PCW/PHEOS UV-VIS SPECTROMETER: AIR QUALITY FROM A QUASI-GEOSTATIONARY ORBIT

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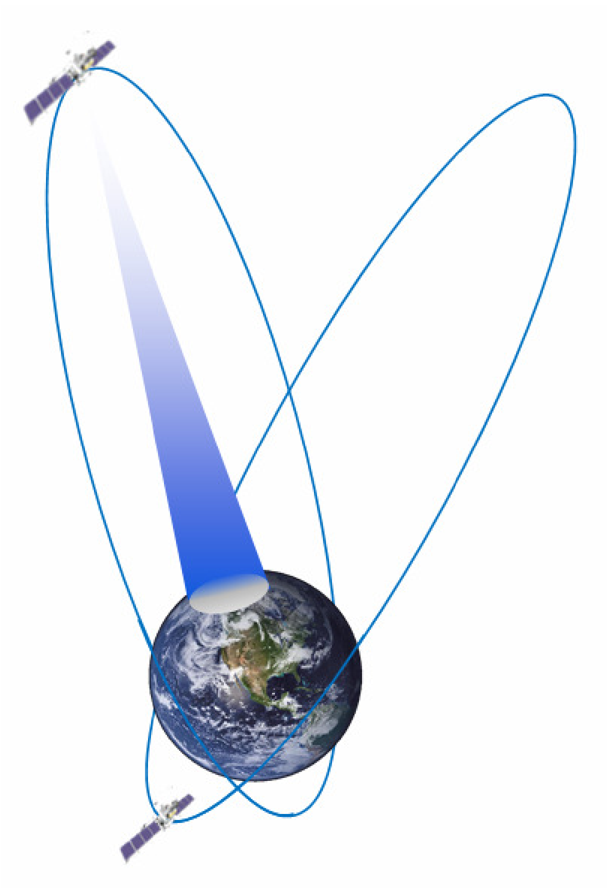
ABSTRACT

A UV-VIS Spectrometer (UVS) is one of two atmospheric monitoring instruments being considered for PHEOS (Polar Highly Elliptical Orbit Science) as part of the weather, climate and air quality measurement suite onboard the proposed Canadian PCW (Polar Communications and Weather) satellite mission. The UVS is an imaging spectrometer that covers the spectral range 280 – 650 nm in the UV and Visible regions. It is intended to measure a number of species including O_3 and NO_2 at 10×10 km^2 spatial resolution - or better - for air quality studies. The PCW two-satellite system will allow the mapping of air quality parameters on an hourly basis over most of the circumpolar area between 55 and 90N and provide substantial, partial coverage down to below 40N. This paper presents the current status of the UVS instrument and also discusses the UVS science objectives as well as the measurement characteristics. The PHEOS study was funded by the Canadian Space Agency (CSA).

1. INTRODUCTION

The proposed Canadian Polar Communications and Weather (PCW) satellite mission [1] is designed to provide coverage of the Arctic from a geostationary-like vantage point. It will carry a communications system to provide satellite communications in the high Arctic where geosynchronous data links are not feasible (latitude >80N) and a 'next-generation' imaging system, similar to the Advanced Baseline Imager for geosynchronous application, to retrieve meteorological information. The current orbit selection is a three-apogee orbit which has two identical satellites in following, highly elliptical orbits. This orbit subjects the satellite to lower radiation exposure levels than other choices such as the Molniya orbit which was initially considered. Figure 1 illustrates the observing principle. When the satellite is near apogee (~40,000 km) it is travelling very slowly (<1 km/s) and spends a considerable fraction of its orbit within viewing range of the arctic region. For a small portion of time the two satellites will be able to provide a stereoscopic view of portions of the region.



A number of atmospheric species of interest for air quality and climate studies are accessible in the UV-Visible region of the spectrum.

2. COVERAGE

Figure 2 shows the coverage that can be achieved using a conventional polar-orbiting satellite. Figure 3 shows the coverage expected from the highly elliptical orbit using two satellites. It would take a

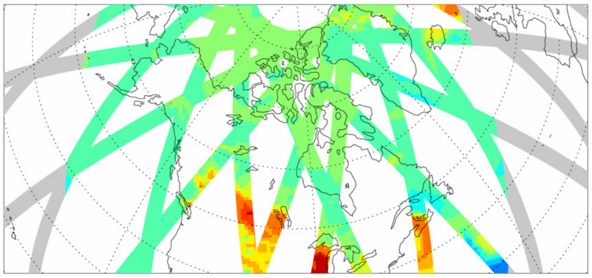


Figure 2 Arctic coverage using polar-orbiting satellites in low Earth orbit.

constellation of more than 20 polar-orbiting satellites to match the coverage of the two PCW satellites. And it would also require a great deal of effort to cross-calibrate the instruments on the various satellites.

