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L. Le Hors

Y. Toulemont

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DESIGN AND DEVELOPMENT OF THE BACKSCATTER LIDAR ATLID FOR EARTHCARE

L. Le Hors (1), Y. Toulemont (1), A. Hélière (2)

(1) EADS Astrium Satellites, 31 rue des cosmonautes, 31402 Toulouse France. E-mail :
lenaic.lehors@astrium.eads.net, yves.toulemont@astrium.eads.net
(2) ESA-ESTEC, European Space Agency, Directorate of Earth Observation Programmes
P.O. Box 299, 2200 AG Noordwijk, The Netherlands. E-mail :
arnaud.heliere@esa.int

ABSTRACT

In the frame of the EarthCARE programme, Astrium France is currently developing one of the mission core instruments: the backscatter lidar ATLID. The EarthCARE mission is the third Earth Explorer Core Missions of the ESA Living Planet Programme, with a launch date planned in 2013. 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 clouds and aerosols physical parameters (altitude, optical depth, backscatter ratio and depolarisation ratio) in synergy with other instruments.

This paper presents the design and performance of the ATLID instrument, and relates the main development issues. The technical challenges and the main innovations are highlighted.

1 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.

The objective of ATLID instrument is to measure, in synergy with the Cloud Profiling Radar, vertical profiles of optically thin cloud and aerosol layers, as well as the altitude of cloud boundaries. Since the UV light of the lidar is strongly attenuated by thick clouds, its results shall be analysed in association with the radar products which provide cloud top, cloud base and ice content inside all ice clouds. The lidar/radar association yields cloud particle size and water content profile.

The unique lessons learnt from the wind lidar ALADIN programme, currently being developed by Astrium France for Aeolus mission (ESA Earth Explorer mission), are thoroughly applied, allowing to anticipate the key issues and propose adapted solutions. The proposed design makes extensive use of qualified technology for each of the key sub-systems (key components of 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 below 2 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.

2 INSTRUMENT TECHNICAL DESCRIPTION

2.1 ATLID measurement principle

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.

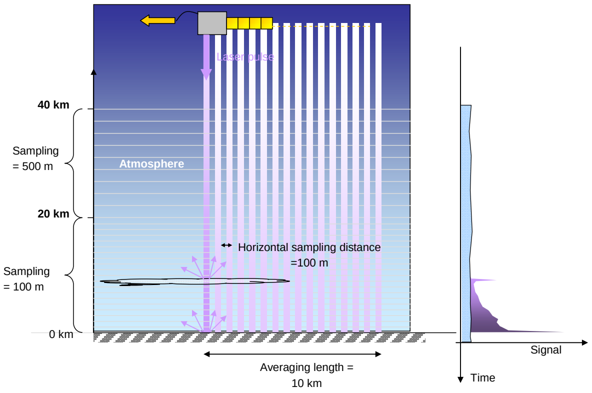


Fig. 1 : ATLID measurement principle

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 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 contributions consists in filtering the backscattered spectrum with a high spectral resolution filter centred on central wavelength, as depicted on Fig. 2.

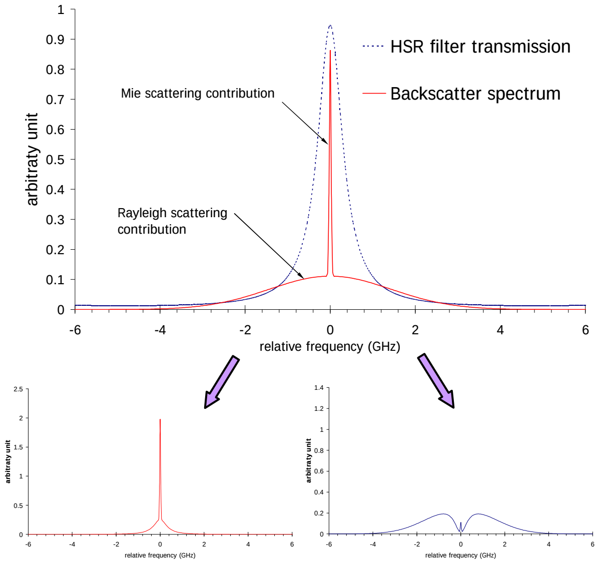


Fig. 2 : Mie / Rayleigh scattering contributions separation principle

This operation can be implemented by means of a narrow bandwidth Fabry-Perot etalon, consisting of two parallel reflective plates that act as an optical cavity. When tuned on the backscattered flux central wavelength, the etalon transmits most of the Mie scattered flux (narrow bandwidth spectrum) and reflects most of the Rayleigh scattered flux. Adding a polariser and a quarter waveplate at the entrance of the etalon allows redirecting the reflected flux (Rayleigh contribution) to the Rayleigh channel.

