International Conference on Space Optics—ICSO 2004

Toulouse, France

30 March–2 April 2004

Edited by Josiane Costeraste and Errico Armandillo

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International Conference on Space Optics — ICSO 2004, edited by Errico Armandillo,
Josiane Costeraste, Proc. of SPIE Vol. 10568, 1056804 · © 2004 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308009

WALES : WATER VAPOUR LIDAR EXPERIMENT IN SPACE

F. Guerin[1] Th. Pain[2] J.L. Palmade[3] E. Pailharey[4] D.Giraud[5] F.Jubineau[6]

[1,2,3,4,5,6]*Alcatel Space, 100, Bld du Midi, BP 99, 06156 Cannes la Bocca, France,*
[1]*francois.guerin@space.alcatel.fr,* [2]*thierry.pain@space.alcatel.fr,* [3]*jean-luc.palmade@space.alcatel.fr,*
[4]*eric.pailharey@space.alcatel.fr,* [5]*dominique.giraud@space.alcatel.f,* [6]*franck.jubineau@space.alcatel.fr*

ABSTRACT

The WAter vapour Lidar Experiment in Space (WALES) mission aims at providing water vapour profiles with high accuracy and vertical resolution through the troposphere and the lower stratosphere on a global scale using an instrument based on Differential Absorption Lidar (DIAL) observation technique, and mounted on an Earth orbiting satellite.
This active DIAL technique will also provide data on the cloud coverage by means of the signal reflection on the cloud layers.
In DIAL operation, backscatter lidar signals at two wavelengths - at least - are detected. One wavelength (λ ON) is highly absorbed by the species of interest, while the other (λ OFF) is backscattered with minimal absorption. This difference in absorption at the two transmitted wavelengths leads to the determination of the concentration of the species of interest.
The DIAL is therefore a dual-wavelength lidar in which the signals detected at the two wavelengths are processed to extract the absolute density of water vapour.
The Phase A study performed by ALCATEL Space and their partners under contract of the European Space Agency has led to a credible and innovative concept of instrument, based on a mission performance modelling.
The challenge is to foster the scientific return while minimising the development risks and costs of instrument development, in particular the laser transmitter.
The paper describes the payload design and the implementation on a low Earth orbiting (LEO) satellite.

1 THE WALES MISSION

WALES is one of ESA Earth Explorer missions: the main objectives are the climatology, the spatial distribution of water vapour, the convergence of the humidity field, the surface fluxes and the energy budget of the Earth/atmosphere system. With respect to these scientific objectives, experimental specifications are considered.

In Differential Absorption Lidar (DIAL) operation, backscatter lidar signals at two wavelengths -at least- are detected. One wavelength (λ ON) is highly absorbed by the species of interest, while the other (λ OFF) is backscattered with minimal absorption.

In practice, several λ ON wavelengths are used to cover the variation of water vapour concentration. For WALES, three λ ONs and one λ OFF are a good compromise.
This difference in absorption at the two transmitted wavelengths leads to the determination of the concentration of the species of interest. The DIAL is therefore a dual-wavelength lidar in which the signals detected at the two wavelengths are processed to extract the absolute density number of water vapour.
Lidar detection by optical means is performed by a correlation procedure or a related technique. The basic principle relies on the ability to carry out a significant signal supposedly attenuated by the noise background. This signal is thus extracted through a reference filter adapted to the optical frequency of the signal.

Recently, airborne programs have been conducted, aiming at replacing the present lidar sources by solid-state laser sources (alexandrite, titanium-sapphire) for improved performance and operation in preparation of spaceborne missions like WALES.

The primary objective of WALES is to measure the water profile on a climatological base:

- With an horizontal resolution from ~25 to 200 km following the ground track that is in agreement with the water vapour horizontal scale of variability, which is close to tens of kilometres.
- With a vertical resolution from 1 to 1.5 km in the troposphere (planetary boundary layer (PBL) and free troposphere) and in the lower stratosphere respectively.
- With an altitude range between the ground level and the lower-stratosphere (~16 km)

The global coverage is required with an air mass sampling for tropical, mid-latitude and polar conditions. The mission analysis leads to the following main parameters of a cost effective mission:

- a single satellite on a low Earth orbit (LEO, mean altitude 430 km),
- heliosynchronous orbit, 6 a.m. local time at descending node (LTDN).

