The ALTIUS Mission: A Belgian Spectral Imager for the Remote Sensing of the Earth Atmosphere

E. Dekemper, F. Vanhellemont, N. Mateshvili, D. Pieroux, G. Franssens, and D. Fussen
Belgian Institute for Space Aeronomy (BIRA-IASB)
Brussels, Belgium

Corresponding Authors: Emmanuel.Dekemper@oma.be and Didier.Fussen@oma.be

ABSTRACT

This manuscript presents a general description of the ALTIUS instrument starting from the scientific context that led to the definition of the mission goals and stressing the advantages of this original instrument: a spectral imager performing measurements in limb scattering and solar/stellar occultation geometries. Then we detail the three acquisition sequences of a typical orbit (dayside, terminator and eclipse). Finally, an overview of the current instrumental design is presented, and an example of results obtained with an optical breadboard is illustrated.

1. SCIENTIFIC BACKGROUND

It is now accepted that the global and polar depletion of the ozone layer can be attributed to the presence of halogen compounds released by anthropogenic emissions (UNEP Conference on the Protection of the Ozone Layer, Vienna, 1985). The actions taken after the Montreal Protocol (1987) have led to 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 recorded minimum at the end of the XXth century. 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 (Scientific Assessment of Ozone Depletion: 2002, WMO/UNEP report n°47). On the other hand, column ozone loss in the 2010/2011 Arctic winter was among the largest ever observed (Manney et al.,

ISBN 978-0-937194-54-9

2011) whereas Antarctic ozone depletion has leveled off during the last decade (Figure 1). Clearly, the monitoring of ozone stratospheric abundances is of crucial importance in assessing the milestones of a clear recovery process.

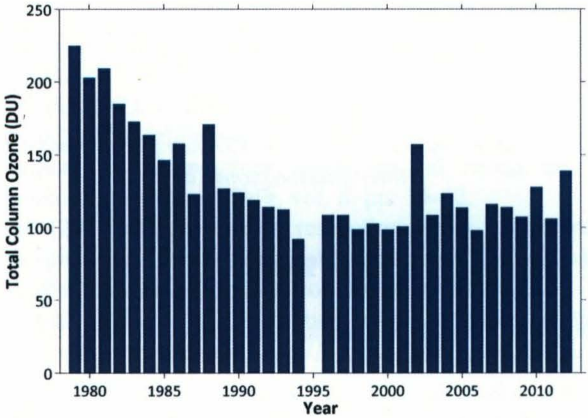

Figure 1. *Minimum mean column of ozone measured between the 21st of September and the 16th of October above Antarctica by the TOMS and OMI instruments. Data: NASA Ozone Watch.*

Among other atmospheric trace gases, methane is very important for its impact on climate through a large radiative forcing effect and the production of stratospheric water vapor (Rohs et al., 2006). A number of studies have shown a global increase from about 0.7 ppm in 1800 AD to 1.8 ppm nowadays (Forster at al., 2007) (Figure 2). However, the global atmospheric methane content has reached a steady state recently (Rinsland et al., 2009). This behavior is difficult to interpret because of the diversity of the sources: wetlands, enteric fermentation, fires, rice agriculture, fossil fuels (Simpson et al., 2012)... Keeping track of the methane atmospheric concentration is necessary to understand the radiative budget of the planet and to track the exploitation of fossil resources or the changes in ground temperature of northern lands (permafrost) for instance.

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 water vapor in the stratosphere. Therefore, it is essential to understand and to monitor the intrusion of water vapor into the stratosphere, especially in the region of the tropical tropopause.

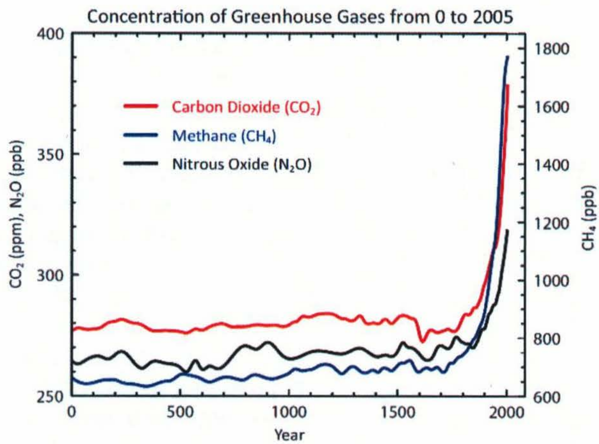

Figure 2. *Evolution of three of the most important greenhouse gases until 2005 (Source: IPCC 4th assessment report). Measurements before 1950 are based on trapped air bubbles in ice, after 1950 they are based on air samples.*

