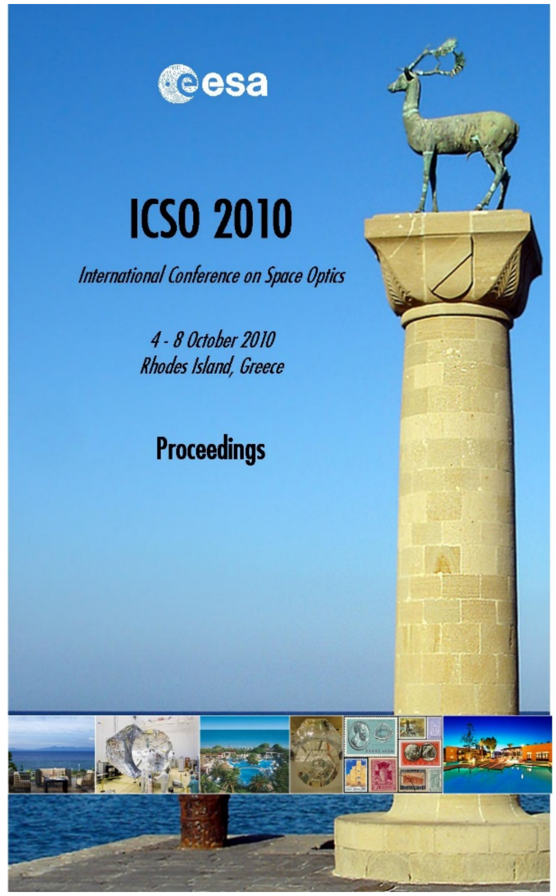
International Conference on Space Optics—ICSO 2010

Rhodes Island, Greece

4–8 October 2010

Edited by Errico Armandillo, Bruno Cugny, and Nikos Karafolas



A new approach to climatology from space: laser occultation

S. Mottini, A. Loescher, M. Aguirre, I. Bakalski, G. Kirchengast

esa icso proceedings cnes

International Conference on Space Optics — ICSO 2010, edited by Errico Armandillo, Bruno Cugny, Nikos Karafolas, Proc. of SPIE Vol. 10565, 1056565 · © 2010 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2552630

A NEW APPROACH TO CLIMATOLOGY FROM SPACE: LASER OCCULTATION

S. Mottini[1], A. Loescher[2], M. Aguirre[2], I. Bakalski[3], G. Kirchengast[4].
[1] *Thales Alenia Space Italia, Strada Antica di Collegno 253, 10146 Torino, Italy (sergio.mottini@thalesaleniaspace.com)*
[2] *ESA-ESTEC, Keplerlaan 1 Noordwijk 2200AG, Netherlands (Armin.Loescher@esa.int, miguel.aguirre@esa.int)*
[3] *Lidar Technologies Inc. 10 Gerard Ave. Timonium, MD 21093, USA (ivbakalski@hotmail.com)*
[4] *Wegener Center/University of Graz, Leechgasse 25, A-8010 Graz, Austria gottfried.kirchengast@uni-graz.at)*

I. INTRODUCTION

Human activities have been identified as critical contributors to climate changes. Modern industrial development and increasing urbanisation have been affecting the environment at an unprecedented scale since the 19th century. In the two last decades the process has become even faster, also due to the impressive development of largely populated countries like India and China. Historical data records testify a direct correlation between increase in atmospheric CO_2 levels and Earth's temperatures but processes underlying climate regulation and changes are only partially known. The improvement of knowledge of atmosphere and climate processes needs the availability of complete and reliable data about atmospheric composition and properties and space-based observations play a primary role.

Implementation of a demonstration mission based on an occultation technique at optical wavelengths is proposed. Observations in the infrared spectral range vest a particular importance because this band exhibits many absorptive spectral lines due to greenhouse gases, identified as the main responsible of global warming, thus H_2O, CO_2, CH_4, N_2O, O_3, and others can be observed with high accuracy. It is expected that the mission will demonstrate technical feasibility of an optical payload for limb sounding observations and provide useful inputs to climatic benchmarking (greenhouse gases and wind profile, as well as atmospheric thermodynamic properties).

The identification and the preliminary definition of the instrument architecture and the identification of the critical technologies have been among the main tasks.

Possible design options for the laser transmitter and the receiver are discussed, considering available technological solutions and technical constraints. Potential technological criticalities are illustrated too.

