DEVELOPMENT OF COMPACT AND LOW DISTORTION IMAGING SPECTROMETER FOR MARS MISSIONS AND AIRBORNE AERIAL VEHICLES

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ABSTRACT

The paper describes a joint development of a compact and low distortion imaging spectrometer system for future Mars sample return mission and unmanned aerial vehicles under the collaboration between the Canadian Space Agency and Defence Research and Development Canada. A Dyson design was selected as the imaging spectrometer due to its compactness, high optical output and low distortion. After briefly describing the requirement of the imaging spectrometer system, the preliminary results of the design of the Dyson spectrometer were reported.

Index Terms **-** Hyperspectral imager, Dyson spectrometer, Mars exploration, unmanned aerial vehicles.

1. INTRODUCTION

Under its Exploration Core program, the Canadian Space Agency (CSA) has funded its industry and completed a concept study for Hyperspectral and Luminescence Observer (HALO). The study was funded for possible inclusion on the proposed ESA-NASA-led Mars Sample Return Network (MSR-NET). The HALO consists of two instruments: an orbital imaging spectrometer and a landed fluorescence spectrometer. Both of them target at understanding geological process on Mars and the MSR-NET. The HALO spectrometer concept builds on lessons learned from previous Mars missions and research conducted as part of a previous concept study - CHIMERA (Canadian Hyperspectral Imager for Mars Exploration and Resource Assessment) [1]

The goals of the HALO imaging spectrometer are: 1) identification of high priority targets for sample return; 2) comprehensive characterization of previously proposed sample return sites: 3) change detection by searching for signs of changes in spectroscopic properties of selected targets that may be indicative of ongoing geological processes

The goals of the HALO fluorescence spectrometer are: 1) mineralogical mapping of the landing site; 2) identification of feldspar mineralogy at the landing site; 3) search for and constraining the nature of any fluorescent materials at the landing site; 4) age-dating the landing site.

Combination of the two instruments offers a degree of synergy: 1) to demonstrate the complementary capabilities of reflectance and fluorescence spectroscopy for surface mapping; 2) to provide linkages between on-the-ground surface characterization and orbital determinations.

The orbital imaging spectrometer is based on CSA's heritage from imaging spectrometer design for Hyperspectral Environment and Resource Observer (HERO) mission [2].

Defence Research and Development Canada (DRDC) has a requirement for a compact hyperspectral imaging sensor operating in the solar reflective spectral region from 0.4 to 2.5 μm to be deployed on a small aircraft, such as unmanned aerial vehicle (UAV) to detect targets of military interest for intelligence, surveillance and reconnaissance applications. Based on the DRDC demonstrations of hyperspectral imagery utility (e.g. HYMEX TDP, etc) [3], their users have indicated an interest in utilizing an airborne operational hyperspectral sensor capable of detecting and identifying high valued targets which cannot be detected easily by other means.

The CSA and DRDC teamed up to fund the design, building and test of compact imaging spectrometers that meets both the CSA and DRDC needs. This is a multi-phase activity requiring funds at various stages of the development based on well defined milestones.

2. REQUIREMENT OF THE IMAGING SPECTROMETER

The requirement of the imaging spectrometer is listed in Table 1. This is a compact low distortion high optical output imaging spectrometer. Dyson and Offner spectrometers are known for their compactness and low optical distortion. Dyson spectrometers have two potential advantages over Offner spectrometers:

- They use transmissive optical elements which can result in more compact designs than designs using mirrors in

Offner spectrometers.

- At the same level of optical distortion, Dyson spectrometers have smaller F-numbers than Offner spectrometers that results in more light gathering capability and thus achieves better SNR.

A Dyson spectrometer design thus has the potential for significant benefit to a Mars Sample Return mission and UAV or small aircrafts. Thus Dyson spectrometer design was selected in the joint development.