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 night-time measurements for a full characterization. On the other hand, these molecules may be converted into inactive forms or reservoirs via the presence of chlorine or bromine species. The measurement of molecules like BrO during the daytime or OClO (originating from ClO and BrO) is very important if they can be correlated with simultaneous NO_2 observations.

The role of polar stratospheric clouds (PSCs) in polar ozone depletion has been described extensively in the scientific literature (WMO/UNEP report n°47). 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 active chlorine-containing species, which act as catalytic ozone scavengers. On the other hand, 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, just after sunset. PMCs were reported for the first time in 1885. They are similar in appearance to thin cirrus clouds, but are located at 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 K). Various pieces of evidence, including direct rocket sampling, suggest that they are composed of very small water-ice particles (0.05–0.1 μm). But the nucleation process or their connection with lower atmospheric layers (acting as a tracer for global atmospheric change) are examples of unsolved questions.

During the past decades, a number of spaceborne instruments have measured these species and many others, providing global data over long time scales and over broad altitude ranges. In an effort to manage the independent initiatives, institutions like the World Meteorological Organization (WMO) regularly assess the state-of-the-art in different measurement techniques, and issue guidelines for future missions in order to increase the overall quality of the datasets. The final goal being to feed numerical atmospheric models with improved data, in order to describe, explain and forecast the observed chemical and physical processes.

According to the last IGACO report (Integrated Global Atmospheric Chemistry Observation, WMO GAW Report No. 159, 2004), it is necessary to obtain a comprehensive set of global observations of the species quoted in Table 1 for the stratosphere by using low Earth orbit (LEO) satellites. The requirements in terms of spatial and temporal sampling, coupled to uncertainty thresholds are also given. A combination of nadir-looking instruments and limb sounders are needed to meet these requirements. It is worth keeping in mind that nadir-looking instruments are characterized by a high horizontal sampling along the orbital track but a poor vertical sampling. On the contrary, limb pointing instruments offer a much better vertical resolution at the price of a limitation in geographical sampling, mostly determined by the orbital parameters and the measurement rate.

Table 1. IGACO Threshold Values for Observational Requirements. A Distinction is made Between the Lower Stratosphere (LS) and the Upper Stratosphere (US) Together with the Mesosphere (MS). Dx, Dz, and Dt refer to Horizontal, Vertical and Temporal Sampling Respectively. Time Scales are given in Hours (h), Weeks (w) or Months (m). Total Error on Concentration Contains Precision and Accuracy Components and Delay refers to the Time Elapsed Between Observation and Data Availability.

Atmospheric Region	Requirement	Unit	O_3	NO_2	CH_4	H_2O	CO_2	BrO	Aerosols
LS	Dx	km	100	250	250	200	500	100	100
	Dz	km	3	4	4	3	4	1	1
	Dt		1d	12h	12h	1d	1d	6h	1w
	Total error	%	20	40	30	20	2	15	-
	delay		w	h	w	w	m	w	w
US, MS	Dx	km	200	250	250	200	500	100	-
	Dz	km	3	4	4	5	4	1	-
	Dt		1d	1d	1d	1d	1d	1d	-
	Total error	%	20	40	30	20	2	20	-
	delay		w	w	w	w	m	w	-

2. TOWARDS THE ALTIUS INSTRUMENT

2.1. The Advent of the Limb Scattering Remote Sounding Method

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

Since the pioneering work of the SOLSE/LORE experiment (McPeters et al., 2000), it has been established that the limb scattering technique is a viable method for the measurement of atmospheric trace gas profiles in the stratosphere. Confirmation of this approach has been recently published for OSIRIS on board ODIN (Haley et al., 2004), for SCIAMACHY on board ENVISAT (Brinksma et al., 2006), and for the SAGE III mission before its premature end (Rault, 2005). Also, the limb scattered light recorded by the upper and lower bands of the GOMOS detector (on board ENVISAT) has been investigated in order to develop an efficient inversion algorithm (Tukiainen et al., 2011).

