Development of advanced miniaturized Dyson imaging spectrometer for Mars rover and small aircrafts

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ABSTRACT

The Canadian Space Agency and the Defence Research and Development Canada are jointly developing an advanced miniaturized imaging spectrometer for future Mars rover and onboard a small aircraft. This work is the further development of the two previous concept studies for Mars: Canadian Hyperspectral Imager for Mars Exploration and Resource Assessment (CHIMERA) and Hyperspectral and Luminescence Observer (HALO). Based on outcomes of the concept studies, a Dyson spectrometer design was selected as the imaging spectrometer due to its compactness, high optical output and low distortion. This paper briefly describes the options of imaging spectrometers proposed in the HALO study. Then the requirements of the advanced miniaturized imaging spectrometer system are provided. Finally the preliminary results of the development of the Dyson imaging spectrometer system will be reported.

Index Terms – Hyperspectral, imaging spectrometer, Dyson spectrometer, Mars exploration, airborne remote sensing, optical instruments.

1. INTRODUCTION

The Canadian Space Agency (CSA) has funded its industry and completed two concept studies of hyperspectral imagers for Mars exploration under its Exploration Core Program: Canadian Hyperspectral Imager for Mars Exploration and Resource Assessment (CHIMERA)[1] and Hyperspectral and Luminescence Observer (HALO).[2] These studies were for possible inclusion on the proposed ESA-NASA-led Mars Sample Return Network (MSR-NET). The HALO study proposed two instruments: an orbital imaging spectrometer and a landed fluorescence spectrometer. Both of them target at understanding geological process on Mars. The HALO imaging spectrometer concept built on lessons learned from previous Mars mission and the outcomes of the CHIMERA which was conducted as part of a previous concept study. The orbital imaging spectrometer is based on CSA's heritage from imaging spectrometer design for Hyperspectral Environment and Resource Observer (HERO) mission.[3]

The Defence Research and Development Canada (DRDC) is also interested in compact hyperspectral imaging sensors operating in the solar reflective spectral region from 0.4 to 2.5 µm to be deployed on a small aircraft. Such a sensor will be suitable for a wide range of applications studied by DRDC (e.g. HYMEX TDP, etc.).[4] The CSA and DRDC recently teamed up to jointly design, build and test an advanced airborne miniaturized imaging spectrometer that meet both the CSA and DRDC needs.[5] For this work, a Dyson design was selected due to its compactness, high optical output and low distortion and this new project will benefit from the HALO concept study discussed in this paper.

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2. HALO PROJECT

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.

On the instrument side the verification of a suitable spectrometer design for the Dyson concept remains a critical question. The focus of the criticality is in the design, building and integration of a prototype imaging spectrometer with high optical throughput and low distortion (Nom 400-2500 nm at f/2.2 (TBC), keystone/smile <+/-0.1 GSD/SSI), which can be used for in-situ and orbit applications.

The development approach built on the Dyson spectrometer designs derived from the Phase A study of the HERO mission. One of these designs was based on two spectrometers using separate but adjacent slits. The spectrometers operate in the Visible/Near Infrared (VNIR) with a silicon detector and in the Short Wave Infrared (SWIR) with a Mercury Cadmium Telluride (MCT) detector. An alternate option might use an extended VNIR-SWIR MCT detector with a single slit.

Possible design options are identified:

a) The HERO Baseline optical design is two Dyson spectrometers (VNIR and SWIR) with separate slits in close proximity with appropriate Si or MCT detectors.

b) An alternative design could consist of a VNIR-SWIR Dyson spectrometer with a single slit with a broad detector (e.g. extended MCT).

A variant design could consist of two spectrometers sharing a common slit with an in-field beamsplitter (or flip-in mirror). This is a variant on item a) above but may only be useful for a Rover or an in-situ application.

3. OPTICAL DESIGN OPTIONS

During the course of the HALO study a trade-off between five different configuration options of imaging spectrometers was made. The trade-off considered the following factors of the design:

1). Keystone and smile distortion
2). Slit complexity
3). Ease of separating grating orders
4). Optimization of grating efficiency for spectral range
5). Alignment sensitivity
6). Maximum deviation of detector from optimum position

7). Moving parts and mechanical mounting complexity
8). Optical complexity and manufacturing complexity

The option A instrument consists of a single Dyson spectrometer with a single slit covering both the VNIR and SWIR regions from 470 nm to 2500nm by using first order of diffraction. The complexity of Dyson block is lower than that of HERO Baseline optical design,[3] as the two internal TIR surfaces are removed. There are no moving parts and the alignment sensitivity is considered to be same as the HERO design. One difficult technical issue is the availability of the grating with such a wide wavelength range. It will be necessary to build such a grating and verify its performance by test.

