

During the second part of the year 2006, the Belgian Institute for Space Aeronomy has conducted a series of feasibility studies for demonstrating the interest, the scientific relevance and the possibility of an atmospheric sounder on board a LEO micro-satellite.

This instrument, named ALTIUS, would combine the technique of limb scattering observation with an imaging capacity when operating on the day side. At the terminator and in the eclipse phase, the spectrometer shall be used in solar and stellar occultation modes respectively.

The results of the preliminary studies were reviewed by the ESA Concurrent Design Facility (CDF) in December 2006.

It was the view of the CDF team that the work done to date constituted a comprehensive feasibility analysis and a proof of feasibility of the ALTIUS instrument with some issues still outstanding including: development timescale, optical design validation, detector availability and further key issues related to the satellite. During the years 2007-2008, a complete phase A has been achieved by a consortium of scientists, engineers and industrial partners.

This paper describes the main objectives and methods that will drive the ALTIUS project.

1 ALTIUS MISSION OBJECTIVES

1.1 The scientific context: evolution of the Earth's upper atmosphere during the 21 century

There is an increasing interest in the understanding and the monitoring of the physics and the chemistry of the troposphere due to their potential importance for the human beings. Yet, the evolution of the climate is fundamentally driven by the entire atmosphere through its global transport properties, its chemical composition and its interaction with the solar radiation.

It is now accepted that the global and polar depletions of the ozone layer can be attributed to the presence of halogen compounds released by anthropogenic emissions. The Montreal protocol has allowed observing a decrease in the stratospheric halogen load and a slowing of ozone decline is expected to be the natural precursor of a complete ozone recovery around the

mid-century. There is presently experimental evidence that the global mean ozone total column is no longer decreasing with respect to the 1998-2001 period. Also, the ozone stratospheric distribution has been relatively constant during the last decade although both dynamical and chemical processes may contribute to decadal changes in the lower stratosphere. On the other hand, column ozone loss in the 2004/2005 Arctic winter was among the largest ever observed whereas Antarctic ozone depletion has probably stabilized during the last decade.

Clearly, the monitoring of ozone stratospheric abundances is of crucial importance in assessing the milestones of a clear recovery process.

Among important trace gases, methane is very important for its impact on climate through a large radiative forcing effect and the production of stratospheric water vapor. A global increase of about 0.7 ppm in 1800 AD to 1.8 ppm nowadays is difficult to interpret because of the diversity of the sources: wetlands, enteric fermentation, fires and rice agriculture.

The odd hydrogen family, HO_x , contains all active species, i.e. radicals that are involved in catalytic cycles that destroy O_x . The HO_x radicals are derived primarily from the oxidation of water vapor in the stratosphere and therefore it is essential to understand and to monitor the intrusion of water vapor into the stratosphere, specially in the region of the tropical tropopause.

Similarly, the NO_x family is known to play an essential catalytic role in ozone destruction with a strong diurnal cycle that requires day- and nighttime measurements for a full characterization. On the other hand, these species may be converted into inactive forms or reservoirs. In particular, the NO_2 reacts with ClO to form ClONO_2 and the measurement of OCIO (depending itself from the presence of ClO and BrO) and BrO (daytime) in the UV is very important if it can be anti-correlated with NO_2 simultaneous observations.

The role of polar stratospheric clouds (PSCs) in polar ozone depletion has been described extensively in scientific literature ([1]). Briefly, in cold conditions, when PSCs are present, the stable reservoir species HCl , ClONO_2 and N_2O_5 disappear in heterogeneous reactions on the surface of the particles to form HNO_3 inside the PSC particles, which are eventually removed from the stratosphere by sedimentation in a process called de-nitrification. The other reaction products are photo-dissociated in the presence of sunlight (at the end of polar winter, when the Sun returns) to chlorine species, which act as catalytic ozone scavengers.

Much remains to be learned about PSCs. The current classification is probably too coarse. We do not know enough about particle sizes, crystal morphology and even composition. On a larger scale, more information is needed about cloud properties such as shape, thickness and density. Satellite measurements can provide this information: PSCs are easily recognized when elevated optical extinctions are observed inside the polar vortex.

Polar mesospheric clouds (PMCs), originally called noctilucent clouds, are (as the name suggests) only visible in the dark sky, long after sunset. PMCs were reported for the first time in 1885. They are similar in appearance to thin cirrus clouds, but are located at the much higher altitudes from 80 to 87 km, near the mesopause. PMCs only occur at high latitudes during summer (a few weeks before and after the solstice), when the mesosphere becomes extremely cold (with temperatures even as low as 100 Kelvin). Various pieces of evidence, including direct rocket sampling, suggest that they are composed of very small water-ice particles (0.05 – 0.1 μm).

1.2 Filling the forthcoming gap for atmospheric data

An extensive compilation performed by Dr. J-C Lambert of past, present and future atmospheric missions ([2]), suggests a forthcoming problem in the monitoring of the Earth's atmosphere with a global coverage (Figure 1).

Clearly, the number of available sounders will drop dramatically and this is particularly true for space instruments having a high vertical resolution. Furthermore, during the period 2005-2006, four very important and successful missions were lost or switched off: SAGE II, SAGE III, POAM and HALOE.

Not only this loss of instruments is detrimental for pure atmospheric research (all together these four instruments capitalize 47 cumulated years of measurements and about 4800 scientific papers) but it has dramatic consequences on the monitoring of long-term trends for essential atmospheric species like ozone or water vapor.

Launching ALTIUS in 2013 is an appropriate answer to fill the forthcoming gap.

Recently, it has been envisaged to extend the ENVISAT mission to 2010 and further, with a degraded functionality, till 2014. This will allow atmospheric instruments to continue their observations even if they are well beyond their nominal lifetimes.

