Technological innovation for the ALTIUS atmospheric limb sounding mission

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ABSTRACT

The ALTIUS Mission (Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere) aims at the development of a limb sounder based on a small satellite concept (i.e. PROBA-Next small platform).

ALTIUS will monitor the distribution and evolution of stratospheric ozone at high vertical resolution in support of operational services and long term trend monitoring. It will provide detailed stratospheric profile information at high vertical resolution, which is a valuable addition to ozone total column for data assimilation systems based on nadir sounders used by operational centers. In addition, some secondary scientific mission objectives are targeted, including measurements of vertical concentration profiles of other atmospheric species.

The ALTIUS Mission was first proposed by the Belgian Institute for Space Aeronomy and, after several studies in different programmes within ESA, is now being developed as an element of ESA's Earth Watch Programme currently with the participation of Belgium, Canada, Luxembourg and Romania.

The ALTIUS Mission concept consists of three spectral imagers flying at an altitude of approximately 700 km Sun-Synchronous Orbit on-board the next generation of PROBA platform. The ALTIUS Instrument shall allow observation of the Earth's atmospheric bright limb in an extended spectral region from the Ultraviolet to the Short Wave Infrared (SWIR). In addition, the ALTIUS instrument shall perform solar and stellar occultation observations in the dark limb.

The ALTIUS Instrument three hyperspectral channels are based respectively on Acousto-Optic Tuneable Filters (AOTFs) in the Visible (440-800nm) and SWIR (900-1800nm) range, and a cascade of Fabry Perot Interferometers (FPI) in the UV (250-370nm). The use of tuneable active spectral filter shall allow the ALTIUS Instrument to perform observations with a spectral resolution ranging between 1nm and 10nm in an extremely versatile operational concept.

The use of the AOTFs and Fabry Perot technologies constitutes a novelty in the limb sounding missions and its development critical aspects as well as its performances have been proven in the frame of an extensive Instrument pre-development phase.

In this phase the critical technologies necessary to ensure the performance and functionalities of the ALTIUS Instrument have been designed, developed and qualified. In particular the following pre-developments were undertaken to pave the way towards Instrument Preliminary Design Review:

- Design, manufacturing and qualification of the VIS AOTF Assembly and RF control electronics;
- Design, manufacturing and qualification of the UV FPI assembly stack and control electronics;
- Development and qualification of UV filters and coatings.
- Design and manufacturing of sensor electronics based on selected CMOS sensor for UV and VIS channels;
- Design, manufacturing and partial qualification of the Instrument mechanism;
- Bread-boarding of the full VIS channel for functionality and end-to-end performances verification.

This paper presents the status and main results of the above-mentioned ALTIUS Instrument pre-development activities. In particular: major outcomes during the development process, achieved performances and lessons learned for the continuation of the ALTIUS Instrument flight model design are being highlighted.

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1. INTRODUCTION

The ALTIUS Mission (Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere) aims at the development of a limb sounder based on a small satellite concept (i.e. PROBA-Next small platform).

ALTIUS will monitor the distribution and evolution of stratospheric ozone at high vertical resolution in support of operational services and long term trend monitoring. It will provide detailed stratospheric profile information at high vertical resolution, which is a valuable addition to ozone total column for data assimilation systems based on nadir sounders used by operational centers. In addition, some secondary scientific mission objectives are targeted, including measurements of vertical concentration profiles of other atmospheric species.

The ALTIUS Mission was first proposed by the Belgian Institute for Space Aeronomy and, after several studies in different programmes within ESA, is now being developed as an element of ESA's Earth Watch Programme currently with the participation of Belgium, Canada, Luxembourg and Romania.

ALTIUS is planned to become operational in the 2023 time frame and to be compatible with a mission lifetime of minimum 3 years.

