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ATLID, THE ATMOSPHERIC LIDAR ON BOARD THE EARTHCARE SATELLITE

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Abstract— **The EarthCARE mission is the sixth Earth Explorer Mission of the ESA Living Planet Programme, with a launch date planned in 2015. It addresses the interaction and impact of clouds and aerosols on the Earth's radiative budget. ATLID (ATmospheric LIDar), one of the four instruments of EarthCARE, shall determine vertical profiles of cloud and aerosol physical parameters (altitude, optical depth, backscatter ratio and depolarisation ratio) in synergy with other instruments. Operating in the UV range at 355 nm, ATLID provides atmospheric echoes with a vertical resolution of about 100 m from ground to an altitude of 40 km. As a result of high spectral resolution filtering, the lidar is able to separate the relative contribution of aerosol (Mie) and molecular (Rayleigh) scattering, which gives access to aerosol optical depth.**

The purpose of the paper is to present the progress in the instrument and subsystem design. The instrument is currently in phase C where the detailed design of all sub-systems is being performed. Emphasis will be put on the major technological developments, in particular the laser Transmitter, the optical units and detector developments.

Keywords- Lidar, High Spectral Resolution, Aerosol profiling

I. INTRODUCTION

The EarthCARE mission has been specifically defined with the basic objective of improving the understanding of cloud-aerosol-radiation interactions in order to include them correctly and reliably in climate and numerical weather prediction models. The goals are to retrieve vertical profiles of clouds and aerosols, and the characteristics of their radiative and micro-physical properties to determine flux gradients within the atmosphere and fluxes at the Earth's surface, as well as to measure directly the fluxes at the top of the atmosphere and also to clarify the processes involved in aerosol-cloud and cloud-precipitation-convection interactions. Specifically, the scientific objectives are:

1 - The observation of the vertical profiles of natural and anthropogenic aerosols on a global scale, their radiative properties and interactions with clouds.

2 - The observation of the vertical distributions of atmospheric liquid water and ice on a global scale, their transport by clouds and their radiative impact.

3 - The observation of cloud distribution ('cloud overlap'), cloud-precipitation interactions and the characteristics of vertical motions within clouds.

4 - The retrieval of profiles of atmospheric radiative heating and cooling through the combination of the retrieved aerosol and cloud properties.

These mission objectives will be addressed by measuring simultaneously the vertical structure and the horizontal distribution of cloud and aerosol fields together with the outgoing radiation over all climate zones. Such observations will enable the performance of current Numerical Weather Prediction models and General Circulation Models to be evaluated so that the various proposed schemes for parameterizing aerosols, clouds and convective precipitation can be compared, any biases and errors within such schemes can be identified, and ultimately such schemes can be improved.

Figure 1. Artist's impression of EarthCARE in orbit

To meet these ends the EarthCARE satellite will carry a suite of four instruments: an ATmospheric LIDar (ATLID), a Cloud Profiling Radar (CPR), a Multi-Spectral Imager (MSI) and a Broad-Band Radiometer (BBR). The instruments will operate individually and in synergy. All instruments will be directed towards the satellite ground track with the exception of MSI which will provide an imaged swath distributed about the satellite ground track. Stringent pointing requirements will ensure co-registration of the three nadir pointing instruments and accurate knowledge of their position in the swath of the imager. A representation of the satellite viewing geometry is shown in figure2.

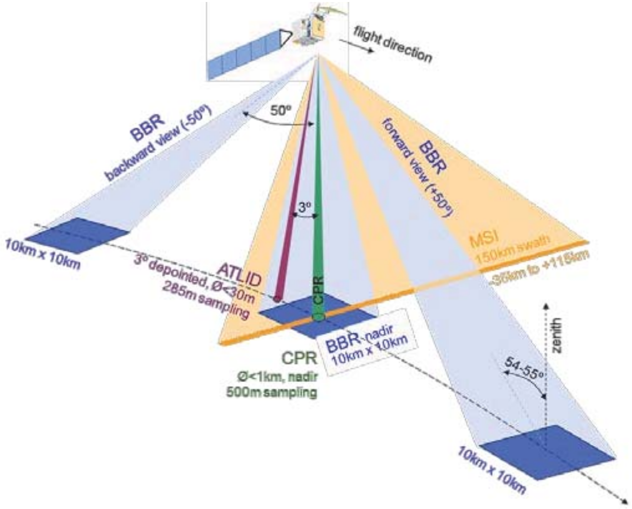

Figure 2. Satellite viewing geometry

The satellite will make global observations from a sun-synchronous orbit at a mean spherical altitude of about 393 km. The orbit has been selected to have a descending node crossing time of 14:00 and will have a repeat cycle of 25 days.

