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## *Development of ATLID, the earthcare UV backscatter lidar*

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## DEVELOPMENT OF ATLID, THE EARTHCARE UV BACKSCATTER LIDAR

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### INTRODUCTION

In the frame of the EarthCARE programme, Airbus Defence and Space SAS is currently developing one of the mission core instruments: the UV atmospheric lidar ATLID. The EarthCARE mission, sixth Earth Explorer Mission of the ESA Living Planet Programme, is developed in cooperation with JAXA. It addresses the interaction and impact of clouds and aerosols on the Earth's radiative budget. For the first time, a suite of four complementary instruments will make simultaneous observations of the same cloud/aerosol scene. ATLID shall determine vertical profiles of cloud and aerosol physical parameters (altitude, optical depth, backscatter ratio and depolarisation ratio) in synergy with the cloud profiling radar (CPR) provided by JAXA, the multi spectral imager (MSI) and the broad-band radiometer (BBR).

Operating in the UV range at 355 nm, ATLID provides atmospheric echoes with a vertical resolution up to 100 m from ground to an altitude of 40 km. 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. The combination of a powerful laser transmitter delivering short pulses at 51 Hz and low noise detection chains based on memory CCD provides capability to measure even faint backscatter from sub-visible cirrus. Radiometric stability is ensured by a continuous active re-alignment system maintaining the accurate co-alignment of emission and reception paths, and by a highly stable injection of the single-mode laser transmitter.

The paper is presenting an updated status of the development of the instrument and subsystem design. While the instrument is completing its detailed design, most of the sub-systems are under manufacturing of their Flight Model (FM) and qualification activities. The paper provides manufacturing status and first equipment test results, in particular for what concerns the laser transmitter development. An overview of the instrument verification and test campaigns is also presented.

### I. THE EARTHCARE MISSION

Currently, clouds and aerosols are the biggest uncertainty in our understanding of the atmospheric conditions that drive the climate system. An improved understanding and better modelling of the relationship of clouds, aerosols and radiation is therefore amongst the highest priorities in climate research and weather prediction. For this purpose, global data on cloud and aerosol occurrence, structure and physical properties together with collocated measurements of solar and thermal radiation are required. By acquiring vertical profiles of clouds and aerosols, as well as the radiances at the top of the atmosphere, EarthCARE (Earth Cloud Aerosol and Radiation Explorer) aims to address these issues. The mission 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, to measure directly the fluxes at the top of the atmosphere. It will allow clarifying the processes involved in aerosol-cloud and cloud-precipitation-convection interactions in order to include them correctly and reliably in climate and numerical weather prediction models.

The EarthCARE mission is the sixth Earth Explorer Mission of the European Space Agency Living Planet Programme. The mission is the largest and most complex Earth Explorer mission to date and is being developed as a joint venture between ESA and the Japan Aerospace Exploration Agency, JAXA. The EarthCARE satellite carries 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 operate individually and in synergy. All instruments are directed towards the satellite ground track with the exception of the Multi-Spectral Imager which provides an imaged swath distributed about the satellite ground track. Stringent pointing requirements ensure co-registration of the three nadir pointing instruments and accurate knowledge of their position in the swath of the imager.



**Fig. 1.** Artist view of the EarthCARE satellite

## II. ATLID MEASUREMENT PRINCIPLE AND OVERVIEW

### *A. Instrument measurement concept*

ATLID measures atmospheric profiles in a direction close to the nadir from a sun-synchronous orbit at 393 km altitude, with a vertical resolution of about 100 m from ground to an altitude of 20 km and 500m from 20km to 40km altitude. The instrument emits short laser pulses with a high repetition rate (51 Hz) along the horizontal track of the satellite, so that several shots can be locally averaged to improve the signal to noise ratio.

