

AVALON – a mission for understanding climate change

Atmospheric water Vapour from an Active Limb-sounding Observing Network

Red Team, Alpbach 2010

Introduction and mission overview

Water vapour is the most important greenhouse gas. The amount in the lower stratosphere, while low, is radiatively incredibly important because it is here that the amount of outgoing longwave radiation is controlled. Current measurements of water vapour are subject to large biases in this key region because of the low concentrations. Here we propose a novel method for retrieving low concentrations of upper air water vapour more accurately by means of Differential Optical Absorption Spectroscopy (DOAS) using an active limb-sounding instrument and a network of counter-rotating retroreflectors. In addition to the DOAS capability, the satellite will also be equipped with limb- and nadir-pointing Light Detection and Ranging (LiDAR) capability, and a nadir sounding infrared spectrometer.

Science case

Background

An understanding of the radiative balance of the climate system is crucial for predicting climate change. The radiative balance of the atmosphere is particularly sensitive to changes in the Upper Troposphere and Lower Stratosphere (UTLS), where most of the Earth's thermal radiation escapes into space and where cirrus clouds and contrails of aircrafts trap this outgoing radiation. As well as the water and ice cloud droplets, the outgoing long wave radiation is absorbed by greenhouse gases (GHGs) such as water vapour, carbon dioxide or ozone. Among all GHGs, water vapour is the most significant and has strong vertical gradients in the UTLS. As the name implies, the UTLS forms the boundary between the relatively unstable troposphere and the vertically stable stratosphere, where trace gases and aerosols have a much longer lifetime than in the lower atmosphere. Most of the stratospheric water vapour originates from the tropical tropopause by deep convection and "overshooting" of water vapour. The tropical tropopause acts as a barrier for water vapour due

to the cold temperatures (about -60°C) and concentrations are low at around 2 and 3 ppm in this region. Hence small changes in the temperature of tropical tropopause layer can have large effects on the absolute amount of water vapour entering the stratosphere and subsequent large impacts on the radiative budget.

The UTLS is also the region where aircraft fly, emitting carbon dioxide, water vapour, nitrous oxide and aerosols, forming contrails and impacting cirrus clouds and the radiative budget. Aerosol-cloud interactions are key here, and also poorly understood. The latest report of the Intergovernmental Panel on Climate Change [1] attributes the largest uncertainties and lowest scientific understanding of radiative forcing to aerosols and their direct and indirect albedo effects. "Indirect albedo effects" refer to the impact of the type and concentration of aerosols on the albedo of clouds through different droplet sizes and concentrations. Whereas low altitude clouds are believed to have a cooling effect on climate, high altitude clouds are likely to have a warming effect. Evaluations of state-of-the-art General Circulation Models (GCMs) revealed significant disagreement in predicting conditions in the UTLS [2,3]. A colder stratosphere in combination with a higher water vapour content will increase the probability of the formation of ice clouds in the lower stratosphere, especially in interaction with aerosols during the formation of polar stratospheric clouds (PSCs). PSCs play a major role in the heterogeneous ozone chemistry and the decrease in ozone in polar spring, and require better characterization for model validation.

A recent study based on balloon soundings from Boulder, Colorado, revealed an increase in water vapour in the UTLS between 1980 and 2000, followed by a small drop in the water vapour concentration around the year 2000 and no significant trend since then [4]. In this study, a sensitivity analysis of GCMs while including or neglecting this increase in water vapour attributed about 30% of the observed warming between 1980 and 2000 to the increase in water vapour in the UTLS. This work highlights the

importance of accurate observations and illuminates the need for further observations, especially on a global scale.

Stratospheric water vapour is problematic for existing observing systems because the concentrations are low. Most nadir-viewing instruments such as AIRS do not have the vertical resolution to resolve the strong gradient of water vapour in this altitude layer. Passive limb sounders such as COSMIC have problems in this region due to the high opacity or high altitude clouds. In order to reduce the uncertainties and improve the GCM results, global and highly resolved observations of water vapour and aerosols in the UTLS are needed. Especially in the tropics, where the sensitivity to climate change is largest, high-quality measurements are very sparse [5].