This principle has been successfully implemented and characterised in ALADIN instrument Pre-Development Model and then Flight Model programmes.

2.2 Instrument overview

ATLID is designed as a self-standing instrument which can be integrated at satellite level as a 'drawer': it allows better decoupling of instrument/platform interfaces and flexibility in the satellite integration sequence.

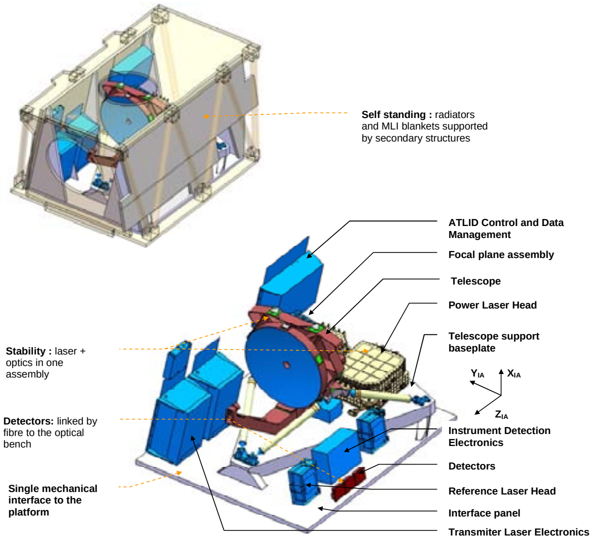


Fig. 3 : ATLID overview

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 **transmitter** includes the power laser head and its transmitter laser electronics. 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.

The **telescope** is an afocal Cassegrain aiming at collecting the backscattered light and providing a large magnification ratio to reduce effect of internal misalignments. The telescope is also used in the transmit path in a monostatic architecture.

The **receiver** includes the emit / receive diplexer and focal plane optics, including background light filtering stage and a High Spectral Resolution filter. A laser chopper is implemented in order to properly isolate the detectors at laser pulse emission. 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.

2.3 Thermo-mechanical design

The ATLID mechanical architecture is orientated to provide the highest stability to the laser and optics sub-assembly. Thanks to CFRP structures, iso-static mounts and combined use of an all silicon carbide telescope directly derived from Rocsat-2 RSI, less than 100 µrad long term stability can be achieved for the instrument line-of-sight, and the co-registration of emitter with respect to receiver can be kept below 10 µrad.

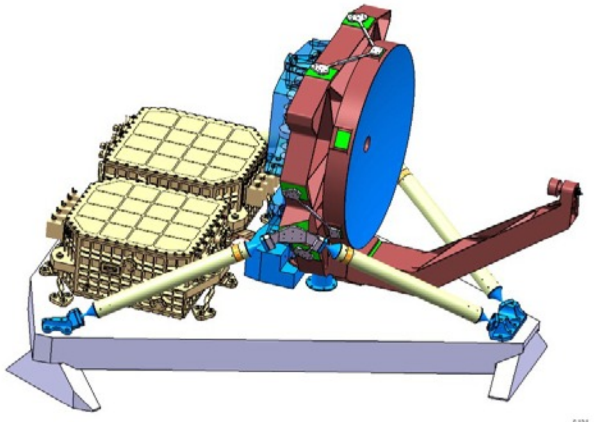


Fig. 4 : Stable optical assembly configuration

All the units that require a high stability are grouped into a stable opto-mechanical assembly mounted on a stiff CFRP structure. This includes the power laser heads emitting the UV laser pulses, the optical units of the focal plane, and the telescope used for both emission and reception.

Iso-static mountings are extensively used for linking the units together. It allows filtering the differential thermo-elastic effects, as well as the distortions at the interfaces with the interface panel (and by extension with the platform).

2.4 Optical design main features

The optical design is based on a monostatic architecture, were one single telescope is used for both emission and reception paths. An afocal 600 mm diameter Cassegrain telescope is used, with a magnification ratio of about 15. This magnification, combined with a beam expander at emitter output provides a global magnification of 55, which allows reducing by the same factor the sensitivity of emit/receive co-registration to internal mis-alignments. Thanks to this design, internal pointing stabilities higher than 100 µrad can be tolerated on several elements while maintaining an emit/receive co-alignment in the outer space lower than a few micro-radians. The receiver field-of-view is thus kept below 40 µrad, minimising the shot noise associated with the acquisition of Earth background signal.

