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A Miniature UV Imaging Spectrometer for Remote Sensing of the Atmosphere

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ABSTRACT

A new miniature ultraviolet (UV)-band spectral imager is proposed with the objective of monitoring important atmospheric constituents: sulphur dioxide, ozone and aerosols. Ideally the instrument will operate in a micro/nano-satellite constellation in order to provide the rapid response and dynamic requirements of a very demanding application such as volcano monitoring based on one of the most important gases they emit: sulphur dioxide (SO_2).

INTRODUCTION

Currently observations in the UV band used to derive concentrations of atmospheric constituents such as Ozone (O_3), Sulphur Dioxide (SO_2) and aerosols are restricted to large platforms and instruments, e.g. NASA's Total Ozone Mapping Spectrometer (TOMS) (which was not designed to monitor SO_2); the Ozone Monitoring Instrument (OMI); ESA's Global Ozone Monitoring Experiment (GOME) and the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY). However, all these instruments have faced various design trade-offs when observing the UV range between 300-315 nm useful for discrimination between O_3 an SO_2.

Sulphur Dioxide (SO_2) and Ozone (O_3)

The ratio of the absorption cross-section (ACS) of SO_2 and O_3 can be used to identify useful channels and spectral resolution for discriminating between these two molecules.

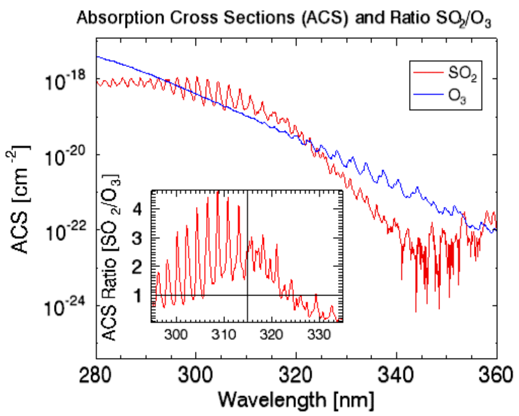

Figure 1: Absorption cross sections of SO_2 at 243K [1] from and O_3 at 241K [2]

From the ratio of the spectral range of interest (Figure 1), it can be seen that at some wavelengths (around 310 nm) the SO_2 molecule can have 4 times a stronger absorption than a molecule of O_3. Furthermore, all wavelengths between ~306 nm and 322 nm show stronger absorption for SO_2. Thus, this band is the most suitable for our purpose of detecting and discriminating sulphur dioxide from ozone, just based on the ACS ratio without taking into account other factors such as the absolute radiance levels; spectral and spatial resolution amongst others.

Unfortunately, because of the wide dynamic range observed in this region, it is common to optically split this region in two channels with different gains, thus degrading the signal to noise ratio (GOME, OMI). This occurs precisely in a region where SO_2 absorption features provide easier discrimination against ozone, which also absorbs in the same region.

UV IMAGING SPECTROMETER

The instrument proposed here must observe this critical UV region with suitable channels (305- 315 nm) and sufficient spectral resolution (<1 nm) to serve the stringent application requirements. Thus, it was designed to obtain a ground sample distance at nadir of 4 x 30 km; this is considered useful according to the Disaster Management Support Group (DMSG) of the Committee on Earth Observation Satellites (CEOS) suggesting 10 to 20 km [3]. The calculated spatial resolution is half the area covered by a normal OMI pixel (12 x 24 km) and 20 times smaller than TOMS (50 x 50 km); it is expected to minimize cloud cover scenes and increase the sensitivity in detecting SO_2 contaminated pixels. A medium swath (~300 km) for a single imager would require the use of two imagers in order to observe large drifting clouds and reduce the revisit time; it would also match the Disaster Monitoring Constellation of micro-satellites imager pair swath [4]. Thus, a baseline for the instrument specifications has been defined:

Table 1: Instrument baseline specifications

Application Requirements		
Specifications	Most Significant Influencing Factors	Baseline Value
Spatial Resolution	Satellite Altitude Optics Focal Length Detector pixel pitch	7 x 31 km
Temporal Resolution (Revisit Time)	Detector array size Spatial Resolution Constellation size	1 day
Spectral Channels and Resolution	O_3 and SO_2 Absorption Aerosols Reflectivity	10 channels : 305 – 315 nm / spectral resolution <1 nm 2 aux channels:331 nm and 360 nm / Spectral resolution ~ 1nm
Sensitivity	Systems Noise Detector Responsivity Spectral Resolution Optics Aperture	Equivalent to < 5 Dobson Units (DU)
Dynamic Range	Cloud Cover Integration Time	Solar angles up to 85 degrees
Timeliness and delivery of products	Downlink rate Number of ground stations User infrastructure	<24 hrs via internet
Spacecraft Requirements		
Mass	Optics (materials, aperture) Electronics (amplifiers)	2- 4 kg
Volume	Optics (focal length, aperture) Electronics (amplifiers)	<0.01 m^3
Overall dimensions	Same as volume	150 mm x 150 mm x 150 mm
Peak Power	Detector operation Electronics	< 2 watts

The low-cost and small size of the optical components (9 x 13 x 6 cm) of the instrument proposed makes it a suitable instrument for an atmospheric mission where the potential of small satellites can be demonstrated.