EarthCARE is designed for an in-orbit lifetime of three years but will carry sufficient consumables for a possible one-year extension of mission. It is intended that the satellite should have an operational availability of 95% during the routine phase.

II. INSTRUMENT TECHNICAL DESCRIPTION

A. ATLID measurement principle

Operating in the UV range at 355 nm, ATLID provides atmospheric echoes with a vertical resolution of about 100 m from ground to an altitude of 20 km and 500m from 20km to 40km altitude. The measurement geometry is displayed in figure 3. Thanks to a high spectral resolution filtering, the lidar is able to separate the relative contribution of aerosol (Mie) and molecular (Rayleigh) scattering, which gives access to aerosol optical depth. Co-polarised and cross-polarised components of the Mie scattering contribution are also separated and measured on dedicated channels.

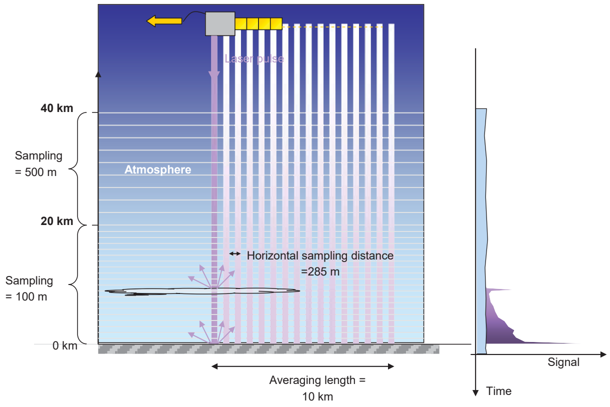

Figure 3. ATLID sampling and measurement principle

The measurement principle which was retained for ATLID uses the fact that interaction of light with molecules or aerosols leads to different spectra. Whereas the Brownian motion of molecules induces a wide broadening of the incident light spectrum, the single scattering with an aerosol does not affect the spectrum shape of the incident light. As a consequence, a simple means of separating the backscattering contributions consists in filtering the backscattered spectrum with a high spectral resolution filter centred on central wavelength, as depicted on figure 4.

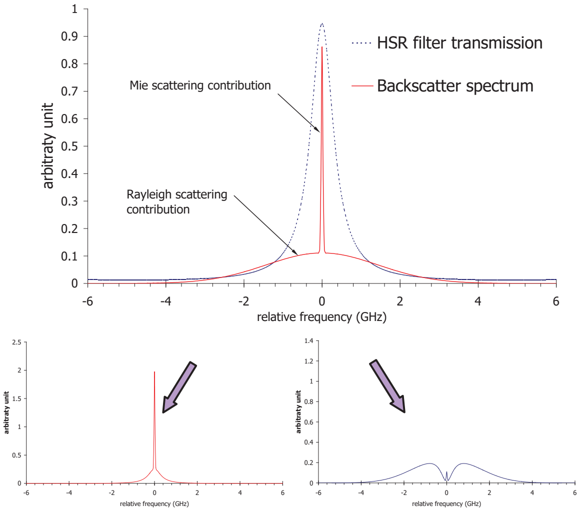

Figure 4. Mie / Rayleigh scattering contributions separation principle

Table 1 summarizes the observation requirements applicable to ATLID. The instrument shall allow retrieval of the pure Mie and molecular backscatter signals. The measurement accuracy is specified for a reference atmospheric scene consisting of thin cirrus at 1o km altitude. A telescope footprint smaller than 30 m is favored to minimize the multiple scattering effects and to reduce the solar background noise by reducing the telescope field of view.

