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GUIDED-WAVE HIGH-PERFORMANCE SPECTROMETERS FOR THE MEOS MINIATURE EARTH OBSERVATION SATELLITE

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ABSTRACT

The MEOS Miniature Earth Observing Satellite is a low-cost mission being developed for the Canadian Space Agency with international collaborations that will innovatively combine remote correlated atmospheric/land-cover measurements with the corresponding atmospheric and ecosystem modelling in near real-time to obtain simultaneous variations in lower tropospheric GHG mixing ratios and the resulting responses of the surface ecosystems. MEOS will provide lower tropospheric CO_2, CH_4, CO, N_2O, H_2O and aerosol mixing ratios over natural sources and sinks using two kinds of synergistic observations; a forward limb measurement and a follow-on nadir measurement over the same geographical tangent point. The measurements will be accomplished using separate limb and nadir suites of innovative miniature line-imaging spectrometers and will be spatially coordinated such that the same air mass is observed in both views within a few minutes. The limb data will consist of 16-pixel vertical spectral line imaging to provide 1-km vertical resolution, while the corresponding nadir measurements will view sixteen 5 by 10 km^2 ground pixels with a 160-km East-West swath width.

To facilitate the mission accommodation on a low-cost microsat with a net payload mass under 22 kg, ground-breaking miniature guided-wave spectrometers with advanced optical filtering and coding technologies will be employed based on MPBC's patented IOSPEC technologies. The data synergy requirements for each view will be innovatively met using two complementary miniature line-imaging spectrometers to provide broad-band measurements from 1200 to 2450 nm at about 1.2 nm/pixel bandwidth using a multislit binary-coded MEMS-IOSPEC and simultaneous high-resolution multiple microchannels at 0.03 nm FWHM using the revolutionary FP-IOSPEC Fabry-Perot guided-wave spectrometer concept. The guided-wave spectrometer integration provides an order of magnitude reduction in the mass and volume relative to traditional bulk-optic spectrometers while also providing significant performance advantages; including an optically immersed master grating for minimal optical aberrations, robust optical alignment using a low-loss dielectric IR waveguide, and simultaneous broad-band spectral acquisition using advanced infrared linear arrays and multiplexing electronics.

This paper describes the trial bread-boarding of the groundbreaking new spectrometer concepts and associated technologies towards the MEOS mission requirements.

1. INTRODUCTION

For IR spectral measurements in the gas-phase, the absorption peaks tend to be much narrower than for the condensed phase. High-resolution measurements of the fine structure of the trace gas absorption bands is often desirable, both to minimize interferences and to provide additional pressure and temperature vertical data. Relevant previous instruments for atmospheric trace-gas studies include bulk-optic dispersive spectrometers such as the SCIAMACHY VIS/NIR spectrometer on ESA's ENVISAT and the ACE FT-IR on CSA's SCISAT-1.

Typically, the current high-resolution spectrometers are based on bulk-optic spectrometers employing a relatively long optical path to achieve the required spectral dispersion. The mass of the current bulk-optic spectrometers typically exceeds 15 kg. This necessitates large and costly space platforms. The long optical path also makes the instrument performance and optical alignment sensitive to thermal variations and microvibrations that can be encountered in space.

Various Fourier Transform Infrared (FT-IR) spectrometers based on Michelson interferometers have also flown, including ACE on CSA's SCISAT-1 [3] and NASA's Thermal Emission Spectrometer (TES [1]). The FT-IR performs the spectral measurements sequentially using a Michelson interferometer to determine an interferrogram or Fourier Transform of the desired spectral data using a scanning mirror to vary the optical path in one arm of the interferrometer. The spectral retrievals require that the optical signal be constant during the entire measurement of the interferrogram. To attain high spectral resolution requires a relatively long 10 to 20 cm precision movement of the scanning mirror.

Instrumentation for space has relatively severe restrictions on mass, power and data transmission rates due to the high launch cost per kg. Therefore, miniaturization of the instrumentation while maintaining or exceeding the performance of bulk instruments is important to maximize the attainable scientific benefit and facilitate more missions through lower costs. Also, extensive use of in situ data processing is needed to extend the amount of information that can be transferred back to Earth.

MPB has advanced its patented IOSPEC technology (**US 7,034,935 B1)** for miniature guided-wave IR spectrometers to provide high performance comparable to large bench-top spectrometer systems but in a very compact and ruggedized footprint [5,6,7]. The technology was originally developed in collaboration with DRDC Valcartier and INO.

MPB's IOSPEC (Integrated Optical Spectrometer) uses an antireflection-coated, high-index, low loss (<0.05 db/cm) IR dielectric slab waveguide structure with advanced IR linear detector arrays and smart multi-channel parallel signal processing. The collected light is focused directly into the waveguide spectrometer through a 60 by 2000 mm slit for the FP-IOSPEC and a programmable 16x16 element slit array for the line-imaging binary-coded, broad-band spectrometers. The high-index waveguide allows a large input acceptance angle (NAi>0.3). The spectrometer waveguide integration precisely defines the position of the diffracted signal at the output focal plane, providing robust long-term optical alignment. IOSPEC spectrometers assembled over 10 years ago are still maintaining their optical alignment.