A classical Dyson spectrometer design consists of a single plano-convex double pass lens and a concave grating. The slit and image are adjacent to each other on the flat entrance-exit surface of the lens; this results in tight space constraints for detector packaging.

Table 1 Requirement of the imaging spectrometer.

Model Parameter	**Value**
Spectral Coverage	0.9 – 3.6 µm (Mars) 0.4 – 2.5 µm (UAV)
Spectral Sampling Interval	<10 nm
Image Space F/#	~2.2
Spectral Distortion (smile)	<0.1 SSI
Spatial Distortion (keystone)	<0.1 GSD
Field-of-view	2.46 deg
Angular Resolution	2.46×10^{-3}
Frame rate	>250 Hz
SNR	>300:1
Volume	Compact
Mass	Light
Power	Low

3. DESIGN AND TECHNOLOGICAL CHALLENGES

From the point of view of the optical design, the most challenging parameters listed in Table 1 are: the very low spatial distortion (keystone) and spectral distortion (smile) and the signal-to-noise ratio (SNR) values that require a high optical throughput. Keystone describes spectral variation of the spectrometer magnification and smile measures the departure from straightness of the spectral lines. Both distortions are characteristic for the pushbroom imaging spectrometers and must be kept at small fractions of Ground Sampling Distance (GSD) and Spectral Sampling Interval (SSI), respectively. Reduction of keystone errors is especially important because keystone combines spectra from adjacent spatial samples Correction of these errors cannot be accomplished without an a priori knowledge of the form of the spectra to be recovered. Spectral errors due to smile, on the other hand, are relatively easy to be corrected in the retrieval process and can be characterized in orbit, using for example the atmospheric features as described by Neville et al [4].

To achieve high optical output (i.e. very low F/#) and low distortion a class of concentric spectrometer designs, in which all optical surfaces have the same or almost the same centre of rotation, have been proposed by Dyson [5] and Offner [6]. Spherical gratings are used in the concentric spectrometer designs. Due to the symmetry of the design, all third order (Seidel) aberrations equal zero, allowing systems to provide sharp imagery, a flat field, minimal distortions without the need for aspherical surfaces. Telecentricity of the designs assures a small dispersion change caused by the focusing errors.

The use of spherical gratings in the concentric designs demands that their groove angle follow the curvature of the substrate in order to keep the grating blaze angle approximately constant. This is especially important in the case when the blaze angle is very small (typically a few degrees for the Dyson cases). Otherwise it would result in a strong efficiency variation across the grating aperture if the groove angle was not adjusted.

4. DESIGN OF DYSON SPECTROMETER

Developments have been carried out to trade off the optical design options, conduct detailed design of the selected option, build and finally integrate into a prototype imaging spectrometer. The prototype imaging spectrometer will be tested on board an aircraft.

The trade-off study and designs of the Dyson spectrometer benefit from the heritage derived from the Phase A study of the Canadian Hyperspectral Environment and Resource Observer (HERO) mission [2]. One of the designs for HERO was based on two Dyson spectrometers using separate but adjacent slits. The spectrometers operate in the Visible and Near Infrared (VNIR) region with a silicon detector and in the Short Wave Infrared (SWIR) region with a mercury-cadmium-telluride (MCT) detector. An alternate option might use an extended VNIR-SWIR MCT detector with a single slit [7].

4.1. Design Options Review

Three design options were identified:

1. The HERO optical design is of two Dyson spectrometers (VNIR and SWIR) with separate slits in close proximity with appropriate Silicon or MCT detectors.
2. An alternative design could be a single Dyson spectrometer with a single slit to cover both VNIR and SWIR. There are three variations in this alternative:

2.1 Using a broad waveband coverage detector (e.g. spectral range extended MCT detector).
2.2 With separated VNIR and SWIR detectors.
2.3 With filter mechanism.

3. A variant design could consist of two spectrometers sharing a common slit with in-field Beamsplitter (or flip-in mirror). This is a variant on bullet 1 above and it is only useful for a Rover or an in-situ application.