However, it is now recognized that the limb scattering technique suffers from a major issue related to 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 (von Savigny et al., 2005).

This is the framework of the ALTIUS mission as proposed by the Belgian Institute for Space Aeronomy (BIRA-IASB): a Belgian spaceborne instrument for the remote sensing of ozone and other important trace gases. ALTIUS will also make use of the limb scattering technique but, moreover, its imaging capability will solve the issues of altitude registration, cloud identification and horizontal gradients of measured species.

2.2. ALTIUS Keys

2.2.1. Measurement Altitude Uncertainty

All limb observation techniques have their inherent advantages. Occultations provide numerous light sources (Sun, stars, planets) and a direct knowledge of the measurement altitude. However, their intensity is sometimes weak (except for the Sun of course) and the global coverage of the Earth can be sparse (occultations can be observed at specific positions along the orbit depending on the source visibility). The limb scattering, in turn, offers the possibility to perform measurements everywhere around the globe provided that the Sun is illuminating the atmosphere. Though, in this case, the diffuse nature of the observed scene (see Figure 3) causes problems in altitude determination for most of the instruments using this technique. These instruments are usually based on the use of a diffraction grating to split white light into small spectral components that are registered by a detector. As a consequence the sensor has only one spatial dimension, the other dimension containing the spectral information. As a result, these instruments have to scan the limb layer by layer, which takes time and causes altitude uncertainties (1–3 km typically).

ALTIUS will overcome this problem by being a real imager, i.e., it will take instantaneous 2D snapshots of the atmosphere at specific optical wavelengths. By doing so, the altitude determination issue will be considerably reduced at the price of a careful selection of the required spectral information.

Figure 3. *Sun-illuminated Earth atmosphere. The bluish halo is produced by the scattering of solar light by the atmospheric limb. Picture taken by an astronaut onboard ISS (24/02/2005, 13:35). Credit: Image Science and Analysis Laboratory, NASA-Johnson Space Center.*

2.2.2. Spectral Imaging

If it was just to take pictures at given wavelengths, a simple filter wheel could be used. But then the number of wavelengths would be fixed, with a not-so-good spectral resolution, and the inherent risk of failure of any mechanical device in space. ALTIUS will use a totally different technology based on acousto-optical tunable filters (AOTF) (Gupta and Voloshinov, 2004 and Voloshinov et al., 2007). These are small birefringent crystals (a few cubic centimeters typically) serving as the interaction medium between the incoming light and a sound wave propagating in the crystal. By carefully selecting the sound frequency, this acousto-optic interaction turns the crystal into a spectral filter that allows only a small part of the light spectrum to reach the detector. Used inside an imaging system, it offers a number of advantages: the device is small, lightweight, contains no moving parts, consumes only 1–3 watts, changes the wavelength in a few milliseconds, works over a broad spectral range (hundreds of nanometers) and has a bandwidth between 0.5 and 5 nm. Such a filter has already been used in a space environment: onboard Venus Express, a successful ESA mission orbiting around Venus since 2006 (Nevejans et al., 2006).

2.2.3. ALTIUS Scientific Requirements

The ALTIUS geophysical targets are summarized in Table 2.

Table 2. ALTIUS mission requirements. The geophysical species have been sorted by priority (three shades of blue). The altitude range is specified in terms of regions: UT = upper troposphere, LS = lower stratosphere, US = upper stratosphere, MS = mesosphere. For each target, the useful spectral range, the total relative uncertainty (ε), the geometry of observation and the spatial sampling of the retrieved products is given (Δx = horizontal sampling along the line of sight, Δy = horizontal sampling perpendicular to the line of sight, Δz = vertical sampling).