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 dispersive filter) are required to achieve such purity and to reject the high amount of Earth background signal around the narrow laser wavelength.

The optical design makes extensive use of optical invariant devices and stable assemblies. For instance, the Fabry-Perot etalon design is based on optical contacting technology with low expansion materials which ensures high frequency stability. The spectral co-registration approach consists then 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.

One of the other optical design drivers is the internal straylight which shall be filtered to avoid over-illumination and saturation of the detectors at laser pulse emission time. An isolation factor higher than 10^{12} is globally achieved by implementing on receiver path a chopper mechanism synchronously closed at laser pulse repetition frequency.

2.5 Transmitter requirements and design

The laser transmitter of ATLID instrument shall deliver high energy pulses at a repetition rate of 74 Hz corresponding to 100 m ground horizontal sampling. 30 mJ 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 Me and Rayleigh scattering contributions by High Spectral Resolution(HSR) technique.

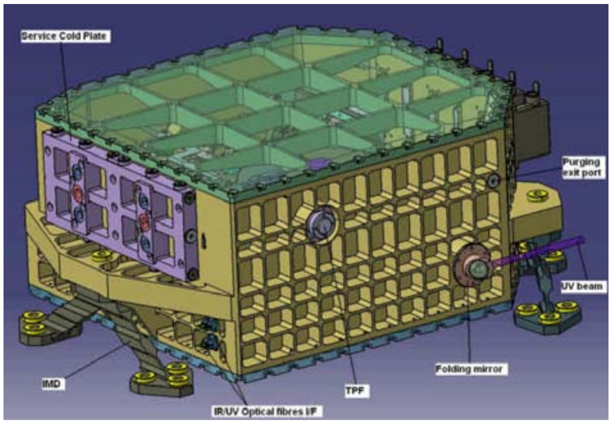


Fig. 5 : ATLID laser transmitter preliminary design

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) 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.
- 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.

2.6 Technical challenges

Despite its heritage from previous programmes such as the wind lidar ALADIN (AEOLUS programme of ESA currently under development at Astrium SAS), the ATLID instrument features several technical challenges which are inherent to space lidar systems.

One can quote the high stability (a few micro-radians) required between emitter and receiver sections, which is a permanent driver for opto-mechanical design.

The acquisition of extremely low level signals is also a challenge which requires a quasi photon-counting capability of the detection chain.

The high level of laser fluence on the optics of the transmitter optical path requires specific coatings which exhibit a high laser induced damage threshold, as well as stringent cleanliness requirements to ensure that no dramatic laser induced contamination occurs on the sensitive surfaces. Dedicated tests are used to allow selecting the best suited materials and avoid sensitive contaminants ; other measures like bake-out of parts and design optimisation to favour the absence of organics or glues will also be applied.

Finally, the demanding requirements of the laser in terms of line-of-sight and frequency stability, beam quality, pulse energy make this major sub-system a technical challenge by itself. The long laser lifetime of 3 years (this corresponds to 7×10^9 shots) leads to adapt the design towards minimisation of total shot number seen by individual diode stacks and minimisation of driving currents.

3 IMPROVEMENTS AND INNOVATIONS

Although extensive reuse of existing units will be favoured in the ATLID design, several improvements and innovations are implemented with respect to previous programmes.

3.1 Extremely 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 fulfil the signal acquisition requirement. As for ALADIN instrument [2], 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 combination of high responsivity read out stage operating and signal processing conceived by Astrium, the detection chain provides an extremely low noise measurement of less than 2 e- rms and a perfect radiometry measurement accuracy and stability, experimentally validated on a dedicated breadboard this year. Accumulation of several consecutive echoes on the chip is also possible with the detector design, enhancing the acquisition chain radiometric performance, especially at night when detection chain noise is limiting the signal-to-noise performance.

3.2 Mini loop heat pipes for laser cooling

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.