The optical signal is guided within the slab waveguide onto a master blazed grating that also serves as a concave reflector. The precision master grating, formed using microfabrication techniques to yield atomically-flat blazed grating elements, provides diffraction efficiencies approaching theoretical limits (> 85% peak diffraction efficiency) with low background signal scattering (<0.05%). Additional integrated optics at the output plane provide a 30-40 mm wide linear output focal plane for efficient coupling to focal plane arrays; facilitating a 4000 nm spectral operating range in first order diffraction (m=1) with spectral resolution to $\Delta\lambda/\lambda = 1/7500$.

The current 1.2 to 5 μm IOSPEC integrated optical spectrometer has been packaged by MPB in a compact module, as shown in Fig. 1, that is only about 20 x 20 x 15 cm in size and under 2 kg in mass. A version for operation from 8 to 12 microns has also been recently prototyped in collaboration with DRDC Valcartier.

Key current IOSPEC features:

- **High-index waveguide provides a large input numerical aperture of 0.3 and an input aperture height of several mm for improved input optical coupling.**
- **Micromachined master grating with diffraction performance near theoretical limits and very low background signal scattering (< 0.05%).**
- **30 to 40 mm wide linear output focal plane using proprietary guided-waveguide design that provides a 4000 nm wide spectral operating range in m=1.**
- **Robust monolithic integration of input optics and output detector array using patent-pending 3-D pin and socket methodology.**
- **Moderate cost to fine-tune the design for specific requirements.**
- **Advanced parallel-processing IR linear detector array technology with active dark signal compensation**
- **Patented iterative smart signal processing for >60 dB signal dynamic range.**

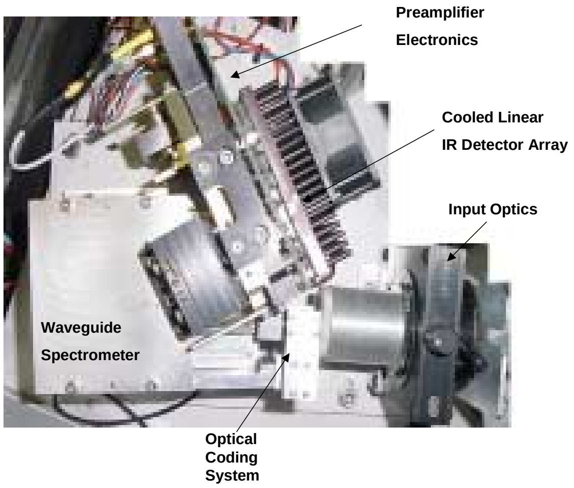

Fig. 1: Photograph of current IOSPEC module weighing under 2 kg including input optics and TE-cooled IR detector array.

IOSPEC employs an electronically-scanned detector array with parallel-processing multiplexing that can provide spectral scan rates exceeding several hundred scans per second to facilitate a relatively high sample throughput. The elimination of moving components and integration of the optical system provides more reliable long-term performance in non-ideal environments.

Even with active cooling and nominal temperature stabilization, infrared detector arrays, such as PbSe, can exhibit some unwanted signal drift and instability that can be comparable in magnitude to weaker optical signals. Proprietary active smart optical signal processing algorithms have been developed by MPB that facilitate a significant increase in the attainable SNR for multiplexed linear detector arrays. Using the traditional signal averaging techniques, the ultimate signal detectivity achievable rapidly saturates due to the increasing contribution of systematic variations in the detector signal, significantly limiting the attainable SNR. However, with the active smart averaging, as shown in Fig. 2 for a 256 pixel PbSe array, no such saturation in noise reduction was observed even for extended measurement times. This provides the potential of over three orders of magnitude improvement in the attainable SNR relative to traditional signal processing techniques.

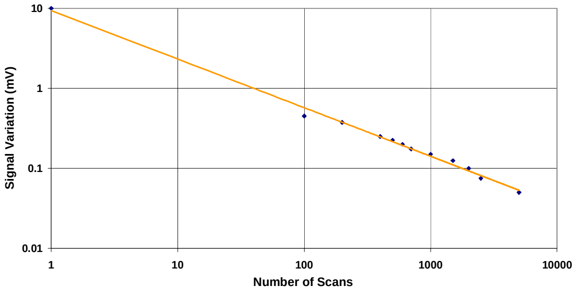

Fig. 2: Variation of the net noise for 256 pixel multiplexed PbSe linear array at 260K with the number of scans in active smart average with a full scale of 10V.

Fig. 3 shows the diffuse reflectance spectra of alunite and gypsum, minerals that are relevant for planetary exploration, that were measured with the current waveguide spectrometer operating at a coarse 8 nm/pixel bandwidth in m=1 using a miniature 3 W light source. These trial spectra were comparable to the reference spectra as provided by the Univ. of Winnipeg using a large bulk-optic spectrometer with 50 W source, providing good SNR and excellent differentiation of various minerals.