The ALTIUS Instrument consists of three independent spectral imagers capable of observing the atmospheric limb in the UV (250-370 nm), VIS (440-800 nm) and possibly SWIR (900-1800) nm. A distinct spectral tuneable filter element will perform observations in each of these three wavelength ranges, being an acousto-optic tuneable filter (AOTF) in the VIS and SWIR and a setup of cascading Fabry-Perot interferometers in the UV. The Instrument is mounted on an agile satellite bus based on an evolution of the PROBA platform. The ALTIUS space segment design implements a small, autonomous multi-mode mission, allowing for atmospheric observations in multiple limb sounding geometries (several bright limb geometries as well as solar and stellar occultation). The ALTIUS space segment is designed for launch into a Sun-synchronous orbit (< 800 km altitude).

The ALTIUS Ground Segment consists of the Flight Operations Centre (FOS), Payload Data Ground Segment (PDGS) and acquisition stations. The FOS is in charge of the satellite TT&C and will be located in the European Space Security and Education Centre (ESEC) in in Redu (Belgium), making maximum re-use of existing infrastructure for the operations of the PROBA satellites. The PDGS provides all necessary functionality for mission planning generation, systematic and timely production, archiving and dissemination of Level 2 products for the primary objective and flexible ground segment processing and product delivery infrastructure in support of secondary objectives. The PDGS is expected to be installed in Belgian facilities in Uccle (Belgium). The paper at hand provides a brief description of the ALTIUS Mission in its main characteristic elements (section 2), a compact description of the ALTIUS spacecraft concept and a more detailed description of the Instrument and its functionalities. Section 3 is, then, devoted to a detailed description of the critical technologies for which an extensive pre-development has been executed and it's currently being completed as a collaboration between the European Space Agency and some of the Belgian and European companies active in the space sector, OIP N.V., QinetiQ Space N.V., BIRA, VTT, G&H. In this section all main obtained results are described and all major lessons learned are shared. Section 4 summarizes the main conclusions and short term planning for completion of all planned activities.

2. MISSION DESCRIPTION

2.1 Mission concept

The ALTIUS mission shall perform observation of 2-D spectral images of the Earth atmosphere's bright limb covering field of 100km x 100km projected at the earth Tangent point. The Instrument aims at gathering data with a vertical resolution equal to or better than 1 km to accurately sample atmospheric layers. In the other direction, the spatial resolution shall mainly be limited by the number of pixels needed to obtain the necessary signal to noise ratio (SNR) for adequate species detection by inversion algorithm. In addition to bright limb observations, other modes will be available such as solar occultation at the terminator, and stellar occultation in the dark limb:

- during bright part of an orbit a sequence of observations containing 4 to 6 spectral images (TBC) for each spectral band will be acquired to achieve a spatial sampling along track of 250km (or better);
- at the terminator the Instrument will be pointed at the sun for solar occultation where a single observations containing 250 spectral images per spectral bands will be acquired during sunset;
- during eclipse the Instrument will perform stellar occultation of (in average) ten stars, resulting for each star in an observation containing 100 spectral images per spectral band.

The ALTIUS Instrument is designed to be able to operate continuously over one orbit in various modes. It will perform acquisitions in a broad wavelength range dealing with large differences in light intensity across the various observed scenes. The ALTIUS mission will follow a sun-synchronous orbit with an altitude baseline of 690 km and a local time of 10:00. Additionally, it will take advantage of the platform agility to operate under different spacecraft (S/C) attitudes allowing for execution of different observation modes with a global coverage to be achieved in three days or less, with a resolution of 5 degrees in latitude and 10 degrees in longitude, which is a threshold requirement for the accuracy of present chemical assimilation models.

2.2 Platform description

The ALTIUS Instrument is foreseen to be mounted on a PROBA P-200 platform, currently under development at QinetiQ Space in the frame of the PROBA-Next activity (part of the ESA GSTP Programme). The P-200 is a 3-axis stabilized multi-purpose platform using three star trackers, four reaction wheels, a GPS receiver and two antennas, three magneto-torques and two magnetometers. This ensures a platform with a high degree of maneuverability for the different observations, modes and operational scenarios.