The performance of the WALES instrument must be established accounting for the spatial variability of the water vapour mixing ratio in order to define the optimal characteristics of the lidar system (vertical and horizontal sampling, emitted energy, …).

The mission duration must be longer than one effective year to dispose of the seasonal variability of the water vapour field.
The water vapour profiles retrieved from WALES measurements will be used in synoptic and mesoscale models. They will be helpful to validate the Global Circulation Models (GCMs), but also to improve the knowledge of the Earth/Atmosphere radiative budget if the relative random error stays lower than 20%.
The occurrences of the main cloud covers have also to be considered (cumulus, stratus, cirrus, …) because the error budget has to be established in cloudy conditions.

The choice between the different measurement configurations has to be made mainly accounting for:

- the use of different wavelength pairs in the spectral domain,

- the optimum altitude range (between 0 to 16 km) and the air mass types (polar, mid-latitude, tropical),

- the signal to noise ratio optimisation over both oceans and continents (both forests and bare soil ecosystems).

A mission performance simulator was built: the parametric analyses lead to the following main characteristics for the Payload of WALES mission, see Fig.1:

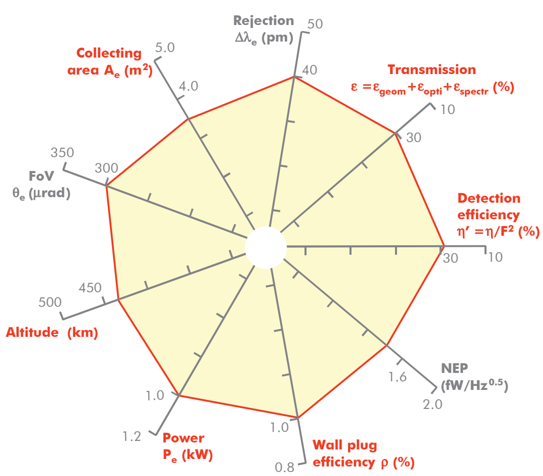

Fig. 1 System parameters of WALES Payload

2 MAIN PAYLOAD CHARACTERISTICS

The different functions and the associated subsystems of the DIAL instrument are identified and presented in the following instrument block diagram illustrated by the schematic of Fig. 2 :

Light emission: the 4 wavelengths of the transmitted beam are produced by 2 (plus one redundant) laser block units housing the distinct power laser heads and sent to the atmosphere by the Transmitter Optics (TO) composed of Tip-tilt Optics (TTO) and Beam Expander Units (BEU).

Light backscattered by the atmosphere is collected by the Collector Assembly (CA) feeding the Wavelength Separator Assembly (WSA) by means of the Collecting Relay Optics (CRO).

Light separation and filtering is ensured by the Wavelength Separator Assembly (WSA) allowing the 4 wavelengths separation and filtering.

At the output of the WSA, light is conveyed to the detection chain by a Detection Relay Optics (DRO) where light is converted by a Detection Electronic Unit (DEU) with a detector for each wavelength.

The detected signal is then conditioned, digitised and sent to the Instrument Control Unit (ICU, not represented on the schematic).

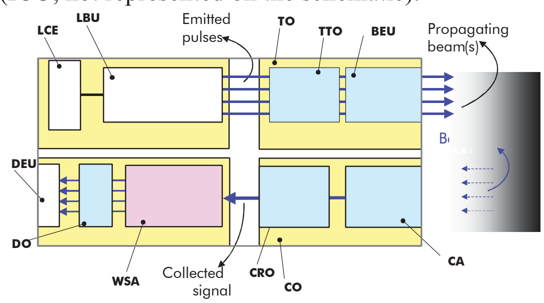

Fig. 2 DIAL instrument Block Diagram

Table 2 provides a synthetic view of the instrument configuration :