The imaging spectrophotometer proposed for PCW will use a 2-D diode-array detector to provide spatial information along one axis and spectral data along the other. A mechanical scanning system will use the line scan generated by the spectrophotometer to create a 2-D spectral image by scanning across the field of regard (Figure 3). A surface area of 3200 x 3200 km^2 will be imaged at 10 x 10 km in approximately one hour.

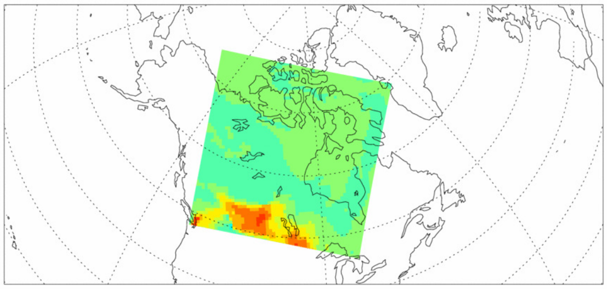


Figure 3 An illustration of the field of regard over the Arctic of a satellite in a highly elliptical orbit.

3. MEASUREMENTS

Figure 5 shows a plot of the absorption cross-sections of a number of chemical species that can be measured in the UV-Visible spectral region using backscattered radiation, as listed in Table 1. For this reason, a UVS instrument is a highly desirable, complementary instrument to fly with the Fourier Transform Spectrometer proposed for PCW.

Ozone and NO_2 are the primary data products of interest for climate change and air quality studies. The other gases listed are measurable under particular conditions. For example, formaldehyde and glyoxal are tracers of combustion and Volatile Organic Compounds (VOCs) [2].

Table 2 lists the performance goals and thresholds for measurements of the primary products, tropospheric and stratospheric partial columns of NO_2 and ozone.

Table 1: UVS principal properties.

Instrument	Spectral Range [nm]	Resolution	Pixel Size [km^2]	Target Species
UVS	280-650	1 nm	10x10	O_3, NO_2 SO_2, BrO OClO HCHO CHOCHO Aerosol O.D.

These data are important for monitoring the distribution and movement of pollutants in the Arctic. They are also important for understanding chemical processes and the role of gases such as ozone in radiative forcing related to climate change.

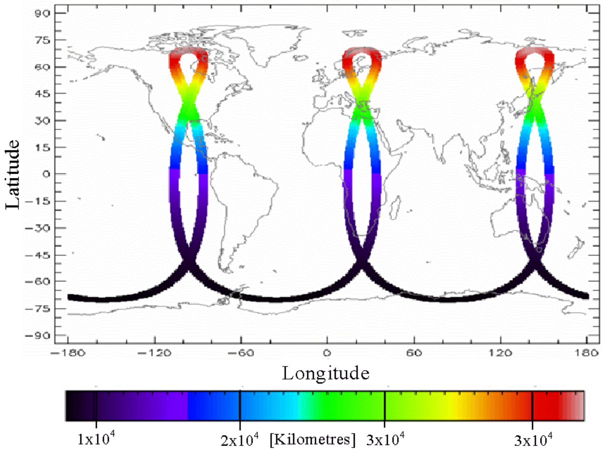


Figure 4 A plot of the ground track of the three-apogee orbit with altitude indicated by colour.

4. PERFORMANCE REQUIREMENTS

A number of studies were performed as part of the work done under Phase A of the PHEMOS development. The material covered a fairly extensive range of activities and, therefore, cannot be reported in full here. However, the activities will be catalogued here as a way of documenting the issues considered important in the design of the UVS instrument.

The issues addressed include the effects of instrumental stray light on retrieval performance, radiometric calibration requirements, spectral resolution, signal-to-noise requirements for the measurement of various species, optimization of free spectral range, spectral over-sampling ratio and the signal dynamic range required. Some of these issues will be discussed.

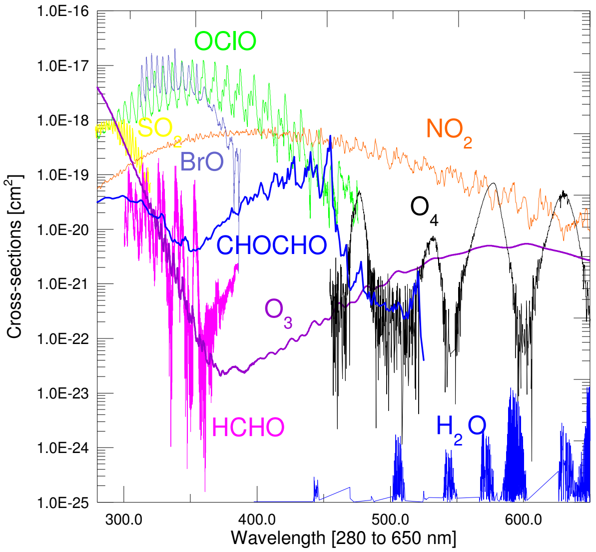


Figure 5 The wavelength-dependent cross-sections of a number of gasses that are accessible for measurement in the UV-Visible spectral region.