While a 4 to 8 nm/pixels measurement bandwidth is adequate for space studies of ground-cover and aerosols, much higher spectral resolutions are needed for atmospheric trace gas studies to resolve the fine structure of the tras gas absorption and minimize various interferences.

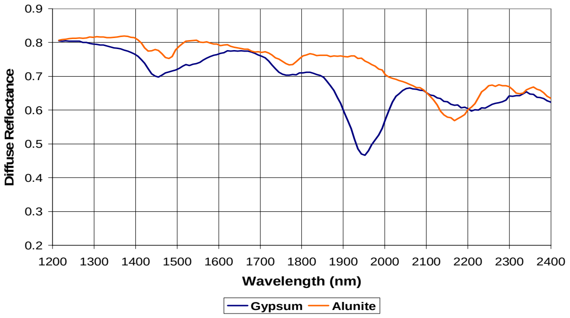

Fig. 3: Spectra of gypsum and alunite measured using 60 degree incidence by an IOSPEC spectrometer with 50 µm input slits, 3 W miniature source and PbSe detector array, relative to a Spectralon reference for R=100%.

The following paper discusses a ground-breaking miniature Fabry-Perot guided-wave spectrometer concept, FP-IOSPEC, that can provide simultaneous multichannel high spectral resolution measurement capabilities for trace gas analysis to below 0.03 nm FWHM with a mass under 3.5 kg and net power requirement under 5 W. The mass and size reduction enables multiple such spectrometers to be accommodated on a single microsat to provide complementary data synergy and enable new science. The technology development targets the instrument requirements for the potential CSA MEOS Miniature Earth Observation Satellite mission.

2. MEOS Mission Overview

MEOS is an advanced low-cost microsat mission that is being developed for the Canadian Space Agency for leading-edge correlated atmospheric/ground-cover studies from a 700 km Sun-synchronous orbit. The MEOS mission fills a strategic need for data to assist understanding the dynamics behind the current climate changes by studying some of the fundamental processes associated with the global water and carbon cycles and their interactions with the land cover, especially the role of the Canadian Boreal forest.

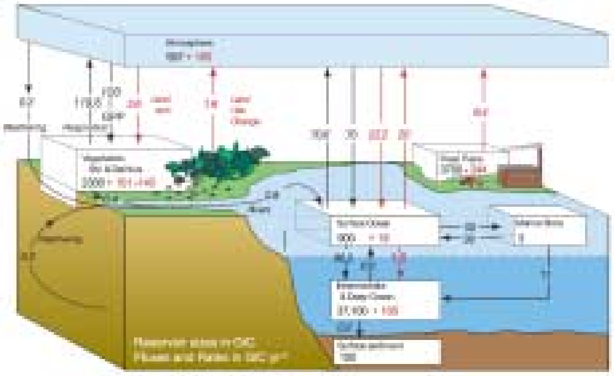

Fig. 4: Global; carbon cycle with pre-industrial ‘natural’ fluxes in black and “anthropogenic” fluxes in red (source: IPCC AR4 WG1, May 2007).

The common thread in the climate-related effects is the interaction between the surface ecosystems and the carbon- and nitrogen-containing gases in the lower troposphere. Uptake of CO_2 by growing vegetation, release of CH_4 and N_2O by soil processes and the effects of carbon and water cycle chemistry all interact strongly in a system that is both extremely complex and poorly understood at the present time (see Fig 4). The natural sources and sinks currently help to moderate the atmospheric GHG concentrations.

The short-term response of the surface ecosystems is sensitive to variations in the composition of the lower atmosphere on the diurnal or seasonal time scale. Fig. 5 shows the diurnal/seasonal near-surface CO_2 variations measured over an extended time period within the Canadian Boreal forest. The CO_2 samples were obtained from a ground monitoring station using the flask method by Fluxnet. As opposed to the steadily increasing 1 to 1.5 ppm/year trend in the well-mixed mean CO_2 levels higher up in the atmosphere, as observed currently from space, the near-surface seasonal and diurnal CO_2 variations over a natural source/sink can exceed 20-30%.

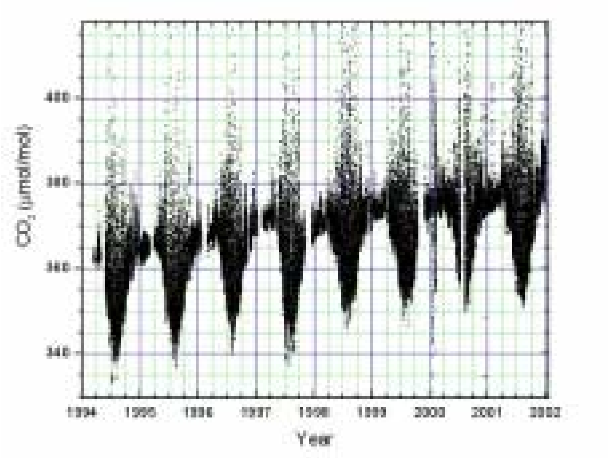

Fig. 5: Annual cycle of CO_2 near-surface concentration in BOREAS region (Canada).