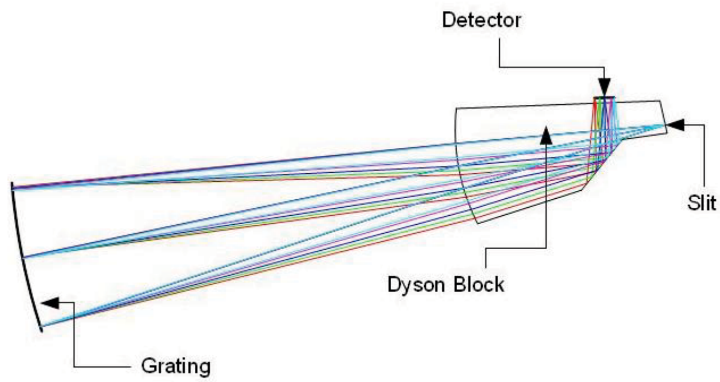

Figure 1. Layout of the optical design of imaging spectrometer option A.

In the option B, the instrument also consists of a single Dyson spectrometer covering with a single slit to cover the both VINR and SWIR regions from 470 nm to 2500nm. The spectral range is split into two by dichroic beam splitter, which is attached to the exit of Dyson block, then focused on a separate detector. The SWIR region from 940 nm to 2500 nm works in 1st order, while VNIR region from 470 nm to 1250 nm works in 2nd order. The manufacturing complexity and alignment sensitivity are at the same level as the HERO design. Also, there are no moving parts. Compared to option A, higher resolution could be achieved in VNIR and it is relative easy to optimize the grating efficiency for the spectral range.

In the design for option C, the instrument also consists of a single Dyson spectrometer covering with a single slit to cover the both VINR and SWIR regions from 470 nm to 2500nm as shown in Figure 3. A filter wheel, which consists of order sorting filters and plano-convex lenses, is used to select the spectral range from different orders to focus on a single broadband detector. The SWIR from 940 nm to 2500 nm works in 1st order, while the VNIR from 470 nm to 2500 nm works in 2nd order. Compared to the options A and B, it is easy to optimize the grating efficiency by using a higher order to narrow the wavelength range. However, the filter wheel is a moving part and increases the complexity of the manufacturing. The whole spectral range cannot be observed simultaneously. Thus whilst of potential use for a rover spectrometer it is recognized that this solution is less than optimal for an orbiting instrument where close to simultaneous spectral sampling is required for interpretation of the geological samples so the concept developed here will not be continued.

In option D, a doublet spectrometer is chosen instead of a single Dyson spectrometer, as it has more room to accommodate the external slit and in-field beam splitter as shown in Figure 4. The SWIR from 940-2500nm and VNIR from 380-1000nm share the common slit. The in-field beam splitter separates incoming rays into each spectrometer. A prism, which is attached to the beam splitter, folds the rays to make the VNIR and SWIR spectrometers roughly parallel and easy to package.

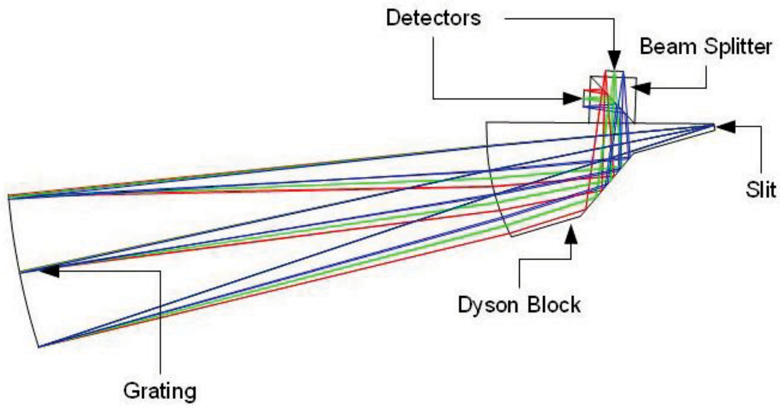

Figure 2. Layout of the optical design of imaging spectrometer option B.