A study of the performance of practical instruments of the array-detector type suggests that the stray light contribution at 300 nm can be expected to be between 2% and 12% of the total signal. While stray light will not be a significant issue for the determination of total column ozone it will impact the ability of the instrument to separate the tropospheric and stratosphere ozone columns. The study suggests that a 12% stray light contribution, if uncorrected, would produce an error as large as 15% in the tropospheric ozone column but only a small error in the stratospheric column because of the larger fraction of the ozone layer that lies in the stratosphere. Stray light will also decrease the sensitivity of the retrieval for gases such as sulphur dioxide if left uncorrected.

Consideration of the performance of other backscatter instruments has led to the conclusion that radiometric accuracy in the range of 2% to 8% is required to meet the goal of better than 15% performance in the determination of the tropospheric ozone column. Gases retrieved in a fully differential mode are much less dependent on knowledge of the absolute sensitivity of the instrument. It is intended to use the analysis of observations of regions such as the high Greenland Ice Sheet and high tropical cloud tops as a means of tracking the absolute stability of the instrument on orbit.

The spectral resolution and signal-to-noise requirements are most strongly driven by the nitrogen dioxide measurement. This is because of the narrow spectral features in the 425 to 450 nm region where the greatest differential absorption occurs and by the relatively small total amount of absorption due to NO_2 contributed to the signal. The conclusion of the study is that a resolution of 1 nm is indicated with a signal-to-noise ratio of 250 in the 325-335 nm region and 2000 in the 425 to 450 nm region.

There is a trade-off to be made between resolution and free spectral range. If complicated order sorting is to be avoided, the free spectral range must be less than a factor of two in wavelength. Depending on the number of pixels provided by the detector, the over-sampling and resolution are controlled by the free spectral range. The spectral range here was optimized at 280 nm to 650 nm so that an over-sampling of nearly a factor of three can be achieved, while still including short enough wavelengths to allow ozone profiling. The extension of the long wavelength end is intended to provide good sensitivity to ozone absorption in the Chappuis band, leading to a high-accuracy total column ozone measurement to constrain the profile measurement to improve performance in terms of separating the tropospheric and stratospheric ozone columns.

5. INSTRUMENTATION

Table 1 summarizes the principal properties of the UV-Vis instrument and lists the species that can be accessed in the UV-Visible spectral region. With a resolution of ~1 nm, a 1024x1024 element detector will provide almost a factor of three spectral over-sampling over this wavelength range. The detector currently under consideration has a pixel size of 13 µm square. If the spectrometer has a magnification of one and the orbital altitude is 41,000 km, the instrument telescope will have a focal length of 67 mm. For F/4 optics the telescope diameter will be about 17 mm. Details of the instrument design as well as the related analyses and trade-off studies can be found in [3].

Figure 6 illustrates the scanning concept for the UVS instrument. The angle required for the scan to cover the 3200 field of regard is ±2.2°. The scanning mirror will turn through half this angle or ±1.1°.

The layout for a potential design meeting the performance specifications for PHEOS is shown in Figure

7. The design is based on an Offner [3 - 5] spectrometer configuration fed by a small three-mirror anastigmatic telescope.

Figure 7 also indicates the physical dimensions of an instrument that can meet the requirements of the PHEOS mission.

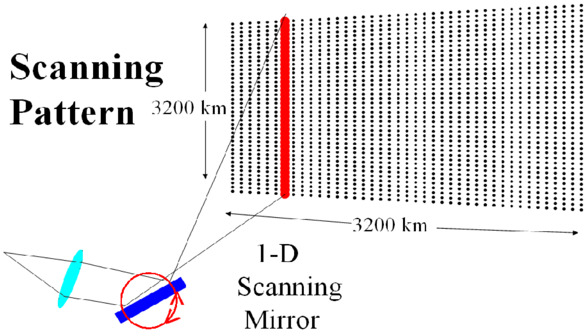


Figure 6 A mechanical scanner will scan the line image field of view across the field of regard to construct a 2-dimensional image

Table 2: Goal and threshold levels for the precision of measurements of ozone and NO_2, primary data products for climate change and air quality studies.