Optics

The optical layout was chosen to have a minimum number of parts whilst maximising the optical throughput (etendue). It uses the largest commercially available holographic transmission grating, matching it with a custom-made area array of Silicon Carbide (SiC) photodiodes at the focal plane. The use of fused-silica lenses will provide good transmission and performance in the UV, and some optical surfaces have an aspherical design to minimise distortions. The optical design was optimised around the central wavelength at 310 nm because of the critical requirements in this region. The performance of auxiliary channels elsewhere in the UV band is not as critical because the spectral resolution needed in those channels is not as demanding as in the continuous region. The layout proposed is shown in Figure 2 below.

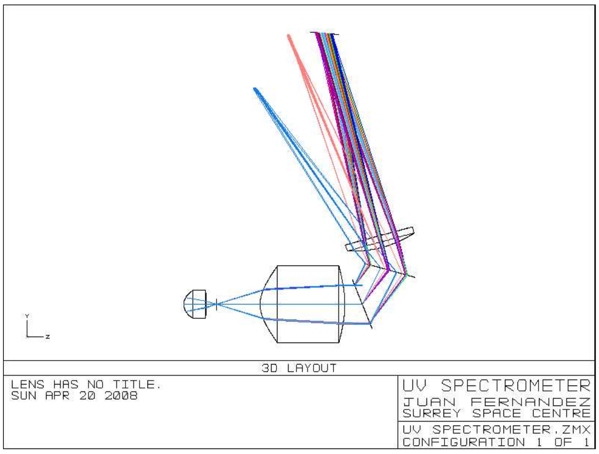

Figure 2: Instrument Optical Layout

On top we observe the three main optical rays of the three wavelength regions, 360 nm, 331 nm and 305-315 nm (left to right.)

The instrument concept proposed here was evaluated in terms of the spectral resolution required at Full Width Half Maximum (FWHM) of the spectral region of interest for discrimination between the gas species of interest. Other channels outside this region (331- and 360-nm) can be used for detecting the presence of some aerosols and for the determination of reflectance for retrieval algorithm purposes.

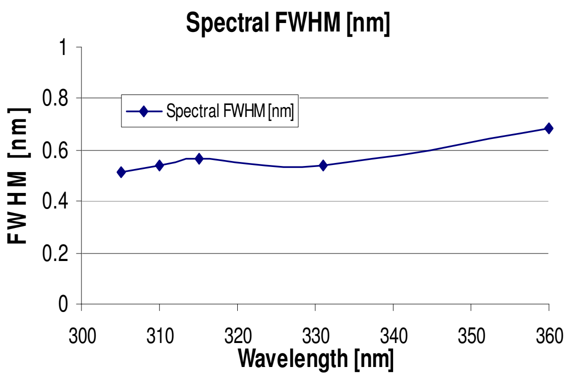

Figure 3: Spectral Resolution (FWHM)

The spectral resolution is defined in the slit function of the instrument, sampled by a photodiode area array at the focal plane of the instrument. The imaging performance of the sampled spectra was also studied given the distortions observed from different angular fields.

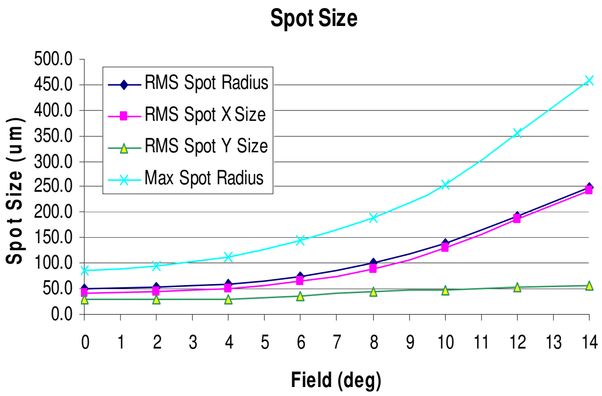

Figure 4: Spot Size vs Angular Field

As shown in Figure 4, an increase in the spot size with angular position of the field is observed. The implications of the spectral resolution and spot size for a given wavelength angular field are directly related to the application. Ultimately, the retrieval algorithms will use the spectral information from these bands (affected by the instrument performance) to derive the final products (SO_2 concentration, etc.).