On the one hand, space-borne operational monitoring of atmospheric composition is valuable:

- To promote scientific research with unique long-term consistent data products
- To contribute to numerical weather prediction, climate monitoring, and, in broader perspective, Earth system monitoring
- To improve atmospheric correction for surface remote sensing
- To strengthen public awareness on environmental themes

On the other hand, the IGACO report ([3]) states explicitly that there is not yet any provision for a system covering high-resolution stratospheric profiles of ozone and other constituents. It is therefore urgent to address the following general recommendations in the frame of the monitoring of our environment from space:

- Continuity: the data products from satellite, which have to be integrated into a global picture, must have assured a long-term continuity.
- Gaps in observational coverage: for each target species and variable, the present gaps in the current spatial and temporal coverage should be filled by extending the existing measurement systems.

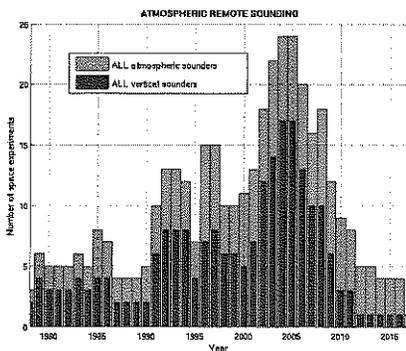


Figure 1: Atmospheric sounders compilation.

- Long-term validation of satellite observations: in order to ensure the accuracy and consistency of satellite measurements, sustained quality-assurance measures, over the entire lifetime of satellite sensors, are essential.
- Validation of vertical profile data from satellite observations: a set of high-performance scientific instruments using ground, aircraft and balloon platforms, possibly operated on campaign basis, must be maintained to provide the crucial validation data.

There remain a few instruments working on ENVISAT, SCISAT, ODIN, TERRA, AURA, and AQUA. Also some new sounders are now active (e.g. on METOP) but this is insufficient to ensure a full spatial and temporal coverage as well as a minimal redundancy in the measurement data set.

Some nadir-looking instruments of the GOME type possess a high horizontal resolution well suited for air quality, troposphere pollution detection and monitoring but at the price of a poor vertical resolution, not compatible with the refinement of modern CTM modeling codes. A correct understanding of the stratospheric chemistry requires ideally a 1 km vertical resolution, whereas a horizontal resolution of about 300 km, typical for occultation instruments, is acceptable.

1.3 User requirements from the atmospheric community

According to the IGACO report ([3]) which was taken as a scientific reference for this phase A study, it is necessary to obtain a comprehensive set of global observations of the species quoted in table I for the stratosphere by using LEO satellites. In addition to the needs expressed in the IGACO report, there are also atmospheric modeling capabilities which embark on the creation of a global picture in the combination of these atmospheric data.

It is worth keeping in mind that nadir-looking instruments are characterized by a high horizontal resolution along the tracks and a poor vertical resolution. On the contrary, limb pointing instruments shall offer a much better vertical resolution be it at the price of a limitation in geographical sampling, mostly determined by the orbital parameters and the measurement rate.

The set of requirements satisfy the user communities concerned with the focus of IGACO (chemistry-climate and stratospheric ozone depletion, as well as the essential "end-to-end" ground-truthing for satellite sensors). They are based on "quantitative science", i.e. on measured concentrations, on published trend assessments, and on known concentration differences in the vertical and horizontal distribution of the various parameters. The development of data quality objectives is an iterative and continuously evolving process, which takes into account user needs and advances in measurement technologies/capabilities.

1.4 The advent of the limb scattering remote sounding method

It is highly desirable to combine the advantages of nadir-viewing and limb-viewing techniques. What is ideally needed is an instrument with a vertical resolution similar to that of an occultation instrument but with coverage similar to that of a backscatter instrument

Since the pioneering work of the SOLSE/LORE experiment ([4]), it has been established that the limb scattering technique is a viable technique for the measurement of atmospheric trace

Atmospheric Region	Requirement	Unit	O ₃	NO ₂	CH ₄	H ₂ O	CO ₂	BrO	Aerosols
	Dx	km	100	250	250	200	500	100	100
Lower strato	Dz	km	3	4	4	3	4	1	1
	Dt		1d	12hr	12hr	1d	1d	6h	1w
	Total error	%	20	40	30	20	2	15	-
	delay		weeks	hours	weeks	weeks	months	weeks	weeks
	Dx	km	200	250	250	200	500	100	-
Upper strato, meso	Dz	km	3	4	4	5	4	1	-
	Dt		1d	1d	1d	1d	1d	1d	-
	Total error	%	20	40	30	20	2	20	-
	delay		weeks	weeks	weeks	weeks	months	weeks	-

Table 1: IGACO threshold values for observational requirements. Dx, Dz and Dt refer to horizontal, vertical and temporal resolution respectively. Total error on concentration contains precision and accuracy components and delay refers to the time elapsed between observation and data availability.

gas profiles in the stratosphere. A confirmation of this approach has been recently published for OSIRIS on board ODIN ([5]), for SCIAMACHY on board ENVISAT ([6]) and for the SAGE III mission before its premature end ([7]).

All the above-mentioned experiments have measured and validated ozone and NO₂ profile retrievals and their results concerning BrO, OClO and aerosols will be published in forthcoming scientific papers. Also, the limb scattered light recorded by the upper and lower bands of the GOMOS detector (on board ENVISAT) is presently investigated in order to develop an inversion algorithm.

However, it is now recognized that the limb scattering technique suffers from a major difficulty associated with the difficulty of an accurate determination of the tangent altitude associated with a particular line-of-sight because of the diffuse nature of the light source ([8]).

ALTIUS will also make use of the limb scattering technique but its imaging capacity will allow solving the issues of altitude registration, cloud identification and horizontal gradients of measured species.