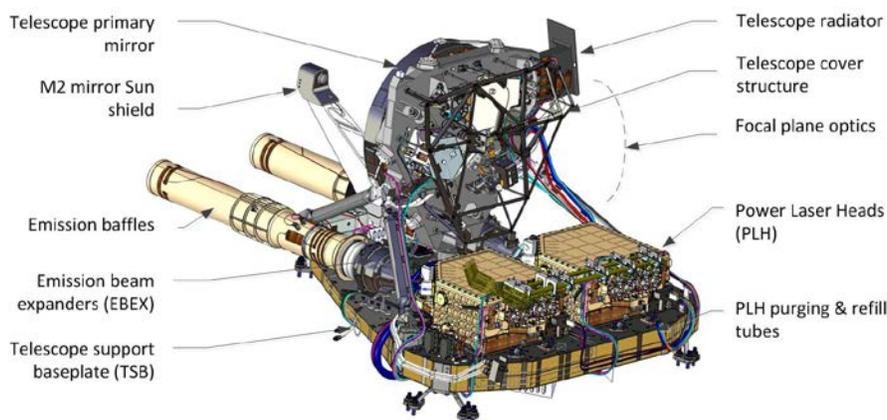
The measurement principle which was retained for ATLID uses the fact that interaction of light with molecules (Rayleigh scattering) or aerosols (Mie scattering) leads to different spectral widths. Whereas the Brownian motion of molecules induces a wide broadening of the incident light spectrum, the single scattering with an aerosol does not affect the spectrum shape of the incident light which remains narrow. 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: most of Mie backscatter flux is transmitted by the filter, while Rayleigh backscatter signal is reflected to another channel. The instrument is thus 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.

The operating wavelength in the Ultra-Violet spectral range was selected as the molecular scattering is high enough to measure accurate extinction profiles and aerosols/thin clouds thickness. The 355nm wavelength can be obtained using Nd:YAG laser technology and frequency tripling conversion ; it also ensures a receiver high response with CCD technology and provides large margin with respect to eye safety.

### *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 instrument is based on a bi-static architecture consisting of two independent main sections, the emitter chain and the receiver chain. This architecture was preferred to monostatic architecture (emission and reception paths share the same telescope) as it allows efficient mitigation of Laser Induced Contamination risk, by avoiding cross-contamination of emission and reception chain, by permitting the full pressurization of the emission path, and by limiting the number of optical surfaces exposed to vacuum.

The instrument functions are shared between a 'high stability' assembly (consisting of the telescope equipped with the focal plane optics, and the optical emission chain, presented in Fig. 2), and a housing structure assembly supporting the electronic units and their radiator, the detection chain and the harness. Stability performance of the 'high stability assembly' is favoured by the assembly of laser and optics on a single CFRP sandwich base-plate, from which all units out of the stability chain are excluded. This sandwich allows optimizing both high stiffness for supporting both 37kg laser units, and low hygro-thermal expansion for stability.



**Fig. 2.** High stability assembly with both emission and the receiver chains

The Emitter chain includes:

- The laser Transmitter Assembly, consisting of a Power Laser Head (PLH) and its Transmitter Laser Electronics, and a Reference Laser Head which provides the stable seed laser. The laser is a diode pumped single-mode laser emitting at 355 nm (tripled frequency of a Nd:YAG laser). It consists of a Master Oscillator section generating low pulse energy of about 8mJ, a Pump Unit amplifying the pulse energy to 150mJ and a harmonic conversion stage doubling, then tripling the laser frequency. The emitted polarisation is linear. The Reference Laser Head seeding the laser oscillator is used to meet the stringent frequency stability requirements. Its frequency is stepwise tuneable to allow frequency scan operations for calibration purposes. The Laser Head includes also a Beam-Steering Mechanism finely adjusting the emission line-of-sight to continuously maintain emission / reception co-alignment in flight, based on information acquired in reception chain by a Co-Alignment Sensor. The laser transmitter is a key driver to the instrument budgets with a power consumption of 300 W, cooled down by an innovative set of mini loop heat pipes developed by Airbus Defence and Space and EHP. It delivers pulses of more than 38 mJ UV energy with duration of about 25 ns at a pulse repetition frequency of 51Hz. The laser transmitter has also stringent spectral requirements with a spectral linewidth below 50 MHz and a 25 GHz spectral tuneability range.