Table 2 Instrument configuration synthesis

Lidar configuration	4 wavelengths around 936 nm, 3 ON, 1 OFF Active bistatic, incoherent detection
Transmitter	3 x2 Ti-Sa pumped by Nd:Yag YAG heads (2 nominal + 1 spare)
Frequency stabilisation	4 Fabry-Perot filters of WSA, and reference to a water vapour cell
Transmitter optics	Beam expander coupled with tip-tilt mirror
Collecting optics	Tri-pupil, optical fibre in primary focus
Wavelength separator	4 capacitance stabilised Fabry-Perot filters
Detection chain	4 silicon avalanche photodiode (Si-APD) channels, in linear mode
Structure	3 laser blocks attached to a dedicated baseplate
Thermal control	Constant Conductance Heat Pipes (CCHP) and Loop Heat Pipes (LHP) to dissipate the transmitter power

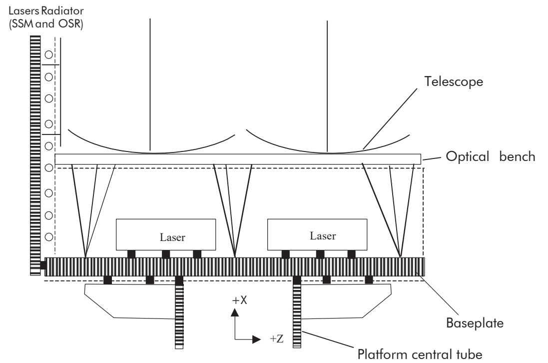

Fig. 3 Schematics of the payload

The instrument baseplate supports mainly the three power laser heads and the radiator & baffle assembly.
The Optical Bench (OB), sustained by a truss composed of three bipods, supports the telescopes and collecting optics.

3 LASER TRANSMITTER ASSEMBLY

The WALES emitter is composed of four lasers emitting four different wavelengths near 936 nm. The lasers are based on Ti:Sapphire cavities, able to reach the specified wavelengths.
To pump the Ti :Sapphire lasers, other lasers called " pump lasers ", emitting at 532 nm, will be used. These lasers are based on doubled Nd:YAG lasers.
In order to reduce the mass and the volume of the WALES transmitter while maintaining an excellent reliability of the payload, each pump laser will pump two Ti :Sapphire lasers. The pump laser emits two pulses separated by 200 µs at 25Hz: using an electrooptical device (Pockels cell with polariser), the two pulses are routed to two different Ti:Sapphire lasers.
The main oscillator is a ring stable resonator, see Fig. 4.

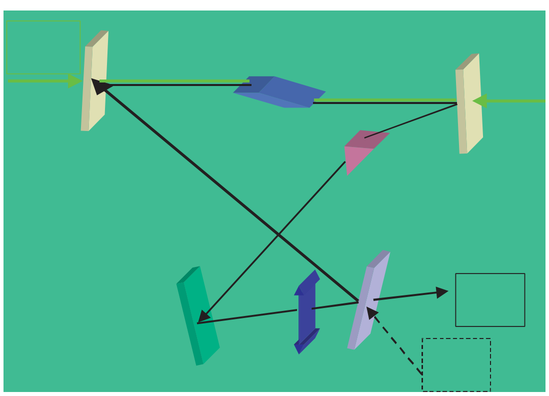

Fig. 4 Ring stable resonator

In this configuration the pump beams at 532 nm pass through the cavity dichroic mirrors (R_{max} 935 nm, T_{max} 532 nm).

The dispersive prism at Brewster angle is necessary for mode selection and linewidth. It is made of fused silica optimised for near infrared.
The mirror $R_{0.8}$ is chosen as an output coupler and is also used as the input mirror for the seeder signal.
The R_{max} 935 mirror will be mounted on PZT for cavity length adjustment.
In order to obtain a stable resonator while all the mirrors of the resonator are plane, a convergent lens is also included in the design.

The second part of the so called Ti :Sapphire cavity is constituted by a double amplifier.
In order to lock the Ti :Sapphire lasers to the required wavelengths in the single longitudinal mode, an injection seeding technique is used and seeders are implemented.
The seeders are based on Extended Cavity Laser Diodes which are tuneable to the required wavelengths and locked by Fabry-Perot filters or water vapour absorption lines.

Each Laser Block Unit (LBU) is composed of one pump laser, two Ti:Sapphire lasers, two associated seeders and a beam combiner i.e. optics able to co-align the two pulses emitted by the same pump laser.

