ATLID: The Technology Development Programme for ESA's Satellite-borne Atmospheric Lidar

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The idea of deploying a lidar system on an Earth-orbiting satellite stems from the need for continuously providing profiles of our atmosphereís structure with high resolution and global coverage. Interest in this information for climatology, meteorology and the atmospheric sciences in general is huge. Areas of application range from the determination of global warming and greenhouse effects, to monitoring the transport and accumulation of pollutants in the different atmospheric regions (such as the recent fires in Southeast Asia), to the assessment of the largely unknown micro-physical properties and the structural dynamics of the atmosphere itself.

Introduction

An Atmospheric Lidar is an active instrument for profiling the structure of the atmosphere. Other types of lidar (acronym from Light Detection and Ranging) also exist — Doppler wind lidars, lidars to trace the concentration of chemical constituents, Raman lidars, etc. — but all of them work on the same principle. A lidar sends a laser beam into the atmosphere and collects and analyses the returned radiation (equivalent to the "echo" in a radar system), which is retro-diffused (back-scattered) by the molecules and the particles present in the atmospheric volume being probed. This returned light signal is collected by the instrument optics (typically a telescope) and detected, i.e. transformed in an electrical signal, by an opto-electronic receiver. In an Atmospheric (or back-scatter) Lidar, the signal is then sampled and processed to retrieve its intensity profile. The signal intensity is proportional to the back-scattering coefficient of the probed atmospheric volume, which in turn is a function of the density and type of particulates present. In this way, the concentration of the scattering media — whether aerosol, molecules or dust — can be measured.

Moreover, the retrieved information is intrinsically range-resolved, i.e. it is recorded as a function of the distance of the lidar from the target. In fact there is a one-to-one relationship between the time of flight of the light signal (the time that elapses between the emission of the laser pulse and the detection of the return "echo") and the location of the atmospheric sample which has back-scattered the light. If we consider a light pulse which travels through the atmosphere, each section of the atmosphere traversed by the pulse retro-diffuses a small portion of the light signal. The lidar receiver sequentially collects all of these contributions, which form an intensity-modulated pulse of longer duration than the transmitted one. By measuring the overall time-of-flight of the pulse and by "slicing" the pulse and assigning to each portion its own time of retrieval, the distance-resolved profile of the atmospheric path can be reconstructed.

For satellite-based measurements, the lidar instrument shoots its laser pulse to the Earth and the return signal contains samples "originating from" different regions of the atmosphere. Knowing the satellite's orbital height and the direction of travel of the laser pulse, one can retrieve a height-resolved profile of the atmosphere. These profiles contain valuable information about atmospheric features of interest, such as the density of particulates or pollutants, the structure of (thin) clouds or banks of aerosols, and possibly the concentration of air molecules. The resolution of the profile will be determined by the "timing" capability (the processing sampling bandwidth) of the detection system.

The lidar instrument consists of a laser source which generates the light pulses that probe the atmosphere, a telescope and optics to collect the back-scattered radiation, and a receiver which converts the light echo into an electrical signal. The direction of the outgoing path is co-aligned with the bore sight of the receiving telescope. If there is a need to probe many different regions of the atmosphere, a scanning mechanism can be added to steer both the telescope and the laser transmission axes in the required direction. In a satellite-based lidar instrument, other units are added to support the operation: a thermal-control system to extract the heat generated by the laser, a counter-inertia flywheel to compensate for the torque induced by the scanner, and a star-sensor to assist in the retrieval of the exact direction of the laser measuring path (Fig. 1).

