A-SCOPE: concepts for an ESA mission to measure CO_2 from space with a lidar

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ABSTRACT
A-SCOPE (Advanced Space Carbon and Climate Observation of Planet Earth) has been one of the six candidates for the third cycle of the Earth Explorer Core missions, selected by the European Space Agency (ESA) for assessment studies [1]. Earth Explorer missions focus on the science and research aspects of ESA's Living Planet Programme [2]. A-SCOPE mission aims at observing atmospheric carbon dioxide (CO_2) for a better understanding of the carbon cycle. Knowledge about the spatial distribution of sources and sinks of CO_2 with unprecedented accuracy will provide urgently needed process information about the global carbon cycle. A-SCOPE mission encompasses a new approach to observe the Earth from space based on a Differential Absorption Lidar. Though building on the efforts deployed by ESA since the early eighties in the advancement of critical technology for lidar systems, the proposed measurement concept is innovative and is supported by different technology developments. The objectives and the proposed implementation of the mission are presented in this paper as well as the instrument concepts, their performance and the status of the technology developments.

1. INTRODUCTION

Carbon dioxide is the most important anthropogenic greenhouse gas. At present it contributes to more than half of the total anthropogenic change in the Earth's radiation budget and its relative contribution is likely to increase in the future. The observed rise in atmospheric CO_2 by more than 30 % since pre-industrial times has been identified in the last assessment report by the Intergovernmental Panel on Climate Change (IPCC) as the main driver for the increase in global mean temperature over the same period. The main cause of this atmospheric CO_2 increase is the emissions from the burning of fossil fuels and from the land-use change. However the atmospheric CO_2 observations reveal also that less than half of the total anthropogenic emissions have remained in the atmosphere. The atmospheric fraction reflects the balance between anthropogenic carbon emissions and the dynamics of terrestrial and oceanic processes that removes CO_2 from the atmosphere. The long-term evolution and the variation in space of this balance are the key to understand and predict speed and magnitude of human induced climate change.

Direct measurements of CO_2 fluxes are difficult to obtain and sparse in time and space which prevent their extrapolation to larger scale. By contrast the atmosphere acts as a large-scale mixer and integrator whose CO_2 variations reflect where CO_2 has been added or removed from the atmosphere. The geographic distribution and the temporal evolution of atmospheric CO_2 can be used to quantify surface fluxes. The interpretation of these variations is not straightforward, but by using information about transport and mixing from atmospheric transport models, one can, in principle, determine where the sources and sinks for CO_2 are and how they vary in time. Space-based measurements of atmospheric CO_2 with high accuracy and true global coverage allow to take full advantages of the inversion method. Initial steps toward obtaining global distribution of CO_2 have come from existing satellite instruments, which are multi-purpose passive missions such as TOVS, SCIAMACHY, AIRS, IASI. However these missions suffer from an insufficient precision, possible bias or have a low sensitivity in the planetary boundary layer. Following the recent launch failure of NASA's OCO (Orbiting Carbon Observatory) mission, the first and only mission devoted to atmospheric CO_2 observation is the Japanese mission GOSAT (Greenhouse gases Observing SATtellite) [3,4]. However it relies on a passive optical technique which imposes some limits on the precision and accuracy as well as on the spatial and temporal coverage. These limitations are less severe in a laser-based technique which forms the main motivation for the proposed second generation of CO_2 devoted space missions, namely ASCENDS from NASA and A-SCOPE from ESA.

In the frame of the implementation of the 7^{th} Earth Explorer mission, ESA had selected A-SCOPE in 2005 together with five other missions for assessment study. Results of these assessments studies have culminated in a User Consultation meeting held in Lisbon early 2009 where decision has been taken for A-SCOPE not to enter a Phase A. However due to the recognized potential of the A-SCOPE approach to provide a major step forward in the understanding of the carbon budget, recommendations have been formulated to mature the instrument concept by pursuing technological efforts. This paper presents the main aspects of the mission objectives, its proposed implementation with a specific emphasis on the instrument concept and performance.