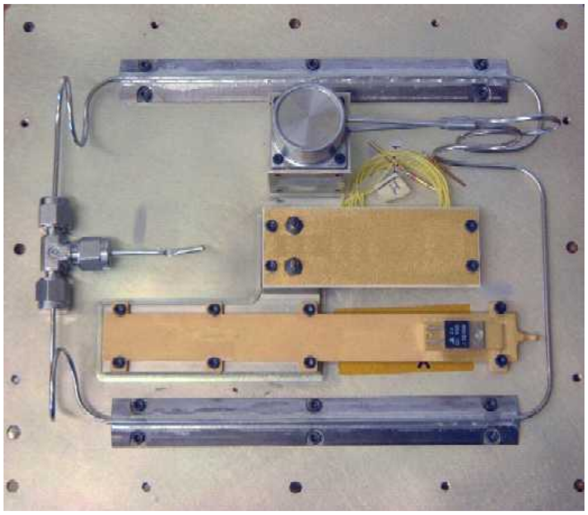


Fig. 6 : Mini loop heat pipes are used to cool and regulate the power laser head

3.3 Fibred focal plane

Unlike its space lidar predecessors, ATLID optical design features fibred links between focal assembly at the back of telescope and the detector units. This implementation choice allows drastic simplification of detector package since deportation of the detectors to the anti-sun instrument wall allows passive cooling, hence avoids active Peltier cooling. This approach also presents the big advantage of simplifying the optical bench thermal control and decoupling the development and testing of the focal plane assembly and the detection chain units.

100 µm core diameter multimode radiation tolerant fibres are used to transport the UV signal over 2 to 3 meters. Performance of the fibre link and its tolerance to radiative environment have been assessed through pre-development activities dedicated to ATLID instrument, bringing a high level of confidence in the suitability of this technical solution.

3.4 A sealed and pressurized laser

A significant evolution of the laser design with respect to the ALADIN transmitter lies in the fact that ATLID power laser head will be sealed and pressurised. 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. This design choice is thus believed to secure the laser lifetime over the 3-years-long operational phase.

4 INSTRUMENT PERFORMANCE

ATLID instrument will be able to measure Mie and Rayleigh scattering contributions between altitudes –0.5 and 40 km. The radiometric performance is expressed in terms of accuracy in Mie and Rayleigh signal retrieval accuracy at instrument input.

Table 1 : ATLID Observation requirements

	Mie co-polar channel	**Rayleigh channel**	**Mie cross-polar channel**
Cirrus optical depth	0.04		
Backscatter sr^{-1} m^{-1}	8 10^{-7}		2.6 10^{-5}
Vertical resolution	100 m	300 m	100 m
Horizontal averaging	10 km		
Required Accuracy	50%	15%	45%

The reference target is an unpolarised subvisible cirrus cloud between altitudes 9 and 10 km, with a backscatter coefficient of 8.10^{-7} $m^{-1}.sr^{-1}$ and an extinction coefficient of 4.10^{-5} $m^{-1}.sr^{-1}$, whose profile is measured in daytime conditions, with a dense cloud deck at an altitude of 4 km.

In the above conditions, and at the maximum geodetic altitude of the orbit (425 km), the absolute accuracy of the derived input signal is below 35% for the Mie scattering signal (with 100 m vertical integration length, within the cirrus) and below 11% for the Rayleigh scattering signal (with 300 m vertical resolution, above and below the cirrus).

The retrieval accuracy of the Mie and Rayleigh scattering in the above conditions is plotted as a function of orbit position on the Fig. 7.

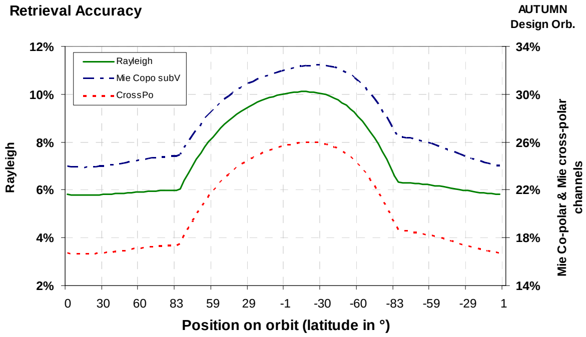


Fig. 7 : Mie and Rayleigh retrieval accuracy over one typical orbit, for a subvisible cirrus target

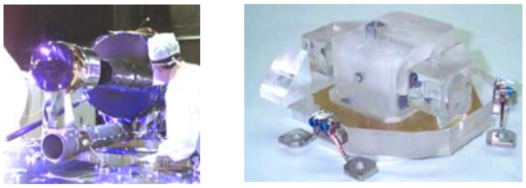
The instrument is also able to measure the depolarised backscatter signal of a subvisible cirrus in the same background conditions : when the cirrus backscatter coefficient is 2.6×10^{-5} $m^{-1}.sr^{-1}$ and its depolarisation ratio is 10%, the absolute accuracy of the derived input signal is better than 30% for the Mie scattering signal.