- The Emission Beam Expander (EBEX), used to enlarge laser beam at Power Laser Head output in order to meet the divergence requirement and to minimise the laser fluence on last dioptré exposed to vacuum. The EBEX is sealed and pressurised for mitigating Laser Induced Contamination.

- The emission baffle: this baffle aims at protecting the EBEX output window from external contamination during instrument and satellite assembly and test, and during flight.

The Receiver chain includes:

- The receiver telescope: it is an afocal Cassegrain with 620mm primary mirror diameter aiming at collecting the backscattered light. It is made of Silicon Carbide to ensure high stability.

- Receiver optics: this goes from telescope output to detector fibres entrance. It comprises the entrance filtering optics (narrow interference filter with less than 1 nm bandwidth), the blocking filtering optics (spatial filtering with a field-stop delimiting the 65  $\mu$ rad field-of-view), and two large Fabry-Perot etalons: the background etalon used to finely filter the Earth background light, and the High Spectral Resolution filter. The signal is transported to the detectors by means of fibre couplers, allowing deporting the whole detection chain on the anti-sun wall for passive cooling. Part of the flux is split at focal plane assembly entrance and imaged on the Co-Alignment Sensor which provides laser spot position information.

- The science channels detection functions: they are ensured by the Memory CCD and the Instrument Detection Electronics. The detection chain shall be able to measure single photon events to meet the worst case radiometric performance requirements. The selected design provides high response together with an extremely low noise thanks to 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 and sampling technique, the detection chain provides an extremely low read-out noise (< 3e- rms per sample). The detection electronics are also responsible for the management and video processing of the Co-Alignment Sensor.

- The control and data management unit: including its own software in order to provide full autonomy in operation management, it ensures the synchronisation between laser emission and backscatter signal acquisition, the data processing and data stretching toward the spacecraft, the thermal regulation functions, the co-alignment control loop software (including co-alignment sensor images processing and centroiding algorithms) as well as the beam steering mechanism commanding, the TM/TC and observability management.

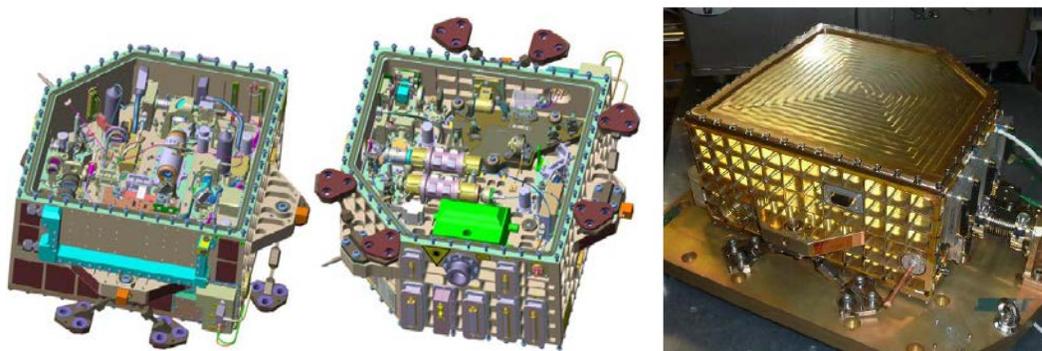
### III. DEVELOPMENT STATUS

#### A. Transmitter and Emitter chain development

While the laser transmitter is largely inheriting from the Aladin instrument development for the AEOLUS mission, a significant evolution of the laser design lies in the fact that ATLID power laser head is sealed and pressurized. This improvement ensures more stable operating conditions to the sensitive components of the laser, and isolates the laser internal space from surrounding contaminants over the ground and operational lifetime. Pressure also improves 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. The mechanical design overview presented on Fig. 3 is based on a double-sided aluminium bench interfaced to ATLID support baseplate via 3 iso-static mounts. The “H” architecture of the bench ensures that bench distortion due to pressurisation is minimised. The Laser Head cavity is closed by its two covers sealed with Viton gasket.