To protect the mission from possible failure of any device of the emitter, a spare LBU is implemented in the emitter. In nominal operation, this redundant unit is switched-off. In case of glitch, the identified LBU is replaced by the redundant LBU.

The block diagram of the emitter is presented on Fig. 5.

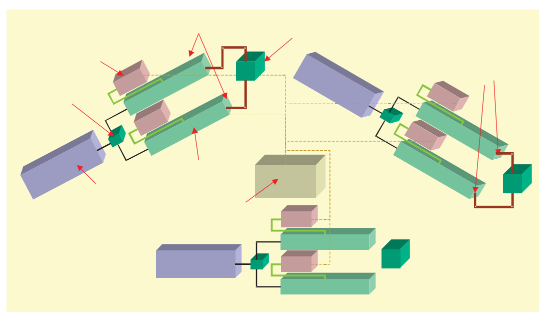

Fig. 5 Emitter block diagram

All blocks (same colour, same size) are identical. The seeders are connected to the WSA as the Fabry-Perot filters used for the locking of the wavelengths are located in this assembly. The green and golden dashed links are optical fibres. The black lines are classical optical paths.

4 OPTICS

One transmitter optics is used close to the output of each laser head (3) and fixed to the Optical Bench.

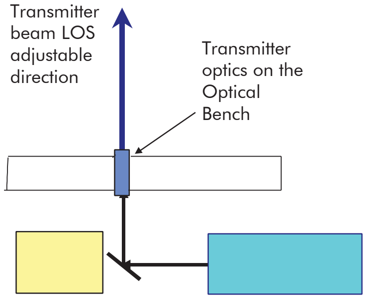

Fig. 6 Tip-tilt and transmitter optics on each (3) laser path

A transmitter optics is a beam expander with 2 functions :

- Reduce the jitter of the transmitter beam LOS with respect to the transmitter jitter.
- Adjust by defocus the divergence of the transmitter beam on ground to meet the eye safety regulations.

The tip-tilt optics is a 45° plane mirror used to correct the transmitter beam LOS periodically during geometrical calibration.

For the backscatter, the required 3.5 m^2 collecting area is not given by a mono-pupil telescope in order to minimise the development costs : a multi-pupil configuration is preferred, the collecting optics are 3 identical co-aligned telescopes.

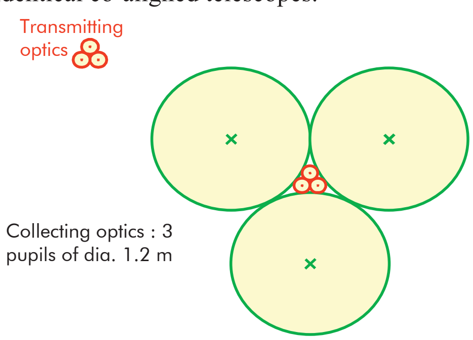

Fig. 7 Tri-pupil collecting optics

Each telescope consists in:

- a primary mirror, diameter 1200 mm, on-axis parabola,
- a field stop placed in the primary focus,
- a lens in afocal layout to optimise the coupling into the multimode fibre, imaging the primary mirror on the fibre entrance.

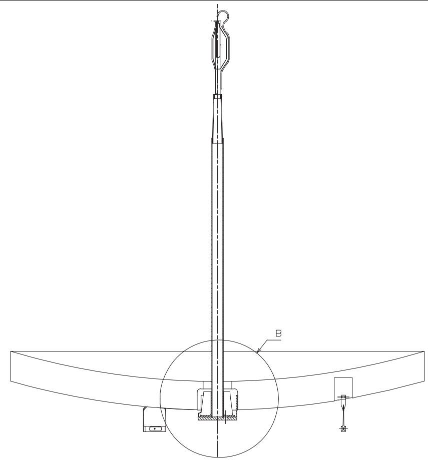

Fig. 8 Collecting telescope optics

The following set of characteristics of the 3 telescopes is proposed in order to maximise the collected backscatter signal:

- Max. misalignment of each telescope w.r.t. Optical Bench reference axis : ≤ 70 µrad (goal 60 µrad).
- Mirror Wavefront Error (WFE) : ≤ λ /3 rms (on axis, excluding defocus, λ=936 nm).
- FOV of each telescope 2θ = 300 µrad.

