Technical & Programmatic Annex

April 2004

EarthCARE	- Earth Clouds, Aerosols and Radiation Explorer
SPECTRA	- Surface Processes and Ecosystem Changes Through Response Analysis
WALES	**- Water Vapour Lidar Experiment in Space**
ACE+	- Atmosphere and Climate Explorer
EGPM	- European Contribution to Global Precipitation Measurement
Swarm	- The Earth's Magnetic Field and Environment Explorers

European Space Agency
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REPORTS FOR MISSION SELECTION

THE SIX CANDIDATE EARTH EXPLORER MISSIONS

Annex to ESA SP-1279(3)
April 2004

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WALES - Water Vapour Lidar Experiment in Space
Technical and Programmatic Annex

European Space Agency
Agence Spatiale Européenne

Contents

1 Introduction

This document provides the technical description of the WALES mission as derived from the preparatory activities at phase A level, for implementation as an Earth Explorer in the frame of ESA's Living Planet Programme. It shows how feasible implementation concepts can respond to the scientific mission requirements defined in the Science Report. To this end, the expected system performance will also be described. A summary assessment of the programmatic framework is also provided.

The system description is mainly based on the results of the work performed during two parallel phase A system studies by two industrial consortia. It is not possible to describe in this report all technical concepts, but, where necessary, two concepts are described in order to present significantly different approaches to meeting the mission observation requirements. The description of particular concepts does not indicate special preferences.

After an overview of the mission architecture and the proposed orbit (in Chapters 2 and 3) the space segment will be described in detail (Chapter 4), followed by the ground segment and operations concept (Chapters 5 and 6). Following an overview of the data products (Chapter 7), the overall performance is described (Chapter 8). The report concludes with programmatic considerations (Chapter 9).

2 Mission Architecture Overview

The WALES mission is devoted to the profiling of atmospheric water vapour concentration on a vertical domain extending from the Planetary Boundary Layer to the Upper Troposphere on a global scale.

The main architectural elements of the WALES mission are depicted in Figure 2-1

The space segment is constituted by a single satellite placed on a near polar sun-synchronous orbit at a mean altitude of about 450 km and operating a nadir viewing water vapour DIfferential Absorption Lidar (DIAL) instrument.

Figure 2-1 *WALES Mission Architecture Elements*

A Soyuz launcher, proposed as the baseline, will achieve injection of the spacecraft into its target orbit. The WALES satellite is also compatible with the Long March and Delta 2 back-up launchers.

The WALES Ground Segment is composed of:

- The Command and Data Acquisition Element (CDAE) consisting of three ground stations for the science data acquisition located in Svalbard, Prince Albert and Gatineau and one ground station for Telemetry, Traking and Telecommand (TT&C) located in Kiruna;

- The Mission and Satellite Control Element (MSCE) located at ESOC and in charge of satellite monitoring and control, mission planning and control and overall ground segment technical supervision;

- The Processing and Archiving Element (PAE) located at ESRIN and in charge of product extraction, archiving and distribution to the end users, acquisition of external auxiliary data from Numerical Weather Prediction (NWP) centres and services to the users.

3 Orbit

The orbit selected for the WALES satellite is a near polar dawn-dusk sun-synchronous orbit with a mean altitude in the range of 425-450 km.

The selection of the orbit altitude is a compromise between the conflicting needs of the DIAL payload (lower altitude translates, for a given performance target, into lower needs for emitted power and/or surface of the collecting optics) and those of the supporting platform (lower altitude translates into higher atmospheric drag impacting the AOCS, propulsion sub-systems and overall spacecraft configuration together with an increase of atomic oxygen concentration that requires adequate protection of the exposed surfaces from the induced erosion)

The dawn-dusk orbit ensures optimal observing conditions for the DIAL instrument by minimising the solar background and the selection of the Local Time of the Ascending Node (LTAN) at 06:00 hours favours the observations over the northern hemisphere where the worst case sun illumination condition expressed in terms of Sun Zenith Angle (SZA) will not be lower than 75 deg (as opposed to about 60 deg worst case over the southern hemisphere).

The selected orbit allows for a relatively simple and robust design of the solar array, which can be maintained at a fixed orientation after deployment, and for one side of the platform to be constantly exposed to deep space. This makes a large radiative surface available for the rejection of heat generated by the high dissipation payload.

The mission requirements do not impose stringent constraints on the orbit maintenance. The only orbital parameters to be controlled are the orbit altitude and the LTAN in order to maintain the same sun illumination conditions over the whole mission duration.

The altitude control in a dead band of ±5 km ensures a maximum change of the LTAN lower than 3 minutes over 3 years and requires manoeuvres only once every 2-4 months, depending on the launch date and the corresponding solar activity.

The eclipse period takes place around the winter solstice over the northern hemisphere. The maximum eclipse duration is about 24 minutes for the 450 km orbit.

4 Space Segment

Modular satellite concepts have been proposed, with clear separation between the payload and the platform modules. The relevant technical descriptions are summarised in the following Chapters 4.1 and 4.2 and complemented with an overview of the overall satellite configuration in Chapter 4.3.

4.1 Payload

4.1.1 WALES Observation principle

WALES is intended to profile the atmosphere in a nadir-viewing configuration as depicted in Figure 4-1. The DIAL technique compares the attenuation of two laser pulses emitted at different wavelengths. The on-line wavelength falls on the centre of a water vapour absorption line and the off-line wavelength falls on the line wing, where absorption is significantly reduced.

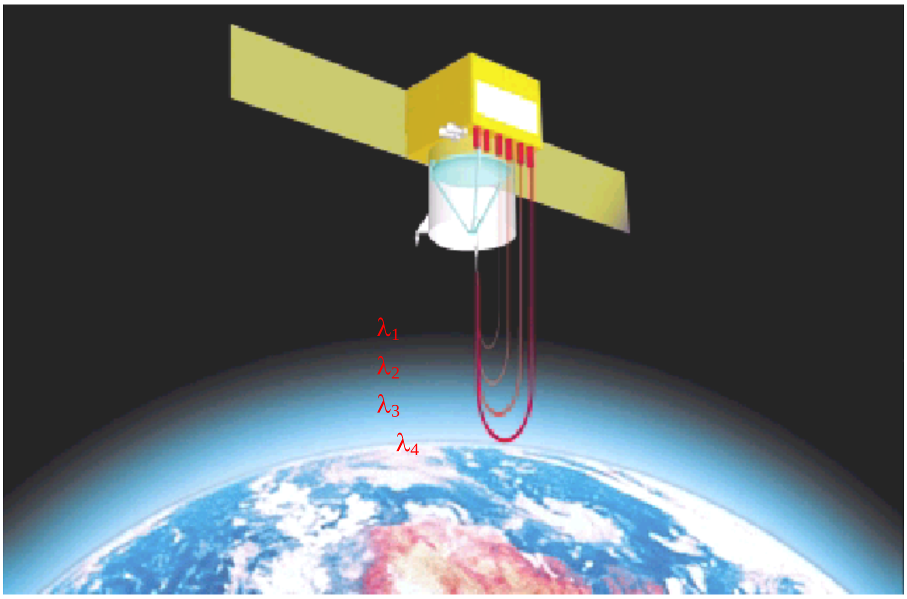

Figure 4-1 *Wales Observational Principle*

With the WALES DIAL instrument the large dynamic range of water vapour is addressed using three on-line wavelengths λ_1, λ_2, λ_3 with different (water vapour) attenuation cross-sections, and one off-line wavelength λ_4, as depicted in Figure 4-2. In this way, different sub-intervals of the dynamic range are sensed by dedicated on-line wavelengths. For typical water vapour profiles, the different on-line wavelengths possess different penetration depths, thus allowing for measurements in different altitude intervals. The location of these intervals varies with climate zone. The strongly absorbing water vapour lines are used for higher altitudes (low water vapour concentration) and the weakly absorbing lines are used for lower altitudes (high water vapour concentration). From near-simultaneous sounding with all four wavelengths, complete profiles across the entire altitude range are obtained.

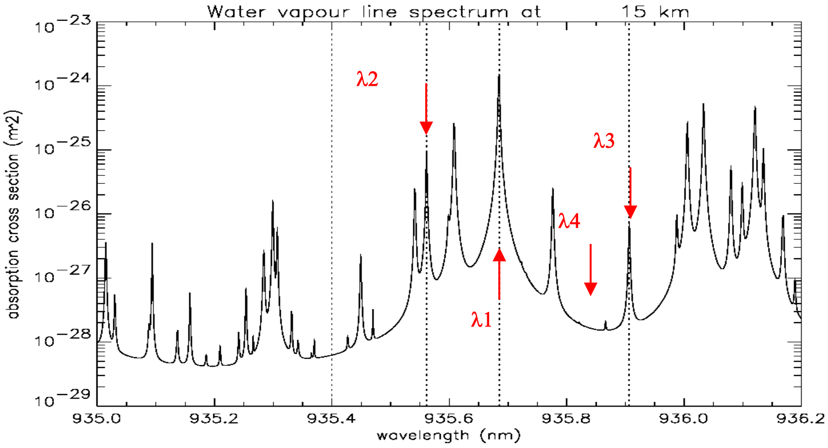

Figure 4-2 *Selected water vapour lines*

Three (on-line) wavelengths are located at the centre of water vapour absorption lines of different attenuation cross section. The fourth one (off-line) is located at a nearby wavelength with low attenuation due to water vapour. The intensity of the echo signal produced by the atmospheric target (molecular and aerosols backscattering) is measured. The evaluation on ground of the signals intensity according to the DIAL principle allows the determination of the water vapour concentration profile.