The prediction of future behaviour depends on the ecosystem response, so an accurate understanding of this response is essential to achieve the goal of good long-term predictions. In summary, it is essential to consider the lower troposphere and surface ecosystem together and determine the behaviour of this coupled system under varying GHG concentrations in order to get an accurate prediction of the future climate response to anthropogenic GHG. These variations and interactions with the natural sources/sinks must be known accurately before global CO_2 levels can be quantified for climate modelling. The CO_2 and CH_4 concentrations and seasonal variations also reflect the health of the forests and the surface ecosystem

In order to extract the lower tropospheric concentrations of CO_2, CH_4, CO, N_2O and H_2O over natural sources and sinks, MEOS will innovatively combine geocolocated limb vertical profiling with follow-on nadir column measurements, coupled with near reat-time modelling. to extend the attainable precision and coverage. The measurements will be accomplished using separate limb and nadir instrument suites to avoid risky satellite manouvers and to maximize the data measurement times for both views. Previous missions have either alternated between nadir and limb measurement modes, such as SCIAMACHY, or only had a single view such as the occultation measurements provided by Canada's SCISAT-1, or the pure nadir measurements planned for NASA's Optical Carbon Observatory (OCO).

The limb Earth tangent point measurements will consist of sixteen 1.5 km x 160 km vertical pixels. This requires high pointing stability that will be achieved using a miniature Star Tracker and momentum wheel system for $+/-0.01^o$ pointing stability, coupled with a GPS for spacecraft position knowledge.

The follow-on nadir view will track the same geolocation/air-space as limb view. The nadir measurements will provide a 160 km swath width with sixteen 5x10 km^2 spatial pixels. The selection of the MEOS nadir ground pixel size involves a trade-off between SNR, resolution of ground sinks/sources and minimization of signal contamination by clouds. Based on the proposed MEOS instrument characteristics, a 5x10 km^2 nadir FOV per spatial pixel can provide SNR>300 for the high resolution channels. Preliminary analysis by CCRS [4] using data over Canada indicates that this will provide MEOS with >20% clear sky probability, a significant improvement over the previous missions (<7% clear skies for SCHIAMACHY using 30x60 km^2 ground pixel size for the CO_2 and CH_4).

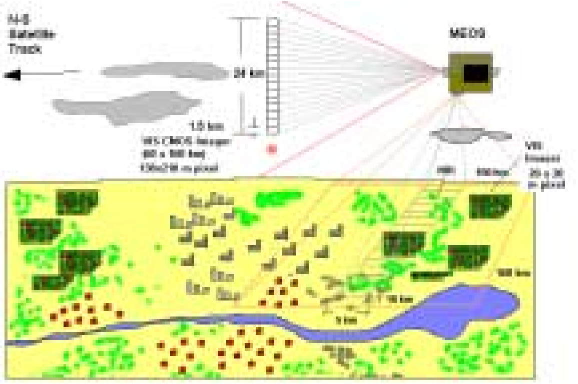

Fig. 6: MEOS dual dedicated suites of miniature high-performance instruments for simultaneous limb and nadir views, including high-resolution CMOS imager.

Each view features a dedicated instrument suite and telescope with 100 mm diameter scanning mirror. The collimated optical signal collected by the hybrid telescope will be distributed to the instruments. For each view, two complementary miniature line-imaging spectrometers will measure simultaneously the broadband solar-illuminated 1.22 to 2.45 μm spectrum at about 1.2 nm resolution for the land cover and aerosol data, and the FP-IOSPEC multiple microchannels at 0.03 nm Full-Width-half-Maximum (FWHM) for the relevant trace gases to improve on the trace gas retrievals relative to previous and planned missions. The collected optical signal will be alternated between the two spectrometers, such that one undergoes its dark cycle while the other undergoes its illuminated cycle. The nadir view also includes a scanning Fabry-Perot 0.02 nm FWHM high resolution spectrometer for the O2 A-band near 0.76 μm to provide estimations of the total column pressure to correct the GHG concentration estimations..

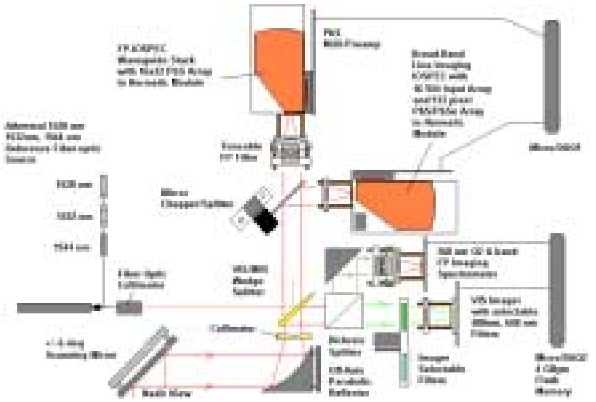

Fig. 7: Schematic of nadir miniature instrument suite. The limb instrument suite is similar but omits the O_2 A-band Fabry-Perot imaging spectrometer.