Selex ES, as prime of the Laser Transmitter, has been developing an extensive set of hardware models as full scale breadboard used for validation and correlation with developed numerical models, a Power Laser Head Laser Induced Contamination test model, consisting in a pressurized enclosure with representative optics and contaminants bay.

A significant achievement in 2013 was the development and the testing of a Power Laser Head Structural and Thermal Model. The model used for qualification of the housing sealing was submitted to vibrations and thermal cycles at qualification level. The sealing of the pressurized housing was thus demonstrated to meet the 3 years lifetime in orbit.



**Fig. 3** Power Laser Head opto-mechanical design – Picture of structural model used to qualify the mechanical design and sealing performance. Credit : Selex ES, TXA development responsible

The integration of a Power Laser Head Qualification Model has progressed with the assembly of the Master Oscillator section and dedicated environmental tests were performed to characterise the performance in advance of the full Laser Head environmental tests. The campaign was successfully completed early 2014, with in particular the confirmation of the Master Oscillator opto-mechanical stability over the specified mechanical and thermal environment. The performance of the Master Oscillator was also confirmed to be compatible with the Power Laser Head requirements. Recently, a dedicated test campaign to characterise the laser performance tolerance to micro-vibration perturbations has been conducted successfully.

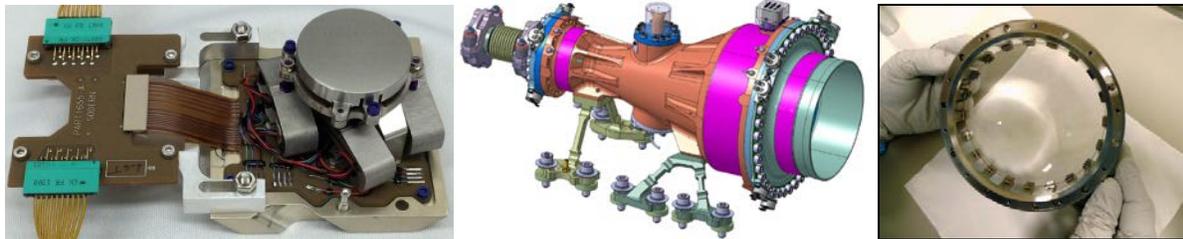
The Laser Amplifier completed successfully its qualification testing at Quantel Laser and is to be integrated in the Laser Head Qualification Model. This will be followed with the UV section alignment before submitting the PLH to full environmental qualification campaign. In parallel, the development of the Transmitter Electronics is supported by two engineering models, one delivered to Airbus Defence and Space SAS, instrument prime in Toulouse, for early functional verification at instrument level, before manufacturing the 2 flight models.

In parallel, an extended programme and systematic Laser Induced Damage measurements for each optics batch (infrared and UV) integrated in the Power Laser Head is carried out as part of the optics qualification programme. These are performed in specialised laboratories at DLR and ESTEC.

The Beam Steering Assembly development by CEDRAT and SODERN is based on a Qualification Model followed by the manufacturing and testing of the 2 flights models to be integrated in the Power Laser Heads.

The Steering Mechanism passed successfully mechanical and thermal vacuum environmental testing and will be further coupled with the Electronics to demonstrate its fine performance (sub-microradian accuracy). A dedicated Optical GSE has been developed by SODERN to allow measurements in the microradian range accuracy.