TABLE I. ATLID OBSERVATION REQUIREMENTS

	Mie co-polar channel	**Rayleigh channel**	**Mie cross-polar channel**
Cirrus optical depth	0.05		
Cirrus backscatter sr^{-1} m^{-1}	$8\ 10^{-7}$		$2.6\ 10^{-5}$
Vertical resolution	100 m	300 m	100 m
Horizontal resolution	10 km		
Required Accuracy	50%	15%	45%

B. *Instrument overview*

ATLID is designed as a self-standing instrument reducing the mechanical coupling of instrument/platform interfaces and allowing better flexibility in the satellite integration sequence.

The lidar functional architecture is organised in four main functions, namely the transmitter, the emit/receive telescope, the receiver and the control unit called ATLID Control and Data Management (ACDM) unit.

The emitter includes the power laser head and its transmitter laser electronics, a beam steering mechanism for ensuring co-alignment of the emitting and receiving lines of sight over the mission life time, and a beam expanding optics. The laser is a highly stable single-mode laser emitting at 355 nm (tripled frequency of a Nd:YAG laser) and therefore requires a reference laser seeding the laser oscillator.

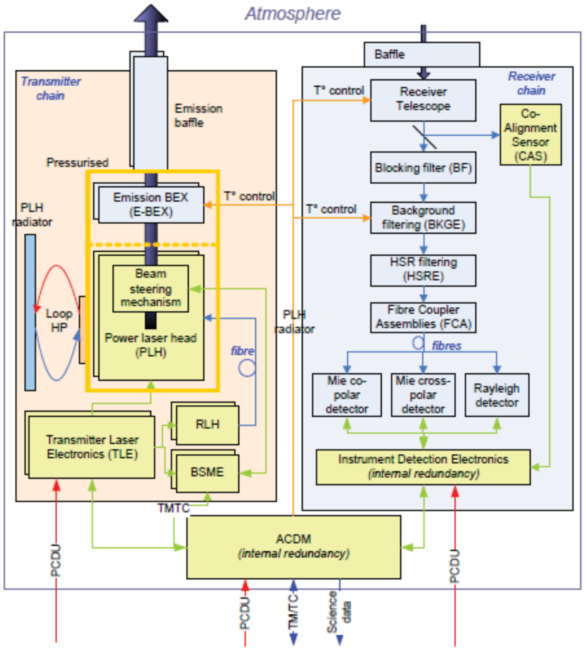

Figure 5. ATLID instrument block diagramme

The receiving telescope is an afocal Cassegrain aiming at collecting the backscattered light and providing a large magnification ratio to reduce effect of internal misalignments.

The receiver implemented at the back of the telescope includes a background light filtering stage, a High Spectral Resolution filter and a co-alignment sensor. The signal is transported to the detectors by means of fibre couplers, which allows deporting the whole detection chain to the interface panel. The receiver also includes all the detection functions that range from the detector to the analog-to-digital convertor.

The control and data management unit ensures the following electrical functions: 1) synchronisation between laser emission and data acquisition ; 2) data processing and data stretching toward the S/C ; 3) mechanisms drive and thermal regulation functions ; 4) TM/TC and commandability/observability management.

The instrument design relies on re-use of technologies developed for the ALADIN wind lidar for the Aeolus mission as the single-mode pulsed laser transmitter, memory CCD detector, receiver high spectral resolution spectral filter. Moreover, the design worked-out since beginning of feasibility phases now features further improvements and innovations which are implemented to match the ATLID mission demanding objectives:

- an improved read-out stage for the memory CCD, which allows quasi photon-counting with a total noise in darkness of 2 to 3 e- rms per sample,
- a fibred receiver allowing decoupling of detection units and focal plane assembly, for mechanical and thermal aspects as well as for development aspects,
- mini loop heat pipes for evacuation of the laser heat,
- sealing and pressurization of the power laser head to tackle the contamination issue and secure in-flight performances,
- bistatic design with full separation of emission and reception paths. This design was selected to reduce cross-coupled contamination between receiver and emitter, as well as allowing a full pressurization of the emission path.