1.5 Spectrometer function

The spectrometer function shall not be based on a classical solution with interference filter wheels that may perturb the pointing accuracy of the platform. Also, filters are known to suffer from temporal degradation. Instead, ALTIUS shall promote the use of Acousto Optical Tunable Filters (AOTF) that allow for a fast and accurate electronic tuning of the observed wavelength, in both scan and differential modes.

1.6 Demonstration of operationality

In order to address the issue of data gaps in the 2010-2020 timeframe, the ESA GMES Sentinels 4 and 5 (nominally one mission flying in geostationary orbit and one in low-earth orbit) are under consideration. These Sentinels should primarily address the needs for climate gases (CO₂, CH₄ and CO) and aerosol monitoring, measurements in the upper troposphere/lower Stratosphere (UT/LS) region for ozone and climate applications, and high temporal/spatial resolution measurements of tropospheric composition for application to air quality.

Therefore, the ALTIUS mission may also be viewed as a precursor for demonstrating its operational potentiality with respect to protocol and trend monitoring in the ozone and climate change themes.

Also, ALTIUS shall serve as a front-end to a 4D-data assimilation system like BASCOE ([9]). Assimilation of satellite measurements of chemical species, notably stratospheric ozone, into an operational weather forecasting system is a relatively recent development. It has been used in numerical weather prediction to improve significantly the assimilation of satellite radiances. It has been successfully applied to forecast the evolution of the ozone hole and to forecast the UV exposure of the Earth's surface. The daily UV forecasts delivered by many meteorological organisations are a visible demonstration of this technique for the general public.

2 ALTIUS MISSION REQUIREMENTS AND SYSTEM CONCEPTS

2.1 ALTIUS geophysical requirements

Considering the IGACO requirements mentioned in section 1.3 and taking into account that ALTIUS is a limb vertical sounder on board a micro-satellite platform, the instrument shall target the following species, with their total error budget (random+bias), wavelength domains, limb conditions and geographical resolution at the turning point.

It should be taken into account that any measurement toward the limb (scattering or occultation) leads to an effective path length along the line-of-sight of about 500 km. Perpendicular to the line-of-sight and parallel to the horizon, the spatial resolution shall be mainly limited by the number of pixels needed to obtain the necessary S/N ratio imposed by the inversion algorithm. Finally, the vertical resolution shall be equal or better than 1 km.

The ALTIUS mission requirements for the target atmospheric species are summarized in table 2 with a particular focus on vertical resolution. The table considers the priority of data collection. The global ozone is the priority 1 whereas priority 2 refers to species explicitly mentioned in the IGACO requirement table (table 1). The other species [priority 3] are mentioned in experimental "demonstration" mode.

The priority scientific target of the ALTIUS mission will be the measurement of the ozone concentration vertical profiles. This concentration should be retrieved with accuracy of 5 % between 10 and 50 km, and of 20 % between 50 km and 100 km. The optimal ozone measurements will be performed around 550-650 nm (Chappuis band) in the lower stratosphere, around 320-350 nm (Huggins band) in the upper stratosphere and 230-270 nm (Hartley band) in the mesosphere in occultation mode only. The instrument has to be able to measure ozone in the

		z [km]	Δ [%]	λ [nm]	bright limb	occultation	Dx, Dy, Dz [km]	full coverage
1	O ₃	10-30	5	550-650	x	x	500,10,1	3d
	O ₃	30-50	5	300-350, 550-650	x	x	500,10,1	3d
	O ₃	50-100	20	250-300		x	500,NA,1	3d
2	N ₂	20-50	30	450-550	x	x	500,20,2	3d
	CH ₄	5-25	20	1600-1800	x	x	500,50,2	3d
	H ₂ O	10-30	20	900-1800	x	x	500,50,2	3d
	CO ₂	10-30	20	1550-1600	x	x	500,50,2	3d
	BrO	10-30	20	320-360	x		500,50,1	3d
3	OCIO	15-50	25	320-400		x	500,50,1	3d
	NO ₃	20-50	25	662		x	500,50,1	3d
	aerosols-PSC	10-30	25	200-2000	x	x	500,20,1	3d/1y
	O ₂	60-100	30	1260-1270, 1530		x emission	500,100,5	3d
	PMC	70-100	50	200-2000	x	x	500,20,1	1y

Table 2: ALTIUS mission requirements for the target atmospheric species.

polar night as well as at different local times in the mesosphere (in particular around the second ozone maximum).

Global coverage has to be performed in a delay equal or less than 3 days revisit time to offer continuity with respect to ENVISAT atmospheric instruments, with a resolution of 5 degrees in latitude and 10 degrees in longitude, a threshold requirement for the accuracy of present chemical assimilation models.

2.2 ALTIUS technical requirements for limb remote sounding

2.2.1 ALTIUS definition

In short, ALTIUS may be summarized as an imaging spectrometer with a moderate spectral resolution.

The ALTIUS instrument shall be a spectral imager capable of observing the atmospheric limb in the UV (250-400 nm), VIS (400-800 nm) and NIR (800-1800 nm) domains, with a resolution better than 10 nanometers. For each wavelength range, a distinct Acousto-Optic Tunable Filter (AOTF) will permit to perform observations of selectable small wavelength windows. Ideally, a typical set of 10 wavelength domains shall be recorded in 1 second to record sufficient spectral information content about the priority 1/priority 2 chemical species with a maximal geographical resolution. However, the measurement time shall be possibly increased up to 50-100 s in the worst case to improve the S/N ratio of the measurement. Also, pixel binning (up to 100) shall also be possible for the same purpose at the price of a reduced transversal resolution.

2.2.2 ALTIUS mission time frame

In order to satisfy the scientific need for continuity in atmospheric measurements with a full coverage, the ALTIUS experiment should not be launched later than 2013. The commissioning phase will last no more than 6 months after which a nominal observation period of 3 to 5 years is planned.

An international science team will be formed by invitation of recognized experts in the field of limb remote sounding. Attention will be paid to distribute only one official version of the operational geophysical products whereas "off-line" scientific products will be distributed freely to the scientific community.

