.

- Dark Current (DC) and read noise measurements (including temperature dependence and dark signal non-uniformity (DSNU),
- Linearity, saturation and non-linearity correction parameter as well as photo response non-uniformity (PRNU),
- Absolute radiometric calibration with quantum efficiency (QE) determination,
- Photon transfer curve (PTC) for system gain determination (necessary for QE and DC determination),
- Signal to Noise Ratio (SNR).

The measurements will be performed using an integrating sphere. The spatial homogeneity of the radiometric sphere is better than 1\%; the intensity stability is better than 0.1% within 30 minutes.
The spectral performance measurements and calibrations will be performed using laser sources and Penray lamps To cover the spectral region from 450nm to 950nm four spectral lamps were used: Hg, Ar, Ne and Kr. This measurement will be also use to measure the spectral smile and keystone effect. The geometrical imaging performance will be determined by measuring the Line Spread Function (LSF) in the detector focal plane in spatial direction and subsequent determination of the Modulation Transfer Function (MTF).

8 Conclusion and Next Steps

It can be built with today's technologies significantly faster, simpler and cheaper (low cost) a hyperspectral system. There is the question of whether it is stable and accurate enough for the current scientific questions.

The engineering model of different instrument will be tested, calibrations will be carried out and performance data are verified. The results show the compliance with the requirements and with the required parameters. In the next step the flight model with the original detector will be accomplished, adjusted, calibrated and verificated.

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