The instrument, which overview is shown in figure 6, is designed, integrated and tested by Astrium SAS as prime contractor leading a European consortium in charge of developing the ATLID sub-systems.

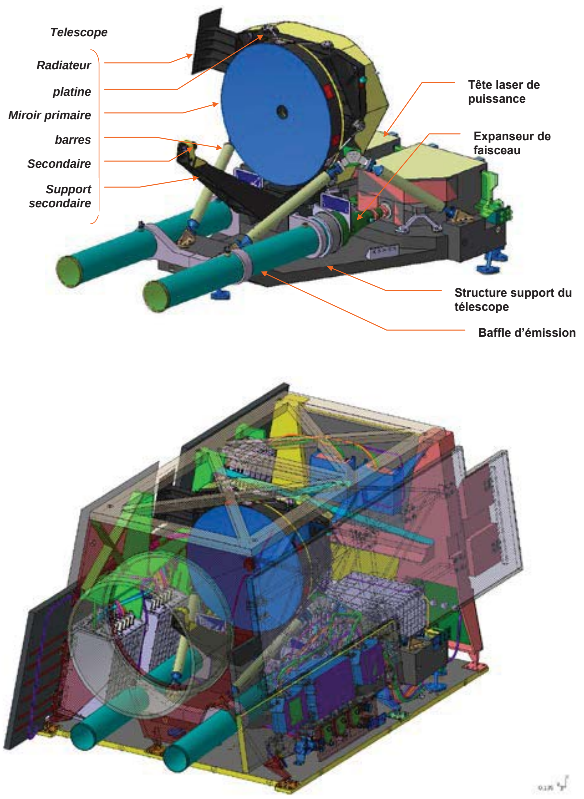

Figure 6. ATLID instrument overview

C. *Optical design*

The optical design is based on a bistatic architecture. This architecture was selected with the objective to separate the emission and reception functions allowing a full pressurisation of the emission path. An afocal 620 mm diameter Cassegrain telescope is used in reception, with a high magnification ratio. The receiver field-of-view is thus kept below 75 µrad, minimising the shot noise associated with the acquisition of Earth background signal.

The design is based on an all-Silicon Carbide mirror and mounts, designed by EADS Astrium and manufactured by Mersen.

Figure 7. Telescope primary mirror made of SiC

The receiver optical design performs a separation of polarisation (co-polarised and cross-polarised signals) and spectral components (Mie or Rayleigh scattering contributions) with the constant goal to limit the cross-talks between each of the three channels, namely the Mie co-polarisation, the Mie cross-polarisation and the Rayleigh channels. Several filtering stages (narrow-band interference filter, spatial filter and Fabry-Perot etalons) are required to achieve such purity and to reject the high amount of Earth background signal around the narrow laser wavelength.

The High Spectral Resolution Fabry-Perot etalon features narrow bandwidth of the order of 0.3pm, so that separation of the Mie and Rayleigh backscatter signals can be efficiently performed. The design developed by RUAG and SESO is inheriting from Aladin spectrometers (figure 8) and is based on a combination of polarizing beam splitters and a Fabry-Perot etalon.

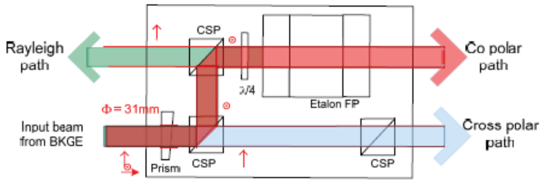

Figure 8.

a- ATLID high spectral resolution filtering stage optical principle

b- Fabry-Perot etalon manufatured for ALADIN

The spectral co-registration approach consists in periodically tuning the laser transmitter frequency to the high spectral resolution filter peak transmittance by sweeping the laser frequency over its tuning range and estimating from the signal distribution on Mie and Rayleigh channels the best frequency command.