Main objective of the mission

The AVALON mission will investigate the direct radiative forcing of water vapour and aerosols in the UTLS, via measurements of an unprecedented sensitivity for a space-borne instrument.

Mission requirements

To achieve the main objective we propose a novel and challenging new space mission. This mission is intended for climatological studies of stratospheric water vapour and aerosols, aerosol-cloud interactions and troposphere-stratosphere exchange. The requirements are shown in table 1.

Table 1: Scientific requirements

	Requirement
Horizontal coverage	global
Horizontal sampling	100 km
Vertical coverage	5 – 35 km
Vertical resolution	100 m
Dynamic range	Aerosol: 0-0.005/km [0.0001 to 0.0025/km] H2O 0.5-20ppm [1ppm]
Mission duration	> 4 years

Secondary objectives

AVALON will provide many opportunities for additional science. The bidirectional LiDAR system acts as a 2D ceilometer, which will provide better cloud edge scanning of upper-air optically thin translucent clouds, such as cirrus, contrails, polar stratospheric and noctilucent clouds. Given a typical cirrus clouds thickness on the order of 1-2 km [6], high vertical resolution is crucial.

Collocated information on all the cloud and aerosol variables, collected at spatial scales that resolve individual clouds, shall provide valuable insights into aerosol-cloud-climate interaction processes, especially for the poorly understood cirrus clouds and ice nuclei.

If there is a suitably large volcanic eruption during the lifetime of the mission we will be able to monitor the stratospheric aerosol with unprecedented accuracy. The addition of aerosols into the stratosphere has been proposed as a geoengineering solution to climate change; this mission would be an opportunity to derive the accurate measurements required if this idea was to be explored seriously.

Space segment

Mission design

AVALON is designed to detect low concentrations of water vapour at high vertical and horizontal resolution with high power monochromatic laser pulses. This requires the primary spacecraft (PSC), carrying the monostatic transmitter-receiver, to be flown in formation with a spaceborne retro-reflector (RSC). Since two satellites flying on counter-rotating orbits would generate only two occultations per orbit, we propose a novel concept of a constellation of multiple counter-rotating retro-reflecting microsatellites in the same orbital plane as the active spacecraft.

We propose a synergistic data processing approach which simultaneously exploits a nadir LiDAR and the more accurate and sensitive path-integrated DOAS limb signal, similarly to panchromatic sharpening of multispectral imagery. The addition of a secondary payload of an infrared spectrometer will allow intercomparison with existing established data sources and allow the derivation of cloud microphysical properties following the method of

[7] The combination of the bidirectional LiDAR and the infrared sounding will lead to new synergistic observations of cloud-aerosol interactions and the investigation of troposphere-stratosphere exchange mechanisms.

Observational principle

For accurate path integrated measurements of water vapour, we propose a DOAS system utilizing dual-wavelength elastic backscatter Differential Absorption LiDAR (DIAL), centred on wavelength λ_{ON} , an isolated vapour absorption feature in the near IR, compared to a nearby off-peak λ_{OFF} . A DIAL system is inherently self-calibrating and provides good daylight performance (we note that our orbit simulations show that our receiving optics must be shielded during approximately 350h/yr to avoid direct sunlight exposure). Integrated absorption of λ_{ON} over the limb path offers a much higher sensitivity (at the expense of horizontal resolution) and increases the dynamic range of vapour detection. The selection of the wavelength pair remains a trade-off between higher accuracy and sensitivity with larger differential absorption cross sections, minimization of systematic errors through smaller wavelength differences and avoidance of absorption bands corresponding to other gases, and finally depends on the frequencies that can be generated by available laser sources [8]. The technology for space-based water vapour DIAL systems has been found to be rapidly maturing in terms of reliable and efficient transmitter sources, receiving optics and detecting technology [9].

Probing the atmosphere with a polarized laser beam yields information on particle shape, since Rayleigh and spherical homogeneous Mie scattering maintain the polarization within a 2-3% limit, whilst non-spherical particles or multiple scattering may induce some depolarization [10]. Our instrument will provide depolarization ratios for the wing wavelength λ_{OFF} .