Table 1: Summary of MEOS Instruments.

Subunit	Power (peak)	Mass
100 mm Tiltable Limb/Nadir Hybrid Telescopes (x2)	1 W	<6 kg
Limb NIR/MIR Spectrometer 900 to 2400 nm at 2 nm/pixel.	2 W	<2 kg
Limb FP-IOSPEC 1500 to 2400 nm at 0.03 nm FWHM in 32 microchannels	2.5W	2.5 kg
Limb 768x488 pixel CMOS Imager	0.5 W	0.5 g
Nadir NIR Spectrometer 1200 to 2400 nm at 1.2 nm/pixel	2 W	<2 kg
Nadir FP-IOSPEC 1500 to 2400 nm at 0.03 nm FWHM in 32 microchannels	2.5W	2.5 kg
0760 nm O2 A-band FP Imaging Spectrometer at 0.02 nm FWHM	1 W	1 kg
Nadir 16 Mpixel VIS Imager	1 W	0.5 kg
16 bit DAQ System with 4 Gbyte Flash (x2)	3 W	1 kg
Microprocessors (x4)	6 W	1 kg
Athermal 1520,1532,1544 nm calibration source	1W	0.25 kg
Enclosure/passive cryoradiator	0 W	3 kg
Total:	22.5 W	<23 kg
Available for CSA Microsat:	32 W	30 kg
Margin (for microsat):	30%	23%

The limb and nadir instrument suites will leverage the advanced fault-tolerant, spacegrade microprocessor-based data acquisition and control electronics that have been developed in collaboration with Xiphos Technologies and CSA for the Fiber Sensor Demonstrator (FSD [7]) on ESA's Proba-2. This is scheduled for launch in 2009. Fig. 8 shows a photograph of the flight CPU PCB. This features a spacegrade DC-DC converter from Interpoint and FPGA from Xilinx, as well as the Xiphos latch-up protection for the DC power lines. Data and command I/O is provided using dual, redundant RS422 differential receivers and drivers. The FSD CPU PCB also contains 768 kbytes of SRAM. This will be augumented with 2 Gbyte of flash memory with fault-tolerant operation.

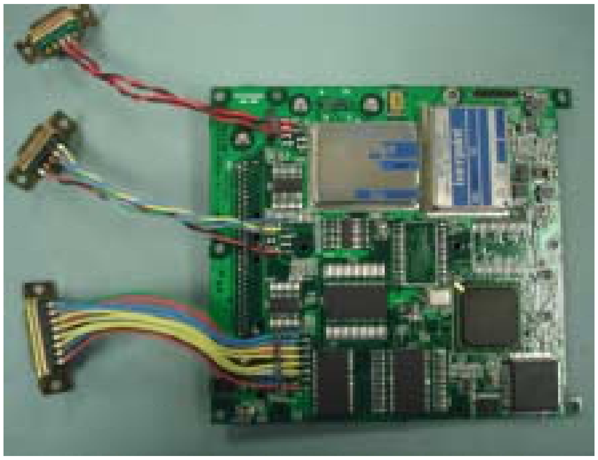

Fig. 8: Photograph of FSD flight CPU PCB designed with Xiphos.

The proposed measurement scenario for the nadir view is **"Step and Track"** consisting of a digitized step between viewpoints on the ground, as shown schematically in Fig. 9. This methodoogly allows an extended signal integration time of 2 to 5 seconds per geographic point for an SNR>400 in the high resolution channels over grasslands while minimizing the background albedo variations. The target tracking will be performed by tilting the primary mirror of the nadir telescope. Accurate geographical positioning information will be provided by the CMOS VIS imager, supplemented by the MEOS GPS and pointing knowledge.

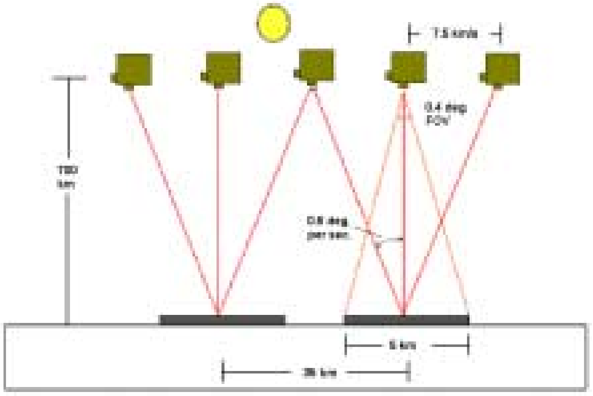

Fig. 9: Schematic of MEOS nadir "Step and Track" measurement methodology.