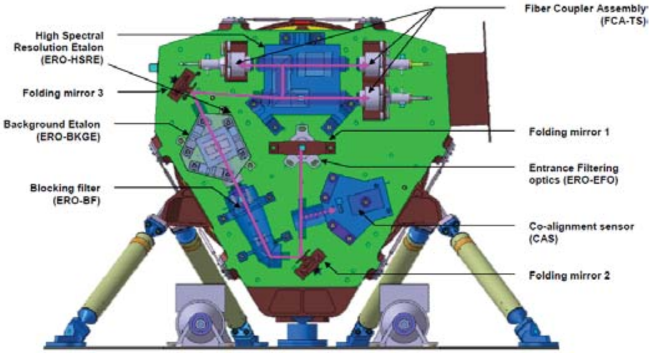

Figure 9. ATLID receiver layout

D. *Low noise detection chain*

The ATLID detection chain shall be able to measure single photon events to meet the worst case radiometric performance requirements. Therefore, a high response together with an extremely low noise are necessary to fulfill the signal acquisition requirement. As for ALADIN instrument, ATLID encompasses a memory CCD. The ATLID design performs fast sampling of the echo signal (1.5 MHz corresponding to 100 m vertical sampling distance) and on-chip storage of the echo samples which allows delayed read-out at very low pixel frequency (typically below 50 kHz). Combined with an innovative read-out stage, the detection chain provides an extremely low read-out noise (< 3e- rms per sample). Accumulation of several consecutive echoes on the chip is possible with the detector design, enhancing the acquisition chain radiometric performance. The detector is developed by E2V while the detection chain electronics is developed by CRISA.

E. Transmitter requirements and design

The laser transmitter of ATLID instrument shall deliver high energy pulses at a repetition rate of 51 Hz corresponding to 140 m ground horizontal sampling. The Pulse Repetition Frequency has been lately changed allowing a relaxation of the Master Oscillator requirements while using the amplifier with the same operation mode as for Aladin development. More than 35mJ at 355 nm (tripled Nd:YAG wavelength) are required at laser output to meet the instrument radiometric performance. At the same time, high frequency purity (line-width of typically 50 MHz) and extreme stability (50 MHz on one month time scale) are mandatory in order to separate the Mie and Rayleigh scattering contributions by High Spectral Resolution technique.

This is achieved by a transmitter architecture based on three sub-systems:

- A reference laser head (RLH) providing a continuous laser seeding signal which frequency is permanently controlled in closed-loop with respect to an ultra-stable reference cavity.

- A power laser head (PLH), shown in figure 10, injected by the reference laser by means of an optical fibre. It generates the laser pulses in its master oscillator section, amplifies the resulting pulses through its amplifier section, and then converts the 1064 nm laser signal into the 355 nm wavelength in its higher harmonics generation section. The q-switched master oscillator is generating single frequency laser pulses of about 8 mJ. The oscillator cavity is folded several times for compactness reasons and the rod shaped active material is laser diode pumped in a redundant configuration. The output of the master oscillator is then amplified in a double pass amplifier delivering about 150 mJ. The zig-zag slab amplifier is double side pumped with a total of eight laser diode stacks of about 700 W (derated) peak output power each for 0.2 ms duration. The second and third harmonic generation LBO-crystals are placed after the power amplifier to generate up to 50 mJ in the ultraviolet (355 nm).

- A transmitter electronics unit which contains all the control and power electronics needed for the operation of previously described PLH and RLH, and provides the TM/TC interface to the ATLID control unit.

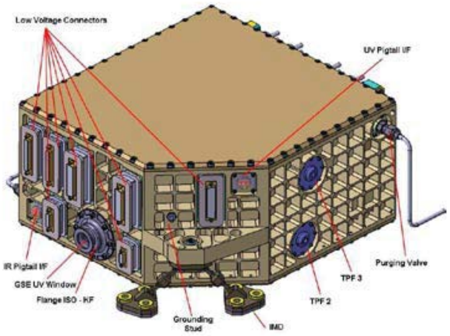

Figure 10. ATLID power laser head

A significant evolution of the laser design with respect to the ALADIN transmitter lies in the fact that ATLID power laser head is sealed and pressurized. This improvement is believed to ensure more stable operating conditions to the sensitive components of the laser, and to isolate the laser internal space from surrounding contaminants over the ground and operational lifetime. Pressure is also deemed to improve tolerance to laser induced contamination, which is the degradation of an optical surface resulting from the interaction of molecular contamination with a high laser illumination level. Such a pressurised design has been extended to the whole emission path, including the beam expanding optics. The laser transmitter is developed under the prime leadership of Selex Galileo with sub-contractors Quantel for the development of the amplifier and laser diodes, TESAT for the Reference Head.