Suitable water vapour absorption lines for an instrument with three on-line wavelengths and a separate off-line wavelength have been identified in the region around 935nm. A close spacing between on- and off-line is always desirable to minimize any wavelength dependence on the unknown backscatter and extinction coefficients of other particles and molecules.

4.1.2 Instrument Description

The WALES instrument operates as a bi-static DIAL that transmits laser light at four wavelengths into the same atmospheric volume. The four wavelengths are precisely controlled with respect to the water vapour absorption spectrum.

Operation Mode

Two different operation modes have been proposed for the emission of the four wavelengths, the so-called ‘continuous’ mode and the ‘burst’ mode.

In continuous mode, the four wavelengths are emitted with a constant temporal separation, however in different pointing directions, as shown in the right panel of Figure 4-3. The advantages of this operation mode are:

- In-field separation can be used in the receiver avoiding the need for frequency or polarisation de-multiplexing of the received echo signals. This allows for the optimisation of the receiver filter chain entirely for the purpose of background light suppression, and hence for the increase of the measurement performance.
- The laser pump units can be designed for continuous pulse repetition frequency operation.

In burst mode, the four wavelengths are emitted with a close temporal separation of 100 to 200 µs with the same direction, as shown in the left panel of Figure 4-3. Bursts of four pulses (in the four wavelengths) are separated by about 40 ms.

The main advantage of this operation mode is the relaxation of the pointing stability requirements to maintain the co-location of the atmospheric volumes sampled by the four emitted wavelengths.

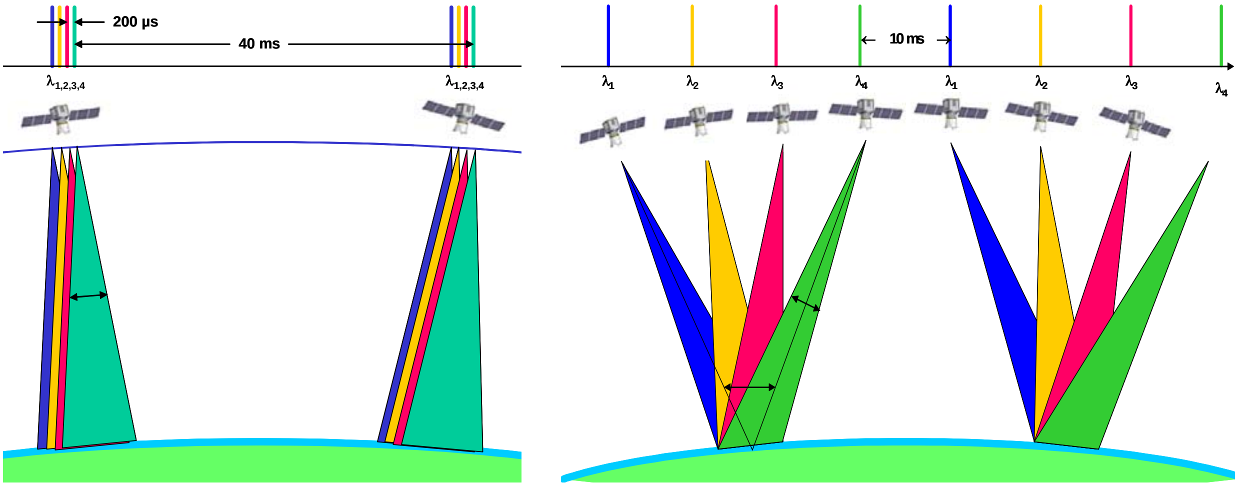

Figure 4-3 *Burst (left) and Continuous (right) Mode Operation Principle*

Instrument architecture

The proposed instrument concepts have the following characteristics:

- Probing the same air volume with all four wavelengths using the ‘continuous’ or “burst” mode operation principle;
- Either a single transmitter telescope with sub-apertures or separate telescopes for all the emitted beams;
- Individual transmitter Titanium:Sapphire (Ti:Sa) laser sources for each emitted wavelength;
- Pump lasers, each pumping two laser sources;
- A frequency stabilisation scheme based on seed lasers locked to a combination of water vapour absorption cell and wavemeter;
- A large aperture mono-pupil or tri-pupil receiving telescope;
- A demultiplexer of the received echo signal to four different receivers, each equipped with a narrow-band filter to suppress background light;
- Calibration signals derived from the seed lasers.

Figure 4-4 shows the different sub-systems in a functional block diagram of the instrument. This configuration corresponds to the instrument based on the continuous operation mode, however both proposed instrument concepts show similar sub-systems breakdown.

The transmitter unit consists of a pump unit and two laser sources. There are three such units to allow the quasi-simultaneous operation of the four wavelengths and provide redundancy. Additionally the frequency stabilisation unit feeds the laser source with long-term stabilised seed lasers and a transmitter telescope or a set of transmitter telescopes emits the light pulses towards the atmosphere.

The receiver assembly functions are to collect the backscattered echoes through large aperture telescope, to separate the four received wavelength, to reject the background radiation through a filtering stage and to detect and digitise the four signals. The instrument provides 50 m vertical sampling from ground to 16 km altitude and 1 km horizontal sampling.

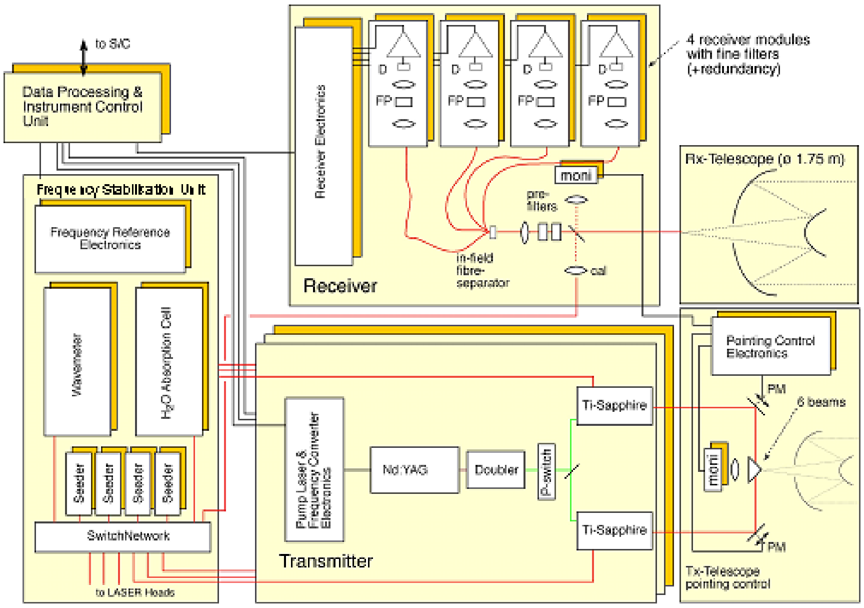

Figure 4-4 *Instrument block diagram for the " continuous mode operation" based concept*

The overall instrument and data-management functions are included in the dedicated instrument control unit, interfacing with the spacecraft controller.
The power electronics, the pump unit, the detector assembly and the instrument control unit are cooled by a dedicated heat pipe assembly, which is connected directly to the satellite radiator.

4.1.3 Transmitter assembly

The transmitter assembly consists of three transmitter units and the frequency reference unit. The transmitter baseline design consists of a pump laser operating at an average pulse repetition frequency of 50 Hz and pumping alternately two Ti:Sa laser sources each emitting 75mJ at 25 Hz. In the whole transmitter laser assembly, two of these transmitter units are active and one is implemented in cold redundancy. Figure 4-5 shows the functional layout of the transmitter units (the redundant unit is not shown).

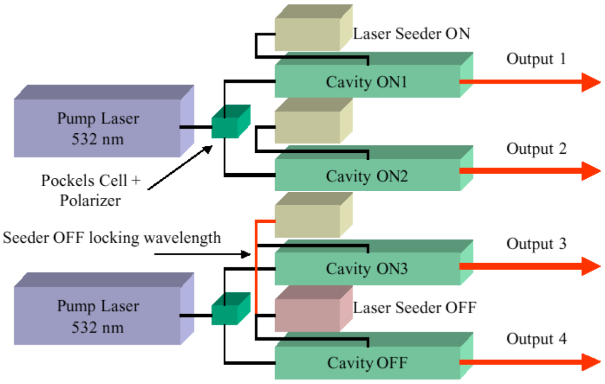

Figure 4-5 *Functional layout of the WALES transmitter*

The requirements applicable to the laser system are given in Table 4-1

Number of wavelengths	4 wavelengths to be transmitted either as a burst of 4 pulses or in continuous mode
Laser pulse energy	75 mJ
Pulse repetition frequency	25 Hz in burst mode (4 pulses emitted each 40 ms) 100 Hz in continuous mode (pulses are emitted every 10 ms)
Inter pulse separation within burst	100 to 200 µs
Wavelength range	935-936 nm
Laser frequency accuracy and stability	< 60 MHz
Laser linewidth (FWHM)	<160 MHz
Laser spectral purity within 1 GHz	>99.9 %

Table 4-1 *Requirements applicable to the laser system*

Laser source

Different technologies were traded in the frame of the system studies and related developments, such as Optical Parametric Oscillator, Ti:Sa or Raman lasers. Ti:Sa laser technology has been found to be the most mature and promising to fulfil both required power and spectral requirements.