The creation of performance models, analytical and numerical, facilitates and addresses the payload design activity, both at instrument level and at general system level.

II. MISSION OBJECTIVES AND OCCULTATION TECHNIQUE

The twentieth century climate has been characterized by a global warming that cannot be explained without taking into account a significant contribution from the increased concentration of the greenhouse gases. But the actual impact of the anthropogenic contribution in the warming trend is only partial understood. The processes underlying climate regulation and changes, such as global circulation, carbon cycle or water vapour cycle, remain poorly quantified because the climatic and atmospheric processes have been observed either with coarse spatial and temporal resolution and coverage and/or lack of sufficient accuracy and/or long term stability.

In the analysis of atmospheric chemistry, occultation measurements from space raise a particular interest. This observation technique has been proposed in several missions like WATS and ACE+ [1][2], based on the use of GPS signals in L band (1.2 GHz ÷ 1.6 GHz) and microwave instruments in X/K band (between 8 and 23 GHz). In occultation measurements the signal propagation path between an orbiting transmitter and a receiver presents a deflection, primarily due to the vertical gradient of the atmospheric refractivity profile. Refractivity profiles derived from bending angles allow retrieving profiles of the atmospheric density and then pressure and temperature without the need of additional information. However, in the lower troposphere microwave refractivity is strongly affected by water vapour content, so that temperature and water vapour cannot be retrieved independently. To improve precision a different observation technique is required, based on spectral absorption. It is possible to retrieve the concentration of a trace gas in the atmosphere by making differential measurements of atmospheric transmittance of radiation at absorption wavelengths and at wavelengths with a lower or negligible absorption (reference). To minimize secondary effects, the ratio between the absorption wavelength and the reference wavelength should be close to unity within 1%.

The extension of the occultation measurement technique to SWIR range (2-2.5 μm) has been examined in the ACCURATE study [3] with focus on the UTLS (Upper Troposphere – Lower Stratosphere) region (5-35 km).

The selected infrared region is of great scientific value because many absorptive spectral lines due to greenhouse gases, identified as the main responsible of global warming effect (H_2O, CO_2, CH_4, N_2O, O_3, CO, HDO, $H_2{}^{18}O$, $^{13}CO_2$, $C^{18}OO$) lie in the that range. Trace gas profiling will be supported by geolocation information, temperature and pressure derived from simultaneous microwave occultation measurements of atmospheric refraction, absorption and defocusing data, as well as information about upper troposphere humidity. In this way a full synergy between SWIR and MW occultation measurements can be achieved.

Secondary science goals are the use of these observations in transport models for atmospheric composition analysis and numerical weather prediction (NWP).

Laser occultation will establish an unprecedented global data set at high vertical resolution (<10 m uncertainty), accuracy and long term stability, essentially independent of model information or other background data leading to a well-posed inversion problem (above the lower troposphere). These data are termed climate benchmark data. Our main objective is to establish a technology demonstration mission to validate the technologies related to the occultation technique in SWIR range, while producing useful scientific results.

III. MISSION ARCHITECTURE

In the frame of a technology demonstrator, the ACCURATE study represents the reference but a simpler design is expected.

Although the focal scientific and technical element of such a mission is the payload, other aspects at system level, e.g. the spacecraft constellation definition, require a careful analysis.

The option with two LEO-LEO counter-rotating satellites at different orbit altitude allows short occultation events which are highly valued from a scientific point of view since data on the whole altitude range almost simultaneously and with a near vertical profile are provided.

A single launch of two counter-rotating satellites is possible, exploiting the RAAN (Right Ascension of Ascending Node) drifting effect, although a time of some months is needed to reach the needed counter rotating orbits configuration. Accommodation considerations led to the selection of VEGA as the most suitable launcher.

The baseline scenario foresees operational orbit altitudes of 500 km (satellite 1) and 600 km (satellite 2). 80° inclination orbits have been selected as current baseline to produce a perfectly repeating geographical pattern of occultation events.

Satellite configuration is based on the standard PRIMA-S architecture with the required customizations due to specific mission needs, primarily the payloads and subsystems accommodation, optimizing the launcher's available room.

IV. PAYLOAD REQUIREMENTS AND ARCHITECTURE

A. Transmitter

The review of laser technology progresses has led to demonstration of power and linewidth parameters that potentially meet the needs of the project (1W at 50 Hz repetition rate and $\Delta f/f$ better than $3\cdot10^{-8}$).