Table 2: Summary of Current MEOS ScienceTteam

MEOS Science Team		
Prof. James Sloan	U. of Waterloo	Mission Science Principle Investigator
Prof. Ed Cloutis	U. of Winnipeg	Land cover modelling
Dr.. Richard Menard	Environment Canada	GEM atmospheric modelling.
Dr. Louis Garand	Environment Canada	Data Assimilation and Meteorology
Prof. Dylan Jones	U. of Toronto	Atmospheric/ Ecosystem Modelling
Prof. Kimberly Strong	U. of Toronto	Instrument calibration and validation, Trace gas analysis.
Dr. Thomas Kurosu Prof. Kelly Chance	Harvard-Smithsonian Center for Astrophysics	Gas Retrievals
Prof. John Lin	Univ. of Waterloo	Ecosystem modelling.
Prof. Randall Martin	Dalhousie University	Atmospheric Modelling
Dr. Alexander Trishchenko	Environmental Monitoring Section, Canada Center for Remote Sensing.	Trace gas radiative transfer modelling and retrievals.
Dr. Shusen Wang		EALCO Ecosystem modelling
International Collaborations		
Prof. Ilse Aben	SRON, Netherlands	Trace gas measurements and retrievals.
Dr. Pieternel Levelt	KMNI, Netherlands	potential ESA TRAQ mission.
Prof. Wang Yeyao	Chinese Research Academy of Environmental Sciences	Greenhouse Gas and Pollution Monitoring.

A multidisciplinary international science/payload team has been assembled, as summarized in Table 2, that has demonstrated international expertise in all areas of the MEOS mission, instrument and science requirements to accomplish the program described above. The mission science is lead by Prof. James Sloan who has gained considerable relevant measurement and analysis experience, as well as scientific publications for the aerosol studies through participation in the ACE instrument on SciSat-1. The team science expertise extends to gas phase and cloud/aerosol measurements and retrievals; atmospheric and surface ecosystem modelling and distributed parallel computing. While the data processing, modelling and computational challenges are demanding, the requirements are within the capabilities of modern distributed computing systems as available to the MEOS science team.

3. FP-IOSPEC Spectrometer

The Fabry-Perot guided-wave FP-IOSPEC spectrometer synergistically combines advanced tunable optical filtering technologies with subsequent guided-wave multichannle wavelength demultiplexing to overcome current performance limitations by innovatively using the two relatively mature technologies in new ways:

1. Monolithic tunable FP etalon with tailored FP Mirror reflectance characteristics to provide the selected Free Spectral Range (FSR) match to the spectrometer pixel spacing with constant transmitted peak Full Width Half Maximum (FWHM) over a broad-spectral range.
2. Broad-band guided-wave miniature spectrometer to precisely wavelength demultiplex the serially-multiplexed FP Etalon optical output onto a multi-channel, parallel processing IR detector array.

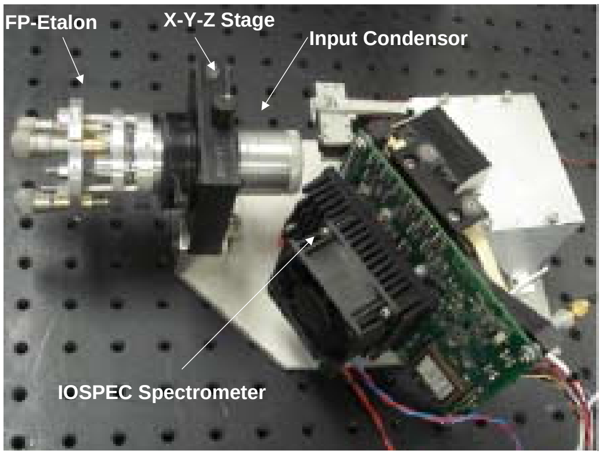

Fig. 9: Photograph of prototype FP-IOSPEC lab breadboard.

The proprietary mirrors for the tunable optical filter were custom fabricated by INO using multilayer vacuum deposition. They are designed to provide a constant transmitted FWHM with wavelength between 1500 and 2450 nm.

Ansys Multiphysics was employed to simulate the design of the tunable FP etalon mechanical stage. This proceeded through two iterations to yield a very stable, but compact monolithic flexure structure using piezo actuators to provide stable tuning of the FP transmission wavelength and stable operation (see Fig 9). An advanced FP Etalon mechanical stage, about 60 mm O.D. by 60 mm long, was fabricated and integrated with three vacuum-compatible piezo actuators to enable electronic tuning of the FP mirror alignment and gap spacing.

4. Preliminary Bread Board Testing

The trial FP etalon provided an excellent measured net transmittance >80% at the FP cavity resonances. This includes about 1 dB of coupling losses. The FP spectral tuning was provided by the monolithic mechanical flexure stage using three piezo actuators with strain-gauge sensor closed-loop feedback. Full wavelength tuning of the FP Etalon was experimentally achieved over the selected 8 nm Free Spectral Range (FSR) to the next adjacent FP resonance (see Fig. 8b).

Fig. 10 shows the variation of the transmitted FWHM as a function of the FP Etalon FSR or mirror spacing. An FP etalon FWHM of 0.04 nm has already been obtained using the trial FP Etalon at a FSR of 1.2 nm, very close to the desired 0.03-0.04 nm FWHM for the FP-IOSPEC flight unit. At the current IOSPEC pixel spacing of 8 nm, the FSR is about 0.18 nm, still excellent resolution that is approaching the 0.1 nm spectral resolution of the relevant NASA OCO [9] and JAXA GOSat [10] instruments for CO_2 remote measurement.