Scientific data will be released one year after the end of the commissioning phase.

2.2.3 Mission autonomy

Between launch and end of mission the spacecraft has to provide full autonomy to the payload to run nominal and dedicated mission scenario's, for which the satellite constraints are automatically verified and executed in a transparent way for the user.

An important "manoeuvrability" is expected in order to perform the respective desired pointing modes as bright limb (forward, backward, and sideward), stellar occultation, solar occultation and occasional calibration/validation cases.

The ALTIUS mission will perform a sustained monitoring of the Earth's atmosphere. Hence, the ALTIUS instrument will drive the complete mission and the application of the spacecraft resources. Therefore the platform has to be completely dedicated to its unique payload.

ALTIUS will be a flexible mission allowing the payload team to plan observations with a minimal notification time of 12 hours prior to the observation allowing for a high reactivity to unpredictable events like explosive volcanic eruptions, pyrocumulonimbus clouds, collocation constraints during intervalidation campaigns and focus on particular meteorological conditions in the polar vortex.

2.2.4 Launch requirements

Launching ALTIUS not later than 2013 is an essential requirement of the mission to play its role of atmospheric data gap-filler.

For a gap-filler, it is absolutely necessary to avoid any delay or constraint imposed by another payload acting as a primary partner. Also, the choice of a circular LEO is very important to ensure a full global coverage based on the combination of heliosynchronicity and of an optimal tuning of the altitude to allow interlacing of ground tracks.

It is an absolute requirement to achieve a full coverage of the globe in at most 3 days.

2.2.5 Main observation technique

In its main observation mode, ALTIUS shall be a limb remote sounder using spectral imagery and has to be inserted in a LEO circular helio-synchronous orbit (650-700 km) with a descending node at 10:00-10:30 am and allowing for a 3-day revisit time, which are close to the ENVISAT orbital parameters.

For a limb imager, the impact on the geophysical interpretation will be very different if the line-of-sight is along a parallel or along a meridian where larger concentration gradients are expected to occur (e.g. at the edge of the polar vortex).

Information about the horizontal gradients will be obtained from a side limb observation and will be mainly influenced by the spacecraft velocity and the acquisition time.

A proven observation technique is “hyper-spectral” remote sounding, where typically nadir-looking instruments are used to build a spectral hypercube consisting of pixel maps at different wavelengths. The acquisition mode of this hypercube is influenced by the spectrometer/detector technology. A grating or prism is combined with a 2D-detector of which one dimension is associated with wavelength, whereas the other dimension is a spatial dimension. The third dimension of the hypercube is constructed by some scanning process.

The ALTIUS instrument will use the hypercube measuring technique in a limb viewing geometry. Instead of a traditional “spatial x (spatial x wavelength)” construction an innovative “(spatial x spatial) x wavelength” approach will be adopted. Therefore ALTIUS will be a spectral camera with wavelength scanning. This approach will allow solving, in a definitive way, the altitude registration problem that is spoiling the traditional limb scatter technique.

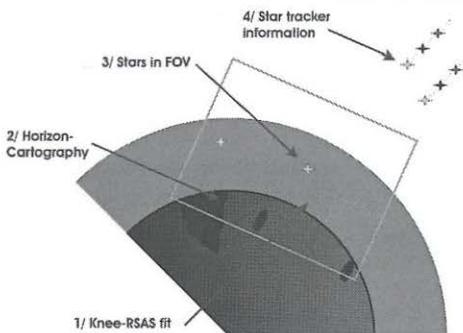


Figure 2: Illustration of the ALTIUS concept. mation.

2.2.6 Typical operating modes

Limb forward, backward and sideward modes ALTIUS needs to be installed on a microsatellite that can be fast (less than 1 minute) and easily pointed in any direction because nominal modes of observation will need pointing toward the limb in the forward and the backward direction or even sideward. Observations in the orbital plane or perpendicular to it (Figure 3) may be interlaced from orbit to orbit in order to optimize the coverage.

The ALTIUS instrument shall be basically an imager with the limb itself as scope (Figure 2). The field-of-view of the instrument (an extended scene of the sounded atmospheric region has to be aimed for) will cover the entire atmospheric limb, hence different solutions will exist to improve the classical (and unsatisfactory) method of total radiance fitting in the UV (“Knee”-methods), such as using: (1) the horizon or geographical details

Limb scattering: forward and sideward modes

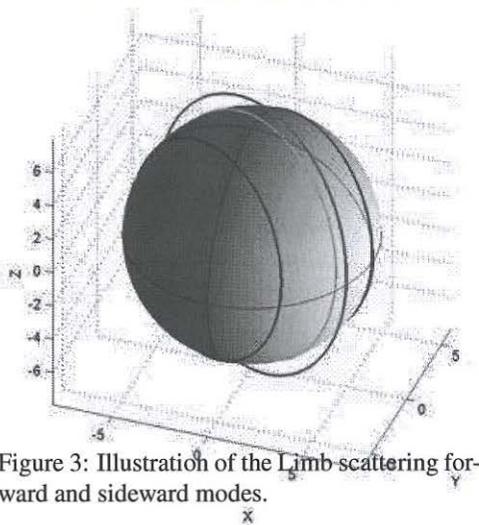


Figure 3: Illustration of the Limb scattering forward and sideward modes.

Dynamic limb tomography ($t=40$ min)

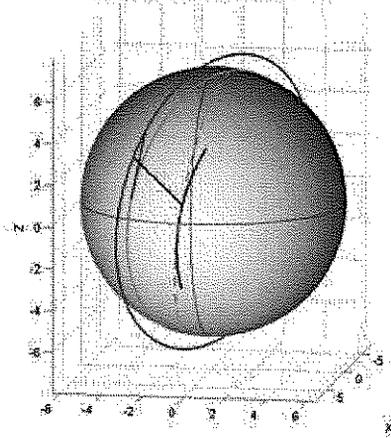


Figure 4: ALTIUS tomography concept: a forward limb observation followed by a dedicated sideward limb observation at the consecutive orbit.