2. A-SCOPE MISSION OBJECTIVES

Currently, one cannot estimate the mean fluxes of CO_2 on the scale of an entire continent to much better than about 1 Pg C yr^{-1} which is very large compared for instance to the fossil fuel emissions of the European Union which were about 1.1 Pg C yr^{-1} in the past decade. The A-SCOPE mission objective is to improve this situation dramatically by enhancing the atmospheric CO_2 observation to the point where CO_2 fluxes can be estimated to better than 0.02 Pg C yr^{-1} at a scale of 1000 km × 1000 km. Constraining the carbon fluxes at the Earth's surface requires deriving

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spatial and temporal variations and gradients of very precise and accurate observations of the column averaged dry-air mixing ratio of CO_2, referred to as XCO_2.
The A-SCOPE mission will provide XCO_2 with a nadir-looking pulsed Integrated Path Differential Absorption (IPDA) lidar. It is recognized that an active CO_2 mission is the only way to get truly global and day/night coverage under both clear and broken cloud conditions and to obtain the scientifically desired accuracy and precision for the atmospheric CO_2 retrievals to solve for the sources and sinks with regional resolution.

The main objectives of A-SCOPE are an improved understanding and a better quantification of the global carbon cycle. Improving the understanding of the fundamental processes governing the exchange of carbon between the atmosphere, land and ocean and their feedback mechanisms with the climate system allows to include them correctly and reliably in Earth System models. Such models are used to predict the rate of greenhouse effect increase and climate change for the forthcoming century. Therefore A-SCOPE objective is as well to contribute to improved prediction of the rate climate change as well as of the fate of natural ecosystems in the context of climate changes.
In addition, the mission will monitor the impact of large-scale climatic disturbances and other factors (like forest fire, afforestation…) on regional carbon budgets which are needed for the development of optimal carbon mitigation strategies. Though the objectives of A-SCOPE focus on the exchanges of CO_2 between the atmosphere and either land or ocean, rather than on fossil fuel emissions, it will nevertheless provide useful data in the context of international emission reduction agreements that may follow the Kyoto protocol.

3. A-SCOPE OBSERVATION REQUIREMENTS

Based on inverse modeling calculation, the measurement precision required to reach the CO_2 flux uncertainty of 0.02 Pg C yr^{-1} is found to be 0.5 ppm for a uniform weighting function assuming an integration length of 50 km. The measurement precision includes both instrument random errors (measurement error, laser frequency) and random errors in ancillary data (spectroscopy, scattering surface elevation, geophysical parameters) with equal contributions [1]. The requirement scales with the weight of the weighting function in the planetary boundary layer. For the proposed set of operating wavelengths, the instrument random errors are given in Table 1 for both threshold and target.
Because CO_2 has a long lifetime in the atmosphere, the background CO_2 concentration is large compared to the spatial and temporal gradients that result from surface carbon fluxes. As a consequence, the requirements on the relative accuracy are very demanding. Simulations have shown that large errors on the fluxes result from regionally and temporally varying biases in the XCO_2 values. Globally uniform biases have no effects on product quality. On the other hand, spatially coherent biases, such as those that can result from the surface altitude or specific spectral features of the surface reflectance are very problematic. As a consequence, it is required that slowly varying biases in space or time shall not exceed 10 % of the random error requirements.

Table 1: *A-SCOPE observation requirements*

Parameters	Requirements		
Level 1b product	Total differential atmospheric optical depth		
Vertical resolution	Total column		
Integration length	50 km		
Relative Random Error		Threshold	Target
	@ 1.57µm	2.2 10^{-3}	7.4 10^{-4}
	@ 2.05 µm	4.5 10^{-3}	1.5 10^{-3}
Relative Systematic Eerror	10% of random error		
Scattering surface elevation accuracy	3 m		

Suitable absorption lines for CO_2 concentrations measurements with respect to absorption cross section and temperature insensitivity can be found around 1.57 µm and 2.05 µm. In both spectral regions, temperature sensitivity and line interference with water vapour or other atmospheric trace gases can be minimized by careful selection of the on- and off-line positions in the vicinity of the absorption line. The exact lines position used during the assessment studies will be optimised in future phase as a results of a trade-off between improved instrument and spectroscopic parameters.