Species	Atmos-pheric region	ε [%]	Spectral range [nm]	Limb	Stellar occult.	Solar occult.	Spatial res. (Δx,Δy,Δz) [km]
O_3	UT/ LS	5	550-650,1020	x	x	x	500,10,1
O_3	US	5	300-350/550-650	x	x	x	500,10,1
O_3	MS	20	250-300, 1260-1280	x	x	x	500,NA,1
NO_2	LS/ US	30	450-550	x	x	x	500,50,2
CH_4	UT/ LS	20	1600-1800	x	x	x	500,50,2
H_2O	UT/ LS	20	900-1800	x	x	x	500,50,2
CO_2	UT/ LS	2	1550-1600			x	500,50,2
BrO	UT/ LS	20	320-360	x		x	500,50,1
OClO	UT/ LS/ US	25	320-400	x	x	x	500,NA,1
NO_3	LS/ US	25	662		x		500,NA,1
aerosol/ PSC	UT/ LS	25	250-1800	x	x	x	500,20,1
O_2	MS	30	1260-1270/1530		x	x	500,NA,5
PMC	MS	50	250-1800	x	x	x	500,20,1
T°	UT/ LS/ US	1-5	NA	x		x	500,50,2

3. ALTIUS MISSION

The acronym ALTIUS means Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere. The ALTIUS mission will be dedicated to the measurement of the vertical distribution of key atmospheric trace gases. The primary target is ozone, but secondary objectives are NO_2, methane, water vapor, aerosols, BrO, etc... (Table 2). The sounding altitude range will be mainly from cloud tops to 100 km, i.e., from the troposphere to the mesosphere. It will be inserted in a sun-synchronous polar orbit 650 km above the ground, ensuring a constant Sun-Earth-spacecraft angle corresponding to a 10:30 AM local time. One orbit will last for 100 minutes and the global coverage of the Earth will be reached in three days. The mission lifetime will be at least three years, targeting five.

ALTIUS will be embarked on a PROBA platform (Project for On Board Autonomy), a micro-satellite class developed for ESA by QinetiQ Space in Antwerp (Belgium), and has demonstrated its capabilities with already two successful missions (PROBA-1 in 2001 and PROBA-2 in 2009). This micro-satellite (about 1 m^3 and 150 kg) shows excellent performance in terms of pointing stability (10 arcsec over 10 s thanks to its miniaturized reaction wheels), attitude knowledge (1 arcsec using two star trackers), agility (rotation of 1°/s/axis) and computing power. Figure 4 shows an artistic illustration of the PROBA platform hosting ALTIUS.

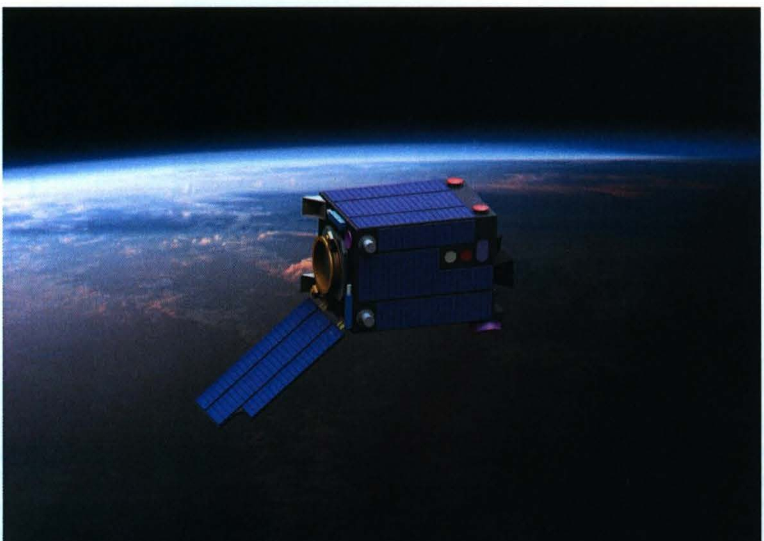

Figure 4. *PROBA-ALTIUS in orbit. The spacecraft is leaving the bright limb at the Sun terminator.*

3.1. Typical ALTIUS Orbit

A typical ALTIUS orbit can be divided into three parts.