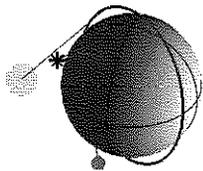
As a serendipitous mode of observation allowing the retrieval of global information, it shall also be possible to perform tomography of a species 3D distribution field in the low latitude regions. Due to the remarkable (and fortuitous) fact that the angular distance to the side horizon is close to the angle by which the Earth will have rotated at the next LEO revolution, it is possible to combine a forward limb observation followed by a dedicated sideward limb observation at the consecutive orbit (Figure 4). This mode is called tomographic because the same location is observed from two almost orthogonal directions, which allows for a 3-D inversion of the geophysical field.

Stellar occultation mode Although the limb observations ensure a dense geographical coverage, the instrument will only be active on the bright side of the Earth. Furthermore, no measurements will be possible during polar night.

Besides limb observations, ALTIUS will therefore perform also stellar occultation measurements during the eclipse (Figure 5). This is an efficient self-calibrating remote sounding technique

requiring a well-defined observation zone.

Star, planet, Moon occultations



Solar occultation

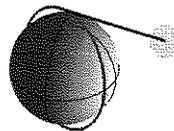


Figure 5: Illustration of the Star/solar occultation modes

Assuming that the satellite has a pointing stability better than 100 microradians, there is no need to possess an autonomous steering front device coupled with a telescope. The use of an imager such as ALTIUS will allow stellar occultation to be performed in an absolute inertial spacecraft pointing mode, where the image of the Earth's horizon moves across the detector. Even atmospheric refraction will be tracked or corrected with a sufficient accuracy by using

a ray tracing model based on climatological values of the atmospheric refractivity. It is also possible to track the star displacement at the detector level.

Star scintillation is a well-known phenomenon in the lower layers of the atmosphere, degrading the efficiency of stellar occultations. However numerical methods exist to circumvent the problem (e.g. [10]).

A number of about 10 consecutive star occultations during the eclipse is set forward.

Performing star occultation in the bright limb, on the contrary, is not recommended due to the overwhelming limb contribution below 50 km.

Solar occultation mode The very high signal-to-noise ratio provided by solar occultations at the terminator (always at high latitudes for a polar orbit) will allow for an accurate identification and measurement of polar stratospheric clouds, pyrocumulonimbus events and polar mesospheric clouds. Solar occultations shall also allow for mesospheric ozone measurements at the terminator that can be related to the ozone diurnal cycle.

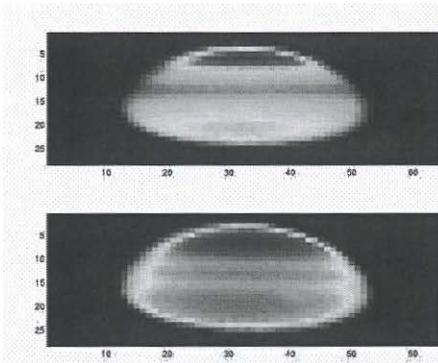


Figure 6: Example of PSC events during two solar occultations measured by the ACE imager at $\lambda = 1 \mu\text{m}$ with a monolayer structure (top) or a twofold cloud (bottom).

In particular, occultation imaging will give valuable information about the structure and the horizontal extent of the clouds, whereas other occultation techniques can only retrieve extinction profiles. In Figure 6 an example is shown of PSC events during two sunsets measured by the ACE imager at a wavelength of $1 \mu\text{m}$ with a monolayer structure (top) or a twofold cloud (bottom).

ALTIUS shall be able to measure identical events at a large number of wavelengths from the UV to the NIR. Simultaneously, the solar flattening due to atmospheric refraction will allow the retrieval of the atmospheric air density gradient and the corresponding high resolution temperature profile up to 40-45 km.

The S/C has to be able to change its pointing direction at an average rate of 1° per second and per axis (e.g. switching from forward to sideward limb observation might take 90 seconds or switching from forward to backward 180 seconds). This requirement is mainly justified by the need of performing dynamical stellar occultation sequences during the eclipse (rallying from one star to the next).

Taking into account a distance to the limb of about 3000 km, ALTIUS shall achieve an absolute pointing accuracy of $100 \mu\text{rad}$ and a precision of $100 \mu\text{rad}$, which corresponds to a resolution of 600 meters (pixel size).

The S/C's star trackers shall be installed in the immediate neighborhood of the instrument to allow for a robust angular intercalibration with the imagers and in such a way that all the star trackers are not blinded together by the sun or occulted by the Earth.

2.2.7 Instrument requirements

Wavelength features ALTIUS will observe several targets (Earth's limb, stellar occultations, solar occultations, dark space and nadir) at any wavelength in the 250 and 1800 nm range. The spectral resolution has to be better than 10 nm. Consecutive snapshot images of the limb at selected wavelengths shall be taken especially in regions where absorption cross section of a particular species has a strong spectral signature. Typically a set of 10 randomly selectable wavelength domains has to be measured in 1 to 10 seconds.

Field of view features Considering an atmospheric domain of about 100 km, limb observations will have to cover an altitude range of 300 km seen from a distance of 3000 km. This will allow for observing the atmosphere as well as reference stars and reference points (geographic features) located on the Earth's surface. The viewing angle in the horizontal direction (parallel to the limb) will have a similar value, so that a 300 km by 300 km section of the bright atmospheric limb with a spatial resolution of 0.5 km can be observed (using a square 2D-detector system).

Light intensity features The instrument has to be designed to observe all the defined targets (Limb, solar, stellar, ...). In case of limb observation, the collected signal will have a high dynamic range because the top-of-atmosphere radiance (TOA) varies exponentially with the tangent altitude of the line-of-sight (Figure 7).