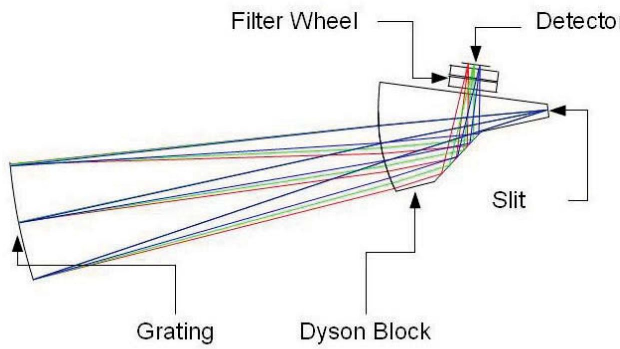

Figure 3. Layout of the optical design of imaging spectrometer option C.

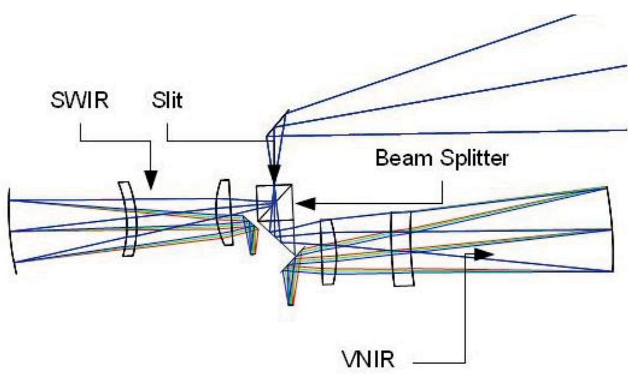

Figure 4. Layout of the optical design of imaging spectrometer option D.

In option E, the instrument consists of two Dyson spectrometers with the two reflective external slits. It could potentially facilitate manufacturing of the Dyson blocks, allowing separate slit fabrication. Both SWIR and VNIR spectrometers work on 1st order. Figure 5 shows the optical layout of the instrument.

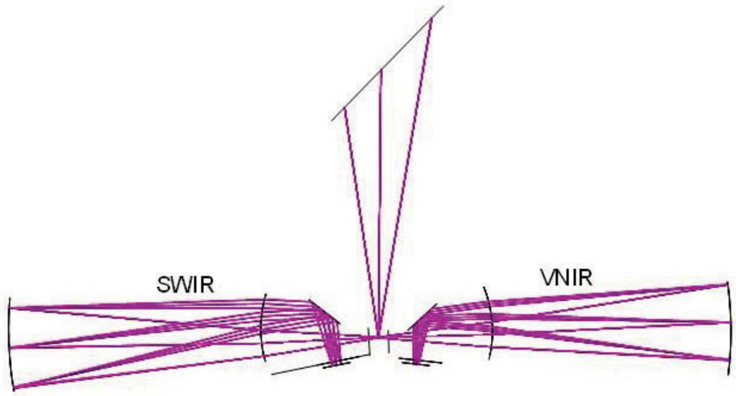

Figure 5. Layout of the optical design of imaging spectrometer option E.

Overall, compared to the HERO Baseline design, each option has lower slit complexity. The image quality and distortion meet the requirements. The major issue is the manufacture challenges of the broadband grating and beam splitter. The comparison of options with respect to the 8 consideration factors is shown in Table 1.

Table 1. Comparison of options with respect to the consideration factors.

Consideration Factor	HERO	Option A	Option B	Option C	Option D	Option E
Keystone and Smile	< 2%	< 2%	<2%	<9%	<7%	<4%
Slit Complexity	complex	simple	simple	simple	simple	complex
Method of separating grating orders	front of detector	front of detector	Beam splitter front of detector	filter wheel	Beam splitter front of detector	front of detector
Optimization of grating efficiency for spectral range	neutral	difficult	neutral	neutral	neutral	neutral
Alignment sensitivity	neutral	neutral	neutral	complex	simple	neutral
Moving Part & Mechanical Mounting Complexity	no moving part	no moving part	no moving part	filter wheel	no moving part	no moving part
Optical complexity and manufacturing complexity	neutral	simple	neutral	neutral	easy	neutral