The collected backscatter signal is transported by fibre optics to the WSA and to the pigtailed detectors (4 channels), see Fig. 9 :

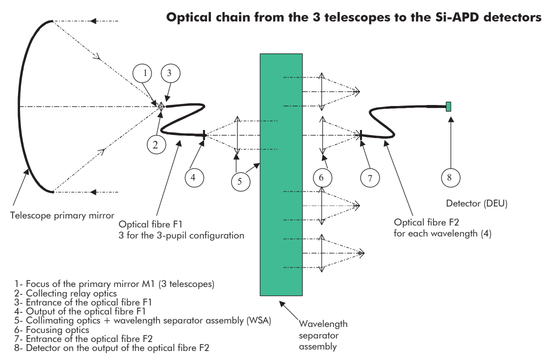

Fig. 9 Optical chain block diagram

5 WAVELENGTH SEPARATOR

The Wavelength Separator Assembly (WSA) of the WALES DIAL is aimed at separating the incoming scattered laser radiation into four distinct wavebands, corresponding to the four wavelengths (three on-line, one off-line) of the emitted laser pulses. This is illustrated by the schematic at the top of Fig. 10.

The WALES wavelength separator concept is shown in block diagram form at the bottom of Fig. 10.

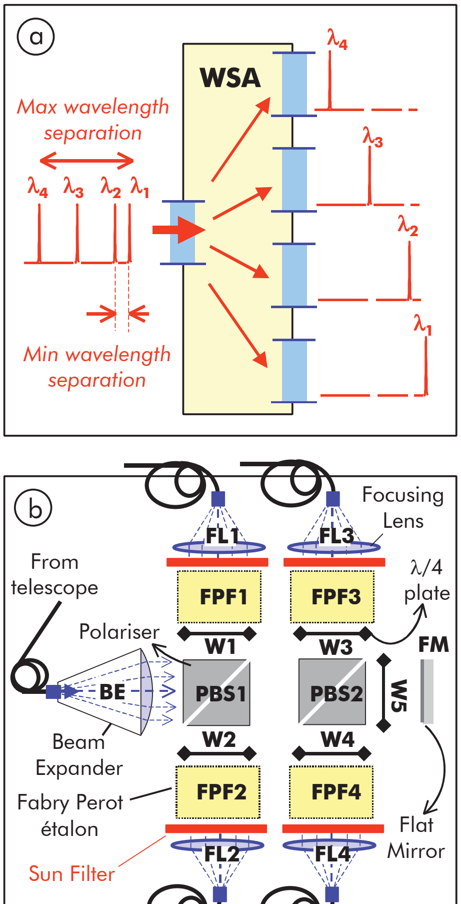

Fig. 10 Wavelength separator

The design provides with the distribution of radiation from the telescope to four Fabry-Perot filter assemblies (FPF 1-4), each of them consists in a sun filter in tandem with a Capacitance Stabilised Etalon (CSE) whose peak transmission coincides with one of the four specific wavelengths to be detected.
The CSE gap spacing is actively controlled by a driver electronics, named Piezo Driver Unit (PZDU).
The bandwidth of each of the filter assemblies (~20 picometers) is set to be much smaller than the minimum separation between the wavelengths, thus allowing good spectral resolution. The narrow bandwidth achievable with the sun filter also allows good background rejection.
The wavelength dispatching is ensured by the Polarising Subassembly (PSA) consisting in two Polarising Beam Splitter cubes (PBS1 and PBS2), a set of Quarter Wave Plates (W1 – W5) and a Flat Mirror (FM).