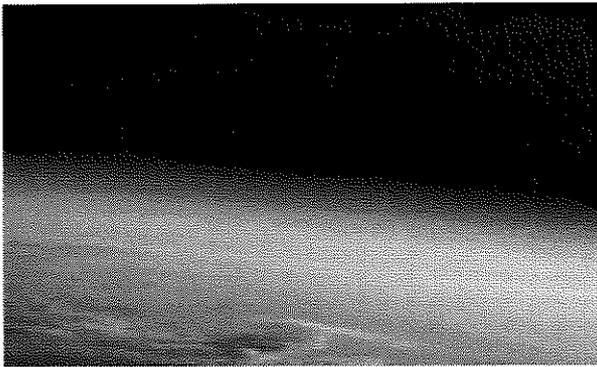


Figure 7: Earth's limb

Summary The table 3 gives a summary of the ALTIUS observation requirements.

2.2.8 Expected atmospheric signal

Bright limb observations The Figure 8 summarizes the expected spectral radiance values for bright limb observations. Spectral radiances for different tangent altitudes of the line of sight are shown in different colors: blue = horizon, green = 5 km, red = 10 km, etc. The maximum value for L under these conditions is $0.02 \text{ W sr}^{-1} \text{ cm}^{-2} \mu\text{m}^{-1}$ at a wavelength of 400 nm.

Wavelength range	250 nm to 1800 nm
Spectral resolution	better than 10 nm
Typical rate	1 image at 10 wavelengths per interval of 1 to 10 s in limb mode
FOV	0.1 rad \times 0.1 rad (in visible range)
Spatial resolution	0.5 km \times 0.5 km
Spatial dynamical range	10^4 - 10^5
Spectral dynamical range	10^3

Table 3: Summary of observation requirements

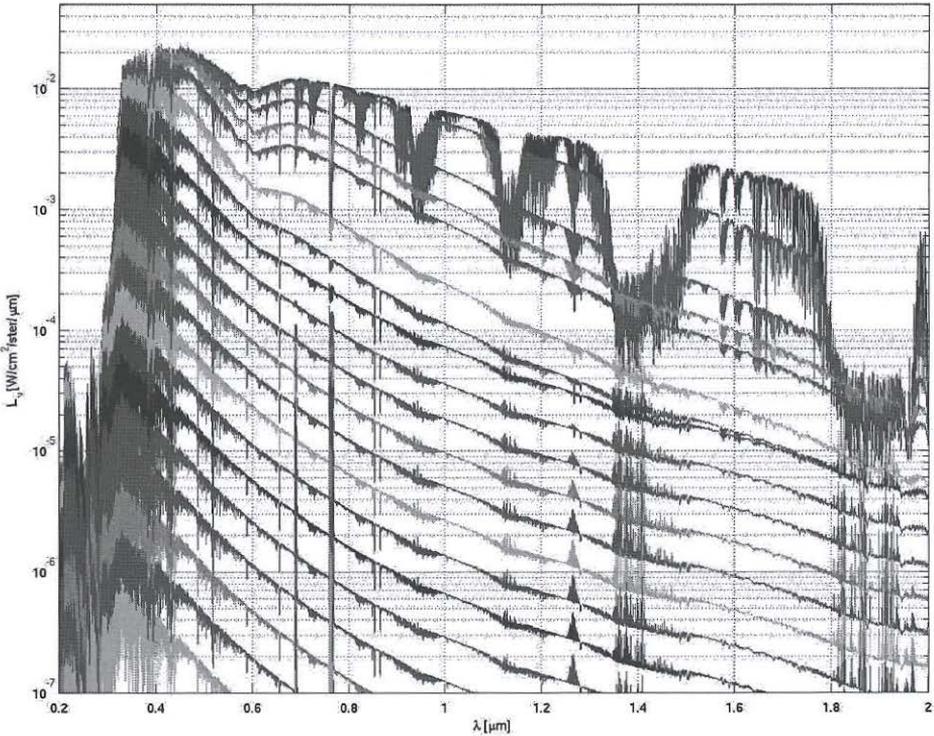


Figure 8: Spectral radiance in the case of a bright limb observation expressed in watt per cm^2 per steradian per μm . Tangent height varies from 0 to 100 km by 5 km increment.

Stellar occultation observations The expected spectral radiance L for the case of stellar occultation observations as a function of wavelength for bright stars with different spectral properties.

Sirius is often used as the brightest light source for stellar occultation observations from satellites. This star is the brightest star at night (magnitude -1.44 and temperature 11000 K). At a wavelength of 600 nm it has a spectral flux of approx. $3 \cdot 10^4 \text{ ph sec}^{-1} \text{ nm}^{-1} \text{ cm}^{-2}$.

The angular diameter of Sirius equals $0.03 \mu\text{rad}$, hence it must be considered as a point source

and not as an extended source similar to the Sun. We cannot use the concept of spectral radiance and we express the star signal as a flux.

Solar occultation observations The light source for solar occultation observations is the Sun. If we make abstraction of the absorption lines in the solar spectrum, it may be approximated by the spectrum of a black body at about 5700 K.

The apparent viewing angle of the solar disc from an orbit around the Earth at 1 A.U. from the Sun is 9.3 mrad, not taking into account refraction effects.

Clearly, the optical design layout of the ALTIUS solar port shall contain an attenuator device (f.i. neutral filter) capable of reducing the solar signal to the level of the bright limb signal.