The baseline transmitter concept is based on a set of identical transmitter modules, each served by a single optical amplifier in a MOPA configuration. The modules consist of 5 DFB lasers, one SOA (Semiconductor Optical Amplifier), associated control electronics and laser calibration and stabilization means. SOA can be operated in a pulse mode and additionally they can amplify two wavelengths at the same time provided that they are not too close.

A modular approach to the demonstrator allows increasing the complexity of missions representing a hierarchy of different scientific returns: from the selection of a minimums set of laser lines (H_2O and carbon dioxide with its primary isotopes) up to the full mission with the coverage of all SWIR A and SWIR B channels. Each module would operate independently of the other modules. New channels can be added by adding new modules. The baseline is the full mission which requires coverage of 11 channels in SWIR A and 10 channels in SWIR B. This requires at least 5 laser modules. If such a modular structure is adopted, the question is how to combine the optical outputs of the transmitter modules.

The wavelength multiplexing has two stages. At the first stage close wavelengths are amplified in pairs by a single SOA. Because of the low power of semiconductor lasers, existing $LiNbO_3$ fiber optic switches can be used to control this routing. The second stage is combining the higher power/wider divergence output of the amplifiers. Spectral filters, diffraction grating and MEMS switches can be used.

The distances between the channels are relatively high (1nm or more), excluding spectral lines used for wind measurement which are only separated by 2pm. Such close proximity cannot be resolved at the detection side except if signal are transmitted in different time intervals. Thus, four measurement wavelengths are emitted in parallel with a reference. Each 20 ms period (50 Hz update rate for a full spectral measurement) is divided in four time slots, each 5ms in duration. In the first 2ms of each slot a measurement is made at the selected wavelength, followed by 0.5ms for reset of the measurement circuit. In the next 2 ms a background measurements is made (followed by other 0.5 ms for reset).

The selection of the wavelengths for each module depends on the following information: i) All the channels have to fit within 4 time periods; ii) Some wavelength combinations may not be possible; iii) Each module emits two wavelengths in every time slot to keep the average load on the SOA constant and iv) The wavelengths for wind must be in one module to enable spectral multiplexing between the modules.

These constraints lead to a more convenient choice of 6 laser modules.

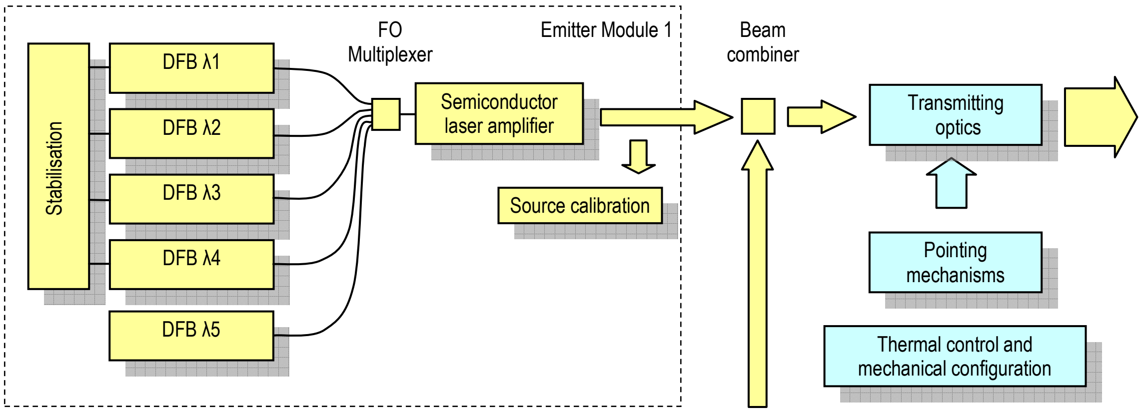


Fig. 1: Basic Emitter Module

The required pulse to pulse intensity stability, better than 0.1%, forces a solution in which all the pumping diodes run continuously, including the amplifiers. The output pulsing could be achieved by disconnecting the outputs of the CW running seed DFBs from the input of the CW pumped amplifier. Stopping the pumping diodes between the events or running them below the threshold is a trade-off driven entirely by lifetime issues. Fifteen seconds of warm-up time should precede each occultation event.

To avoid pulsing of the amplifiers it is proposed that they run at the same average power all the time, always amplifying two wavelengths.

Monitoring the laser pulse energy, but also the laser wavelength and the laser beam intensity profile (in the vicinity of the optical axis) is recommended since they can all affect measurements in similar way.