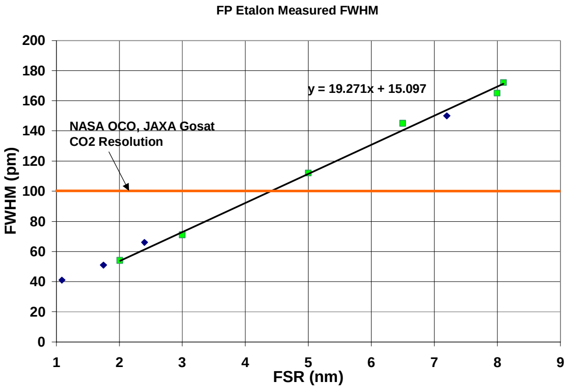

Fig. 10: Experimentally achieved FWHM using the trial monolithic FP Etalon equipped with INO-custom-fabricated dielectric mirrors.

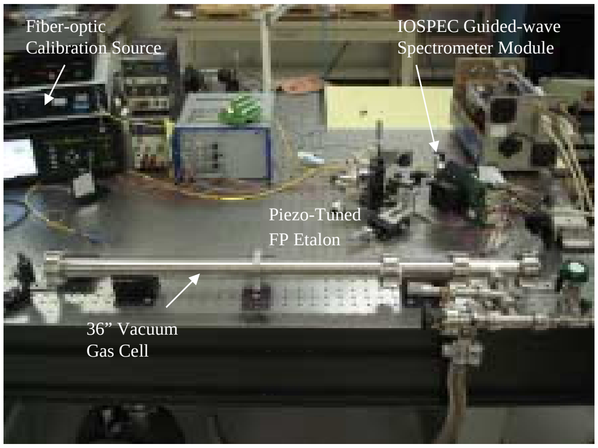

Fig. 11: Photograph of lab test set-up for CO_2 and CH_4 transmittance measurements.

Fig. 11 shows the MPBC laboratory test bed that combined the integrated FP-IOSPEC with a 36” long vacuum gas cell. The gas cell was evacuated to provide a T=100% reference spectra. The net transmittance through the CO_2 or CH_4 samples in the gas cell was referenced to the corresponding reference spectra measured with the gas cell evacuated. First, coarse resolution spectra of the gases were taken using the current IOSPEC native 8 nm/pixel bandwidth. These provided an excellent fit of the absorption peak positions with corresponding MODTRAN and Hitran simulations of the CO_2 or CH_4. The Modtran (Modest resolution atmospheric Transmittance) simulator was developed for the US Air Force and is used extensively for predicting remote sensing measurements at moderate resolutions to about 1 nm.

A high-resolution spectrum of the CO_2 absorption band near 1572 nm was measured using a fine sampling step of about 0.01 nm by the current IOSPEC spectrometer (see Fig. 12(a)). Through the combination of narrow-band fine-filtering of the input optical signal using a tunable optical filter with subsequent signal wavelength demultiplexing and measurement by the IOSPEC miniature guided-wave spectrometer, the FP-IOSPEC spectrometer is capable of providing resolution of the CO_2 fine-line spectral features. The experimental measurements and 0.28 nm line spacing provided a good fit to the corresponding Hitran simulations given in Fig. 12(b).

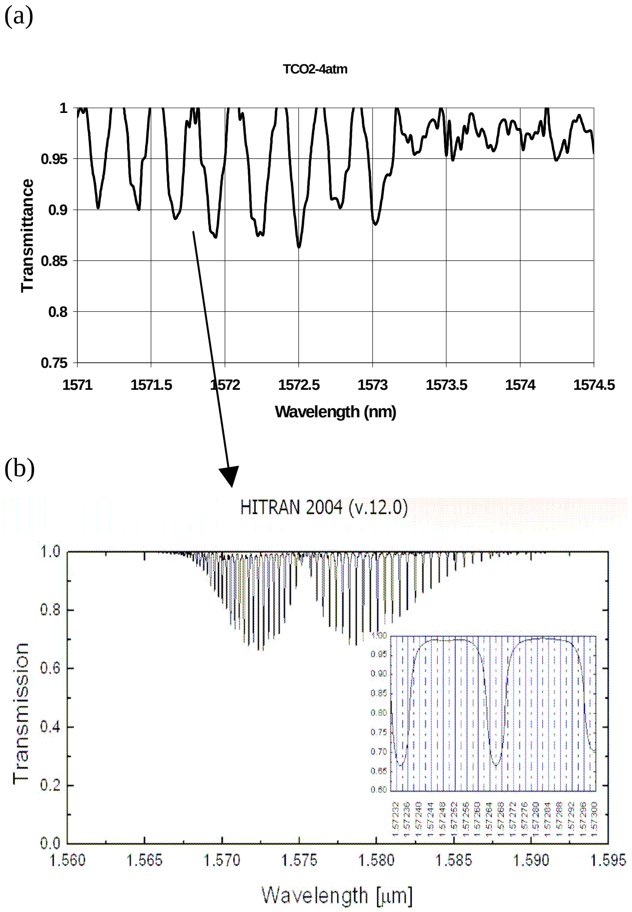

Fig. 12: (a) Preliminary IOSPEC high-resolution spectrum of CO2 1573 nm band using tuned narrow-band source (12' path length at 4 atm.) - 0.28 nm peak spacing and (b) Simulation of CO_2 1573 and 1580 nm absorption bands for 1 standard atmosphere using the Hitran data base [8] - about 0.3 nm CO_2 fine peak spacing near 1573 nm.