4. A-SCOPE MISSION CONCEPT

A-SCOPE will follow a near-polar sun-synchronized orbit with 6 hours Local Time Descending Node, at a relatively low reference altitude in the range of 325 to 400 km. The low altitude has been chosen to improve the lidar radiometric budget and the dawn-dusk orbit to provide a stable thermal environment. The typically low Earth reflected Sun background light is further reduced by the measurement geometry, the solar zenith angle being always larger than 60 degrees.
The proposed satellite platform concepts have significant heritage from satellite systems under development in the frame of already approved Earth Explorers (ADM-Aeolus, EarthCARE) and of GMES Sentinel missions. The overall satellite configuration offers a modular approach with a clear separation between the payload module and the platform module. The platform structural concept is based on a central cylinder providing the main load path to the launcher and supporting the propellant tanks. Four shear panels connect the cylinder to the lateral panels, where the platform equipment and the thermal radiators are accommodated. The baseplate of the optical bench is connected to the platform via isostatic mounts in order to thermo-elastically decouple receive and transmit telescopes from the platform structure. In order to improve the instrument LOS pointing knowledge the attitude sensors are mounted directly on the optical bench. The stability of the pointing knowledge through the mission lifetime implies a limit to the contribution of the attitude sensor bias as well as an adequate characterization/calibration of the misalignment between the attitude sensors and the telescope caused by launch and thermo-elastic effects in orbit.
Table 2 summarises the main satellite budgets. The ranges correspond to the budgets for the instruments concepts at 1.57 µm and at 2.05 µm. Both spacecraft configurations are depicted in Figure 1.

Table 2: *A-SCOPE main satellite budgets*

Parameters	Specifications
Mass Payload	280-380 kg
Mass platform	570-730 kg
Power payload	490-520 W
Power platform	500-800 W
Payload data rate	0.38-1.7 Mb/s
On-board raw data storage	2-9 Gb/orbit

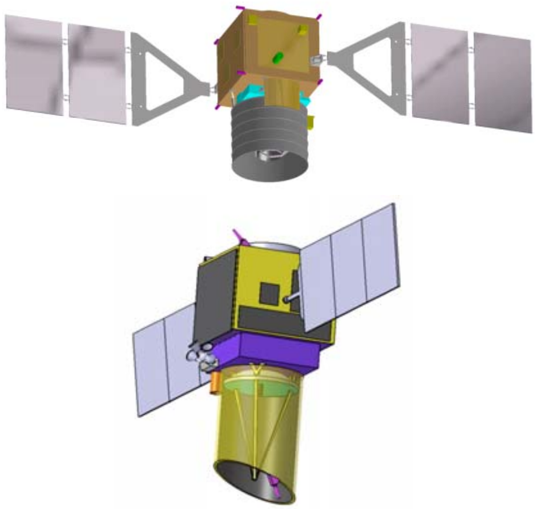

Figure 1: *A-SCOPE spacecraft configuration with IPDA lidar concept at 2.05 um (top) and 1.57 um (bottom)*

5. INSTRUMENT CONCEPTS AND PERFORMANCE

In order to achieve an accurate measurement of atmospheric CO_2 from space the A-SCOPE measurement concept is based on the integration of the whole atmospheric column relying on the echo from the backscattering surface (ground, canopy or thick clouds). Such measurement technique is called Integrated Path Differential Absorption (IPDA). The A-SCOPE lidar instrument transmits two laser pulses at slightly different wavelengths. One laser wavelength (on-line) is selected within a CO_2 absorption line while the other wavelength (off-line) is selected close to the first one but with sufficient separation to encounter a significantly smaller absorption. The ratio of the return signals correlated with the associated transmitted laser energies gives a measurement of the CO_2 Differential Absorption Optical Depth (DAOD). From the DAOD, the column-averaged dry air CO_2 mixing ratio is calculated using the hard target DIAL equation with ancillary atmospheric and spectroscopic data. Sizing of the lidar is dictated by the random error requirements of 0.5 ppm for the CO_2 mixing ratio. A power-aperture of 2 to 3 Wm^2 results, assuming detectors with Noise Equivalent Power below 100 $fWHz^{-0.5}$. Systematic errors contributing to spatial or temporal varying biases have to be 10 % lower than random errors. They drive many of the A-SCOPE instrument and platform design: radiometric calibration system, receiver architecture, detector linearity, frequency stability and spectral purity of the transmitter as well as the pointing stability. Table 3 summarises the main technical specifications of the A-SCOPE instrument for both concepts proposed at the end of the assessment studies.