An Emission Beam Expander is used to further expand the laser beam and reduce the laser beam divergence to about 45 microradians so that it is coupled within the narrow receiver field of view.

The expansion of the beam brings also a significant reduction of the energy density on the last optics submitted to vacuum, thus beneficial for minimizing risk of laser induced damage and contamination. An expansion of about 7 is achieved through a 3 lens design bringing the beam to more than 100mm diameter. The Emission Beam Expander is developed by SODERN.

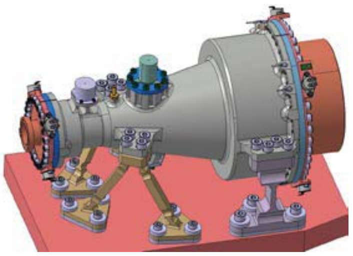

Figure 11. Emission Beam Expander view

F. Co-Alignment Sensor

The instrument is equipped with a Co-Alignment Sensor that is aimed at measuring the direction of the laser emission with respect to the receiver field of view. The measured information is fed back to a beam steering mechanism correcting for any mis-pointing of the laser. The control loop is operated at low speed as it corrects mainly the variation in the line of sight due to thermo-mechanical deformations along the orbit and lifetime of the instrument.

The Co-Alignment Sensor is a small camera measuring the integrated backscatter signal from ground to top of the atmosphere. It includes the following functions as rejection of the solar background, separation of the optical signal with the scientific channels, acquisition and sampling of the integrated signal with a CCD. The camera is developed by a consortium led by CRISA.

G. Thermal control design

Another innovation is related to the thermal control of the power laser head. This sensitive active sub-system presents high heat dissipation (around 150 W) and requires stable interface temperature (0.5K). Mini loop heat pipes are used in ATLID design to efficiently evacuate the laser heat while offering a low stiffness mechanical interface ; the flexible pipes which transport the ammonia from evaporators to the anti-sun side radiator allow a good mechanical decoupling of the laser with respect to its radiator, thus minimising the stress experienced by the laser optical bench. This new technology was successfully validated in flight during FOTON experiment, and a life test has been running for the last 2.5 years to demonstrate the lifetime of such devices. High conductance, low sensitivity to gravity orientation during ground tests are other decisive advantages which make the loop heat pipes preferable to standard heat pipe technology for ATLID application.

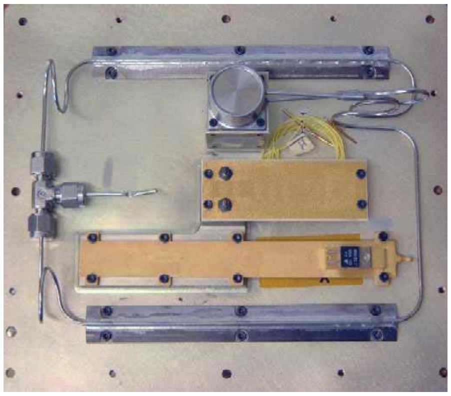

Figure 12 : Mini loop heat pipes are used to cool and regulate the power laser head

III. DEVELOPMENT STATUS

The instrument is currently in development is phase C/D. Considering the heritage from the ALADIN instrument, a proto-flight approach is proposed for the instrument development. Furthermore, the instrument test programme is supported by an Electrical and Engineering Model aiming at validating electrical interfaces, functions and the performance of the detection chain.

The laser transmitter involving several critical technologies, its development is supported by several models validating the technologies and the performance:

- A structural and thermal model aiming at validation of the housing sealing over the 3-year mission,
- A qualification model of amplification stage,
- A breadboard of the master oscillator,
- A dedicated test model addressing laser-induced contamination.