Orbits

Polar orbits have been chosen for the PSC and the RSCs to suit the scientific requirements and the technical constraints of the novel mission concept. The orbital parameters, shown in Table 2, were selected for the following reasons:

- Estimations of number of profiles acquired per day and precision of acquisition showed that **counter-rotating circular orbits** between the PSC and the RSC lead to an optimal occultation system for the limb LiDAR
- **Polar orbits** were selected to avoid relative precession between the PSC and the RSC, and simplify the RSC pointing/tracking system. Both being in the same plane, the multispectral imager and the nadir-looking LiDAR measurements are on the same track as the limb LiDAR measurements, allowing synergistic analysis of the observations.
- A 10-day repetition period of the ground track was selected to set the **altitude** of the PSC, as a compromise between: global coverage of the Earth, rate of repeat measurements for a given location and the nadir-looking LiDAR signal-to-noise ratio (decreasing with respect to the altitude). The RSC **altitude** was selected below the PSC as a compromise between launcher performances and collision risks.

The main compromise is that the sampling of all local times for a given location takes approximately a year. In some regions of the world, a strong correlation exists between the phenomena that the mission aims to sample and the diurnal cycle. Further investigation would be needed to determine whether this low sampling of the diurnal cycle (in comparison to other orbits considered, e.g. equatorial orbit) is the optimal solution for the scientific requirements. The number of profiles expected with such a configuration is **450 per day**.

Table 2– Orbit parameters

Parameter	Primary Spacecraft	Retroreflector Spacecraft
altitude	582 km	550 km
eccentricity	0	0
inclination	90°	270°
number	1	15

Primary spacecraft design

Combined DOAS/LiDAR system

AVALON's primary payload comprises a dual-wavelength bidirectional transmitting system, receiving optics, a polychromator for beam splitting, a data acquisition unit and control unit and a pointing and tracking facility based

on novel (albeit proven) optical communication technology (figure 1).

The coaxial alignment of emitted and received beams facilitates the optical link search pattern and locking between our satellite and the RSC. The link for DOAS measurements is established shortly after orbital crossing and maintained during the descent of the limb sounding throughout the atmosphere down to 5km. Measurements are recorded from 100 to 80km for free space background calibration, then from 35 to 5km for the scientific data. The data acquisition phase during an occultation lasts for 10.46s with a vertical descent of about 2.8km/s in simplified geometry. To avoid pulse return overlap during the maximum distance (~5000km) between emitter and reflector in the lower atmosphere, a maximum pulse repetition frequency of 25Hz is imposed. The vertical sampling resolution is thus constrained by the PRF to an elevation difference between samples of roughly 110 m. As single pulses should generally provide an acceptable detectability using the DOAS method, the resolution could be improved by using the laser at a higher PRF (50Hz) during the main scan. As the scanning is only performed for a part of the time, this does not impose major additional power requirements. Pulses can be integrated to raise the signal-to-noise ratio (SNR; proportional to the square root of the number of shots), coarsening the actual vertical resolution.

As illustrated in figure 1 an emitted pulse will be split and fed into both the nadir and limb LiDAR systems, or can be directed directly into the limb LiDAR/DOAS system only. A small part of the pulse is sampled for calibration and transient recorder triggering. During the time necessary for the nadir pulse to travel to the ground and back, only the nadir receiving optics diaphragm will be open, to avoid contamination of the signal by the limb telescope. Thereafter, the limb LiDAR only will provide input to the polychromator until the pulse returns from the retroreflector for the integrated DOAS signal. Low dark current analogue avalanche photodiodes (APDs) provide sufficient gain ($\sim 10^2$ - 10^3) and dynamic range (4-5 orders) for the DOAS signal, though higher-gain ($\sim 10^6$ - 10^8) NIR photosensor modules or photo-multiplier tubes (PMTs) with single-photon counting capabilities may be required for both LiDAR signals in order to provide acceptable SNRs. The field of view of the detector will be large enough to

accommodate the maximum Doppler shift of 0.05nm induced by the converging spacecraft.