2.3 Requirements for atmospheric sounding and monitoring from a LEO micro-satellite

2.3.1 General requirement for data transmission

Data transmission rate between S/C and G/S and data storage both on board and on ground must be sufficient to perform the baseline scenario continuously and fluidly. Too low transmission rate, too low downloadable telemetry volume or lack of available storage memory must not hamper the execution of the imposed scenario. On board data treatment and compression has to be envisaged. In the baseline scenario, three types of measurements are defined, all generating a specific amount of scientific data:

- Limb measurements
- Star/planets occultations
- Solar occultations

Typically 600 full detector images and 7200 reduced (windowed) images have to be processed per orbit, i.e. stored on board, transmitted and stored again on ground. Assuming 3 detectors of 512 x 512 pixels (max), pixel values represented on 14 bits, and taking into account overhead for package headers and housekeeping data, it results in an estimated data volume of approximately 2.5 Gbits per orbit and 37.5 Gbits per day.

Communication between S/C and G/S will have to be established preferably through a single ground station. Assuming a typical contact time with the ground station of between 5500 seconds per day for a northern station as Svalbard and 2000 seconds per day for a 50° North station as Redu, a transmission rate between 6.75 Mbits/s and 18 Mbits/s has to be sustained. X-band communication infrastructure has to be available in the ALTIUS G/S.

3 ALTIUS SCIENTIFIC COMMUNITY

As promoter of the ALTIUS concept, the Belgian Institute for Space Aeronomy will remain deeply involved in the project during the development, commissioning and exploitation phases.

Similar to past experiences in Earth remote sounding, the "ALTIUS Science Team" comprising an international panel of experts in the field and instrument engineers will be created. This team will play a fundamental role in discussing all scientific issues related to the measurement mission scenarios, particular campaigns or instrumental validation activities. During the commissioning phase, the Science Team will be collocated on a regular basis in order to assess the nominal performances of both instrument and mission. In case of unexpected behavior, the Team will be in charge of analyzing the situation and to propose mitigating strategies based on information provided by the technical team of the science operation centre.

Basically, the Science Team shall play an advisory role with respect to the ALTIUS Steering Board and will be responsible for scientific reporting and analysis of the mission status.

4 ALTIUS MISSION OUTCOMES

4.1 Geophysical products

4.1.1 Validated level 2 data

The ALTIUS Data Operation Centre shall be responsible for the production of:

- level 1 data that will contain calibrated instrumental data that are normally distributed to a restricted number of users for the sake of instrument characterization and algorithm development
- level 2 data that consist of vertical concentration profiles of the species mentioned in table 2, together with the associated error budget and related quality flags. The level 2 data will be considered as the official product distributed by the Centre and will evolve according to the recommendations of the ALTIUS Science Team.

The ALTIUS Data Operation Centre shall closely associate scientists and engineers involved in the mission scenario definition, the instrument characterization and the exploitation of the data processing model.

4.1.2 Inputs for atmospheric boards

The ALTIUS Science Team shall be responsible for the quality control of the released geophysical data.

Independently of scientific analyses produced by external scientific teams from official level 2 data, the Science Team will produce scientific reports that make a synthesis of observed and validated trends that may be used as official atmospheric data inputs by international scientific boards in charge of climatic change assessments (f. i. IPCC panel).

4.1.3 Integration in the BIRA-IASB scientific strategy

Scientific services BIRA-IASB is more and more involved in the definition of atmospheric core services related to the GMES themes for climate change and ozone monitoring. As modeling, data assimilation, monitoring and forecasting certainly address the global component of

the GAS Core activities, a service portfolio will exist at the Institute in which the outcomes of the ALTIUS will perfectly fit.

First of all, the ALTIUS Science Operation Center will become a central node of the advanced integrated satellite data service as an operational server for limb products. These products will consist of retrieved stratospheric ozone and secondary species profiles as well as normalized multispectral limb radiances. Such a data node shall be able not only to achieve a quasi-global monitoring of the Earth but also to answer to specific request of users like dedicated validation campaigns, focus on unexpected or exceptional events and customized data processing.

More specifically, the ALTIUS data flow will also feed the global stratospheric long-term re-analysis BASCOE-REA that is aimed at the chemical assimilation and forecast of O₃ and of the chemically connected species: NO₂, ClO, BrO, HNO₃.

Assimilated level 3 data Level 3 data (gridded, global, and validated) shall be produced by 4-D assimilation techniques, a standard practice for obtaining the best possible spatio-temporal estimators of the measured fields. BIRA-IASB has developed a powerful 4-D assimilation tool named BASCOE that should be used to assimilate ALTIUS level 2 data by using ECMWF analysis.

The scientific team involved in this assimilation process shall be in close contact with the Data Operation Centre in order to get a full knowledge of the instrument characterization and the issues related to the error budget covariance matrix.

Intervalvalidation with other sensors The ALTIUS concentration profiles will be used for intervalvalidation with other space borne instruments or ground based observations, and might be vertically integrated to produce column densities. Appropriate determination of averaging kernels will be provided by ALTIUS in order to allow for resolution matching.

Comparison with other sounders like OMPS on NPP will be very specific to validate the limb scattering technique promoted by ALTIUS.

Off-line products and climatologies From the official level 2 products corresponding to a particular version of the data processing model, the ALTIUS scientific team will produce monthly climatologies of the retrieved species, with and without 4-D assimilation of measured data.

The level 2 products will be released with radiance and transmittance normalized signals. This shall permit other teams to apply their own algorithms that might reveal to be superior to the nominal processing scheme and might induce improvements of the official data processing model.

Also, off-line products will be developed by external parties for difficult or unforeseen spectral signatures. A typical approach for this kind of processing requires the statistical binning of a large number of observations to increase the S/N ratios.

Depending on the maturity of a concept recently introduced, the direct assimilation of measured radiances will be considered to become an official ALTIUS product.

4.2 Technology certification

4.2.1 Proof of concept for limb sounding by imaging

The ALTIUS mission shall demonstrate that the observation of scattered light by the limb is now a mature concept that may considerably be improved by the use of imagers. In particular, the recurrent problem of tangent altitude registration will be solved and cross-validated with accurate satellite attitude information delivered by the star trackers.