The laser source consists in a high-energy oscillator in a ring cavity configuration, directly pumped by the pump source and injected by the seed laser (Figure 4-6). An alternative design could consist of a low power oscillator followed by an amplifier.

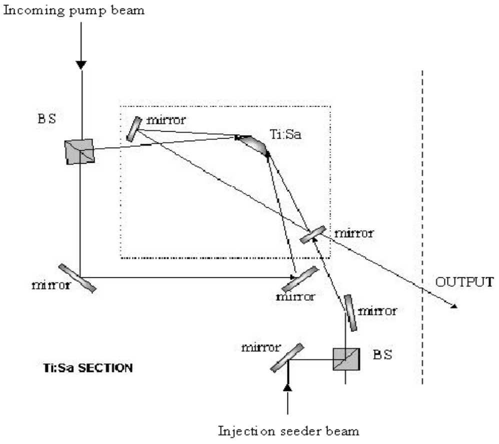

Figure 4-6 *Ti:Sa laser layout in high energy configuration*

Pump source

The pump source is based on a frequency doubled Nd:YAG laser emitting at 532 nm where most of the basic technologies have been developed for the ALADIN Doppler wind lidar of the ADM-Aeolus mission. A three-stage laser, composed of a medium energy oscillator followed by two amplifiers is proposed.

The selection of Ti:Sa technology for the laser allows relaxing the requirements applicable to the pump source with respect to the ALADIN laser for what concerns the spectral and beam quality performance.

Parameter	Value
Wavelength	1064 / 532nm
PRF	25Hz double pulses or 50Hz continuous
Output Energy	~600mJ @ 1064nm / ~300mJ @ 532nm
Longitudinal Mode	Multi-mode
Beam Quality	$M^2 > 2$ (flat top)

Table 4-2 *Pump source requirements*

In addition, to ensure high spectral purity and long-term stabilisation of the emitted wavelengths the Ti:Sa laser source must be complemented by a frequency stabilisation unit. This unit can be integrated in each transmitter unit or separated as a self-standing unit.

Frequency stabilisation unit

The frequency stabilisation unit consists of injection seeders used to lock the Ti:Sa laser source and of frequency stabilisation or frequency references to ensure the long-term stability. The baseline design for the frequency reference stabilisation is to lock one seed laser to a water vapour absorption line and to lock the other three seed lasers relative to the first one. The frequency stabilisation unit is therefore made of four seed lasers, a wavemeter and a water vapour cell used as the frequency reference.

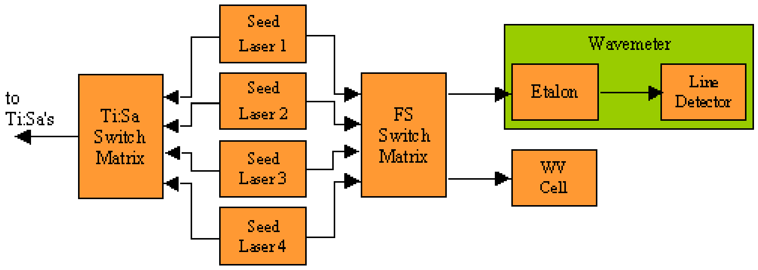

Figure 4-7 *Example of implementation of the Frequency Stabilisation Unit*

The frequency stabilisation unit is working in a quasi-continuous mode and a switch matrix is employed to route the signals from the seed lasers to the wavemeter and water vapour cell.

The wavemeter could consist of a Fabry-Perot interferometer with CCD line detector for measuring the fringe position. Alternatively the wavemeter can be replaced by the Fabry-Perot etalons implemented at receiver level.

The overall performance of the frequency stabilisation is defined by the seeder line width of 5 MHz and the frequency stability and accuracy of 50 MHz.

4.1.4 Receiver assembly

The receiver assembly consists of a telescope assembly made of one or three sub-pupils, a demultiplexer assembly separating the four received wavelengths, a filtering stage limiting the background radiation and a detector assembly. Two different concepts have been proposed for the receiver.

One concept is based on a three-pupil telescope featuring an equivalent aperture diameter of 2.1 m. This 3-pupil concept allows decreasing the criticality of the telescope compared to a single pupil, as each telescope aperture diameter is 1.2 m. Telescopes of this size are being developed for other space programmes such as ADM-Aeolus. The demultiplexer and the filtering stages are combined in a common assembly called the Wavelength Separator Assembly (WSA). This implementation is linked to the “burst” mode where wavelengths are emitted in the same direction.

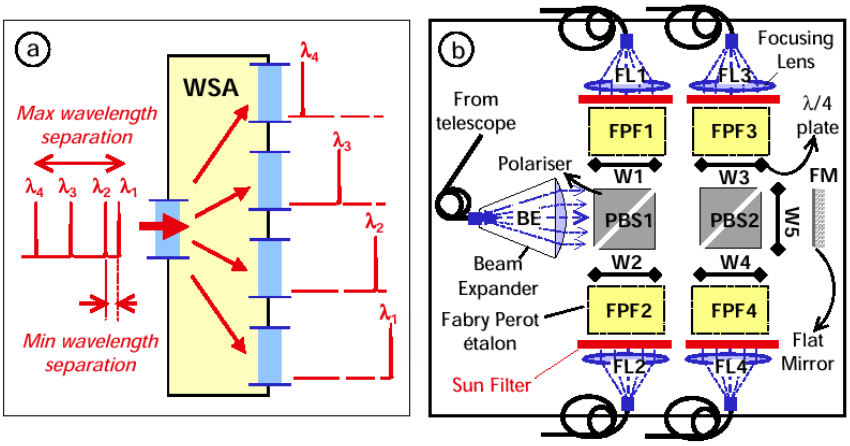

Figure 4-8 *Wavelength Separator Assembly*

The WSA consists of 2 major sub-elements:

- Four narrow bandwidth (20 pm) tuneable and capacitance-stabilized Fabry-Pérot etalons (FPF)
- A polarising sub-assembly (PBS)

As each Fabry-Perot etalon is centred on one emitted wavelength, the filter will transmit only the signal coming from one of the four emitted wavelength and will reflect the other part of the spectrum. By optimising each of the four etalons to one emitted wavelength, the demultiplexing is achieved together with the background filtering. The transmitted signal is then conveyed to the detector assembly through optical fibres. Avalanche photodiodes in analogue mode are proposed as low-noise and highly efficient detectors.

A second concept is based on a single aperture telescope of 1.75 m diameter. The receiver concept, linked to the “continuous” operation mode, receives echoes with slightly different angles due to spacecraft motion in the time between the transmissions (30 ms between first and last emitted wavelengths). The demultiplexing is therefore performed by in-field separation with a fibre-interface to separate the echoes from the four channels.

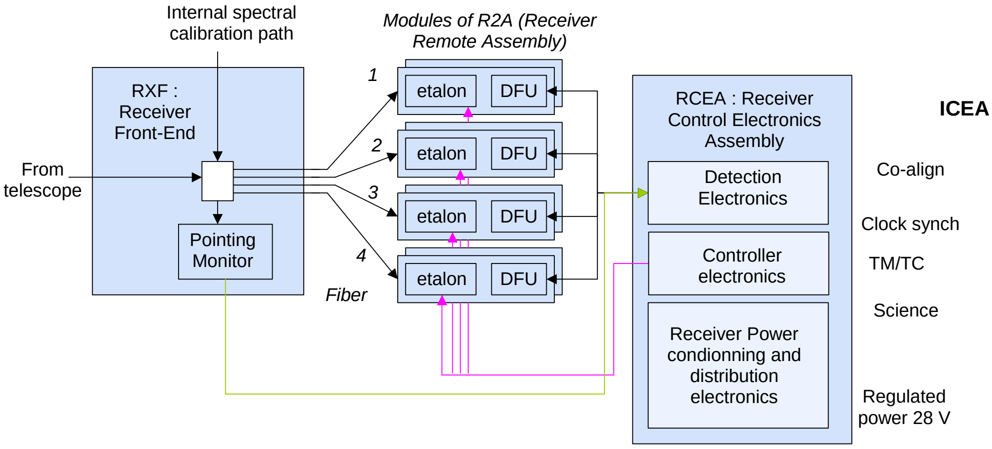

Figure 4-9 *WALES Receiver architecture*

The background filtering assembly consists of an interference filter common to all channels and narrow bandwidth Fabry-Perot etalons (40 pm) tuned to the centre wavelength of the respective channel. The detector concept is based on newly developed Low Light Level CCD (L3CCD) detectors with direct readout technique that offer high vertical resolution at low noise. The architecture is presented in Figure 4-9.

4.1.5 Mechanical layout

The mechanical layout consists of two baseplates, a lower baseplate supporting the high dissipating units, such as the transmitter lasers and electronics, while the upper baseplate is dedicated to units needing a stable thermal environment, such as the receiver and frequency stabilisation assemblies. The lower baseplate provides the mechanical interface to the platform whereas the upper baseplate supports the transmitter and receiver telescopes.

Two mechanical layouts are proposed (Figure 4-10) corresponding to the different receiving architectures (mono or tri-pupil).