Concerning the laser source, preliminary transmitter studies for the WALES candidate mission [11] that had been commissioned by ESTEC converged on Ti:sapphire resonators, pumped by frequency doubled Nd:YAG heads and seeded by tunable ECLD masters which set the frequencies¹. Two sets are required for generating two wavelengths, plus one in cold redundancy. After further studies on the pulse energy budget and transmitter development, we may consider an additional channel from the Nd:YAG pump for enhanced aerosol retrieval or adding another laser source in the NIR for deuterium retrieval

Infrared spectrometer

The main purpose of the radiometric imager is the retrieval of cloud macro- and microphysical properties at high spatial resolution (cloud resolving scale). This simple standard instrument shall provide comparable channels to AVHRR, will consist of a pushbroom configuration, with an array of detectors for two visible channels (0.65 and 0.9 μm), of a microbolometer array for the TIR channels (10 and 12 μm) and an array of HgCdTe detectors for the MIR channel (3.7 μm). It will offer a 100m GSD for a 100km swath. Its standard components do not require a cryo-cooler, are well-understood and will not be further characterized hereafter.

Retroreflector spacecraft design

The role of the retro-reflective spacecraft (RSC) is to reflect the laser pulses back in the direction they came from, and the design performance directly determines the quality of the DOAS measurement. A properly sized effective reflective area of 0.22 m² will be required, as determined by optical link budget calculations. Three concepts of RSCs have been investigated: option A is a completely passive sphere without attitude/orbit control systems (AOCS),

¹ System adopted and adapted from WALES, though further investigation is needed. A comprehensive account on water vapour DIAL design and band choices can be found in Ertel (2004). Though open issues with maturity demonstrations remain, development will be aligned with efforts for ALADIN and ATLID; and Ti:sapphire lasers for spaceborne applications had been tested by NASA as early as 1995, with accuracies for LASE of better than 6% or 10ppm over wv concentration dynamic ranges of 4 orders.

option B is a 'smart' sphere with simple AOCS, and option C is a highly sophisticated "off the shelf" nanosatellite with full AOCS. The options are summarized in table 3.

Option A: passive spherical spacecraft

The passive spherical RSC concept consists of aluminium spheres covered with corner cubes. Since they have no AOCS this kind of RSC must have a high mass to surface ratio in order to limit orbit perturbations. This principle is already flown in the LAGEOS mission. A frequently performed ground-based orbit determination through laser ranging will be necessary to overcome their intrinsically chaotic orbital behaviour. The laser ranging resulting in forecasted ephemeris data will then have to be uplinked to the PSC. The drawback here is the additional costs due to frequent laser ranging observations, but these will consequently provide ground based measurements of atmospheric drag, thus positively contributing to the mission's data return.

Since the passive spheres cannot make manoeuvres to adjust their orbits, problems may arise such as inconvenient spatial distribution (which would affect the coverage of the measurements in time and space). Sophisticated Monte Carlo simulations and appropriate measurement campaigns (e.g. on space debris of comparable size, mass, and shape) are suggested in order to validate the statements describing this long term behaviour.

Potential space debris issues can be mitigated by applying a passive de-orbiting system, consisting of coils arranged in all three axes of the SC (similar to magnetic torques). By closing an electrical circuit between the coils and electrical resistors an electrical current arises, thus "burning" kinetic energy, resulting in a deceleration of the RSC and an earlier de-orbiting. A reliable mechanical clock timer will have to be applied as the switching system for this kind of deceleration system.

Option B: smart spherical spacecraft

Option B is designed to mitigate the lack of orbit control of option A by equipping the spheres with on-board AOCS. The RSC is able to make small manoeuvres and attitude correction by its cold gas propulsion system. Orbit determination is based on measurements of the Earth's

magnetic field by a vector magnetometer, then rolling manoeuvres are achieved through magnetic torques.