Target Species	Horizonta Ressolution [km^2]	Typical Column [mol-cm^{-2}]	Precision
O_3 TC	10x10 G 20x20 T	$8x10^{18}$ to $3x10^{19}$	3% G 5% T
O_3 SC	10x10 G 20x20 T	$3x10^{17}$ to $2x10^{18}$	5% G 15% T
NO_2 TC	10x10 G 20x20 T	10^{15} to 10^{16}	3% G 5% T
NO_2 SC	10x10 G 20x20 T	10^{14} to 10^{16}	$1x10^{15}$ G $2x10^{15}$ T

SC - Stratospheric column
TC - Tropospheric Column
G - Goal
T - Threshold

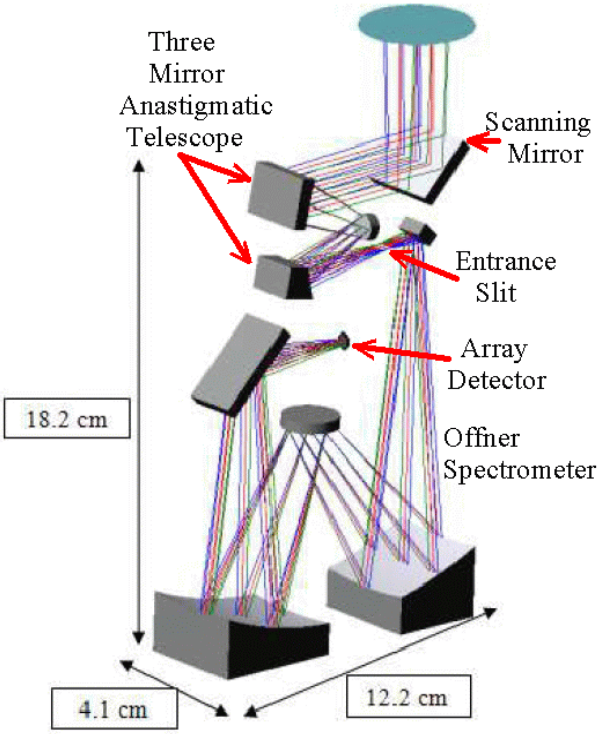


Figure 7 A model of the optics of the UVS instrument showing representative dimensions.

The mass and power allocation currently being specified for the PHEOS payload at this time is very restrictive. There is some expectation that as the design of the satellite firms up that some power and mass margin may be freed up allowing for more resources for PHEOS. The current limit on power is 100 W and the maximum dimension of the payload is 30 cm in all three directions. As a result, there are three very similar versions of the PHEOS payload under consideration at this stage of development. Two include a UV-Visible component and one does not. The two smaller versions - one with and one without the UV-Visible instrument - will meet threshold requirements for the infra-red measurement goals but only meet the goals for most but not all species. The middle-sized version slightly exceeds the volume limit specified for the PCW satellite by about 10% but includes the UV-Visible imager. This is only about 2% extra in linear dimension. The version which meets all measurement goals and also includes the UV-Vis image is a substantial 3.8 time the volume and increase of about 60% in linear dimension if shared among all three directions. Figure 9 depicts the three different potential designs for PHEMOS.

6. CONCLUSIONS

Preliminary design studies indicate that a UVS imager can be designed to operate in the highly elliptical orbit proposed for the Polar Communications and Weather satellite. The measurements proposed will compliment the data collected by the infrared, Fourier Transform Spectrometer proposed as part of PHEOS and extend the view of the Earth provided by geosynchronous satellites into the polar region.

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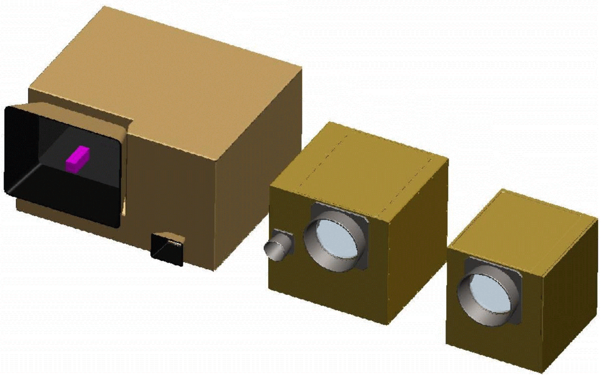

Figure 8 Three possible configurations for the PHEOS instrument package. The left one meets all science goals but it 3.8 times the current volume allocation. The centre one meets all threshold requirements, most goals and includes a UV-Visible instrument. The smallest meets all IR threshold requirements and most goals but has no UV-Visible capability. It meets the current power and mass requirements.

8. REFERENCES

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