3.1.1. Dayside

In the dayside, ALTIUS is taking spectral pictures of the bright atmospheric limb at a sufficient number of wavelengths to be able to retrieve the concentration profile of the target species afterwards. As an example, simulations and past experiments show that ozone can be retrieved over the whole stratosphere by using 5 wavelengths in its absorption spectrum: 2 in the UV and 3 in the visible range (see Figure 5, von Savigny et al., 2003). The exposure time of each snapshot will depend on a tradeoff between acceptable signal-to-noise ratio and the colocation of the snapshots (the orbital speed will be 7 km/s).

Such measurement technique has been used by pioneering instruments, first by SOLSE onboard the Space Shuttle Columbia in 1997 and then by other satellite borne instruments like SCIAMACHY (ENVISAT), OSIRIS (ODIN), and OMPS (NPP).

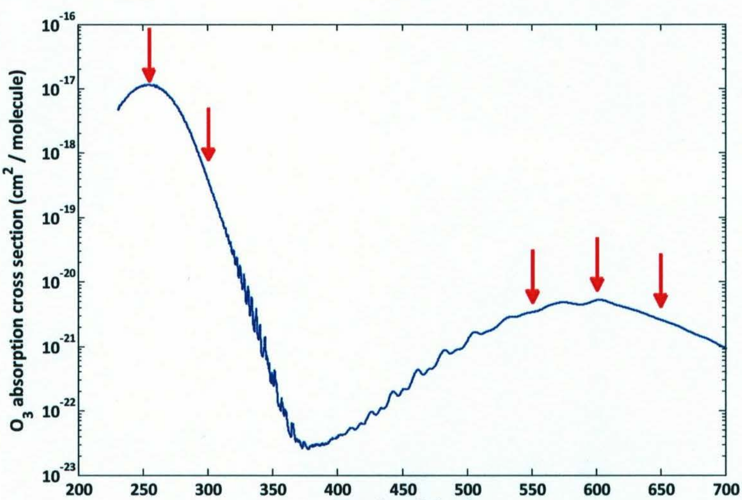

Figure 5. *Ozone absorption cross section at 293 K. A standard measurement may consist of five snapshots at the wavelengths indicated by the red arrows in order to retrieve the ozone concentration profile.*

3.1.2. Terminator

After having spent almost 60 minutes in the day side, the PROBA platform will rotate in order to look straight towards the setting Sun. Here, signal-to-noise ratio is very high and precautions must even be taken to prevent damaging optical parts or detectors. As ALTIUS keeps moving along its orbit, a solar occultation will be measured. The imaging capabilities of ALTIUS offer here extra possibilities: by analyzing the flattening of the solar disk caused by atmospheric refraction, measurements of pressure or temperature profiles are possible. Figure 6 shows a simulation of what the solar disk would look like as observed by ALTIUS at the end of the sunset.

The solar occultation technique was already used in the 1960's for ozone and aerosols measurements. Since then, many other instruments have applied this method to the remote sensing of a wide range of other atmospheric species (ACE, POAM, SAGE,…). Some of them obtained very long time series of data (like SAGE II, 1984–2005), which is invaluable for trend analysis and validation of other instruments.

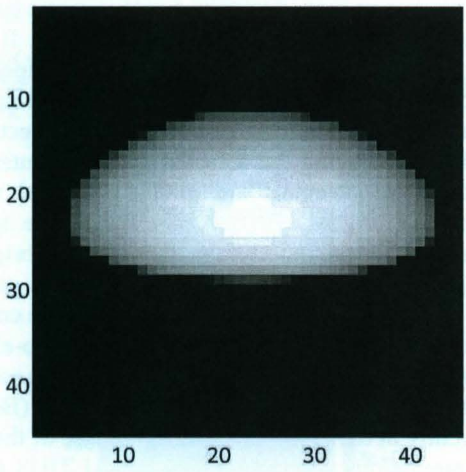

Figure 6. *Simulation of a picture of the solar disk at the end of a sunset observed by ALTIUS. The flattening is due to the bending of the solar rays by the atmosphere. Observed from space, this effect is twice as large as what can be observed from ground, due to the doubled optical path.*

3.1.3. Eclipse

The complete sunset lasts only for two minutes. Once in the eclipse, ALTIUS will start observing the occultation of other stars. In the entire known star catalogue, only the 200 brightest radiate enough energy for ALTIUS (the

ALTIUS aperture diameter is 6 cm). Moreover, depending on their ephemeris, only a few of them per orbit are available to be occulted by the atmosphere.