For the ALTIUS application, to meet the required power needs, four deployable solar panels will be accommodated in the platform. In nominal operational mode, the ALTIUS Instrument will be backward looking, i.e. limb looking in the anti-velocity direction. The Instrument will be protected from the Sun over an orbit using a dedicated sun shield panel.

The mass (below 300kg) and volume of the spacecraft allows the launch of the satellite as secondary passenger on VEGA or VEGA-C, the baseline assumed launchers for the ALTIUS Mission. The PROBA platform has currently successfully completed its structural-thermal Model (STM) test campaign with a dummy ALTIUS Instrument as test payload.

2.3 Instrument description

The ALTIUS Instrument is integrated on top of the PROBA platform. The payload is composed of an optical bench which contains all optical elements and a Channel Control Unit (CCU), placed next to the bench, which contains most of the Instrument electronics and control system. This payload general layout onto the platform is shown in Figure 1.

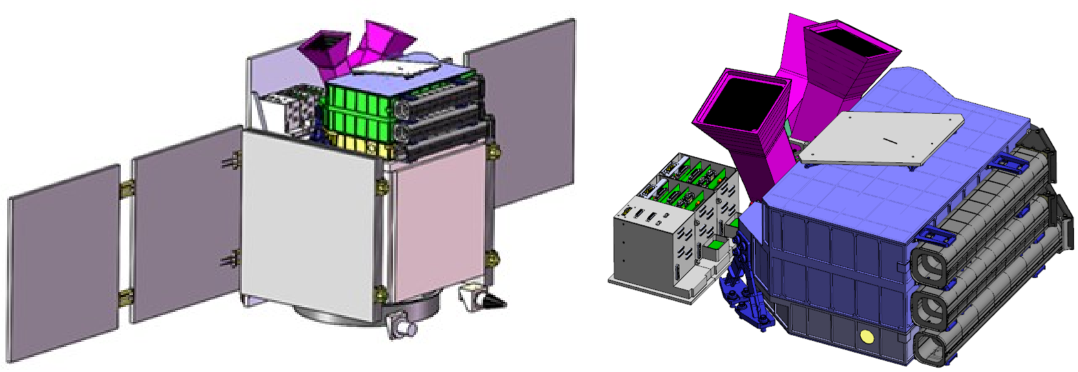

Figure 1. (left) Illustration of the ALTIUS Instrument on top of the PROBA-Platform ; (right) ALTIUS Instrument

The ALTIUS Instrument integrates three independent hyperspectral channels observing the limb respectively in the UV (250-370nm), the Visible (440-800nm) and the SWIR (900-1800nm) spectral range. In order to fit to tight volume constrains, the optical bench is developed based on a modular and compact concept. Each sub-bench containing an optical channel, are stacked on top of each other and co-aligned while can be seen as individual units with their own independent control electronics.

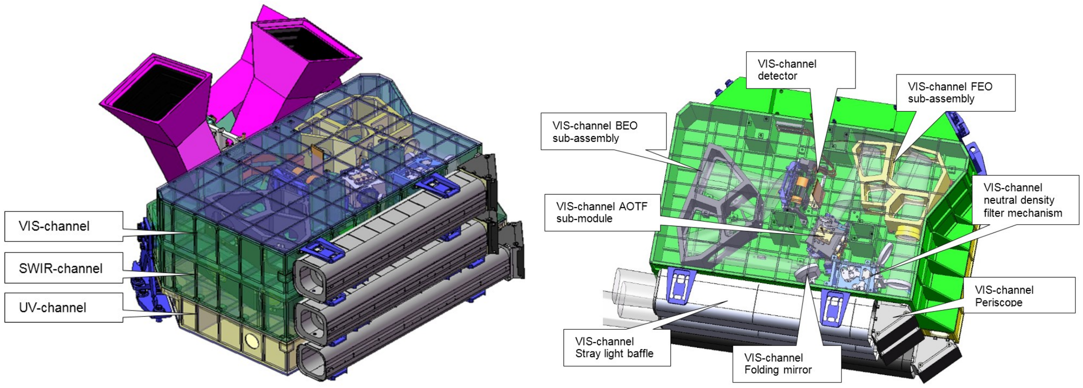

Figure 2. (left) ALTIUS optical bench; (right) internal VIS channel layout

Each channel is based on a reflective optical design and contains the following main optical elements:

- A front baffle to protect the Instrument from out of field straylight;
- A front periscope mirror which is allowing fine co-alignment of the different Instrument Lines Of Sight (LOS's);
- A Front End Optics (FEO) Module that collects the light and passes it to the spectral filter;
- A spectral filter which enables to select the required wavelength band (AOTF in the VIS and SWIR, Fabry Perot in the UV);
- A Back End Optics (BEO) Module that forms an image of the selected spectral band in the observed scene onto the detector;
- The Focal Plane Assembly which consists of the detector and its proximity electronics (i.e. ADC and serializers).

The optical design is conceived such that each channel complies with the requirements summarized in Table 1 together with very challenging SNR requirements. In addition, to cope with the large dynamic range between limb, stellar and solar occultation, it was necessary to foresee in each channel the possibility to match the radiometry of the sun scene to the high sensitivity of the Instrument required for the limb preventing saturation effects. This is done in each channel, by means of a mechanism which is integrating a neutral density filter positioned every orbit prior to solar occultations and removed at the end of the sun observation.

Table 1. Key requirements applicable to the ALTIUS Instrument

Parameter	Value
Observation modes	Occultation modes (Stellar and solar) Bright limb mode
Observation type	Direct 2D hyperspectral imaging
Spectral range channels UV VIS SWIR	 250 - 370 nm 440 - 800 nm 900 - 1800 nm
Spectral resolution UV VIS SWIR	 Better than 2.5 nm Better than 10 nm Better than 10 nm
FOV1 for each channel (low light levels)	3.4mrad at least
FOV2 for each channel (high light levels)	34mrad (1.95°)
Volume of the optical bench (approximately)	< 410 x 580 x 320 mm³

ALTIUS UV Channel Concept

The layout of the UV channel optical design is shown schematically in Figure 3. The UV channel has two apertures, used respectively for Bright Limb (BL)/Solar Occultation (SoO) and Stellar Occultation (StO).

The entrance pupil of the bright limb channel is located in the middle of the Fabry-Pérot assembly. In the stellar occultation mode, a flip mirror is moved in the optical path to switch between the BL and StO line of sights. For StO measurements, it is important that the aperture is as large as possible to maximize the signal on the detector. A larger aperture is realized by means of magnifying optics at the cost of a smaller FOV. The magnification of the optics is the ratio between the stellar occultation aperture and the Fabry-Pérot filter aperture.

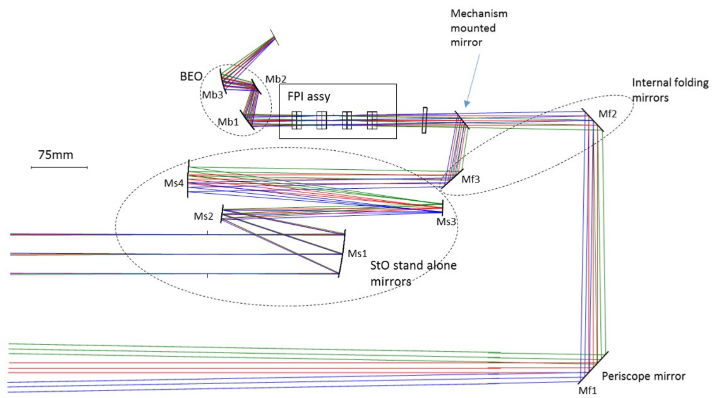

Figure 3. ALTIUS optical UV channel layout

The signal detection is realized thanks to a CIS115 CMOS sensor developed by Teledyne-E2V in the frame of the JANUS project (on board the ESA JUICE Mission) for which anti reflection coating has been adapted for the UV range for the ALTIUS.