4. MINIATURIED DYSON IMAGING SPECTROMETER

An advanced miniaturized Dyson imaging spectrometer system is currently under development. This imaging system should outperform commercial off-the-shelf imaging spectrometers. The performance of the imaging spectrometer system will be measured in terms of signal-to-noise ratio (SNR), compactness, optical distortion, number of cross-track pixels, etc. A contract has been awarded to Canadian industry to develop, build and test in laboratory conditions a portable prototype Dyson spectrometer imaging system including fore-optics that can be tested in field on-board small aircrafts typically used for aerial photography. The imaging system will be installed on the floor of the aircraft on a shock absorbing mount and look through an opening at the bottom of the aircraft (nadir looking position). Another option is to install it in a gyro-stabilized mount, such as a Zeiss (T-AS). Table 2 lists the requirements of the Dyson imaging spectrometer system.

Table 2. Requirements of Dyson imaging spectrometer system.

Parameters	**Mandatory**	**Goal**	**Comments**
Signal-to-noise ratio	>600:1 @600nm >400:1 @2200nm	1000:1@650nm 600:1 @2200nm	@23.5º solar zenith angle, cross and along track sampling of 0.25mrad, 0.5 flat reflectance, integration time <25% flight time for 1 spatial sampling interval
MTF	>0.3 @ Nyquist		
F number	Better than f/2.2	Better than f/2.0	
Spectral distortion	≤0.1 pixel		
Spatial distortion	≤0.1 pixel		
Spectral range	400nm-2500nm	380nm-2510nm	If separate VNIR and SWIR spectrometers are used, VNIR should cover 400-1000nm and SWIR cover 900-2500nm
Spectral interval	8nm	5nm	
Linear field-of-view (Swath)	>800 pixels	>1000 pixels	
Ground sample distance (GSD)	2.0m@7000m 0.5m@1500m		
Spatial resolution	<1.2GSD@FWHM		
Radiometric range	0 to max Lambertian radiance		@100% reflectance target, 0º solar zenith angle
Spatial registration VNIR & SWIR	<0.1pixel		
Radiometric accuracy & stability	>95%		
Polarization sensitivity	Low sensitivity to light polarization		
Frame rate	>125 Hz		
Digitization	>14 bits		
Thermal stability	Optical components thermally stabilized to a fixed temperature		The temperature should be equal or superior to the cooling temperature of the detectors
Data recording capacity	Up to 4 hours imaging during flight		
Electrical power	<20W		
mass	<25kg		

The developed imaging spectrometer system will provide a modular Dyson pushbroom imaging spectrometer prototype optimized for operation in the two key spectral regions, 380 to 900 nm and 900 to 2530 nm, using a ruggedized opto-mechanical structure. The high mandatory 600:1 SNR and low distortion in both spectral and spatial domain will provide good quality hyperspectral data to meet the needs of the users.. The mass under 25 kg is suitable for use on low-cost unmanned aerial vehicles, small aircraft, microsatellites, as well as a future CSA Mars rover. The off-axis f#2.0 imaging telescope provides high optical throughput with a cross-track field of view of 16.3º in 1000 spatial pixels to allow the differentiation of local features for mineralogy, resource and land-use mappings.

In terms of the Canadian Space exploration strategy and DRDC requirements, the Dyson imaging system development project addresses several key themes including: (1) development of new miniaturized, high-performance instrumentation for stand-off, atmospheric and land-cover studies based on Canadian expertise; (2) validation of spectral measurement techniques in support of DRDC terrestrial requirements and future potential space missions; (3) applicability to a series of missions such as Mars sampler return, stand-off aerosol and biohazard detection; (4) accommodation on low-cost unmanned aerial vehicles, microsatellite and rover platforms.

CONCLUSION

The Canadian Space Agency and the Defence Research and Development Canada are jointly developing an advanced miniaturized imaging spectrometer for future Mars rover and onboard a small aircraft. Based on outcomes of the previous concept studies, a Dyson optical design is selected as the imaging spectrometer to achieve the compactness, high signal-to-noise ratio and low distortion. This imaging system should outperform commercial off-the-shelf imaging spectrometers and closely match or outperform existing Government off-the-shelf imaging spectrometers. The development currently is ongoing and the outcomes will be reported when they become available.

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