Distant stars act like point sources so they offer a perfect knowledge of the sounding altitude. Again, the imaging capabilities of ALTIUS are a strong advantage: the pointing accuracy can be relaxed as one only needs to keep the star in the field of view. The agility of the PROBA platform is also an asset: going from one star to the other at the speed of 1°/s makes the full sky available at each orbit.

For the stellar occultation method, ALTIUS can only benefit from the heritage of a single experiment: GOMOS onboard ENVISAT (2002–2012). But it definitely validated the method and contributed for ten years to the monitoring of concentration profiles of key species.

4. ALTIUS INSTRUMENTAL CONCEPT

The instrumental concept of ALTIUS has been driven by the mission requirements and the platform accommodation constraints. It consists of three independent channels, each of them operating in a specific spectral interval: 250 to 450 nm (UV), 450 to 900 nm (visible) and 900 to 1800 nm (near-infrared). Each channel contains a set of mirrors responsible for directing the incoming light into the AOTF then relaying the selected spectral content to the detector (see Figure 7). The three channels are almost identical with only minor differences. For instance, in the UV, the star magnitude is so faint that a telescope with a dedicated aperture is foreseen next to the bright limb aperture, whereas in the two other channels, the three observation geometries use the same entrance hole. In the near-infrared, the detector will be cooled by a Stirling cooler in order to reduce thermal noise, while simple thermo-electric coolers are used in the remaining channels. The optical design and most of the technical studies were performed by the company OIP in Oudenaarde (Belgium).

ALTIUS is currently in the preliminary design phase of the instrument. This involves a lot of computations and simulations. As ALTIUS is very innovative in some technical aspects (mainly the use of an AOTF in an imaging system), the need for acquiring practical expertise quickly arose. In 2010, a breadboard of the visible channel was designed by OIP and built by BIRA-IASB, following the key parameters of the future instrument. In 2011 and 2012, laboratory tests, then field campaigns were carried out in order to test its capabilities. For instance, one of the experiments was to detect the presence of NO_2 in the dense plume released by a waste incinerator at a distance of 3.5 km (Figure 8) (Dekemper et al., 2012).

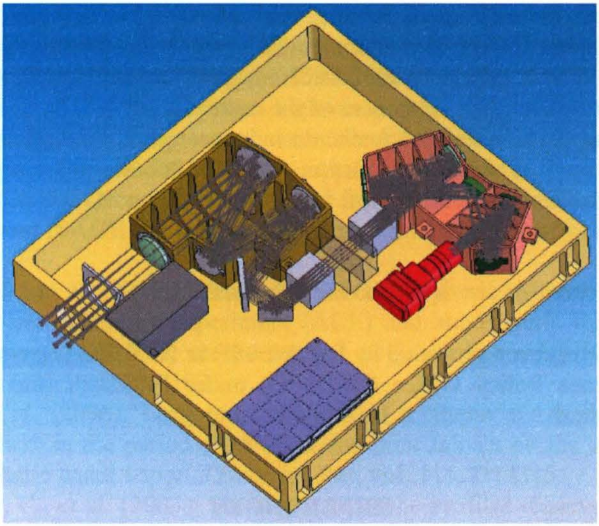

Figure 7. *Conceptual design of the visible channel of ALTIUS. The aperture on the left is the entrance hole for the light, the cubes in the center represent the AOTF and the associated polarizers. The red element is the detector.*

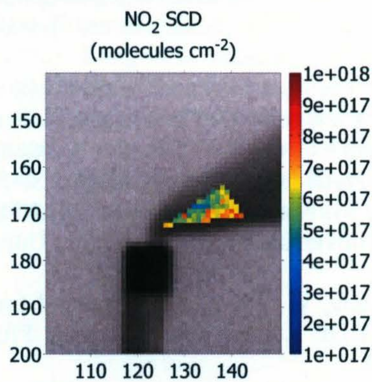

Figure 8. *ALTIUS visible channel breadboard application: DOAS remote sensing of NO_2 in the dense and turbulent plume released by a waste incinerator. X- and Y-axes indicate the pixel number, the color bar is a measure of the level of NO_2 in the plume.*

With the excellent results obtained by the visible channel breadboard so far, new campaigns are foreseen. One of them could be a flight as one of the payloads of a stratospheric balloon. The altitude reached (40 km) would place the instrument above the ozone layer, getting closer to a limb measurement from space. At the same time, the development of a breadboard of the UV channel has also started. It will eliminate the concerns about the AOTF for this specific channel. In parallel, the development of the current phase and the following ones will continue. No specific launch date is set yet, although the lack of atmospheric vertical sounders constitutes one of the strongest arguments for keeping the timeline short.