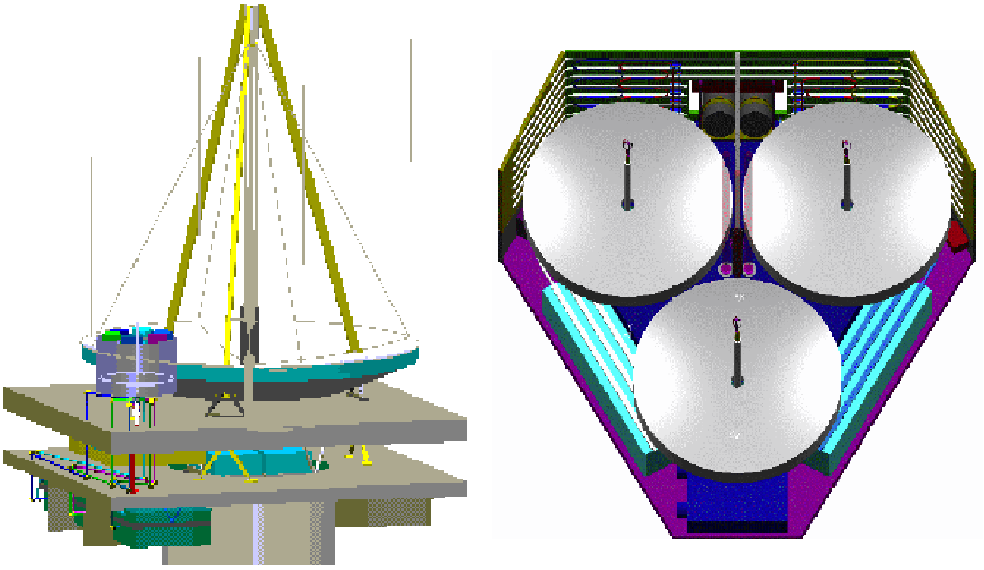

Figure 4-10 *Instrument mechanical configuration: mono (left) and tri-pupil (right) concept*

4.2 Platform

Structure

The structural concept of the platform module is driven by the need to provide a stiff support to the payload module. Both concepts studied during the Phase A are based on a central cylinder providing the structural support to the payload module and the load path to the launcher adaptor. The sidewalls of the platform module are connected to the central cylinder via shear walls and support the internal equipment as well as the required radiating surfaces. The resulting box-shaped module has a limited height to increase the overall stiffness.

Thermal Control

The thermal control design of the platform is driven by the need to radiate the significant amount of heat dissipated by the payload units accommodated in the platform module (Laser Control Electronics) and by the platform units. In the mono-pupil concept the anti-sun side of the platform is used to support the instrument radiator, which is connected via heat pipes to the laser transmitter heads located in the payload module.

In the tri-pupil concept the laser heads radiator is placed on the anti-sun side of the telescope baffle and is therefore physically separated from the payload module.

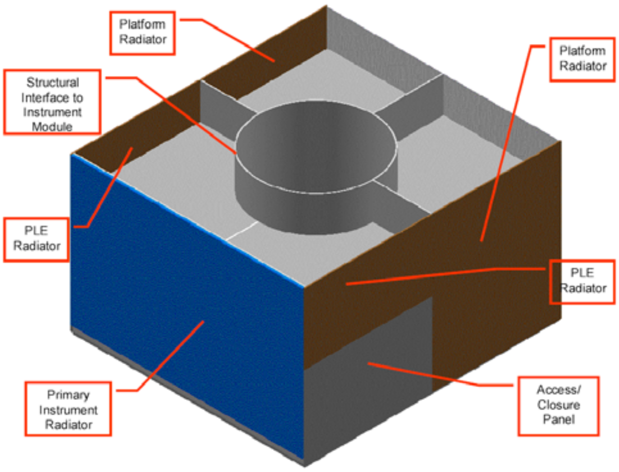

Figure 4-11 *Platform structure – mono-pupil concept*

Thermal decoupling between the payload module and the platform is ensured by Multi Layer Insulation (MLI) blankets. Heat pipes within the platform module are used to provide the heat-conducting path between the high dissipation units (Laser Control Electronics, battery) and the relevant radiating surfaces.

Power and Energy Storage

The electrical power generation is provided by two solar array wings with four panels each, located on the velocity and anti-velocity sides of the platform and connected to it by a yoke. GaAs triple junction cells are used. Power conditioning is based on the Direct Energy Transfer approach. The power bus concept is either a single voltage unregulated 28 V bus (tri-pupil concept) or a dual voltage one (unregulated 50V for the instrument, regulated 28 V for the platform and the payload units accommodated therein). Energy storage is provided by a Li-Ion battery pack.

Data Handling

The Data Handling subsystem is based on two fully redundant on-board computers. The first is the Central Data Management Unit (CDMU), which is in charge of overall satellite management (command acquisition and distribution, AOCS, platform sub-systems monitoring and control, house keeping telemetry acquisition and storage). The second computer is in the dedicated Instrument Control Unit (ICU), which is in charge of instrument control, raw data acquisition, pre-processing and storage.

Communications

The communication sub-system consists of a S-band transponder for TT&C and an X-Band transmitter for the downlink of the scientific data. The payload data rate and the operational constraint are compatible with a midrange rate capacity for the X-band downlink (10-20 Mb/s) to download the 1.2 Gb of instrument data generated every orbit.

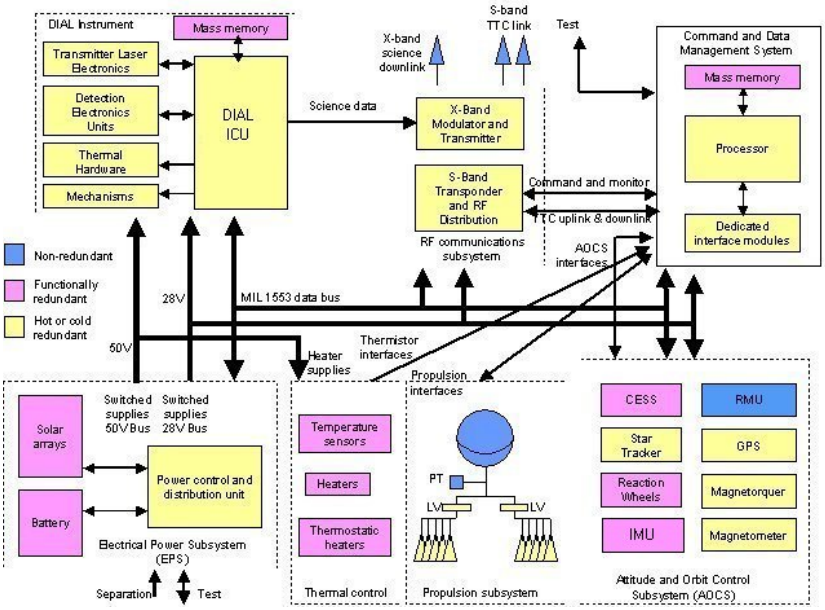

Figure 4-12 *Data Handling Architecture*

Attitude and Orbit Control

The Attitude and Orbit Control Sub-system (AOCS) is based on star-trackers and gyroscopes for attitude determination and reaction wheels as actuators complemented by magnetotorquer bars for wheel momentum unloading. A steering law (yaw or pitch) of small amplitude at orbital period is foreseen to compensate the effect of Earth rotation on the co-location of the probed air volumes in continuous operation mode and to limit the Doppler effect on the received signals. Timing and positioning data will be provided by the on-board GPS receiver. The pointing requirements for the WALES mission are not demanding (1° accuracy) and are compatible with standard LEO AOCS equipment. On the other hand, the continuous operation mode requires pointing stability (better than 2.8μrad in 40ms and 70μrad in 1 s) that is outside the AOCS control bandwidth. The stability will therefore be achieved by controlling the micro-vibration environment.

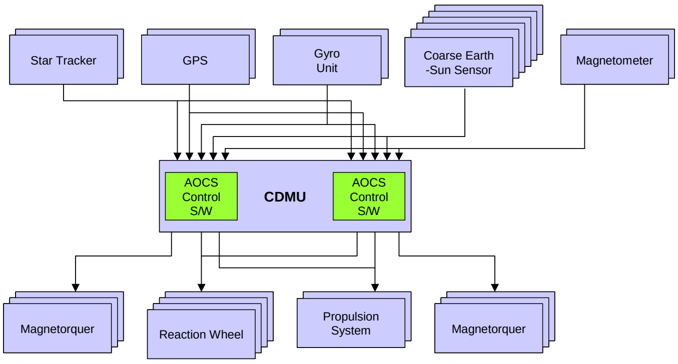

Figure 4-13 *AOCS architecture*

Propulsion

The propulsion system is a conventional mono-propellant (hydrazine) system in blow-down mode used for initial orbit correction and orbit maintenance. Two-by-two or four-by-four (nominal-redundant) thrusters configurations have been found adequate.

4.3 Satellite

4.3.1 Configuration

The following figures show the satellite configuration for the two concepts studied.

Both concepts lead to a satellite configuration based on separate platform and payload modules, with a few instrument units placed in the platform module (Instrument Control Unit, Laser Control Electronics).