A total of 13 aluminium spheres (thickness between 6-8 mm) with a diameter of 60 cm and a total mass of 40 kg (including electronics, propulsion, reflectors, etc.) was found to be the most promising set-up for this type of RSC. The number of spheres is a compromise between launch constraints and the number of measurements needed to match the scientific requirements. The position of the RSCs can still be tracked from the satellite laser ranging ground network.

Power for the AOCS will require 13% of the sphere's surface ($0,15 \text{ m}^2$) to be covered with solar panels, while an effective retro-reflecting area of $0,22 \text{ m}^2$ must remain. Further surface optimization will be required, along with sophisticated manufacturing of specially-shaped solar panels and retro-reflectors, significantly contributing to the cost budget.

Option C: retroreflector-bearing nano-spacecraft

Option C consists of a nano-satellite carrying a retroreflector with an effective retro-reflecting area of 0.25 m^2 . The nano-satellites from the CanX-4&5 mission provided by UTIAS-SFL² could be the base for the envisaged RSC. They already provide AOCS (MGM, star tracker, GPS, cold gas propulsion, etc.), communications and formation flight capabilities, requiring a total of 10 W power consumption [12]. By scaling them up to the AVALON mission requirements, such a structure seems feasible and as such will be almost "off the shelf".

The RSC must be capable of pointing its retro-reflector towards the PCS with a precision better than 0.05 radians in order to fulfil the science requirements, which the proposed "off the shelf" satellite already fulfils [11].

Mission performance

PSC delivery of science requirements

It will now be demonstrated that the design proposed above can meet the science requirements for the mission. The principles of LIDAR return from a retroreflector are described as a link budget equation for the LAGEOS spacecraft in [13]. The number of returned photons, N , is given by

²<http://www.utias-sfl.net>

$$N = \frac{E}{hf} \cdot G_t A_r G_r A_t \frac{T^2}{R^4} \epsilon$$

where E is the pulse energy, h is the Planck constant, f is the laser frequency, G_t is the transmitter gain, A_r is the effective reflector area, G_r is the reflector gain, A_t is the area of the receiving telescope, T is the atmospheric attenuation, R is the distance from between the transmitter and the reflector, and ϵ is the system efficiency. The LIDAR parameters used in the calculation are given in Table 4. For the reflector gain G_r , [13] gives various values for different configuration angles. For the purpose of determining the reflector link budget, a conservative estimate of 10^8 is used. The effective area A_r of the LAGEOS satellites is given in [13] as 0.014 m^2 ; this value is adopted here. The spacecraft are assumed to be at the maximum separation distance of 5300 km, but free-space attenuation is reduced as they approach each other. Atmospheric loss is ignored at this stage ($T=1$); we use 0.3 for the efficiency of the optical system (including the beamsplitter loss but not laser heat loss). Using the single-pulse energy and beam divergence from Table 4, a value of 5 million returned photons per pulse at the on channel is obtained.

Exploiting the symmetry of the spacecraft setup, atmospheric extinction by water vapour is calculated as four passes of the LIDAR pulse from the minimum altitude point of the beam to the top of the atmosphere. The measured signal is the ratio of the pulses at the "on" and "off" frequencies. This eliminates much of the calibration required for an absolute measurement, and is unaffected by the variability of the laser pulse energy (typically 3%-5%) and the effects of reflector inhomogeneity. There is still noise in the signal in the form of statistical variation of photon count, which in the UTLS will dominate over systematic error sources [14] This noise can be quantified in terms of the Poisson distribution: while the proper ratio distribution is highly complex, we can consider (while acknowledging that this leads to a slight underestimation) that the variance of the ratio $N_{\text{off}}/N_{\text{on}}$ is dominated by N_{off} which is smaller and thus has the larger relative variance.

Simulations of the signal for different water vapour concentrations have been made using a simplified model atmosphere. The signal curves are compared against the detection limit. This indicates that 0.1 ppm of water

vapour can be detected up to an altitude of 27 km, 0.3 ppm to 36 km and 1.0 ppm to 40 km, fulfilling the science requirements. While various factors can degrade the detection capability, square root dependence of the detection threshold on the pulse strength, and the exponential behaviour of the signal (as a function of altitude) cause the threshold to be rather insensitive to the exact values used to estimate it. Thus, the major conclusions hold for a relatively large range of assumptions.