For the maximum spectral resolution considered useful (1 nm) the absorption features of SO_2 are reduced in magnitude as shown below for an ACS spectra convolved with the instrument function with this resolution. (An offset has been introduced for clarity).

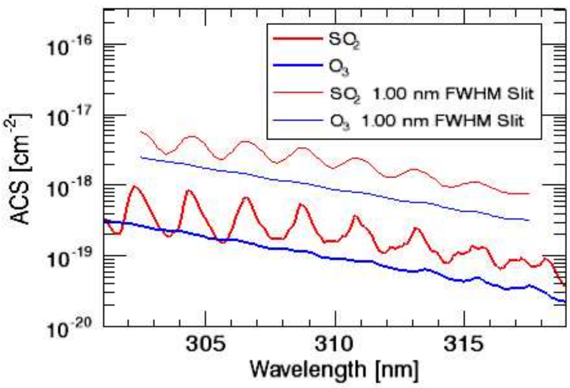

Figure 5: Effect of Spectral Resolution of a 1-nm FWHM Slit Function.

GRATING AND DETECTOR

The instrument design exploits the excellent response of silicon carbide photodiodes in this region; its blindness to visible radiation (two orders of magnitude higher than silicon) provides a simple optical design based on transmission gratings to offer a high sensitivity [5].

Grating

After a careful evaluation of available gratings, the best option was a holographic transmission grating from Ibsen Photonics. It is a general purpose 100% fused silica grating for UV applications. Some of its features and benefits are:

- Equivalent to the cost of replicated gratings
- Temperature stability, environmental tolerance and power damage threshold
- High Grating resolutions up to 5000 l/mm
- High diffraction efficiency with high dispersion
- Low polarization dependence over broad spectral range
- Combined wavelength dispersion and folding elements

This Commercial-Off-The-Shelf (COTS) component is the best option available for the proposed spectrometer. Its advantages in terms of simplicity of layout with plane dispersive optics were considered to be key.

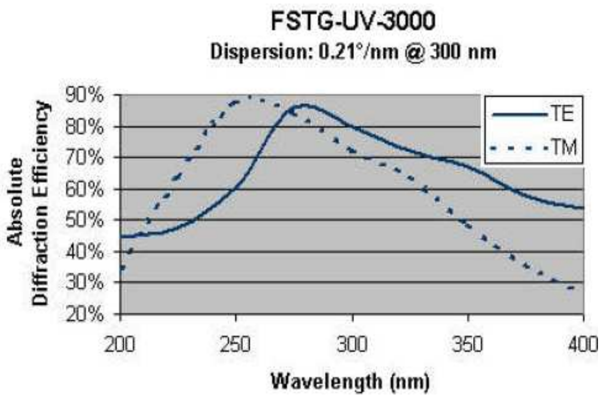

Figure 6: Grating Diffraction Efficiency

Detector

Silicon carbide with its outstanding physical properties is a material of choice for special optoelectronic and electronic devices working under extreme conditions. [6]. These devices have excellent UV responsivity characteristics and very low dark current even at elevated temperatures [7]. They are responsive between 200 and 400 nm and not responsive to longer wavelengths because of the wide 3-eV bandgap.

Its natural blindness to visible radiation is the greatest advantage for the considered instrument. SiC responsivity presents a natural cut-off response thus isolating the spectral range of interest. This will effectively reduce stray light problems without the need for optical splitting of the channels. Furthermore, the low dark current noise of SiC will be an advantage on the signal-to-noise (S/N) performance of the proposed instrument.

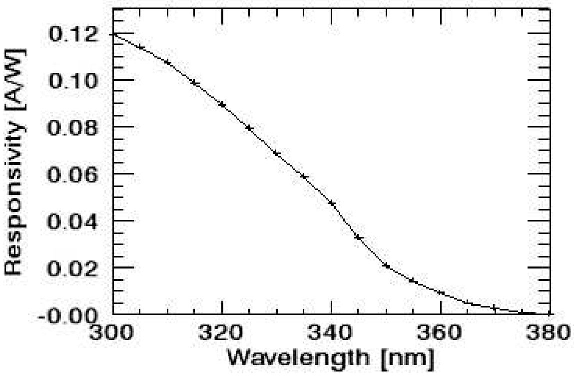

Figure 7: Silicon Carbide Responsivity

Given the extreme low noise expected from the photodiode array, the electronics should be accordingly designed to keep noise levels low. They are indeed a limiting factor for the overall noise performance.