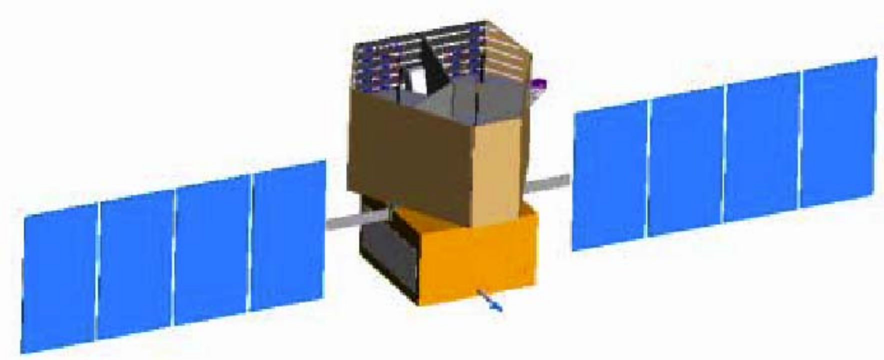

Figure 4-14 *WALES tri-pupil concept*

The main differences reside in the instrument module configuration, due to the different instrument concepts proposed. In the tri-pupil concept (Figure 4-14), the large baffle required to protect the three telescopes is used to support the main instrument radiator, while in the mono-pupil concept (Figure 4-15) the radiator is mechanically supported by the anti-sun panel of the platform.

The consequences on the configuration are mainly on the different height of the platform module, the base dimensions being nearly equivalent: the mono-pupil concept requires larger radiating surfaces on the velocity and anti-velocity panels as the anti-sun panel is used for the instrument radiator. This is obtained by an increased height of the platform module, which is made possible by the lower mass of the payload module.

The tri-pupil concept requires a limited height of the platform module to ensure a stiff support to the heavier payload module. The reduced availability of radiating surface is compensated by the different implementation of the payload radiator and the availability of the anti-sun panel of the platform for the platform radiators.

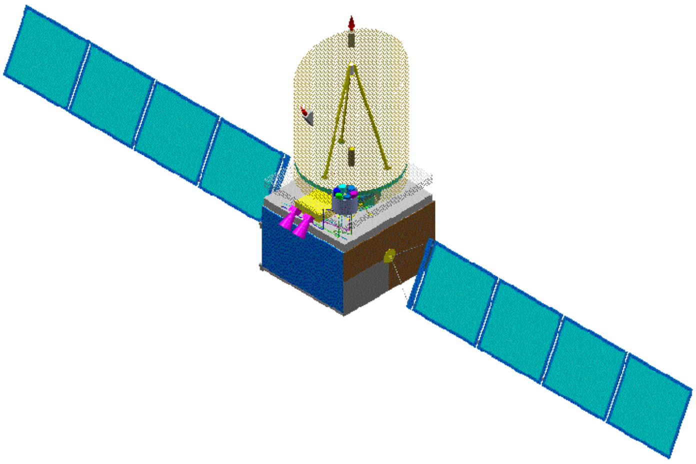

Figure 4-15 *WALES mono-pupil concept*

4.3.2 Budgets

The following tables summarise the main satellite budgets. The range corresponds to the budgets relevant to the two concepts studied during the phase A.

Mass Budget	**(kg)**
Payload Module	400-500
Platform	700-800
Satellite (Dry Mass, including margins)	1300-1320
Propellant (3 years)	140-170
Satellite (Launch Mass)	1440-1490

Power Budget	**(W)**
Payload	1500-1800
Platform	400-500
Battery Charging	1000
Total	2900-3300

Payload Data Rate	
Instantaneous raw data rate (accumulation over 1 km)	200 kb/s
On-board raw data storage	1.2 Gb/orbit

Delta V and Propellant Budget (3 years)	
Orbit Insertion Dispersion	22 m/s
Orbit Maintenance	145-210 m/s
Propellant mass (3 years plus margins)	140-170 kg

Table 4-3 *WALES Satellite budgets*

4.4 Launcher

The launcher selection is driven by the satellite dimension. Soyuz is the selected baseline for both concepts. Long March and Delta-II have been identified as suitable back-up launchers. The mono-pupil concept has the potential for accommodation in a lower cost launcher (DNEPR) if the current performance margins are confirmed.

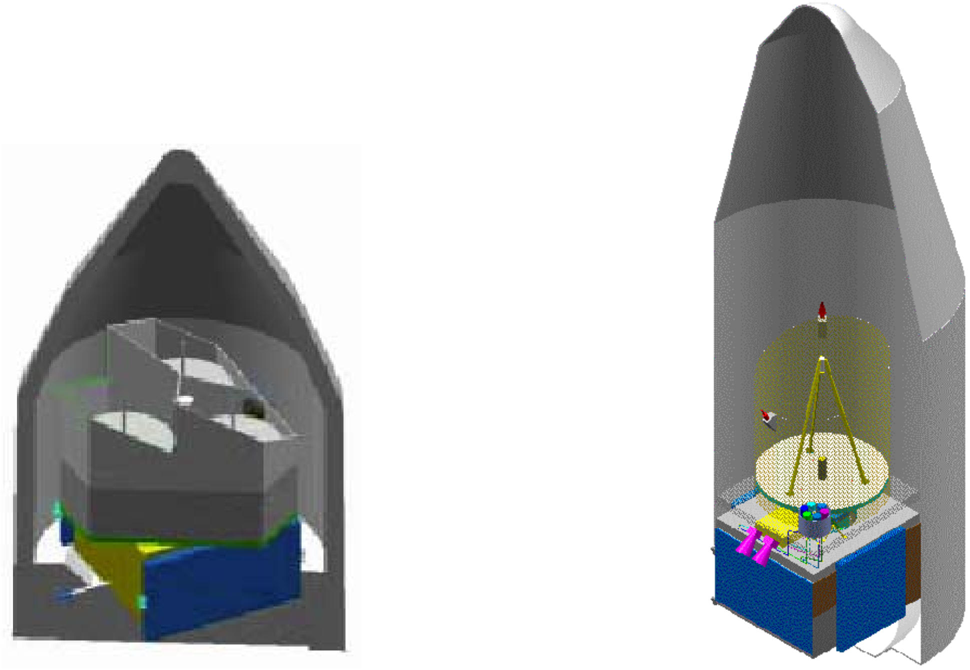

Figure 4-16 *Under fairing (Soyuz) accommodation of the WALES satellite: tri-pupil concept (left); mono-pupil concept (right)*

5 Ground Segment

5.1 General

The ground segment will be based on the infrastructure being developed to support the Earth Explorer and other missions. The breakdown of the ground segment into its constituting elements and functions is outlined in Figure 5-1. It consists of three main elements:

- The Command and Data Acquisition Element (CDAE)
- The Mission Operations and Satellite Control Element (MSCE)
- The Processing and Archiving Element (PAE)

These three elements implement the Flight Operations Segment (FOS) and the Payload Data Segment (PDS) functions. The FOS will be developed and operated according to the concept of "family of missions" by which several missions share resources and staff for reduction of costs and reutilisation of expertise. Concerning the PDS, the principles and infrastructure developed for the open – operational, "oxygen" initiative will be reused as well as the infrastructure procured for previous Earth Explorer missions.

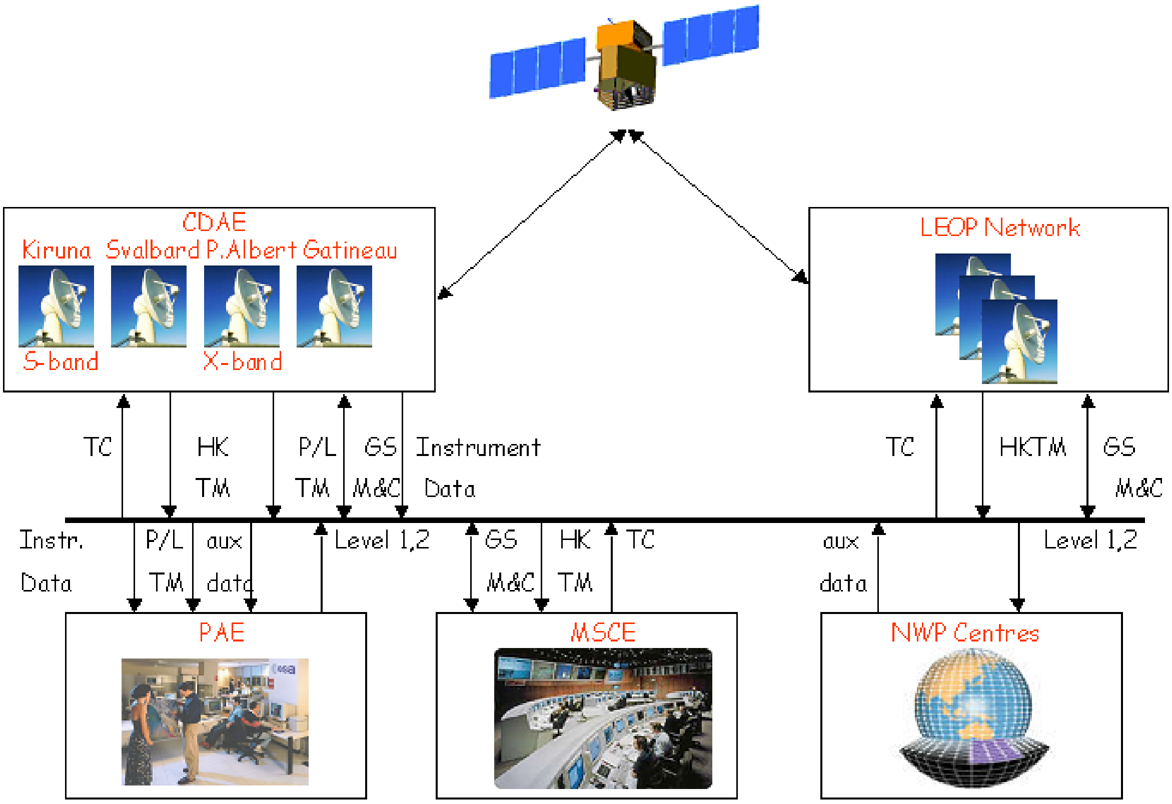

Figure 5-1 *WALES Ground Segment breakdown*

5.2 Ground Segment Elements

The CDAE implements the following main FOS functions:

- Telemetry acquisition, telecommand uplink and satellite tracking (TT&C), and
- Transmission of telemetry to the MSCE.