ACKNOWLEDGMENTS

ALTIUS has been proposed by BIRA-IASB in 2006 and is supported by the Belgian Science Policy Office (BELSPO) under PRODEX and GSTP ESA funding programs.

REFERENCES

Brinksma, E.J., et al. (2006): Geophysical validation of SCIAMACHY Limb Ozone Profiles. *Atmos Chem Phys*, vol. 6 (1), pp. 197-209.

Dekemper, E., et al. (2012): Tunable acousto-optic spectral imager for atmospheric composition measurements in the visible spectral domain. *Appl Opt*, vol. 51 (25), pp. 6259-6267.

Forster, P., et al. (2007): Changes in Atmospheric Constituents and in Radiative Forcing, in Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller, (Eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Gupta, N., and Voloshinov, V. (2004): Hyperspectral Imager, from Ultraviolet to Visible, with a KDP Acousto-Optic Tunable Filter. *Appl Opt*, vol. 43 (13), pp. 2752-2759.

Haley, C.S., et al. (2004): Retrieval of stratospheric O_3 and NO_2 profiles from Odin Optical Spectrograph and Infrared Imager System (OSIRIS) limb-scattered sunlight measurements. *J Geophys Res*, vol. 109 (D16), pp. 303-322.

Manney, G.L., et al. (2011): Unprecedented Arctic ozone loss in 2011 echoed the Antarctic ozone hole. *Nature*, vol. 478, pp. 469-475.

McPeters, R.D., et al. (2000): The retrieval of O_3 profiles from limb scatter measurements: Results from the Shuttle Ozone Limb Sounding Experiment. *Geophys Res Let*, vol. 27 (17), pp. 2597-2600.

Nevejans, D., et al. (2006): Compact high-resolution spaceborne echelle grating spectrometer with acousto-optical tunable filter based order sorting for the infrared domain from 2.2 to 4.3 μm. *Appl Opt*, vol. 45 (21), pp. 5191-5206.

Rault, D.F. (2005): Ozone profile retrieval from Stratospheric Aerosol and Gas Experiment (SAGE III) limb scatter measurements. *J Geophys Res*, vol. 110 D09309.

Rinsland, C.P., et al. (2009): Trend of lower stratospheric methane (CH_4) from atmospheric chemistry experiment (ACE) and atmospheric trace molecule spectroscopy (ATMOS) measurements. *J Quant Spectrosc Rad Transfer*, vol. 110 (13), pp. 1066-1071.

Rohs, S., et al. (2006): Long-term changes of methane and hydrogen in the stratosphere in the period 1978-2003 and their impact on the abundance of stratospheric water vapor. *J Geophys Res*, vol. 111, D14315.

von Savigny, C., et al. (2003): Stratospheric ozone profiles retrieved from limb scattered sunlight radiance spectra measured by the OSIRIS instrument on the Odin satellite. *Geophys Res Lett*, vol. 30 (14), 1755.

von Savigny, C., et al. (2005): Spatial and temporal characterization of SCIAMACHY limb pointing errors during the first three years of the mission. *Atmos Chem Phys*, vol. 5 (10), pp. 2593-2602.

Simpson, I.J., et al. (2012): Long-term decline of global atmospheric ethane concentrations and implications for methane. *Nature*, vol. 488, pp. 490-494.

Tukiainen, S., et al. (2011): Retrieval of ozone profiles from GOMOS limb scattered measurements. *Atmos Meas Tech*, vol. 4 (4), pp. 659-667.

Voloshinov, V.B., et al. (2007): Improvement in performance of a TeO_2 acousto-optic imaging spectrometer. *J Opt A*, vol. 9 (4), pp. 341-347.