4.2.2 Multi-mode complementarity

From its multi-mode of measurements, ALTIUS will allow to address two important issues

- to fill the data gap for polar night experienced by all sounders using the Sun as the original light source
- to validate and intercompare geophysical fields measured by the same instrument in different modes (limb, stellar, solar)

4.2.3 AOTF based spectrometry

ALTIUS shall demonstrate the usefulness of AOTF devices in atmospheric remote sounding in terms of simplicity, robustness, speed, compliance to imaging capacity ([11]).

4.3 Compliance to operational needs

4.3.1 Micro-satellites as a solution for future atmospheric sensors

As mentioned in section 1, spaceborne operational monitoring of atmospheric composition is expected to contribute to the following topics

- To promote scientific research with unique long-term consistent data products
- To assist numerical weather prediction (NWP), climate monitoring, and, in a broader perspective, Earth system monitoring
- To improve atmospheric correction for surface remote sensing
- To strengthen public awareness on environmental themes

However, the development time of large platforms is known to frequently exceed the delay that is necessary to ensure continuity and/or overlap between successive atmospheric missions.

ALTIUS should demonstrate the pertinence of micro-satellites as efficient sensors that could become operational within a 5 year implementation period. Also, such micro-satellites, designed by definition to host only one or two payloads, offer an exceptional versatility to accommodate for different observation modes as well as a fast reactivity to special events like volcanic eruptions or validation campaigns.

4.3.2 Integrated mission

The ALTIUS project calls upon a limited amount of resources. This shall promote the concept of atmospheric missions initiated by scientific institutions, universities or national agencies, and possibly supported by or integrated in international agency programs.

Beside the moderate funding level needed to perform the mission goals, the small scale nature of the project shall allow to conceive ALTIUS (and possible successors) as an *integrated mission* articulated along the following steps:

- identification of atmospheric data needs related to environmental themes
- innovation or consolidation of remote sounding techniques capable to address global coverage objectives
- payload development and optimization of mission scenario's
- full instrument characterization and knowledge by a core team
- commissioning phase
- full data retrieval including algorithm development for the data processing model, the cross-validation and the data quality assessment
- official level 2 data distribution to the user community and archiving
- scientific evaluation of the geophysical products, assessment and monitoring of trends, generation of level 3 data
- integration as an active node in international networks for global monitoring

4.3.3 Matching of GMES requirement subset

ALTIUS is expected to demonstrate its potential to address the following issues (table 4) related to the GMES requirements for themes A (ozone layer) and C (climate change).

ALTIUS shall demonstrate that it may be considered as a precursor for operational missions dedicated to global monitoring.

4.3.4 Gap filling

In view of the expected lack of global atmospheric sensors in the next decade, ALTIUS shall de facto be considered as a gap filler between important missions like Sentinel 4/5 or NPOESS and present or past successful missions.

Even if some new sensors are presently developed with the same objectives, the ALTIUS mission shall always remain as a potential validation experiment of atmospheric data measured by other instruments and/or ground based networks. This is a consequence of its versatile concept of remote sounding from a micro-satellite that allows easily adapting the mission scenario for validation campaigns with a short notification time.

	Theme A: Ozone Layer	Theme C : Climate
Protocols	Montreal and subs protocols Stratospheric ozone, halogen distribution and trend monitoring	Kyoto Protocol; climate policy EU GHG/aerosols distribution and trend monitoring
Services	Stratospheric composition NWP assimilation and re-analysis	NWP assimilation and re-analysis Climate monitoring Climate model validation
Assessments	Long-term global data records WMO ozone assessment Stratospheric chemistry and transport processes UV radiative transport processes Halogen source attribution	Long term global data record IPCC assessments Earth System, climate, radiative forcing processes UTLS transport-chemistry processes

Table 4: Issues related to the GMES requirements.

4.3.5 Cost/efficiency ratio

There exists a very ambitious project like GEOSS that is envisioned as a large national and international cooperative effort for the federation of global Earth observation systems consisting of measurements of air, water, and land made on the ground, from the air, or from space. Historically observed in isolation, the current effort is to look at these elements together and to study their interactions.

Clearly, from the point-of-view of atmospheric chemistry and climate change, an efficient "system of systems" will require different sensors and complementary observation modes. Recently, important projects for an Earth Observing system from a large constellation of satellite have been proposed to the user community (see f.i. <http://www.tridentsensors.com/royalsociety.html>).

The ALTIUS instrument aboard a micro-satellite shall demonstrate its capacity to become a standard solution to participate as a node to such a dynamical network of Earth observing systems.

In particular, the ALTIUS mission shall demonstrate:

- the moderate development and exploitation costs of a global coverage sensor for an atmospheric remote sounding mission.
- the standardization of a dedicated class of micro-satellites whom design can be easily refurbished to ensure successive missions or even to support constellation of sensors
- the power of direct limb observation that combines global coverage capacity with high vertical resolution

5 Conclusions

ALTIUS is a limb sounder spectrometer, capable of a 1-km vertical resolution. It consists of three spectral camera's (optics+AOTF+2-D imager) in the UV-Vis-NIR range. The instrument, on board a heliosynchronous micro-satellite, can be operated in different viewing modes (limb, solar occ, stellar occ) and/or scenarios by the scientific user. It is optimized for on board signal processing (including image compression). The main geophysical targets are stratospheric/mesospheric ozone profiles and some minor trace gases (NO₂,H₂O, BrO, aerosols,..). The retrieval of these quantities requires a considerable inversion algorithm and associated computing power.

The fundamental motivations of the project can be summarized as follows:

- Monitoring of global changes is impossible without stratospheric measurements.
- Dramatic decrease of available (and, in particular, European) instruments capable of a vertical remote sounding of the atmosphere.
- New and promising technologies are emerging.
- Many potential communities to use data and to promote the ALTIUS concepts from a scientific level to an operational capacity.

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