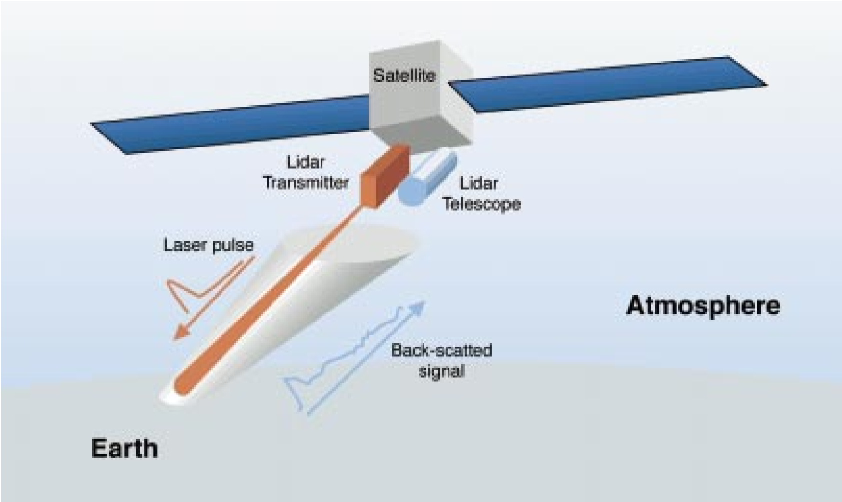


Figure 1. Schematic of the operating principle of a spaceborne lidar. The pulse sent to the atmosphere is back-scattered and the instrument collects and analyses the radiation, retrieving the profile of the measured parameters

ATLID: the European Atmospheric Lidar

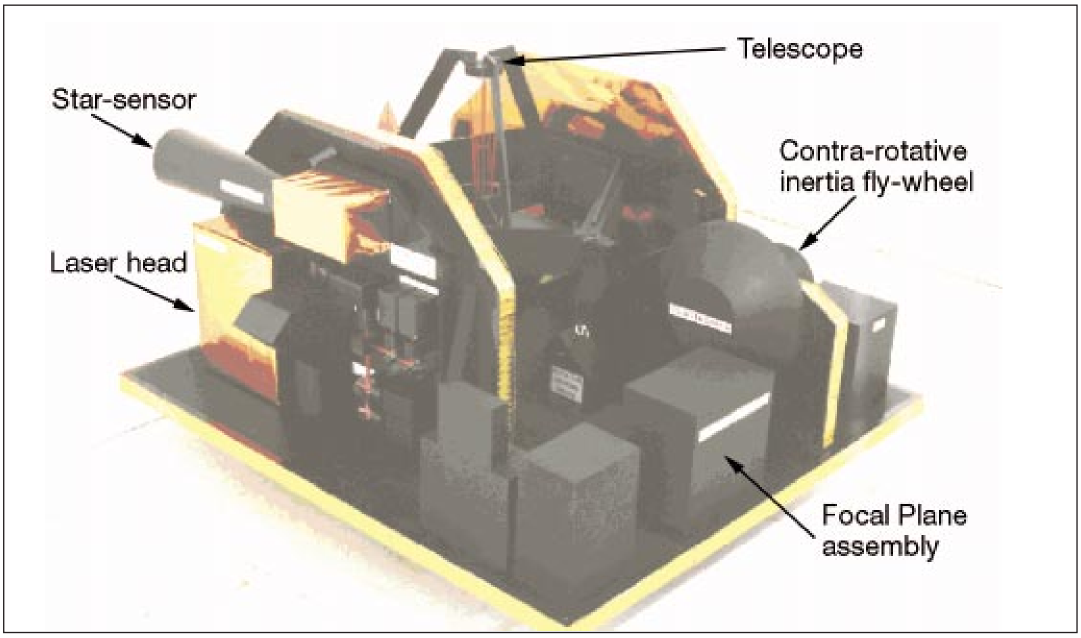
For more than a decade, ESA has been conducting studies and technology development efforts to evaluate the usefulness of lidars for remote sensing of the Earth's atmosphere from space*. These studies culminated in the definition of an Atmospheric Lidar concept known as ATLID, suitable for accommodation on the Agency's Envisat satellite.

ATLID is designed primarily to provide satellite measurements of cloud-top height both day and night. It is also capable of measuring the heights of cloud bottoms for thin clouds and the extent of the Planetary Boundary Layer (PBL) and of aerosol banks. These atmospheric features can be measured to an altitude of 20 km with a 50 m resolution in height and an accuracy of ± 100 m (3 σ). In order to provide 3-D mapping of atmospheric features, the ATLID telescope is scanned transverse to the spacecraft's flight direction. The scan angle of ± 23.5 deg at an orbital height of 800 km results in a swath width on the ground of 700 km. With a footprint 140 m in diameter, and operating at 100 pulses per second, the instrument can obtain more than 100 measurements within a 100 x 100 km^2 area.