Table 3: *A-SCOPE IPDA design parameters*

Parameters	Unit	Values	
Wavelength	nm	1572	2051
Laser pulse energy	mJ	50	55
Pulse Repetition Frequency	Hz	50	
Spectral stability (drift)	kHz	70	100
Telescope diameter	m	1	1.2
Detector		APD	

The different subsystems of the IPDA instrument are shown in the block diagrams of Figure 2. A bistatic configuration is proposed as it offers the advantage of polarization insensitivity and a mechanical decoupling of the receiver from the transmitter.

The receiver optical subsystem is based on a 1 m class Cassegrain-like telescope and low-noise avalanche photodiode detector. For each of the bands, a laser source has been selected. Both options need the generation of a pair of pulses (on- and off-line wavelengths) separated by about 250 µsec at an overall pulse repetition frequency of 50 Hz. For the generation of double pulses at 1.57 µm with 50 mJ energy per pulse, the Nd:YAG MOPA (Master Oscillator, Power Amplifier) laser at 1.06 µm combined with an OPO/OPA (Optical Parametric Oscillator/Amplifier) as frequency converter is preferred. For the generation of double pulses at 2.05 µm with 55 mJ energy per pulse, the same approach or a direct emission laser based on a Thulium (Tm) pumped Holmium (Ho) power oscillator can be implemented.

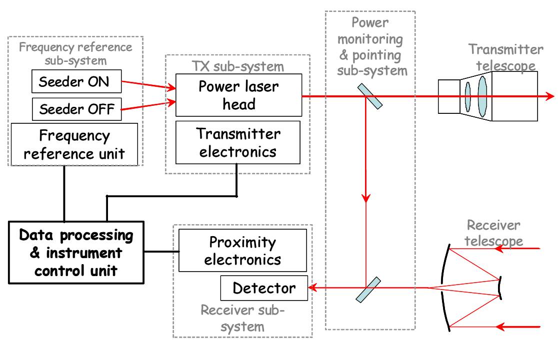

Figure 2: *Functional block diagram of the IPDA instrument architecture*

For the nominal instrument parameters, the radiometric performance is computed against surface scattering elevation for the two extreme cases of lidar reflectivity. A minimum value of 0.035 sr^{-1} is associated with an average lidar reflectivity over ocean, while a maximum value of 0.3 sr^{-1} accounts for strong scattering as could be observed above desert. Figure 3 shows that the performance of both concepts meets the threshold requirement with good margins. Besides, most of the contributors of systematic errors have been identified: spectral purity and stability of the laser, accuracy of the relative power monitoring and stability of the linearity of the detector response, as well as pointing knowledge. However, it remains to be verified that the combination of the current best estimates of the instrumental parameters can indeed be achieved. A complete description of A-SCOPE performance can be found in [5].

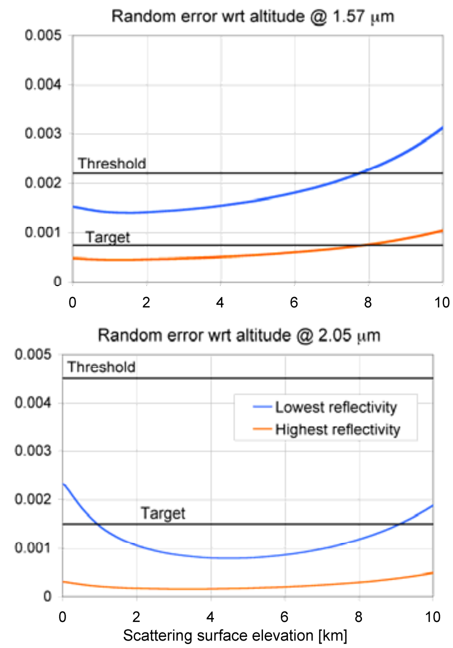

Figure 3*: DAOD relative random error performance computed as a function of the ground elevation*