ELECTRONICS

The challenging requirements of the application such as: wide dynamic range and low-noise demand an extremely low circuit noise matched to a highly sensitive detector to ultimately define the system sensitivity. For this purpose a low power (<2 W) electronic solution comprising a switched integrator and 20-bit analog-to-digital (A/D) converter in a miniature device is proposed.

The DDC232 is a 20-bit, 32-channel, current-input A/D converter. It combines both current-to-voltage and A/D conversion so that 32 separate low-level current output devices, such as photodiodes, can be directly connected to its inputs and digitized. For each of the 32 inputs, the DDC232 provides a dual-switched integrator front-end. This configuration allows for continuous current integration: while one integrator is being digitized by the onboard A/D converter, the other is integrating the input current. Adjustable integration times range from 166ms to 1s, allowing currents from fA's to mA's to be continuously measured with outstanding precision. The DDC232 uses a +5V analog supply and a +2.7V to +3.6V digital supply, operating over the temperature range of 0°C to +70°C.

Every channel input contains a network of capacitors used for the current integration. A series of signals are applied to logical switches to command the integration time, full-scale range, and the serial output to the 16-bit A/D converter.

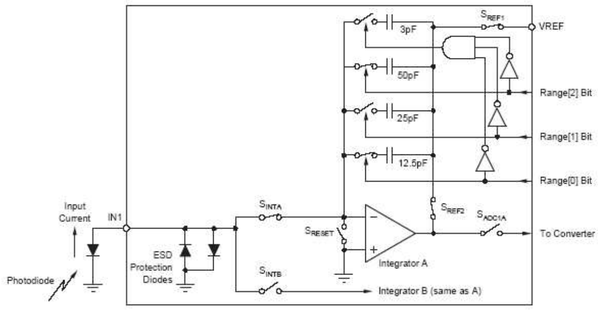

Figure 8: Basic integration configuration

Calibration coefficients have to be applied post-detection to account for gain differences, offsets and other differences in the capacitor network.

Radiative Transfer Modelling

Radiative transfer simulations show the differential Top of Atmosphere (TOA) radiances under various scenarios with atmospheres contaminated with different concentrations of SO_2. A fixed height homogeneous layer of SO_2 was introduced with various concentrations to analyse the effect on radiance with respect to a Clean Tropical Atmosphere.

Taking into account the estimated slit function, an estimated Noise Equivalent Radiance (NEL) was calculated to define the system sensitivity from where existing and new algorithms can be applied.

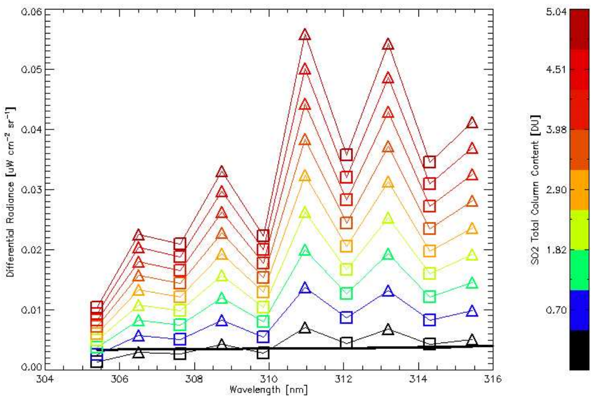

Figure 9: Noise Equivalent Radiance Differential radiance of SO_2 laden w.r.t. Tropical Atmosphere

The Noise equivalent radiance (NEL) is indicated as the thick black line at 0.004 μW sr^{-1} cm^{-2}. The conditions simulated are a 30% surface albedo and a tropical atmosphere with 30 degrees solar zenith angle.

CONCLUSIONS

The paper shows the design for a miniature UV imaging spectrometer, able to distinguish SO_2 and O_3 in the upper atmosphere for volcanic plume monitoring applications.

The demanding requirements to consider when designing such system were discussed with analysis on: the ground sample distance aimed (7 km x 32 km) to be comparable to that of the OMI (50 times smaller than GOME).

The optical design and its spectral imaging properties across its field-of-view were discussed together with the requirements for atmospheric analysis applications. The instrument imaging performance fulfils the application needs according to radiative transfer simulations of realistic atmospheric scenarios. The detection limits, based on the expected detector performance, are aimed ideally to observe minor concentrations of SO_2 produced by passively outgassing volcanoes ≤5 DU SO_2 and certainly should be capable of monitoring volcanic events releasing >10 DU. A sensitivity analysis based on the electronics' performance was carried out.

The relatively low-cost and small size of the instrument proposed makes it a suitable instrument for a micro-satellite-based atmospheric remote sensing mission.

Acknowledgments

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