The development of the Emission Beam Expander by SODERN relies also on new technologies, as the unit is sealed and pressurised with dry air and shall expand the laser beam to more than 100mm diameter: this requires large brazed windows, large lenses mounts development with stringent requirements in WFE, high transmission and qualification for laser irradiation. The development of the EBEX has been supported by a number of qualifications activities (large lens mount, brazed windows) successfully concluded and the FM units parts are now under manufacturing.



**Fig. 4.** Beam Steering Mechanism (SODERN) - Emission Beam Expander design and its lens mount

#### *B. Receiver development*

The receiver development is now well advanced, as all Flight Models (FM) manufacturing or assembly has started. As shown on Fig.5, the silicon carbide FM telescope structure is assembled, and the two mirrors are ready to be aligned.



**Fig. 5.** Telescope (designed by Airbus Defence and Space) and secondary mirror (SAFRAN)

The focal plane optics have different development approaches, depending on their criticality and complexity. The Entrance Filtering Optics (polarisation control and narrow bandpass interference filter) and the Blocking Filter (spatial filtering) shown on Fig.6 are developed by Bertin Technologies in a proto-flight approach; the flight models are fully assembled, and are ending their qualification test sequence before delivery.



**Fig. 6.** Entrance Filtering Optics and Blocking Filter (FM models) produced by Bertin Technologies

Based also on a proto-flight approach, the two Fabry-Perot etalons flight models manufacturing is on-going at SESO, with challenging tolerances (only a few nanometers parallelism are tolerated over a 40 mm distance), and will be delivered by RUAG Space in 2015.

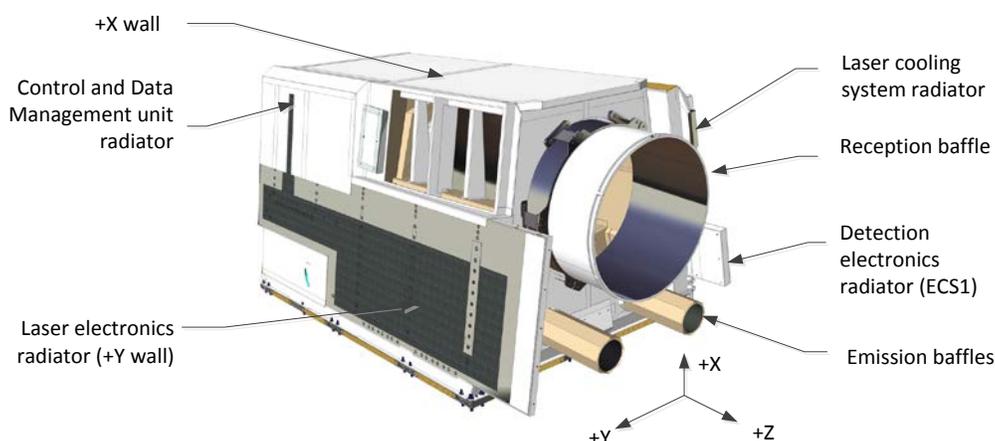
The fibre couplers developed by Bertin Technologies have undergone successful qualification on qualification models, and FMs assembly is about to start. The Co-Alignment Sensor, developed by CRISA and aiming at measuring the retro-reflected laser spot with better than 1/10 pixel accuracy, is currently ending its mechanical and thermal qualification sequence before start of FM manufacturing.



**Fig. 7.** From left to right : Fibre Coupler Assembly (Bertin Technologies), High Spectral Resolution Etalon (RUAG Space) and Co-Alignment Sensor STM (CRISA)

### C. Mechanical and thermal units developments

Due to the large number of units, the strong dissipation induced by the laser transmitter, and the interface on carbon fibre panel, ATLID mechanical and thermal functions are particularly complex to design. The high stiffness and high stability required for the Stable Structure Assembly (developed by APCO) supporting the telescope and the laser heads impose thick double-stages CFRP sandwich panel and strong titanium brackets. The large dissipation (above 600 W) of the units together with the inhomogeneity of materials (aluminium for electronics, carbon-fibre for interface panel) requires for the housing structure assembly a complex assembly of aluminium sandwiches, aluminium structure, titanium blades and brackets, and carbon-fibre panel designed by Airbus Defence and Space. The critical design reviews of the structures and cooling systems are now passed, as well as the qualification on breadboards of critical technologies (high load inserts, embedded titanium mounts) and the manufacturing has started, in a proto-flight approach.