The spectral selection is based on a stack of four Fabry Pérot interferometers used as spectral filter and an objective that images the light from the bright limb aperture on the detector. The aperture of a Fabry-Pérot filter determines the aperture of the BL path. The Fabry Pérot air gaps are tuned such that selected interference orders overlaps only for one selected central wavelength which is getting transmitted, as shown in Figure 4 [01].

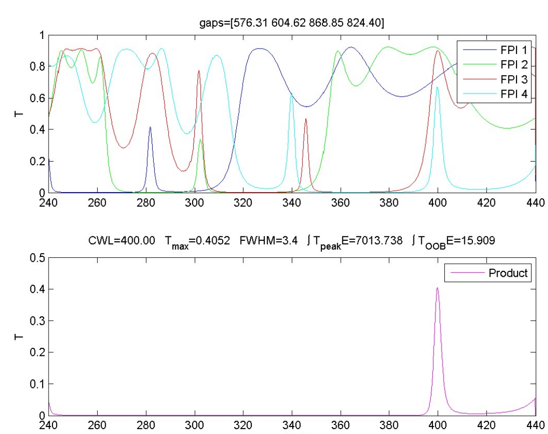

Figure 4. Principle of the FPI stack spectral selection

ALTIUS VIS and SWIR Channels Concept
In the VIS and SWIR channels, the optical design is based on the use of an Acousto-Optic Tuneable Filter (AOTF). Such filter rely on the diffraction effect created in the bulk of a TeO_2 crystal by an acoustic wave. The selected diffracted wavelength is defined by the phase matching conditions with the corresponding acoustic wave frequency travelling within the AOTF [02].

The AOTF is used in combination with wire grid polarizers which are selecting the appropriate polarization and order of diffraction. The Front End Optics assembly is telecentric and forms an image 5 mm behind the exit surface of the AOTF to reduce the influence of the acoustic wave on the homogeneity of the image. The Back End Optics relay the image onto the detector and match the image size with the size of the Focal Plane Assembly.

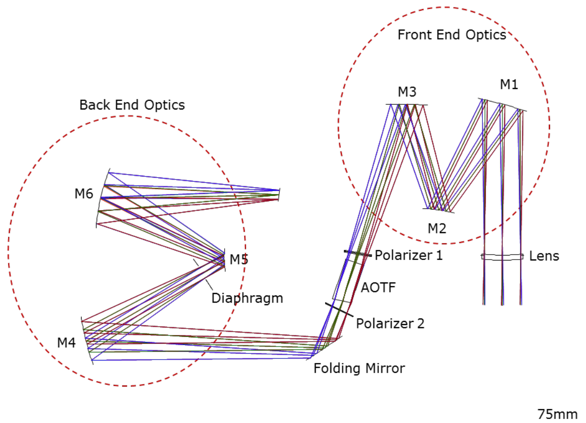

Figure 5. ALTIUS optical VIS channel layout

The signal detection is in the VIS channel also realized by means of a CIS115 CMOS sensor while a Hybrid MCT NEPTUNE sensor developed by LYNRED is baselined for the SWIR channel.

3. KEY TECHNOLOGIES PRE-DEVELOPMENT

As part of the Instrument preliminary design concept consolidation, the critical technologies necessary to ensure the performance and functionalities of the ALTIUS Instrument have been designed, developed and qualified. In particular the following pre-developments were undertaken to pave the way towards a smoother and successful Instrument Preliminary Design Review:

- Design, manufacturing and qualification of the UV FPI assembly stack and control electronics;
- Development and qualification of UV filters and coatings;
- Design, manufacturing and qualification of the VIS AOTF Assembly and RF control electronics;
- Design and manufacturing of sensor electronics based on selected CMOS sensor for UV and VIS channels;
- Design, manufacturing and partial qualification of the Instrument mechanism;
- Bread-boarding of the full VIS channel for functionality and end-to-end performances verification.