The occultation measurement can detect typical amounts of stratospheric aerosols. Using aerosol extinction given in [15], we use similar path-integrated attenuation calculations as for water vapour to estimate a two-way transmission through stratospheric aerosols of about 0.7. This allows a good dynamic range for both smaller and larger concentrations than in the typical conditions. Cirrus clouds, except for the thinnest, are expected to effectively block the extinction sounding. These can, however, be detected by ranging. The backscatter from cirrus was estimated as 500 photons/km, which should allow the use of the laser as a horizontal ceilometer with a range resolution in the order of 1 km. The extinction in cirrus will prevent any cloud penetrating measurements with the limb-looking LiDAR. The nadir-looking system is expected to have performance comparable to existing orbital LIDARs, being able to resolve aerosol distributions in the troposphere and make cloud-penetrating measurements of thin clouds. In conditions of increased aerosol concentrations, such as after major volcanic eruptions, stratospheric aerosol can also be monitored.

In general, the strong signal, and the long measurement path through the atmosphere, together permit the detection of weak extinction by water vapour and aerosols in the UTLS from single laser pulses, fulfilling the scientific requirements set in table 1. This allows AVALON to significantly improve the detection limit and vertical resolution of currently available measurements.

Power and mass budgets

PSC requirements

The platform functionalities needed by the PSC are fairly standard, hence one can rely on commercially available satellite platforms. Considering the structure, a standard

launcher and payload mechanism is needed, and a payload of 400 kg needs to be carried. For the thermal control, the main challenge is the LiDAR system, which will dissipate about 800 W of heat, due to the inherently inefficient laser generation process. To deal with this excessive heat, a system of heat pipes connected to radiators is necessary. Accommodating the difference in equilibrium temperature between eclipse and sun-lit conditions can be done by equipping the radiators with louvers.

There are no specific demands for the orbit and attitude control, but accurate knowledge of the position and attitude of the PSC is needed for aiming the laser beam at the RSC. Star trackers can reach a precision of 1 arcsecond and are commonly used on spacecraft. 3-axis stabilization is needed to have the solar arrays oriented towards the sun at all moments during local daytime.

The power generation is the most challenging part of the platform: about 2700 W needs to be produced. The Proteus platform produces 1050 W, but more efficient solar cells can be used, and extra panels and wings can be added to the platform. Alternatively the PRIMA platform, which will be used for Sentinel 1, reaches an amount of 5900 W, but the use of this platform will imply a mass penalty.

RSC requirements

For option A the spheres are completely passive and require no power at all. For option B, the surface is partly covered with solar cells as described above.

For option C, the RSC utilizes six solar cells on each face and it has a battery storage up to 10 W and a nominal consumption of 5.6 W. Attitude sensing is provided by coarse and fine sun sensors located on each face of the satellite, and a magnetometer on a pre-deployed boom. Liquid-fuel cold-gas is used for the propulsion system

Launchers

The counter rotation and total system size of the PSC and RSC components require two independent launchers. For both launches, ROSKOSMOS' Dnepr launcher has been chosen. ESA's Vega launcher has been considered but was not chosen due to its launch site, Vega is not attractive for the polar orbit. Furthermore, it is not re-ignitable and also does not offer enough space for the RSC constellation.

Dnepr can carry the PRT (~1100 kg) and the RSC in separate launches. Due to its launch site it is favourable for polar orbits (e.g. CryoSat-2) and, furthermore, the use of the same launcher type for both satellites simplifies operations and provides a cost benefit.

Ground segment and operations

The ground segment will be based on Earth Explorer infrastructure. Data does not require near real time delivery as the mission is focussed towards research rather than operations.

Link budgets were calculated both for the transmission of housekeeping and telemetry data in S-band, and science data in X-band. For housekeeping and telemetry a data rate of 8Mbps is reached, for science data this increases to 150 Mbps. Ground coverage is mainly provided by two ground stations: one in Kiruna, Sweden (~ 6000 s/day), and one in Svalbard, Norway (visibility of ~ 9600 s/day).