The trade-off study of the design options was carried out in terms of the following criteria:

- Ease of separating grating orders
- Optimization of grating efficiency for the spectral range
- Optical complexity
- manufacturing complexity
- Slit complexity
- Moving parts and mechanical mounting complexity
- Alignment sensitivity
- Maximum deviation of the position of the detector from a position of axial symmetry relative to the pole of the concave grating while meeting the distortion requirement
- Keystone and smile distortion
- Recommended detector(s) for each configuration
- Classification of input optics for airborne, on-orbit or in-situ application.

4.2. Selected Optical Design and the Preliminary Results

An optical design of the spectrometer as shown in Figure 1 (based on Option 2.2) was selected after the trade-off study. This design consists of a single Dyson block, one concave grating, one slit and one dichroic beam splitter. The spectral range is split into two by the dichroic beam splitter, which is attached to the exit surface of the Dyson block, then focuses on the separated detectors. The VNIR (from 380 nm to 1250 nm) works in -2^{nd} order, while SWIR (from 940 nm to 2500 nm) works in -1^{st} order.

Table 2 lists the parameters of the selected Dyson spectrometer design and the preliminary results.

In the design we assumed a Teledyne Hybrid Visible Silicon Image (HyViSI) for VNIR detector and a same pitch size MCT detector for SWIR with the same readout integrated circuit (ROIC). A 1000×*n1* pixels and 1000×*n2* pixels focal plane arrays (FPA) for the VNIR and SWIR are also assumed. The *n1* and *n2* are spectral band numbers for VNIR and SWIR respectively. With recent advancement in MCT detectors technology, their cut-on wavelength has been lowered from 1µm to 0.4µm by substrate-removing. This leads to a potentially simpler optical configuration of the instrument, comprised of just one Dyson spectrometer covering the 0.4-2.5µm range. The complexity of the multi-blazed grating fabrication and its lower spectral efficiency would have to be carefully traded against the benefits of simplicity if such a solution were adopted. This single broad wave-band detector option (Option 2.1) was not selected at this moment mainly due to the fabrication issue of the multi-blazed grating.

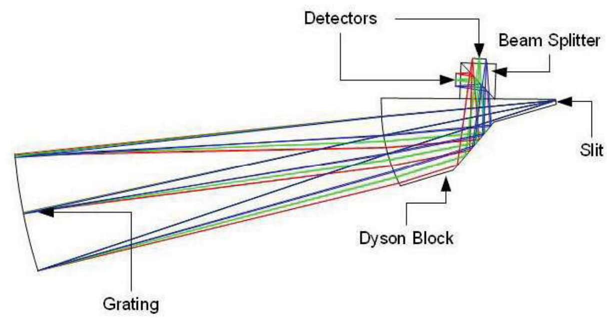

Figure 1. Layout of the optical design of the selected Dyson spectrometer

Table 2 Parameters of the selected Dyson spectrometer design.

Slit size	30 mm×30µm
Detector size	1000×*n1* pixels×30µm 1000×*n2* pixels×30µm
Grating orders	2^{nd}: 380 nm to 1250 nm 1^{st}: 940 nm to 2500 nm
MTF	>0.80 @380nm >0.90 @700nm >0.85 @9400nm >0.70 @1720nm >0.50 @ 2500nm
Keystone across entire spectrum	<0.02 GSD
Smile across entire spectrum	<0.02 SSI

5. SUMMARY

The Canadian Space Agency started the development of imaging spectrometers for future Mars missions since 2005. The study of Hyperspectral Imager for Mars Exploration and Resource Assessment was completed by its industry in 2006. The concept study on Hyperspectral and Luminescence Observer has been completed in early 2011. A Dyson spectrometer design has been selected and the preliminary design results have been produced. The next step will be to build a prototype imaging spectrometer and airborne test of the prototype system.

6. REFERNCES

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7. ACKNOWLEDGMENTS

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