5 HERITAGE AND DEVELOPMENT PHILOSOPHY

5.1 A strong heritage from previous programmes

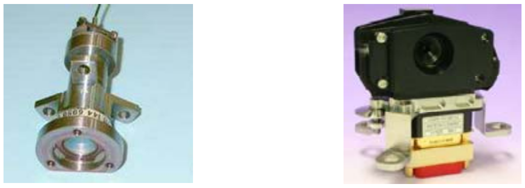
ATLID development benefits from Astrium SAS experience as prime contractor in charge of the development of ALADIN lidar instrument.

Main potential sources of hardware heritage regard the all-SiC telescope derived from Rocsat-2 RSI instrument, the high stability fibre coupler or spectral splitter from LOLA airborne optical telecommunication terminal (DGA demonstration programme). Several units will directly benefit from ALADIN programme, such as the high stability Fabry-Perot etalon, the laser chopper, the flip-flop mechanisms, and of course the laser transmitter.



High stability all-SiC telescope (ROCSAT-2 programme)

High performance Fabry-Perot etalon (ALADIN programme)



High stability fibre coupler (LOLA programme)

Laser chopper mechanism (ALADIN programme)

Multi-path spectral splitter (LOLA programme)

Single frequency tripled Nd :YAG laser (ALADIN programme)

Fig. 8 : Heritage from other programmes

5.2 Instrument pre-development activities

Outcomes from breadboarding activities led by ESA in the frame of instrument pre-development phase will be used as inputs for the development. This regards in particular :

- the fibre link performance and radiation tolerance assessment
- the verification of Fabry-Perot etalon performance in ATLID operation conditions (incidence and divergence representative conditions)

- the assessment of a new lidar detector design based on e2v L3 technology, which allowed to validate some parts of present ATLID CCD design architecture
- the development and assessment of pulsed laser diode bars and stacks used for pumping the laser transmitter. The ATLID instrument requires up to 7 Gshots and more than 50 % electro-optical efficiency. Several activities have been initiated aiming not only at assessing but also at developing stacks specifically suited for the requirements of space operation. With respect to the stacks qualified for the ALADIN instrument, several major changes have been introduced on the stacking technology. Environmental testing (thermo-mechanical tests, vacuum compatibility and radiation tests) and endurance tests of half the required lifetime are concluding these developments. The Laser diode stacks have been manufactured and the test benches commissioned. The endurance testing has been started and will allow drawing conclusions for the EarthCARE programme.

5.3 Development philosophy

Based on the background brought by Astrium previous programmes and especially by the wind lidar ALADIN programme, a protoflight philosophy has been selected for the development of ATLID. This production policy is supported by validation programmes at sub-system levels for schedule risks mitigation.

The structural and thermal programme (STM) aims at verifying the structural stability of the transmitter-receiver chain. For this purpose, a preliminary integration of the flight stable opto-mechanical assembly, equipped with blank mirrors and representative laser mock-up, is performed. This model is submitted to a full mechanical and thermal qualification sequence which declares the qualification of the stable structural design.

The focal plane assembly programme (FPA) is performed at the end of integration of the optical components of the focal plane, before the final instrument integration operations. The flight stable opto-mechanical assembly, equipped with the fully integrated and adjusted optical chain is submitted to a full mechanical and thermal qualification sequence which validates the critical mechanical interfaces and their workmanship. This validation successfully passed authorizes the continuation to the definitive integration and qualification of the instrument. The electrical programme (EEM) is performed with dedicated engineering models of the electrical units. The objective of this programme is to demonstrate the full operationability of the instrument through functional tests and to verify the compatibility of the electrical and detection chain to the electromagnetic environment through conductive and radiative EMC tests.

The ATLID instrument being integrated in flight configuration is qualified under a full set of mechanical, thermal vacuum, and EMC environments.

In addition to this formal instrument qualification, a specific lifetime test is performed on a specific laser assembly model to verify the good behaviour of the laser performances along a representative mission profile during 1 year.

The duration of the development and production phase is 49 months, from the kick-off of the ATLID programme up to the flight model delivery to the Satellite.

6 CONCLUSION

ATLID will fly on the EarthCARE satellite with launch scheduled in 2013. 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 Astrium France, 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 to propose a secured development approach to meet the programmatic constraints of the EarthCARE programme.

7 ACKNOWLEDGEMENTS

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