The principle of wavelength separation is described hereafter. Radiation from the receiving telescope is carried by a multi-mode fibre optic to a beam expander which provides a collimated beam that is input to the Polarising Subassembly (PSA). The two components of the randomly polarised radiation (p- and s-polarised) are first separated by the action of PBS1. This beam splitter allows transmission of the p-polarised component whilst reflecting the s-polarised component into the first Fabry-Perot Filter (FPF1). Radiation incident on FPF1 is filtered and only that within the transmission waveband is transmitted to the detection system, the rest being reflected.
The quarter wave plate (W1) positioned in front of FPF1 performs the task of rotating the plane of polarisation of the reflected radiation by 90° (since it passes twice through the plate) allowing the light to propagate through PBS1 to the second Fabry-Perot Filter (FPF2).
This process is repeated until all Fabry-Perot Filters are exposed to the incident radiation. Radiation that is initially p- polarised, and therefore transmitted by the two beamsplitters, is reflected by the flat mirror (FM), passing twice through the quarter-wave plate (W5). The resulting rotation of the plane of polarisation produced by the quarter-wave plate allows this component to be distributed to the four Fabry-Perot Filters in the same way as the incident s-polarised component.

6 DETECTION CHAIN

The design requirements are given here after :
- four detection channels,
- wavelengths around 936nm,
- pulses for the four channels staggered (100 µs), but the backscattered signals may overlap,
- pulse repetition time (for each wavelength) 25 Hz,
- all acquisition chains working synchronously,
- the acquisition start marked by the laser trigger pulses (distributed to the APD receiver modules),
- acquisition of a series of calibration samples, waiting a selectable time of 2 to 3ms, acquisition of typically 120µs useful signal with two series of samples before and after (typically 100µs TBC),
- electronics powered all the time for stability reasons.

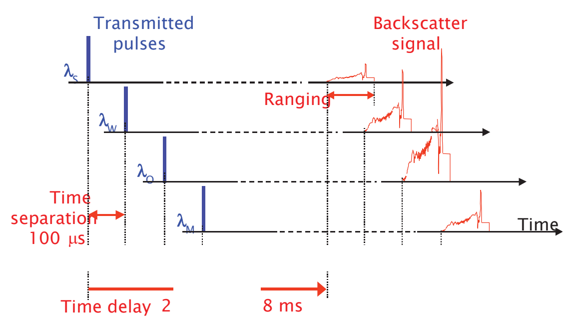

Fig. 11 Pulse Time Scale

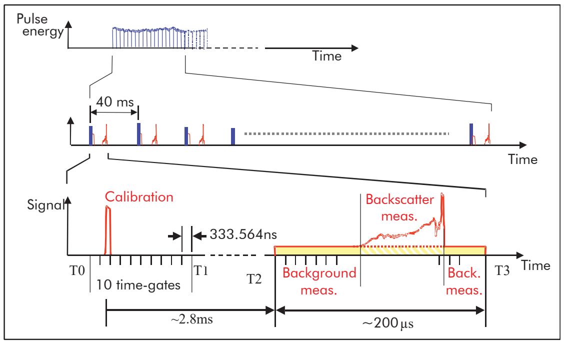

Fig. 12 Pulse form (details)

Requirements for the detector chain are:

- Expected signals:
  1-1000 photons/µs background,
  1-1000 photons/µs useful signal,
  $4*10^{3}$ photons/µs on cloud return (shall be measured),
  $7*10^{5}$ photons/15ns single pulse on ground return (may saturate the sensor).
- Quantum efficiency of detector: $\eta \geq 80\%$ at 940nm.
- Excess noise factor: $F^2 \leq 3$.
- Noise equivalent power: NEP ≤ 1.5 fW/√Hz.
- Linearity ≤ 0.1% over ADC dynamic range.

The APD reference design consists of four identical APD Modules (APDM 1 to 4) with the APD front-ends (including the high voltage control), data acquisition systems, sequencer, and housekeeping units (HK). The APDMs are controlled by the interface unit (IFU). The IFU receives commands from the Instrument Control Unit (ICU), decodes them and distributes them to the APDMs. The IFU also collects the measured data and HK data from each APDM, puts them together into frames and sends them to the ICU.

The parameters for the APDMs are programmed by the ICU via the interface. In addition for each module a master sampling clock and a start conversion signal (from ICU and/or laser pulse generator) is provided.

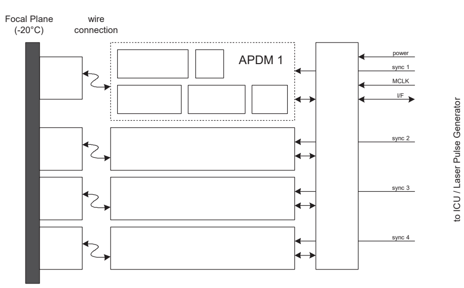

Fig. 13: APD Functional Overview

The APDMs are identical (except the calibration voltages) and are fully interchangeable. Also the APD front-ends are identical and interchangeable.