ATLID is based on a pulsed diode-laser-pumped solid-state (Nd:YAG) laser, which delivers high-energy pulses in the near-infrared (at a wavelength of 1064 nm). The back-scattered light is collected by a lightweight 60 cm-diameter telescope, mounted on a single-axis scanning mechanism, which also provides the co-alignment of the outgoing and incoming light beams. The incoming radiation is filtered against the background light and sent to a receiver based on a high-sensitivity avalanche photo-diode. The torque generated by the scanning mechanism is compensated by a flywheel and the pointing is assisted by a star-sensor and fine-tuned by a so-called "lag-angle compensating mechanism". This device introduces corrections to the deviations that the beam suffers due to the scanning and spacecraft motions during the time of flight of the pulse. The variety of atmospheric targets which ATLID is called upon to measure requires a versatile electronic processing chain, able to handle signals with a large dynamic range.

As mentioned above, the present instrument design (Fig. 2) was tailored to its accommodation on the Envisat remote-sensing

Figure 2. Full-scale mockup of the ATLID instrument layout resulting from the design study (courtesy of MMS-F)



* See "Laser-Based Remote Sensing from Space", by E. Armandillo and H-P. Lutz, in ESA Bulletin No. 66, May 1991

platform. As a result of the workshop held in Granada (Spain) in 1995 for the assessment of the nine candidate Earth Explorer missions, recommendations were made to include an Atmospheric Lidar in the model payload of the Earth Explorer - Earth Radiation Mission, to provide height-resolved cloud-aerosol and planetary-boundary-layer height information for assimilation into a general Earth radiative model. A non-scanning ATLID design is presently proposed for the Earth Radiation mission, for which a different spacecraft concept is foreseen. The elimination of the scanning feature is dictated primarily by the need to achieve the best possible synergy between ATLID and the cloud radar, which is part of the satellite's basic instrument package.

The ATLID technology development programme

The study of the complete instrument was followed - starting in 1994 - by an extensive breadboarding programme. The instrument breadboards and assemblies realised in this programme were then tested to verify their functionality and also their compliance with environmental requirements. This activity was largely completed by the end of 1996, by which time most of the breadboard units had been tested and delivered.

The complexity and multi-disciplinary nature of the development work called for a joint effort by ESA, industry and several specialised institutions in the Member States. The ATLID development programme was therefore structured like a small project, with a team of experts drawn from the Directorate of Technical and Operational Support working in close consultation with Earth Science Division and Earth Observation Preparatory Programme Division staff. The industrial consortium, led by Matra Marconi Space France, included 25 companies from 10 different ESA Member States and Canada.

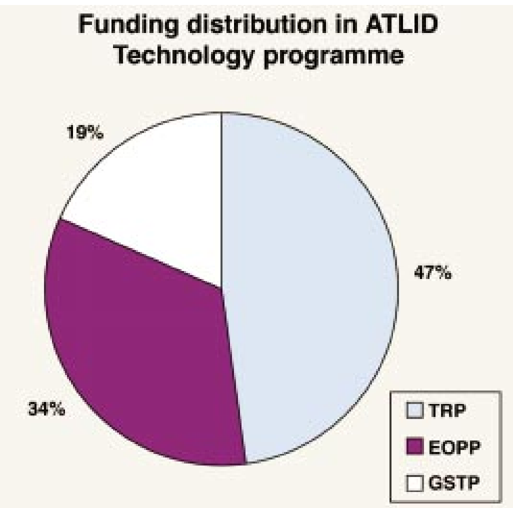
The development programme was financed through joint contributions from the ESA Basic Technology Research Programme (TRP), the General Support Technology Programme (GSTP) and the Earth-Observation Preparatory Programme (EOPP), totalling about 7 MECU (Fig. 3).