6. TECHNOLOGY DEVELOPMENTS

Demanding and unusual instrument specifications, early identified in the assessment study have led to initiate several pre-development activities.

6.1 Transmitters at 1.57 μm

The development of an Optical Parametric Oscillator/ Optical Parametric Amplifier (OPO/OPA) laser system meeting the A-SCOPE requirements with the exception of the spectral stability and purity has been initiated. Following a first theoretical trade-off phase concerning the crystal material, KTP has been retained.

A low-power oscillator design has to be chosen so that it provides an optimum beam profile which is generally achievable near oscillation threshold and that can be maintained through the amplification process. The technique of injection seeding will guarantee that the parametric devices emit in a narrow bandwidth with the highest possible spectral purity. A KTP-OPO has already been setup and several KTA-OPA designs are being tested. Energies up to 52 mJ have been obtained with a non-optimised pump laser. Further work will include coupling of an improved pump source, optimisation of the oscillator design before addressing the full characterisation of the transmitter

6.2 Transmitters at 2.05 μm

Two developments have been initiated to develop laser sources respectively based on an OPO/OPA concept and on a fibre laser concept.

A promising NIR transmitter concept is a frequency converter based on a master-oscillator power amplifier (MOPA) arrangement. At 2.05 μm, the development aimed at delivering pulses of 40 mJ at 50 Hz with more than 30 % optical to optical conversion efficiency. The implementation of an entangled cavity, doubly resonant OPO (DROPO) has been selected as it delivers a tunable single mode emission (from 1.5 to 4.3 μm) with high spectral purity from a robust and compact arrangement without the need of an external seeder. In the first stage, a type II ppLN crystal coverts the 1.064 μm laser pump into the 2.05 μm signal. To reach the required energy, the DROPO output is amplified in several stages. A breadboard has been setup demonstrating around 11 mJ of signal for 86 mJ of pump incident on the KTP crystals and a total pump energy used of 93 mJ. An overall conversion efficiency of 12 % is thus obtained for the signal beam alone. High signal beam quality is achieved with M2 value better than 1.9. Stabilisation of the frequency has been measured with standard deviation of 3 MHz over 30 s.

A second development aims at demonstrating the technical feasibility of a laser diode pumped all-fibre pulsed laser. At a pulse repetition frequency in the range of 2 - 4 kHz the fibre laser source (FLS) shall deliver output pulses of several tens of nanoseconds pulse duration with an energy of minimum 2 mJ per pulse at the on-line and > 0.2 mJ at the off-line with 250 μs time separation between both lines. In addition the FLS output pulses shall exhibit a narrow line width in the range of few tens of MHz with a line width stability of better than 10%, a central frequency stability of better than 0.2 MHz and a spectral purity of 99.9% within 1 GHz. A breadboard based on a DFB diode laser and a novel fibre amplifier concept is being built. Three thulium-doped fibre amplifiers are needed to reach 2 mJ. The final one requires a larger core than produced previously for thulium doping employing a microstructured fibre or novel glass host.

6.3 Detectors at 2.05 μm

A recent development has been initiated to develop 2 μm APD relying on Mercury Cadmium Telluride (MCT). With MCT very low excess noise factor is expected in combination with a high gain. The geometry of loophole junction formed in LPE grown short wave material is ideally suited to APD operation. The proposed design permits low doping levels resulting in high breakdown voltages and very low excess noise. Preliminary performance simulation indicate that a Noise Equivalent Power smaller than 100 $fW/Hz^{0.5}$ for a detector/pre-amplifier bandwidth larger than 20 MHz is achievable.

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