The analogue signal path consists of the APD front-end with an integrated trans-impedance amplifier (TIA) which is connected via symmetrical shielded cable and a multiplexer to the signal conditioning stage (signal span adjusting, offset control, clipping and low pass filter) and the analogue to digital converter.

The included TIA has the advantage to be matched to the APD, short signal lines and therefore higher possible bandwidth because of low parasitic capacitance. The low temperature also decreases thermal noise within the TIA.

The expected signal range leads to a maximum of about 2000 photons/sample (333 ns). To cover this range a 12-bit ADC is necessary and a 14-bit ADC is chosen to give 2 bits reserve and minimise the quantisation noise.

Each APDM samples the data with a rate of 3 MHz (one sample per 333 ns). Each sample consists of a 16-bit word, the 14-bit data word from the ADC and the 2-bit pulse identification. One APD Module generates a total of ~500 data words for each laser pulse, that is to say every 40 ms (pulse repetition frequency of 25 Hz).

The data link to the ICU is a SpaceWire interface operating at 42 Mbit/s, which can easily handle the expected 4*500*16bits/40ms = 800 kbit/s (without the overhead for additional housekeeping data and control commands).

7 CALIBRATION

The lidar configuration is unique because it does not require any additional dedicated hardware but takes advantage of the extended capabilities of the operational hardware. Calibration is relative except the spectral calibration owing to the principle of DIAL measurement that refers to well defined absorption lines.

- For geometrical calibration, the 3-telescope field of view is scanned by tilting step by step the axis along which the laser beam propagates whilst the ground echo is acquired. At last, the nominal line of sight (LOS) is retrieved from the radiometric plot obtained at completion of the scan and the laser beam is positioned in this direction.
- Spectral calibration takes benefit on the tuneability capacity of Capacitance Stabilised Etalon. The procedure is based on the principle of scanning the Free Spectral Range.
- For radiometric calibration, a fraction of the laser transmitter energy is picked off, and injected into an optical fibre whose output

illuminates the entrance of the carrying optical fibre of the telescope. It is a way to guarantee that the calibration flux performs in the same way as the backscatter without any discrepancy. The filter of the wavelength separator can be tuned to attenuate the impinging signal and derive fruitful information about the detection chain itself.

8 MECH. / THERMAL ARCHITECTURE

The instrument is supported on the satellite platform by means of a spacer structure aiming at providing both an effective stiffening of the instrument baseplate and a free access to the interface attachment points necessary for the mating on the satellite platform.

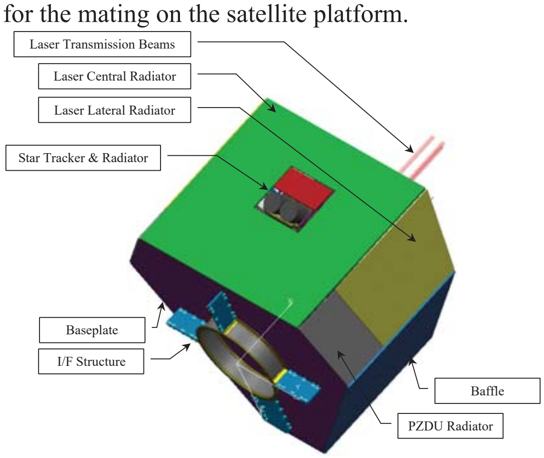

Fig. 14 : Instrument bottom perspective

The instrument baseplate supports mainly three power laser heads and the radiator & baffle assembly. It is made of a CFRP-skinned sandwich panel, a classical technology suitable to stiff and stable structures. The panel height is 100 mm in a conservative approach in order to guarantee a high stiffness.

The spacer structure is composed of a ∅900 mm CFRP tube equipped with two fixation rings made of titanium and four CFRP sandwich plates corresponding to the P/F internal shear walls.