For the PDS, it implements the following main functions:

- Payload data acquisition,
- Demodulation and formatting,
- Processing to appropriate level,
- Short-term archiving and
- Transmission to the PAE.

For the WALES mission, the TTC functions will be supported by the Kiruna ground station in S-band. The CDAE concept requires three high-latitude ground stations (Svalbard, Prince Albert and Gatineau) for the acquisition of the payload data in X-band at each orbit in order to fulfil the requirement on the availability of the water vapour data to the end users (NWP and Climate Research Centres) within three hours from acquisition.

During Launch and Early Orbit Phase (LEOP), operations will be supported by additional suitable ground stations.

The MSCE will be located at ESOC and will provide the following main functions:

- Overall satellite operations planning
- Satellite monitoring and control
- Flight dynamics and manoeuvre planning
- On-board software maintenance
- Mission simulation
- FOS supervision
- Interface with the launch site for LEOP

Figure 5-2 *A dedicated control room at ESOC. After operation from the main control room during LEOP, operations are conducted from these rooms dedicated to the Earth Explorer missions*

The PAE will be located at ESRIN and will implement the following PDS functions:

- Acquisition of payload data (including platform ancillary data) from the CDAE
- Acquisition of the required auxiliary data (pressure and temperature profiles) from NWP Centres
- Generation of products at Level 1 and 2 (water vapour profiles) by means of Instrument Processing (IPF) and High Level Processing facilities (HPF) respectively
- Long-term archiving (LTA) of mission products, including re-processing of archived data as needed
- Payload operations planning by means of a Reference Planning Facility (RPF) and transmission of plans to the MSCE
- Monitoring of payload and PDS performance by means of a Monitoring Facility (MF)
- Quality control (QC) for all products and media distributed to users.
- Distribution of mission products to the user community
- Provision of user services (USF) based on the existing EO Multi-mission User Services located at ESRIN

Appropriate communication infrastructure will ensure the exchange of data flows between the elements of the ground segment and the interface with the users. The infrastructure being set-up within the "oxygen" initiative will be used as much as possible such as the high speed network (Figure 5-3) that connects the various ESA ground stations and centres.

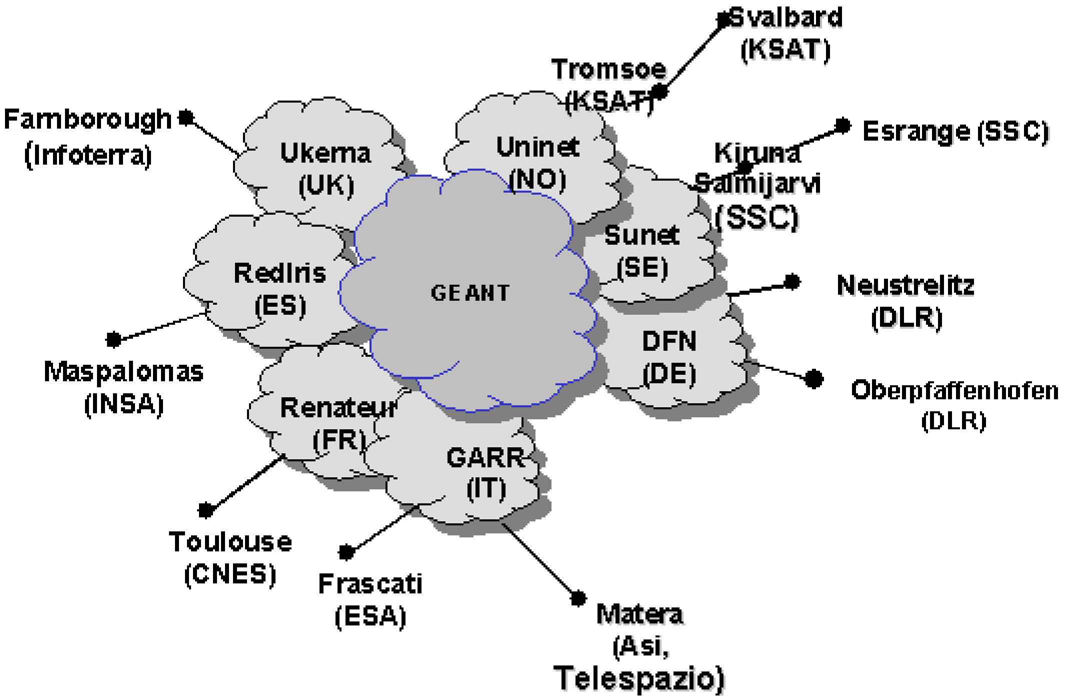

Figure 5-3 *High Speed ESA EO Network based on the GEANT / NREN (Academic) Backbone*

6 Operations and Utilisation Concept

The WALES mission does not present any challenging operational aspects.

Following LEOP and commissioning phase, the instrument will be operated with a 100% duty cycle. Nominal instrument operation requires minimum intervention from ground. This will be limited to the execution of the geometrical calibration procedure (during commissioning and possibly a few times during the mission) and periodic (2 weeks) upload of look-up tables. These tables provide the prediction of satellite altitude over the Earth surface with an accuracy of approximately 500 m and an estimate of the ground velocity accurate to about 10%.

This information is required to adjust the timing of the instrument operations (background acquisition, sampling of backscattered signal, ground echo acquisition) as the vertical extension of the probed atmospheric domain (ground to 16 km) is smaller than the altitude variations over the orbit (approximately 20 km) due to the oblate shape of the Earth.

In the continuous instrument operation concept, this information is mandatory for adjusting the temporal inter-pulse separation in order to maintain the co-location of the probed atmospheric volume.

The remaining instrument calibration procedures (spectral, radiometric) are part of the nominal instrument operation and do not require any intervention from ground.

All operations will be conducted from the MSCE at ESOC in a “non-real-time” fashion but with a rather short operational turn-around, aiming at processing telemetry in a time frame allowing to uplink any resulting commanding action at the next station pass.

Nominal WALES operations will be conducted by uplink of a master schedule prepared by a dedicated mission planning system. Spacecraft commanding during the nominal operation phase is expected at a frequency not higher than once per week.

7 Data Processing

The primary Level 2 data products of the WALES mission are vertical profiles of atmospheric water vapour concentration in a vertical domain from the planetary boundary layer to the upper troposphere.

Besides the main products, several by-products can be generated:

- Cloud top heights
- Atmospheric backscatter profiles
- Relative aerosol backscattering profiles
- Albedo

7.1 Raw data acquisition and on-board processing

The four instrument receivers produce a continuous data stream with a fixed sampling rate corresponding to the raw vertical resolution of 50 m (3 MHz), from which data blocks for backscatter signal, background calibration and internal calibration are selected. A timing unit in the instrument electronics generates the gating signal performing this selection.

Onboard processing of the backscatter and calibration data consists of accumulating typically three or four consecutive echo data blocks (onboard along-track integration) and accumulation of the background and internal calibration data for each shot.
In addition, ancillary data are added describing the timing of the echo data, position and attitude of the spacecraft, pointing of the instrument and instrument health.

7.2 Payload/auxiliary data acquisition and ground processing

The raw data acquired and formatted at the CDAE are transmitted to the PAE together with the payload telemetry. Auxiliary data (temperature, pressure profiles) from NWP centres are also acquired at the PAE.

An overview of the data processing steps is shown in Figure 7-1.

Level 0 data are processed to Level 1 (calibrated and geo-located backscatter profiles). Quality indicators are derived from the analysis of payload telemetry data. In addition to the primary Level 1 products (backscatter profiles), secondary products at Level 1 are also extracted. The Doppler estimator module extracts from the ancillary platform data the information required to estimate the Doppler shift.

The primary Level 1 products are then used to feed the water vapour profile estimator together with ancillary information (cloud top height, generated at Level 1, Doppler estimates and temperature/pressure profiles).

The retrieval of water vapour profiles can be performed - at the expenses of degraded performance with respect to the clear air case - also in presence of optically thin clouds and above cloud decks of higher optical thickness. The water vapour estimates in the presence of clouds will be flagged accordingly and the relevant estimate of the random and bias error will be provided.