In view of the mission opportunities now foreseen within the Earth Explorer Programme, the scope of the ATLID Technology Development Programme has been enlarged to include the demonstration and early validation of the technologies for all key units and sub-systems. It is in fact recognised that ATLID is a very complex instrument relying on a variety of advanced technologies, ranging from high-energy laser sources to narrow-band optical filters, high-sensitivity detectors, large heat-lift thermal-control systems, lightweight optics and precise scanning mechanisms. With such a large and complex class of instrument, it is imperative not only to test the individual units, but also the sub-systems and their interfaces if one is to realistically assess the technology's readiness for such a satellite mission. The effort spent in analysing and testing the critical technologies and sub-system interfaces at an early stage will result in lower costs during the subsequent instrument development phases and hence in overall cost savings.

The ATLID sub-systems verification activity foreseen within the GSTP Programme (total envelope 3 MECU) focuses on the integration and testing of the laser head with the laser-diode power supply, the Q-switch and the thermal-control assembly, on the end-to-end verification of the detection process, and on the full integration and testing of the telescope and the optics.

Technical results to date

The technology-development activities so far



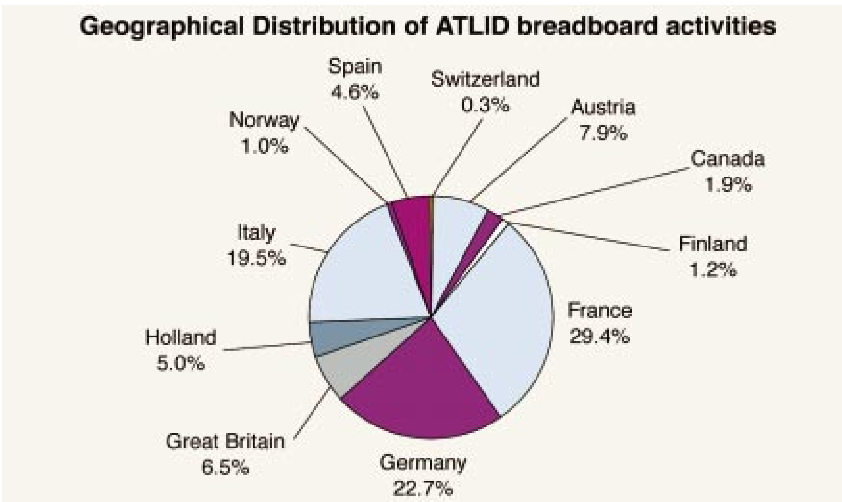


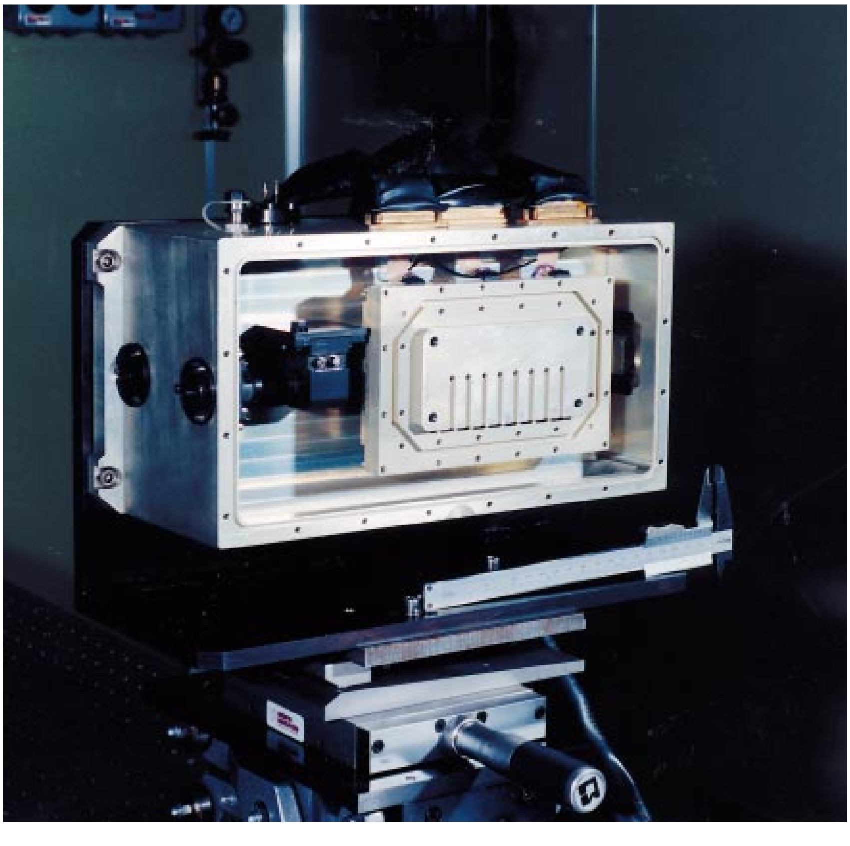
Figure 3. The ATLID funding shares, and geographical distribution of the technology-development activities