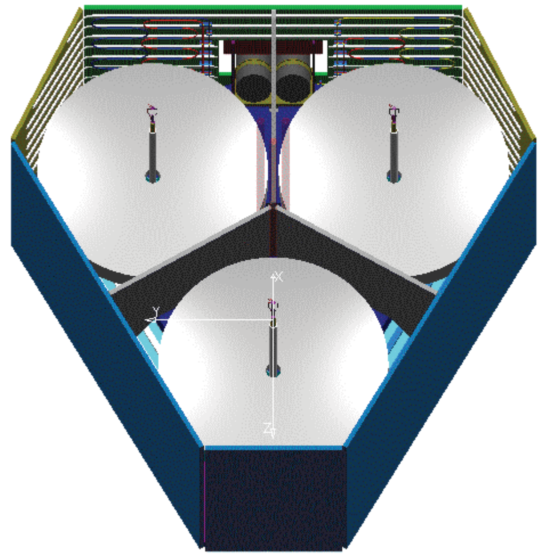

Fig. 15 Instrument – Top view showing the 3 telescopes on the optical bench

The Optical Bench (OB) is a sandwich plate with CFRP face sheets, simply supported thanks to a truss composed of three bipods.

Each telescope is composed of a wide mirror and a small low-weight focal group. A simple mast supports that small element, providing both sufficient stiffness and stability together with the minimum mass.

The budget of mirror wavefront error is $\lambda/3$ rms (for λ=936 nm).

The thermal control of the laser units is demanding because of the large dissipated power (> 700 W). A fully redundant network connects each of the laser units to the global radiative surface. The laser cooling system is represented in Fig. 16 :

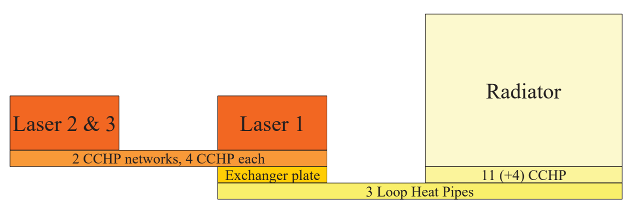

Fig. 16 Laser cooling concept

Three loop heat pipes (LHP) distribute the heat collected on the exchanger plate to the radiator CCHPs. The LHP proposed routing along all the radiator CCHPs provides the redundancy necessary to compensate for the failure of any LHP.

9 MAIN BUDGETS

Volume along X (optical axis)	2200 mm
Volume along Y	2800 mm
Volume along Z (normal to anti-sun face)	2500 mm
Power consumption	1490 W
Mass	587 kg nominal 673 kg max.
Data rate (science)	800 kbits /s (for 4 detection channels)
Radiative required area (total)	5.1 m^2

10 DEVELOPMENT ASPECTS

WALES mission leads to stringent requirements in particular for the laser transmitter such as :
- High energy (75 mJ per wavelength and per pulse).
- High stability.
- High reliability, considering a duty cycle of 100 % and a life time of at least two years.
- High power to be dissipated, because of the poor efficiency of the electrical to optical conversion of the power laser : this leads to a thermal control of the laser heads and Laser Control Electronics designed with a network of LHPs and CCHPs.

Development risks are currently mitigated by technological developments in progress.

The detection chain based on Si-APD detectors has two critical points:

- the required high quantum efficiency of the APD for the wavelengths around 936 nm,
- the low noise requirement.

A specific development to reach the high values of quantum efficiency and to implement an integrated TIA in the APD is feasible at low risk.

A tentative schedule for the development of WALES payload is :

- duration of phase B : 18 months
- duration of phase C/D : 54 months (4.5 years)

The driver is the development of the laser transmitter.

Acknowledgements :
The authors thank greatly their partners in the study contract who contributed significantly to the design of WALES payload: MM Heinz-Volker Heyer and Bernard Voss from Kayser-Threde GmbH, Robert Bond from AEAT Ltd, Paul Wazen from Quantel S.A., Didier Bruneau from CNRS / Institut Pierre-Simon Laplace, Patrick Chazette from CEA / Laboratoire des Sciences du Climat et de l'Environnement, and the WALES team of Alcatel Space.

References:

[1] WALES Phase A Executive summary
WALES-ASP-RP-77, Issue 1, February 2004