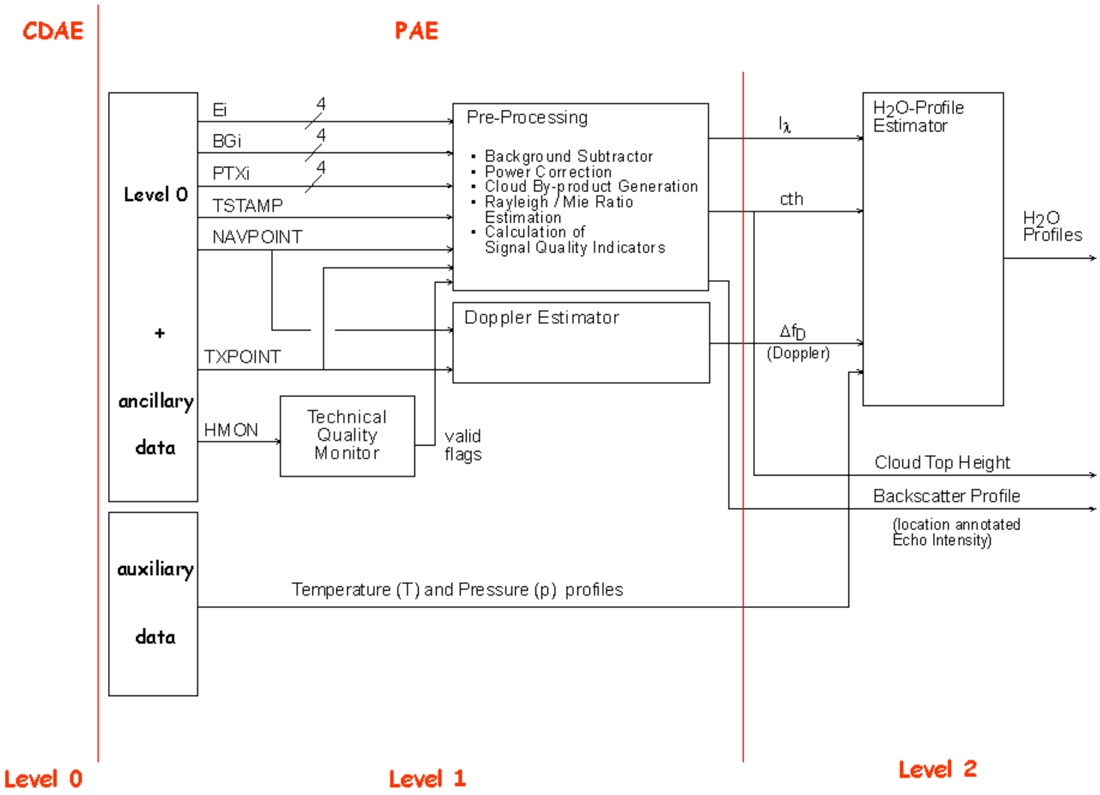

Figure 7-1 *WALES Data Processing*

8 Performance Aspects

8.1 Water Vapour Absorption Lines Spectroscopy

A suitable set of line parameters is given in Table 8-1; other suitable lines around 943 and 944nm have also been identified and could provide an alternative set. The review and identification of lines were carried out on the basis of the HITRAN 2000 database. The desired water vapour lines have been carefully selected such that only lines with lower state rotational energy values in the range 100 cm^{-1} <E" <500 cm^{-1} are considered. For these lines the DIAL measurement error caused by uncertainty in the atmospheric temperature is <0.5%/°K.

Water vapour absorption line cross-sections in the 920-960 nm range have been measured in the past (Ref. [4]) with high accuracy, however the measurements did not cover the lowest absorption regions. Recently, the water vapour line characterisation in the 940 nm spectral range has been improved (Ref. [5] and [6]) with extended measurements of lines intensity. The RMS errors reached for the strong and medium lines were around 2.5%.

	Wavenumber $1/\lambda^{vac}$ [cm^{-1}]	**Wavelength in vacuum [nm]**	**Lower state rotational Energy E" [cm^{-1}]**	**Line strength [cm^{-1}/cm^{-2}]**
Weak line	10684.830	935.906	382.517	4.15E-24
Medium strength line	10688.772	935.561	488.108	5.40E-23
Strong line	10687.364	935.685	136.762	6.45E-22
Off-line	10685.46			

Table 8-1 *Line parameters and cross sections as derived from the HITRAN 2000 database*

Additionally, a dedicated spectroscopy study to improve the characterisation of water vapour lines in two spectral domains identified for WALES (935 nm and 943 nm) is on-going. Preliminary results show high accuracy cross-sections measurements of the lowest absorption features as shown in Figure 8-1 for weak and off line wavelengths.

The Cavity Ring Down Spectroscopy technique has been used to provide high spectral resolution and low measurement noise over the wide domain of temperature and pressure relevant for WALES.

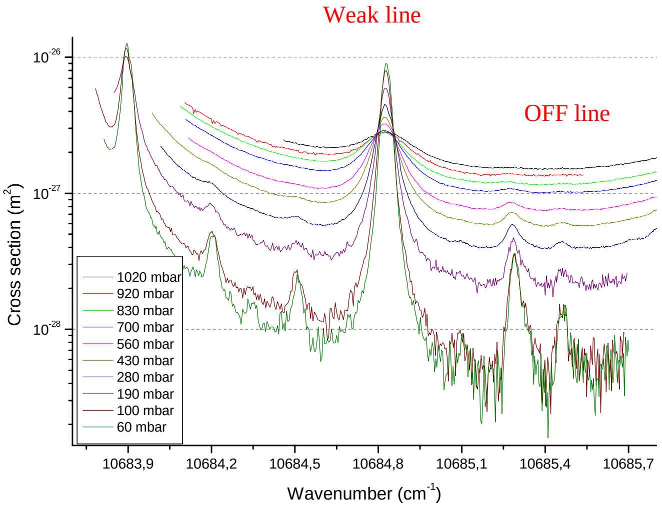

Figure 8-1 *Water vapour cross-section measurement in 935nm range. Weak and Off line wavelengths are shown.*

Preliminary cross-section accuracy budget of the measurements is in average about 2%. An anticipated budget for the cross-section measurement accuracy has been used to consolidate the systematic error budget of Table 8-3, based on this dedicated study results and on available literature.

8.2 Random error

Assumptions

The instrument parameters used for the performance assessment are recalled in Table 8-2. The key features of the DIAL are the large receiving collector aperture, allowing a reduction of the laser emitted power and then reducing the demand for this critical sub-system, the narrow field of view, the narrow bandwidth filters reducing the background level and the photon-counting detection chains.

Parameter	Unit	Value
Vertical resolution [0-10/10-16km]	km	1 / 1.5
Horizontal resolution [0-2/2-5/5-10/10-16km]	km	25 /100 / 150 / 200
Observation condition	-	Daytime (SZA 75°)
Spacecraft altitude	km	450
Receiver Telescope Optic (circular) Aperture	m	1.75
Laser Pulse Emitted Energy (for each wavelength)	mJ	72
Transmitter divergence (FWHM) (set according to eye safety)	µrad	65
Pulses Repetition Frequency	Hz	25
Spectral Filter Width	pm	45
Receiver Transmission	-	0.38
Receiver Field of View	µrad	115
L3CCD equivalent noise (for amplification of 50)	electrons	0.57
L3CCD Quantum Efficiency	-	0.6

Table 8-2 *Summary of DIAL performance parameter*

Results

The results for random error budgeting are presented in Figure 8-2 for clear air and in Figure 8-3 with cirrus and altostratus clouds respectively for the mono-pupil concept. The relative statistical water vapour error (or random error) is displayed as a function of altitude and for different climates. The specified random error (horizontal line; constant at 20 percent) is overlaid in the plots. The 20% random error is however specified for altitudes where the water vapour density is higher than 0.01 g/kg, corresponding to altitudes below 10-12 km (arctic-tropical).
Three reference water vapour profiles (tropical, sub-arctic winter and mid-latitude winter) have been used for the performance simulations and instrument sizing. These reflect large variations of water vapour content (from 0.002 g/kg to 16 g/kg) and cover the major part of the global humidity range.

In clear air, the average performance over the whole dynamic range is 10 % to 15 % for the three water vapour profiles considered. The instrument is able to measure water vapour up to around 14 km with a relative random error less than 20 % for tropical climates. In mid-latitude and sub-arctic winter, the random error is less than 20% up to 12 km altitude. The error is about 50 % at 16 km, because of the very low humidity at this altitude (about 0.002 g/kg). The 20% random error performance requirement is also met near ground altitude (500 m) with associated resolution of 1 km vertical and 25 km horizontal.

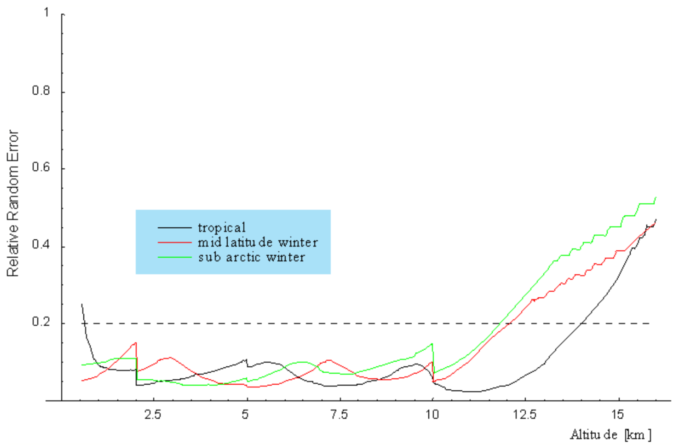

Figure 8-2 *Relative random error performance computed for the three reference profiles of water vapour, clear air conditions. Vertical and horizontal resolutions are changed at 2, 5 and 10 km (according to table 8.2) explaining the jump of the curves for these altitudes*

The effect of cirrus and altostratus clouds on the random error performance has been simulated and is displayed in Figure 8-3. Simulations have shown that the instrument is able to measure below thin clouds with a random error less than 20 %. The main difference with Figure 8-2 is caused by a loss of signal due to the cirrus absorption. For the stratus case, the higher background radiance due to the cloud deck at 3 km degrades the performance, though this remains close to 20 %. WALES is then able to provide precise measurements above the clouds with only small degradations with respect to cloud-free conditions.