**Fig. 8.** ATLID self-standing architecture and the complex Housing Structure Assembly developed by Airbus Defence and Space SAS

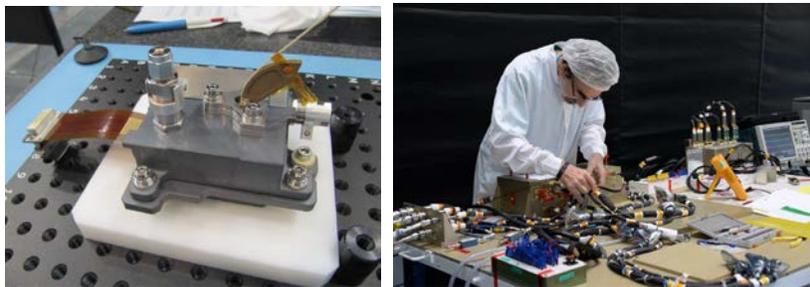
#### IV. INSTRUMENT VERIFICATION AND TEST PROGRAMME

The instrument development programme is based on a proto-flight approach: after assembly and characterization of the FM optical assembly, the stable assembly and the equipped housing structure assembly are coupled before starting the full qualification of PFM model. Several activities are however conducted to secure this PFM approach.

The detection chain, as a key contributor to the radiometric performance, has been validated through several steps, starting with detection breadboard aiming at validating the specific accumulation CCD designed for ATLID with representative proximity electronics. Then, the final proximity electronics design, developed by CRISA, has been coupled to the MCCD, cooled down to  $-30^{\circ}\text{C}$ , and operated for the first time with Airbus Defence and Space's developed oversampling filters, to demonstrate less than 2 e- rms total noise in darkness.

In parallel, the Engineering Electrical Model (EEM) is built with all electronics Engineering Models, allowing complete electrical, EMC, and functional verification. This on-going step is of prime importance in the validation of electrical design and cross-compatibility, but is also a major input to ATLID software correction and final version specification.

The opto-mechanical design is mainly validated at unit level, but the Detector and Fibre Assembly, for which less than 5 microns stability is required, has been successfully qualified in mechanical and thermal environment in advance of FM manufacturing. The mini loop heat pipes, which is a technical innovation for laser cooling (8 loops in parallel are used to cool down each PLH), have also been successfully tested in a breadboard configuration to validate ability of start-up, heat sharing, and inhibition.



**Fig. 9.** On the left : detector and fibre assembly (QM) – On the right : EEM programme led by Airbus Defence and Space at Toulouse is of prime importance for the validation of electronics and software design

Finally, a major validation step has been reached recently with the successful testing of Laser Induced Contamination effect on representative optical coating, exposed in vacuum to representative contamination (simulated with material samples) and UV laser fluence. More than 400 millions of shots have been performed during 7 weeks, and transmission loss, lower than 10% has been found acceptable for the mission.

#### V. CONCLUSION

ATLID will fly on the EarthCARE satellite with launch scheduled in early 2018. This Earth Explorer Core mission of ESA will allow better understanding and modelling of radiative effect of clouds and aerosols and their impact on the climate.

ATLID, one of the core instruments of the mission, is currently being developed by Airbus Defence and Space, on the basis of a mature design which nevertheless features innovations such as ultra-low noise detection chain, optical fibre links, mini loop heat pipes. The large extent of the heritage allows proposing a secured development approach to meet the programmatic constraints of the EarthCARE programme.

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