Furthermore, lifetime limited components like the laser diodes are submitted to endurance testing to secure the mission duration.

Given the criticality of this unit, the flight models are manufactured after qualification of a representative model that undergoes mechanical, thermal, electromagnetic environmental testing. This model is then lifetime tested for several months in order to verify the stability of performance over a significant period of mission duration.
Other units of the instrument are under preliminary and detailed design phases.

IV. PERFORMANCE

The retrieval of thin cloud optical depth and aerosols physical parameters requires the knowledge of both backscattering contributions of molecules (Rayleigh scattering) and aerosols (Mie scattering). The reference target is an unpolarised subvisible cirrus cloud between 9 and 10km altitude, with a backscatter coefficient of $810^{-7}m^{-1}.sr^{-1}$ and an extinction coefficient of $510^{-5}m^{-1}.sr^{-1}$, measured in daytime conditions above a dense cloud deck at an altitude of 4 km. At the maximum geodetic altitude of the orbit (425 km), the expected absolute accuracy of the derived input signal is below 40% for the Mie scattering signal and below 11% for the Rayleigh scattering signal. The retrieved signals are corrected from spectral and polarization cross-talks and represent thus the pure Mie and Rayleigh attenuated backscatter signals at the top of the atmosphere.

The retrieval accuracy of the Mie and Rayleigh scattering in the above conditions is plotted as a function of orbit position on the figure 13.

The instrument is also able to measure the depolarised backscatter signal of a subvisible cirrus in the same background conditions ; when the cirrus backscatter coefficient is $2.6\ 10^{-5}$ $m^{-1}.sr^{-1}$ and its depolarisation ratio is 10%, the absolute accuracy of the derived input signal is better than 15% for the Mie scattering signal.

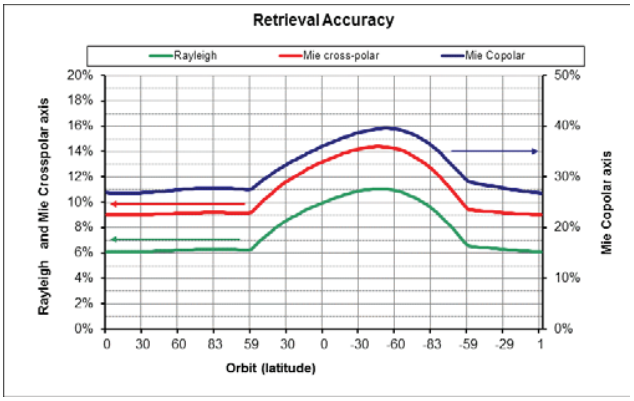

Figure 13. Mie and Rayleigh retrieval accuracy over one typical orbit, for a subvisible cirrus target

V. CONCLUSION

EarthCARE satellite is now progressing in Phase C/D with the development of the ATLID instrument, sub-systems and in particular the laser transmitter. The scientific objectives set by the scientific community are also under consolidation, with the predicted instruments performance meeting observational requirements. EarthCARE satellite is planned to be launched in 2015. The mission will be realised through cooperation between ESA, JAXA and NiCT covering both technical and scientific areas. ESA will contribute the platform, the ground segment, the launcher and three instruments, namely the Atmospheric backscatter Lidar, the Broad Band Radiometer and the Multi-Spectral Imager, while JAXA and NiCT will contribute the Cloud Profiling Radar. The spacecraft flight operation segment and most of Payload Data Ground Segment is under the responsibility of ESA. This applies to the Level 1 data processing with the exception of the CPR data that will be processed by JAXA. The design of algorithms for the extraction of higher-level instrument and synergistic products is undertaken by a joint team of Japanese and European scientists.

In parallel with the Flight and Ground Segment development, an EarthCARE end-to-End mission simulator (ECSIM) is being developed as a framework for the science and industrial teams in Europe, Canada and Japan to allow integration of representative instrument models and processing modules. This tool is supporting the assessment of the overall EarthCARE performance and the preparation of the EarthCARE data processing that includes, beside each instrument's data products, a series of synergetic products.

The instruments embarked on EarthCARE are all expected to have an operational potential in future weather and climate monitoring missions.

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