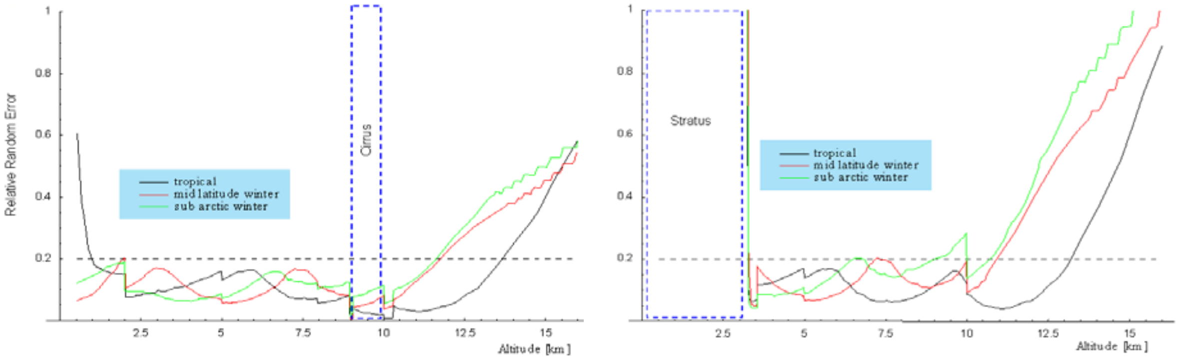

Figure 8-3 *Random error performance computed with presence of clouds (cirrus on the left, alto-stratus on the right). This set of simulations assumes a cirrus cloud, 1 km thick at 9 km altitude and with an optical thickness of 0.2, and alto-stratus at 3 km altitude*

Similar performance is obtained considering the instrument parameters of the tri-pupil concept. The above results in clear sky and cloudy conditions are in very good agreement with those independently determined based on the application of an end-to-end performance model and discussed in chapter 6 of the science report.

8.3 Instrument Calibration

The instrument calibration consists of spectral, radiometric and geometric calibrations. The spectral registration from the receiver filters to the emitted wavelength is ensured by the tuneable Fabry-Perot etalons of the receiver chain and the seed lasers. For the radiometric calibration, a continuous monitoring of the laser energy allows to compensate for energy fluctuations on a shot per shot basis. The background correction is performed acquiring on each shot the background signal at both high altitude and after the ground echo. The geometrical calibration (i.e. the co-location of the transmitters and receiver field of views) is achieved by angular scanning of the four transmitter beams within the receiver field of view and by acquisition of the ground echo.

The latter is allowed by the large dynamic range detection chains or by a dedicated chain. Additional benefit of the ground echo acquisition is to provide information on the water vapour density down to ground altitude.

8.4 Systematic Error

Table 8-3 shows a detailed budget for the bias error. Concerning the systematic error associated with different laser specifications, the effect of laser detuning (< 60 MHz), finite laser bandwidth (< 160 MHz) and spectral purity (> 99.9 %) on the bias is approximately 1 % for each of these contributors.

The accuracy of the water vapour spectroscopy available in literature and based on dedicated study leads to an anticipated uncertainty of ± 2 %.

Contributors	Systematic Error	Comment
Laser spectral purity	1.0 %	Considering 99.9 % requirement
Laser frequency knowledge	1.2 %	Considering 60 MHz requirement
Laser line-width	1.2 %	Considering 160 MHz requirement
Doppler uncertainty	0.18 %	Considering 0.2° LOS pointing knowledge
Detection chain non linearity and distortion	0.5 %	
Temperature knowledge	1.5 %	Considering 2 °K temperature uncertainty
Water vapour line cross-section knowledge	2 %	Derived from spectroscopy study accuracy budget
Doppler broadening correction	0.5 %	Assuming an error of 30% on the lidar ratio
Total budget: RMS sum of the above	3.3 %	

Table 8-3 *Bias or systematic error budget*

The cross sections of the selected water vapour absorption lines are calculated using temperature and pressure profiles from NWP analysis or short-term forecasts. While pressure information from numerical models is highly reliable, RMS errors in atmospheric temperature are about 2 K up to 100 mbar. Simulations from the end-to-end model led to a maximum bias of 1.7 % with a mean bias up to 14 km of 1.1 %.

Rayleigh-Doppler broadening of the narrow-band laser line is corrected using a modified version of the DIAL equation. The correction can be routinely performed and the residual error is typically 0.5 % in the free atmosphere and 1.5 % inside cirrus clouds.

Effects associated with the application of different non-linear operators present in the DIAL equation are found to cause minor additional sources of bias, generally not exceeding 1 % up to 14 km. Using the processing scheme presented in chapter 5 of the science report, together with vertical averaging, needed for reducing statistical fluctuations of the raw lidar signals, causes a bias error of < 1 %.

Assuming the different sources of systematic error to be independent, the overall bias error is less than 4 % and compliant with the required 5% bias error in clear air.

9 Programmatic Aspects

The technical maturity of the WALES mission was assessed in the frame of the pre-phase A system study. The development risks were associated with several well identified elements of the instrument, namely:

- Transmitter
  - Laser Source
  - Frequency Stabilisation Unit (wavemeter, water vapour cells, frequency reference seeder)

- Receiver
  - Telescope
  - Background filters

A number of activities have been initiated by the Agency to consolidate the assessment of critical technologies. A summary of the maturity and development status of the critical technologies is reported in Table 9-1. These activities are still in progress, yet the results available in the course of the Phase A system studies have allowed to consolidate critical design options and feasibility issues.

The development of the WALES instrument remains on the critical path and would require pre-development activities in the following areas:

- Transmitter System
  - Power Laser Head (pump laser, pump switch, Ti:Sa laser)
  - Transmitter electronics
  - Frequency Stabilisation Unit (seed laser, switch matrices, etalon, water vapour cells, frequency stabilisation electronics)
- Receiver System (interference and narrow-band filters, focal plane and detection front-end unit)

The overall instrument development approach is based on an Engineering Qualification Model (EQM) program to achieve a full qualification at unit and instrument level, followed by a Flight Model (FM) programme.

No critical elements have been identified for the platform development since there is a strong heritage from on-going Earth Explorers and other Low Earth Orbit (LEO) missions.

Unit	Maturity and development status
Transmitter	
Pump source	Based on ALADIN high power laser source with some modifications to raise the output power. No criticality identified, all components to be qualified through ALADIN development.
Pump switch	Preliminary assessment shows that this component could meet the requirements over the mission lifetime.
Ti:Sa laser source	2 activities are running to develop a breadboard of a high energy Ti:Sa laser suitable for WALES. Ti:Sa Laser performance already demonstrated by NASA for airborne sensors. Reduced criticality with the current output energy demand.
Frequency stabilisation unit	3 activities are currently running to develop seeders and a complete stabilisation scheme for the four wavelengths identified for WALES. Requirements are deemed achievable. A seeder with its stabilisation unit has been breadboarded and tested showing good performance in the frame of the Ti:Sa laser source contracts.
Receiver	
Telescope	Large telescope technology demonstrated through the ALADIN instrument
Fabry Perot etalon and background filtering stage	Activity running to breadboard both background filtering and tunable narrow bandwidth etalon with requirements higher than for WALES. Manufacturing is completed and tests are currently running. Requirements for WALES are deemed achievable.
Detector	The L3CCD technology has been preliminary assessed. Operation mode for lidar signal acquisition has been shown. Specific development is initiated to demonstrate the performance.

Table 9-1 *Maturity of critical DIAL technologies and development status*

The overall development schedule is therefore driven by the instrument development and pre-development of critical units. The development plan proposed by the industrial teams is summarised in Table 9-2.

Development Phase	Duration (months)
Instrument pre-development (pre-phase B)	16-18
Phase B	12-15
Phase C/D	54-60

Table 9-2 *Development phase durations*

The above assumes overlaps between phases to avoid gaps and clear milestones at key transitions to reduce risks. The plan should lead to launch in 2011 / 2012.

10 References

[1] Phase A System Study for the WALES mission, (EADS Astrium), Contract Report, ESTEC contract 16368/02/NL/MM

[2] Phase A System Study for the WALES mission, (ALCATEL Space Industries), Contract Report, ESTEC contract 16367/02/NL/MM

[3] WALES – Water Vapour Lidar Experiment in Space, Report for Assessment, ESA-SP-1257(2)

[4] Empirical Line parameters of $H_2{}^{16}O$ near 0.94µm: Positions, Intensities and Air-Broadening Coefficients. L.R.Brown, R.A.Toth and M.Dulick. Journal of Molecular Spectrosocpy. 212, 57-82(2002).

[5] Water line parameters for weak lines in the range 9000-12700 cm^{-1}. Roman N. Tolchenov et al. Journal of molecular spectroscopy, 221, 99-105 (2003).

[6] Water vapor line parameters in the range 13000-9250 cm^{-1} region. Marie-France Merienne et al. Journal of Quantitative Spectroscopy and radiative Transfer. 82, 99-117 (2003).