Because of the refraction of the beam in the atmosphere the laser beam will experience variable degree of bending and atmospheric density fluctuations causes jitter. If the distribution in the spot is non-uniform during the time of measurement this could introduce an error.

Also frequency requirements are similar to intensity requirements in the sense that, if the line moves, the intensity at a fixed wavelength changes. The required accuracy can be achieved by stabilizing only the seed lasers.

The short term stability (2×10^{-8}) should be considered on a time scale of 20 ms (one measurement cycle).

The long term stability (2×10^{-8}) should be considered on a time scale of 20 s (one occultation event).

During the event the wavelength stabilisation would rely of control of current and temperature and will not probably include wavelength measurement (depends on treatment of kinematic Doppler shift compensation for transmitter satellite motion). After the event wavelength calibration can be repeated for diagnostic purposes.

The absolute wavelength reference could be a gas absorption cell or a gas filled photonic fibre. These have been proven to provide locking to single MHz. Wavelength meters with the required accuracy are also available commercially.

Pointing in transmission must ensure that the laser spot covers the receiver location and is centred enough to allow for a maximum power collection. The angular shift of one satellite seen from the other is predominantly in a direction that is predictable and close to the orbital plane. It would be more efficient to envisage an elliptical beam that would concentrate the radiation in the area of the FOV that is crossed by the other satellite. The use of a top-hat distribution should relax the pointing requirements and/or reduce transmitted power. The addition of beam shaping optics is feasible, but not trivial. The shaping optics must be designed to create a near field compatible with the expected far field distribution. Moreover, the distribution is subjected to the transmission function of the atmosphere.

B. Receiver

The basic idea is to split the channels in two groups, SWIR A and SWIR B, and cover each group with a separate receiver module. The benefit of this approach is that the design is simplified by keeping the working ranges of each module relatively narrow, preserving the high spectral resolution. The channels in SWIR A could be served by a single receiver module and the channels in SWIR B could be served by another receiver module, with both modules sharing a single optical input. The only significant difference between the two modules is in the working spectral range. It is therefore possible to use a single opto-mechanical design for both. Because of the large number of channels using discrete components would be not efficient and has been discarded in favour of a spectrometer based solution.

When the absorption line is excessively close to its reference, it is preferable to extract it by a dedicated filter such as a Fabry-Perot etalon used as a rejection filter. This would be beneficial to increase the etendue of the spectrometer. The separate filter would be large enough (not less than ~120 pm FWHM) to accommodate the kinematic Doppler shift due to the setting/rising movement relative to the atmosphere, and narrow enough (not exceeding 150 pm) to suppress crosstalk between the channels better than 36 dB. Since this imposes very strict requirements to the filter transfer function, a simpler alternative for Doppler shift compensation would be to use two fixed FP filters detuned from the working wavelength at plus and minus the Doppler shift, depending on the type of the occultation event. Care should be taken to limit the additional sources of errors appearing as a result of this added complication. These additional sources of error come from the temperature drift of the FP and variations of the sensitivity of the different detectors

Recently, the choice to shift of the (demonstration-only) absorption line of $^{13}CO_2$, from 4770.813 cm^{-1} to 4772.176 cm^{-1} allows the distance between the reference and the closest adjacent wavelength to be increased enough to avoid the need of a separate filter, but from the point of view of the overall technology demonstration it makes sense to still consider it.

A solution based on holographic diffraction gratings generates very low stray light, giving high-efficiency and very high quality. Anyway, it is deemed inefficient due to the required high cross-channel attenuation. This dictates the selection of an alternative solution: the Spatial Heterodyne interferometer.

Spatial Heterodyne Spectrometry (SHS) allows the design of compact, high throughput, high resolution spectrometers without moving parts. To date, SHS has mainly been used in the UV and visible. The first orbital flight of an SHS was performed in 2002 with the proof of concept mission of SHIMMER (Spatial Heterodyne Imager for Mesospheric Radicals) on the Space Shuttle [4]. An improved version of SHIMMER, including a monolithic interferometer, was scheduled to be placed in low-earth orbit on STPSat-1 in late 2006.

A key feature that is relevant to the present stage of the investigation is that it is an interferometer and not a dispersive device. Its etendue is identical to that of the Fabry-Perot filter with the same spectral resolution. However it is a feature of the standard Michelson interferometer to use only 50% of the incoming light because the other 50% are directed to the input. Given the importance of the application and the need of redundancy, a double detector solution is actually beneficial so that 100% of the light is detected.