5. CONCLUSIONS

The MPBC guided-wave spectrometer miniaturization provides an order of magnitude reduction in the mass and volume relative to traditional bulk-optic spectrometers while also providing significant performance advantages; including mechanical simplicity, robust optical alignment of the spectrometer optics on a high-performance dielectric IR slab waveguide structure, and wide spectral range of operation in first-order diffraction (m=1).

The MEOS payload encompasses ground-breaking innovation in miniaturized high-performance infrared (IR) spectrometers to enable substantial new atmospheric science and Earth observation to be accomplished on a low-cost microsat platform. The MEOS instrumentation is based on the advancement of MPBC's patented technologies [US 7,034,935 B1) for high performance miniature guided-wave IR spectrometers [5,6] that are currently being bread-boarded with the assistance of the Canadian Space Agency.

The spectrometer miniaturization is a significant and original advance that facilitates the use of multiple dedicated spectrometers on the same microsat platform to allow simultaneous and coordinated measurements to improve the achievable mission science. The net resources required in terms of power (<23 W) and mass (<22.5 kg) for the proposed baseline suite of MEOS instruments (see Table 1) is less than the mass and power typically required for a single bulk-optic IR spectrometer. The MEOS innovative instrument miniaturization provides the following significant capabilities:

- Separate limb and nadir instrument suites to enable simultaneous nadir column and limb vertical slant Earth tangent-point measurements to provide complementary geolocated data.
- Each view will employ two miniature waveguide NIR spectrometers; one optimized for broad-band measurements at a moderate spectral resolution of about 1.2 nm (SNR>2500 (near 1550 nm in nadir), and the Fabry-Perot Integrated Optical Spectrometer (FP-IOSPEC) to provide high-resolution microwindows at 0.03 nm FWHM (SNR>400 near 1550 nm in nadir).
- VIS imagers in the nadir and limb views to provide precise pointing information and geolocation, as well as additional information for cloud detection, aerosols and landcover.
- Mission accommodation on a low-cost microsat platform with about 25% margin (mass, power).

The significant benefits of the FP-IOSPEC instrument include :

- substantial order-of-magnitude savings in cost, size and mass relative to current FT-IR and dispersive bulk-optic spectrometers for earth observation and planetary exploration,
- simultaneous measurement of 256 to 512 high-resolution micro channels,
- channel FWHM below 0.03 nm is theoretically feasible with a relatively large spectrometer input aperture to enable high SNR for measurement of trace gas fine-line structure,
- relatively broad-band infrared spectral measurements,

- Scanning to provide intermediate points at user selectable wavelength steps to below 0.005 nm for full spectral definition of trace gas fine features,
- direct measurement of the spectral data to minimize required data processing and provide high transmittance accuracy,
- compact instrument package (<3.5 kg, < 5 W, < 20 x 26 x 14 cm) enables use of a low-cost microsat platform.
- short optical path enables robust long-term optical alignment.

Table 3: Comparison of MEOS to previous/planned relevant EO missions.

Parameter	SCIAMACHY (ESA)	OCO (NASA)	MEOS (MPBC/CSA)
Satellite	Envisat	Largesat.	Microsat
Views	Alternating limb and nadir	Rolling Nadir	Simultaneous limb and "step and track" nadir.
Ground Pixel Size	30x60 km^2	1 x 1 km with 10 km swath width	5x10 km^2 with 160 km swath width
Spectral Res. for CO_2	1.48 nm BW near 1550 nm	about 0.1 nm	Both 1.2 nm BW and micro channels at 0.03 nm FWHM,
Imager	No	No	CMOS Imagers for geolocation, cloud detection and aerosols.
Instrument Mass	215 kg	430 kg total	<22 kg
Instrument Power	155 W	160 W	< 23 W

Table 3 compares key MEOS characteristics to several relevant current and planned missions. The previous missions have been based on large, bulk-optic instruments that require costly platforms. Through the innovations proposed for MEOS, a significant atmospheric science mission can be performed on a low-cost microsat at fraction of the previous costs. Relative to previous/planned missions, the MEOS instrument suite provides a self-sufficient, geographically collocated data set with improved spectral resolution of the trace gas fine-line features. The MEOS instrument development will have a tremendous impact on the cost/performance of future atmospheric and EO missions to meet the sustained long-term measurements required to study climate change.

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