Preliminary link budget calculations show that more than enough link reserves will be available in order to provide reliable communications. Furthermore, ground station flyovers will happen roughly every 155 minutes with a PSC-to-ground station visibility of roughly 10 minutes each. Considering the set-up a total daily data volume of roughly 173 GB can be transmitted to earth.

In terms of product retrieval, the water vapour vertical profile can be retrieved from the measurements using, for example, the "onion peeling" algorithm used with many limb sounding systems. In this algorithm, the top layer vapour content is determined first, and the previously measured layers are subtracted from the subsequent values. The performance of the algorithm will determine the final vertical resolution, which will be lower than the sampling resolution.

Retrieving profiles of atmospheric aerosol size distribution, backscatter and extinction coefficients from elastic backscatter LiDAR signals generally relies on at least two widely spaced laser wavelengths. However, the ill-posed problem of determining the latter from a single wavelength LiDAR can be solved using the Fernald and Klett inversion algorithms, assuming an extinction-to-backscatter ratio and the extinction at a reference altitude [15], providing better relative than absolute values.

Constraints

Programmatic risk assessment

High

The LiDAR system is based on laser technology demonstrated in previous spacecraft. The dual-beam laser concept has been used in existing airborne laser systems (TRL 6) [9]. The lowest readiness is that of the active target finding subsystem, which can, however, be based on e.g. existing military target tracking applications (TRL 3). The current mass/power budget for this system is preliminary and carries the risk of further revisions.

The active spherical reflectors of RSC option B would need to be developed.

Medium

The RSC for option C are based on an existing and space-tested nanosat platform. The requirement for modification of this platform to accommodate the reflectors will reduce the readiness (TRL 5-7).

For the passive reflector option A, constellation dispersion due to orbit perturbations presents the highest uncertainty, in particular due to the variability of atmospheric drag. The passive spacecraft themselves are relatively simple and reliable.

Low

The infrared spectrometer is based on space-tested and qualified instruments (TRL 9).

The new measurement concept presents challenges for retrieval algorithms. However, stellar/radio occultation is a well understood concept and thus the algorithms can be developed from existing ones.

Descoping

In case of exceeding the projects budget limitations, there are several possibilities for descoping. One option would be to use fewer retroreflectors, although the cost reduction would not be very high, since their marginal production costs are relatively small. Another option is to remove the IR spectrometer. We would then still have the possibility to look at nadir due to the beam-splitter of the

LiDAR, though again this is not an expensive or risky component of the mission.

Further descoping could consist of removing the beam-splitter of the LiDAR and therefore reducing the power consumption of the whole spacecraft. The largest cost reduction, but the least wanted option, is to design the mission without the retroreflectors, which results in only using one launcher. However, we would lose the advantages of the active limb sounding, which delivers the largest science gain in the improvement of water vapour and aerosol detection limits.

Costs

	PSC	RSC Option C
Amount	1	13
Total Spacecraft Cost	150 Mio. EUR	42.5 Mio. EUR
Launch Cost	25 Mio. EUR (Dnepr)	25 Mio. EUR (Dnepr)
TOTAL COST	242.5 Mio. EUR	

References

1. IPCC 4th Assessment Report, 2007
2. Eyring et al 2006, JGR
3. Eyring et al 2007, JGR
4. Solomon et al 2010, Science
5. Trenberth et al 2007, IPCC chapter 3
6. Dowling, 1990
7. Rosenfeld 1998, BAMS
8. Calpini and Simeonov, Laser Remote Sensing, 2005
9. Browell, Measurements from air and space, Appl. Phys 1998
10. Larcheveque, Applied Optics 2002
11. Zyer, ESTEC report, 2005
12. Orr, Proc. 2008 Small Satellites Systems and Services
13. Arnold, NASA Technical Report, 1978
14. Kovalev and Eichinger, 2004
15. Balin, Appl Phys, 2004