The transformation of 2D interference patterns into 1D greatly simplifies the detection part. This is possible because the spectrum of the incoming signal is known in advance and only the intensity of the discrete spectral lines needs to be measured, not their location.

It is proposed that a modified SHS (1D instead of 2D output) is used in combination with the already existing European InGaAs 512x1 infrared array from Xenics, Belgium. This array has already been used in a satellite application (EgyptSat) and has a version covering SWIR B too. Clearly there is a trade-off between the SNR ratio and the dynamic range that needs to be investigated. Another issue is the fact that shrinking the interferogram in one direction implies that the interference lines are strictly vertical; therefore a tight alignment tolerance must be used to avoid the introduction of an additional error. In contrast the 2D detection uses intentionally introduced misalignment and is insensitive to its variations. This issue could be resolved by envisaging a piezo tuning in one of the mirrors and taking advantage of the presence of a local narrowband laser source. The alignment can be easily automated if the contrast of the laser interference projected on the detector array by the interferometer is maximized by adjusting the mirror position.

Extending the SWIR A design to SWIR B should take into account the wider wavelength coverage. The problem is that SWIR B has to cover a 5 times wider wavelength range while keeping the FWHM of the instrument function the same. This leads to more spectral components than can be extracted with a linear array detector. One option is to resolve this issue is to use a 2D detector to cover the SWIR B range. Such MCT array detectors are produced by AIM and Sofradir and the technology has been space qualified. This would mean that the potential full mission solution would be built entirely by existing detectors and no significant detector development would be required. A second option is possible where SWIR B is split in two bands covered by two spectrometers. Both spectrometers would have relatively high resolution and would measure only few wavelengths that are well separated. This is beneficial for better background cancellation.

Pointing in reception must ensure that the collected energy is properly guided in the detector field of view, typically smaller than the collector field of view. The task is further complicated by the fact that the movement has variable speed partially due to the refractive bending in the atmosphere. The required correction can be achieved by moving the whole platform or by moving some optical component to shift the line of sight.

C. Baseline System Design and Technology Readiness Level

The baseline design consists of two spectrometer modules – one for SWIR A and one for SWIR B, a calibration module and a transmitter section which can include one or several transmitter modules.

This organization is beneficial in terms of scalability. It allows the number of wavelengths to be expanded by adding more transmitter modules and following some simple compatibility rules in the organization of time multiplexing. In the same time since the receiver is a spectrometer instead of a combination of discrete filters no changes are needed there to handle the expansion.

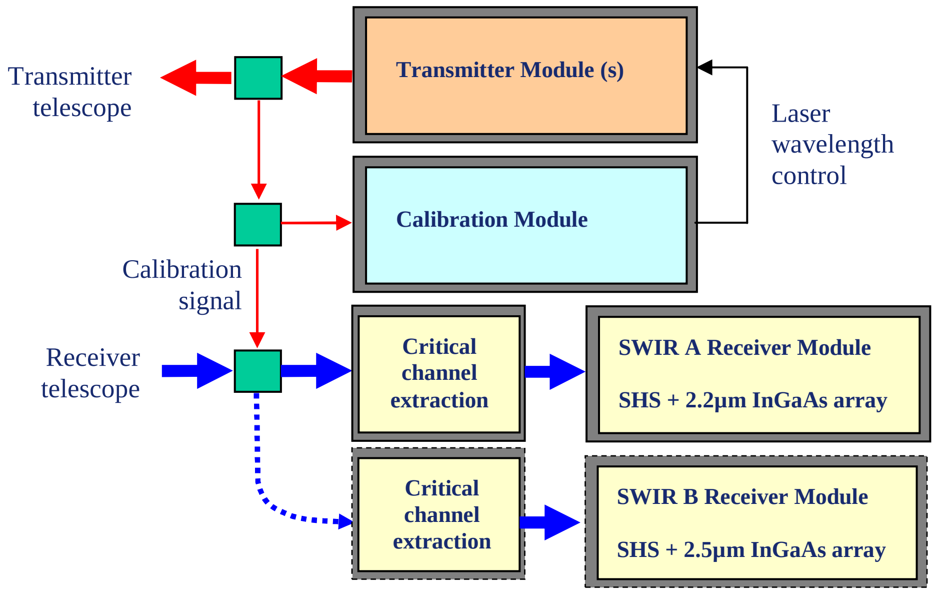


Fig. 2: Selected baseline infrared design. Every satellite caries both a transmitter and a receiver

The calibration module is a critical element of the instrument payload. The mission analysis has shown it is more efficient that every satellite has a transmitter and a receiver module. It is then possible to use the satellite's own transmitter as a calibration source for the receiver. This would mean that in the time available between the occultation events the receiver module will be calibrated against the local transmitter, while during the event it will operate with the opposing satellite's transmitter. Provided that a good reference is available on every satellite, such operation provides effective use of the satellite resources.