have been concentrated on the critical units of the three key sub-systems:
– the *transmitting sub-system*, composed of the laser head assembly, the laser thermal-control assembly and the beam-shaping optics
– the *receiving sub-system*, including the scanned lightweight telescope, the optical bench with the filter and the receiver
– the *pointing/scanning sub-system*, including the lag-angle compensating mechanism, the scanning mechanism with the contra-rotating inertia flywheel, and the star sensor.

Several of the critical technologies/units have already been breadboarded and tested, including the transmitter laser, laser Q-switch, laser diode power supply, thermal control, narrow-band filters and the optical coatings, detection chain, lightweight telescope and scanning mechanism.

The transmitter laser for ATLID is a 10-W diode-pumped Nd:YAG laser operating at a wavelength of 1.064 micron, which emits laser pulses with energies up to 100 mJ and lasting 20 ns, with a 100 Hz pulse repetition frequency (Fig. 4). The laser head is pumped by high-energy pulsed laser diodes and emits a beam of good spatial quality and high pulse stability with an electrical-to-optical efficiency (conversion ratio from prime power to laser radiation) of 6.5%. The generated heat of about 100 W is transferred to the thermal-control system by means of a conductance plate. The laser diodes are driven by a high-current pulsed power supply, which has also been breadboarded. The unit, which was tested in vacuum and with different thermal cycles, achieves 74% efficiency.

Figure 4. The ATLID laser head, with the heat-exchanger plate of the laser diodes visible in the foreground

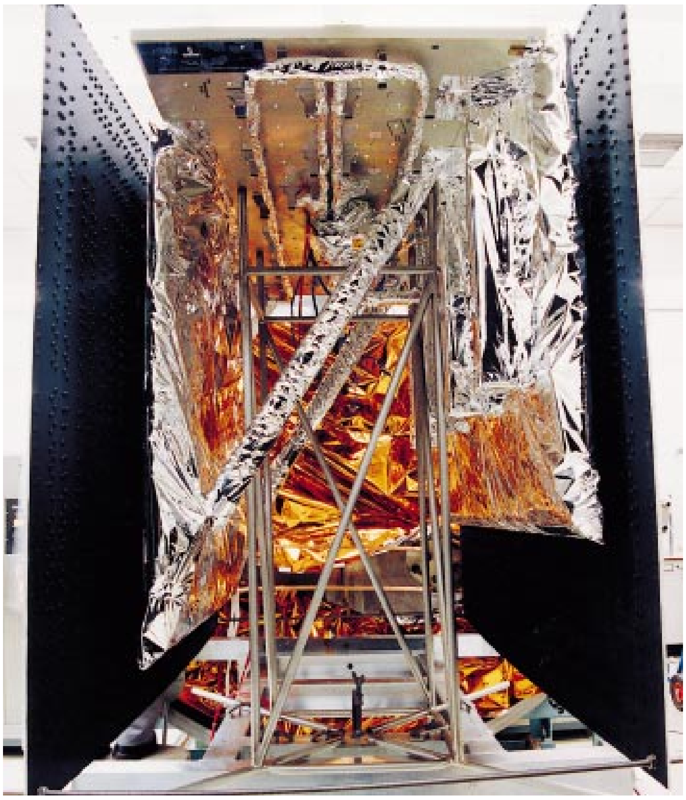


Another key element of the laser head, the laser Q-switch, is presently being breadboarded. It triggers the build-up and release of the laser pulse and consists of an electro-optic crystal, whose non-linear optical properties are modulated by a high-voltage pulse. Due to the very high energy flux of the laser beam, the Q-switch is subject to optical damage and therefore both accurate screening of the electro-optic crystal and a high-quality surface coating are required in order to produce a high-reliability device suitable for prolonged operation in space.

As already indicated, heat removal from the laser head is another key issue for prolonged operation of the laser transmitter. A high thermal load has to be dissipated under the extreme temperature conditions in orbit. A capillary-pumped two-phase loop has been selected for its high heat-lift capability and absence of moving parts. The fluid (ammonia) in the loop changes phase when in contact with the conductive plate to which the diodes are thermally coupled. The vapour expands via the ducts to the radiator, mounted on the satellite's anti-sunward face, where it returns to the liquid phase. The fluid is pumped by capillary effect through a sintered nickel wick and the fluid level is maintained constant throughout the whole range of thermal loads and operating cycle by a reservoir (Figs. 5a,b). The breadboard, including the large radiator assembly, has been submitted to both vibration and thermal-vacuum testing and the capillary pump was shown to still operate successfully even under 1 g conditions (i.e. when pumping against gravity).

The back-scattered radiation is collected by a 60 cm lightweight Cassegrain telescope, weighing less than 10 kg. The primary mirror is realised in C-SiC (Fig. 6), coated with a 100 micron SiC vapour-deposited layer, and supported by a non-hygroscopic CFRP structure. The large primary C-SiC mirror has already been breadboarded and polished to specification (surface roughness < 20 nm p-v) and the next step will be integration of the overall telescope.

The telescope is mounted on a single-axis scanning mechanism (Fig. 7), suspended between two liquid-lubricated bearings, designed for a lifetime of 1.8×10^7 cycles. The scanning-induced torque is compensated by a



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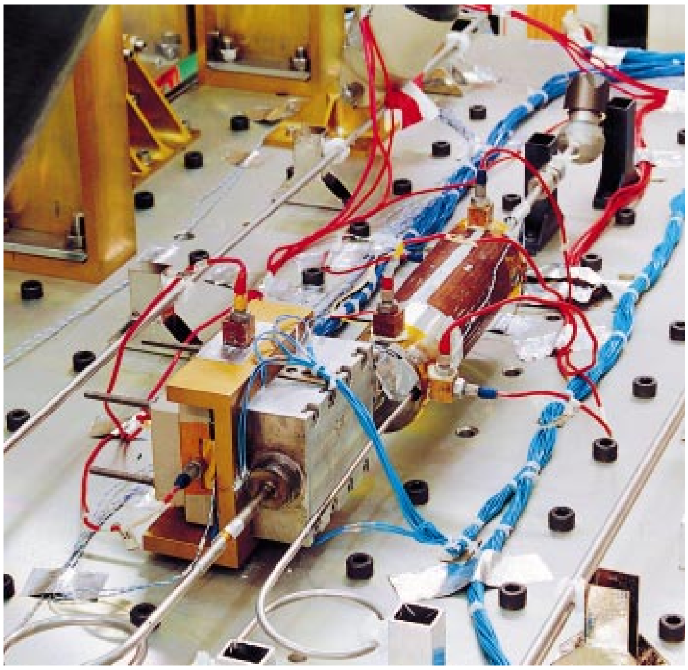

a

Figure 5. The laser thermal-control system: (a) evaporator/reservoir assembly with the ducts, ready for vibration testing; (b) overall breadboard assembly ready for thermal-vacuum testing

contra-rotating flywheel. The scan-mechanism breadboard includes the motor and bearing assembly and an optical encoder for angle restitution and monitoring, the electronic controller, the flywheel, and a locking device for the telescope during launch. The overall scan assembly, with a dummy mass for the telescope, has successfully passed its vibrational and thermal-vacuum testing. The bearings have also successfully completed an extended life-test in vacuum.