One of the priorities of this study is to use as much as possible existing technology to enable faster mission implementation. The technologies which are critical for the mission are the laser emitters, the wavelength shift control and the receiver spectrometer.

It should be noted that the DFB seed laser proves to be a challenging system component, especially for the longer wavelengths (above 2.3 μm). However, the starting point of this technology is relatively high and the industry is positive with respect to the required parameters. The detailed review showed also a fast development of an alternative technology that can potentially provide a solution (VECSEL). Presently however the combination of DFB and SOA is the baseline because of the possibility of sharing the SOA with associated benefits at system level.

With respect to the receiver spectrometer, where SHS is the main candidate, the effort should target the development of the instrument using existing components rather than the development of the components. If the detailed study of the spectrometer cannot prove the required performance is achievable, the back-up solution would be to implement multiple Fabry-Perot filters. This would present a significant engineering challenge because of the number of the channels, but does not require technology developments. The last option would be using a diffraction grating spectrometer, which can be implemented without significant technology development. However it would greatly increase the pressure on the lasers because of the much smaller optical throughput which must be compensated by increased laser power.

The detector readiness should be considered relatively high in spite of the switching to a detector array. This is because meanwhile the technologies for SWIR arrays have reached production status. Existing detectors from Xenics can be used for the SWIR A and for SWIR B prototypes exist, but technology development will be required.

V. CONCLUSIONS

This document outlines the baseline design for a demonstrator of an innovative occultation measurement technique based on infrared differential absorption. The design is built on a modular principle and includes transmitter modules, receiver modules and a calibration module. Different satellites will include the same groups of modules. The transmitter modules share the same opto-mechanical design. The receiver modules also share the same design.

The receiver for the demonstration mission could use only one spectrometer for SWIR A covering ~40nm around 2.1µm and measuring 11 wavelengths and one spectrometer for SWIR B covering ~180nm around 2.4µm and measuring 10 wavelengths. As an alternative it may use two spectrometers for SWIR B covering respectively ~80nm around 2.3µm and ~50nm around 2.45µm. An intermediate mission could cover only a fraction of the SWIR B wavelengths by using discrete Fabry-Perot filters.

The Doppler shift in the receiver satellite would only affect the design if fixed filters are used for certain wavelengths. In that case two filters for each wavelengths shifted in opposite directions are needed. The baseline design envisages the use of spectrometers only and will not be affected by the Doppler shift. The Doppler shift on the transmitting satellite can be handled by tuning of the laser wavelength.

Increasing the number of wavelength is achieved by adding laser modules. One laser module provides 5 wavelengths. Six laser modules will be needed for the full mission. This arrangement follows certain convenient combinations of wavelengths and provides redundancy in all missions.

The calibration module provides the laser tuning control by using a gas absorption reference and wavelength measurement. The seeding CW lasers are connected in turns to the module that sets their wavelength before the occultation events. During the events (for less than 1 min) the wavelength stability is guaranteed by the laser module design.

The proposed baseline design features simplicity, flexibility and scalability. Further to that, using a modular approach, it offers a good potential for an overall cost effective solution concerning the infrared payload of the occultation satellites.

REFERENCES

[1] ESA SP-1279(4) – ACE+ - Atmosphere and Climate Explorer, April 2004

[2] ACE+ - Atmosphere and Climate Explorer – Technical and Programmatic Annex to ESA SP-1279(4), April 2004

[3] “Science Objectives and Observational Requirements of the ACCURATE Mission Concept – ESA IRDAS Study”, DMI/ESA-IRDAS/ObsReq, October 2009

[4] John M. Harlander, Fred L. Roesler, Joel G. Cardon, Christoph R. Englert, and Robert R. Conway, "Shimmer: A Spatial Heterodyne Spectrometer for Remote Sensing of Earth ’ Middle Atmosphere," Appl. Opt. 41, 1343-1352 (2002)