Focal-plane optics direct the incoming photons to the detection chain via an ultra-narrow-bandwidth filter for rejecting the background light originated by Earth albedo. The breadboarded filter is a Fabry-Perot device (Fig. 8), which has been shown to transmit up to 63 % of the return signal within a bandwidth as narrow as 0.21 nm. A Lyot filter was also breadboarded, but it proved less robust in meeting the accuracy and stability requirements.

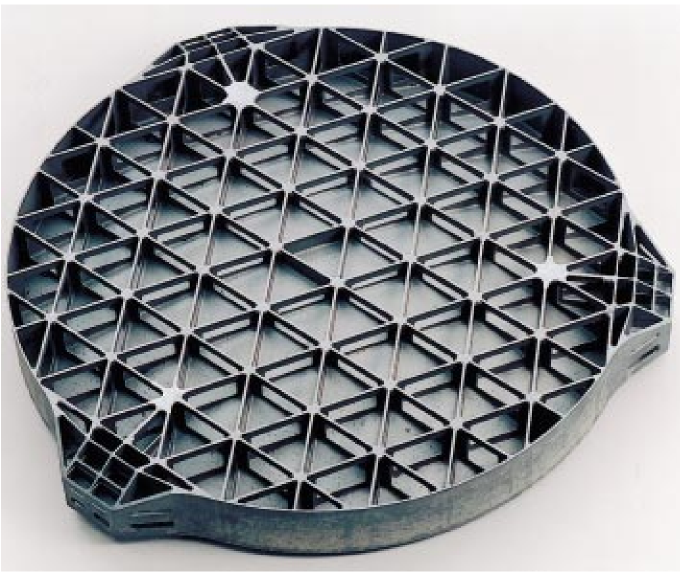

Figure 6. The ATLID telescope's C-SiC lightweight primary mirror (rear side)

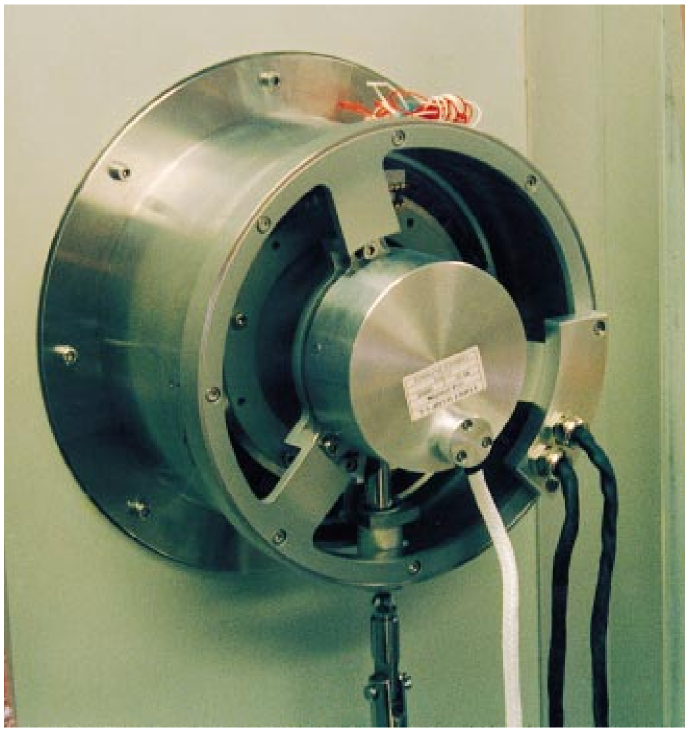

Figure 7. The scan mechanism, with the optical encoder in the foreground

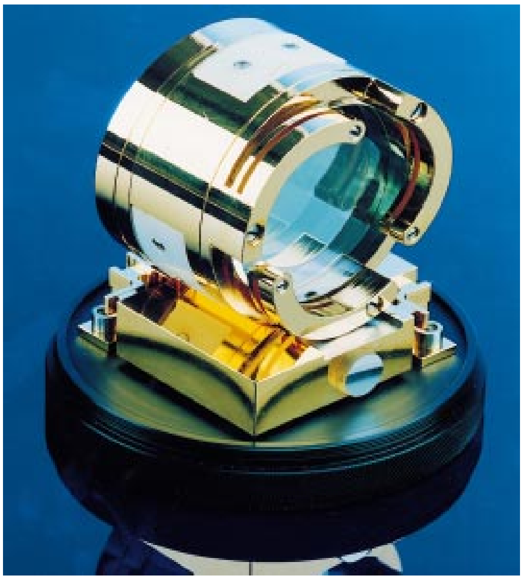

Figure 8. The hybrid front-end detector module of the ATLID receiver

The ATLID receiver consists of a detection module and a post-detection electronic chain. The detection module is based on a silicon APD, DC-coupled to a low-noise trans-impedance amplifier, integrated in a hybrid circuit. The latter has already been built to flight standard and provides an exceptionally low level of noise current. In order to perform the twin roles of cloud-top-height and aerosol-density measurement, the post-detection electronics is split into two parallel chains. The peak detection chain deals with high-intensity and sharp signals like those coming from the tops of thick clouds, and basically operates on a logarithmic amplifier. The radiometric chain is a high-gain high-linearity electronic assembly, able to trace minimum variations in the signal even at very low intensities, such as occur in the profiles generated by thin clouds or aerosol layers. The measured performances of the ATLID detection chain, in both day- and night-time operation, are outstanding: the measured signal-to-noise ratio meets — and more often exceeds — specification for all atmospheric targets, and the timing capabilities ensure a vertical resolution of 40 m, in a measurement range reaching to 25 km altitude.

On the basis of the architecture selected and the breadboard results, the estimated mass and power consumption of the complete ATLID instrument are 240 kg and 450 W, respectively.

The future of ATLID

As reported above, all of the key units have been successfully breadboarded and tested against their functional — and in most cases already also against their environmental — requirements. Although the focus has been on meeting functional requirements, the design standard of the units has permitted a substantial verification of the engineering performance against vacuum operation, temperature range and thermal cycling and random/sine vibrations and shocks. The availability of units of this standard will make the development and qualification of the future flight unit much more straightforward and efficient.

After subsystem integration and testing, following the programme of work planned for the years 1998 — 2000, the ATLID subsystem concepts and the maturity of the technology will be proven, in readiness for exploitation in the context of the Earth Explorer Earth-Radiation Mission.

All breadboarded models and units will then be available for further experimentation, either for further laboratory tests of specific lidar functions or to be assembled in a ground-based (or airborne) lidar model for supporting campaigns, ground-truth validation of other lidar missions and – possibly – for refurbishment and utilisation in flight tests.

Aside from the hardware heritage, the ATLID Technology Development Programme is providing a valuable return in terms of the day-by-day learning process, generating experience that can be exploited for other future technology developments. The ATLID work has also been a valid test-bench for the method of approaching the conception and initial development of complex innovative instruments like lidars. Rather than committing the R&D on single critical technologies to isolated specialists, a multi-disciplinary approach has been pursued to exploit throughout the synergies between the development of both the units and the sub-system, typical of a mature project environment.

The ATLID Programme can be seen as a successful R&D experience that has exploited the synergies between several different domains of space instrumentation technology in order to pave the way for the first European Lidar in space.

Acknowledgements

ATLID is the result of the joint efforts of many people, who have contributed over many years to ensure its success. The inputs of the following ESTEC colleagues who supported the development programme with their ideas and expertise are gratefully acknowledged: I. Arens, E. Armandillo, P. de Boer, A. Culoma, C. Garcia Marrirodriga, B. Harnisch, P. Ingmann, H-P. Lutz, R. Meynart and W. Supper. Nor would the programme have been so successful without the efforts and enthusiasm of our industrial partners, who actually realised the ATLID breadboards and units. In particular, the dedication and relentless efforts of D. Morancais, the ATLID Project Manager at Matra Marconi Space France, are gratefully acknowledged