3.1 VIS AOTF Assembly and RF control electronics

AOTF crystal assembly

An AOTF is composed of a birefringent crystal (or cell) onto which is attached a transducer actuated through an impedance matching network by an appropriate RF signal. The detailing of an AOTF design can be found in [06]. For the ALTIUS Mission the manufacturing of a 22mm x 22mm crystal clear aperture is required together with its integration into a housing capable of surviving the stringent vibration shock loads for the mission while ensuring a proper thermal stability of operation. An initial demonstration model already available in OIP was fully integrated and an EQM is currently under manufacturing in order to validate suitability of the design from environmental standpoint.

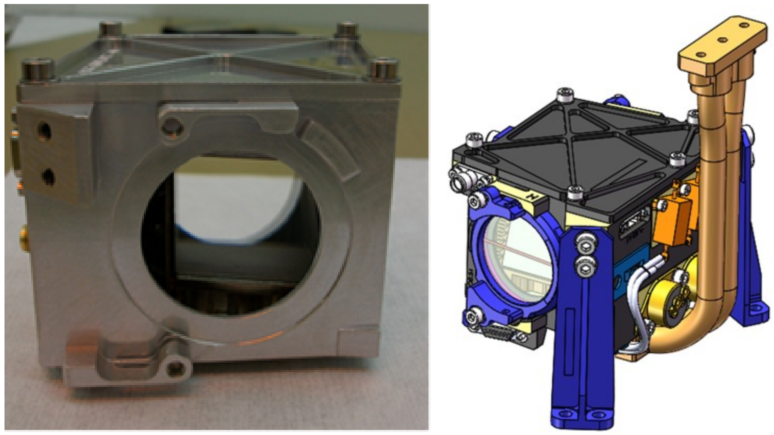

Figure 6. VIS AOTF crystal integrated in its mechanical housing and final configuration of the AOTF assembly with wire grid polarizers

The detailed design of the VIS AOTF crystal is the outcome from an iterative process of fine-tuning the design parameters which could be summarized below.

- The aperture size of an AOTF is mainly limited by the availability of optically qualified TeO_2. Furthermore, acoustic adsorption leads to a variation in diffraction efficiency across the aperture and is proportional to f^2 (applied RF signal). This means that the upper RF drive frequency limits the aperture depth. The RF drive power also increases in direct proportion to the aperture height.
- The tuning frequency is proportional to the material birefringence divided by the optical wavelength and the birefringence is non-linear w.r.t. the wavelength. This has the effect of stretching the frequency range, and/or compressing the wavelength range. The biggest issue here is to make the transducer efficient over the frequency range. This includes effective impedance-matching which is difficult to achieve with large area transducers at high frequencies. By pushing the bottom wavelength down, the upper RF drive frequency gets pushed up. Additionally, the requirements for the minimum separation angle (0-th order to the diffracted order) tend to push the RF drive frequency up.
- The acceptance angle or FOV in the plane of diffraction is set by the acoustic divergence and thus transducer length. The acceptance angle is also linked with the resolution as an increase will result in an increase of the pass-band resolution.
- In the low efficiency limit, the optical band shape function will be shaped as a typical $sinc^2$-function distribution. Through apodization the acoustic intensity profile can be controlled. The intensity of the side lobes can be suppressed by about 25-30 dB by a technique demonstrated by Gooch & Housego (G&H). This is done by shaping the transducer and controlling the acoustic energy distribution along the interaction length by changing the electrode pattern of the AOTF. On the other hand, shaping the optical band shape function with apodization increases the effective pass-band width and this increases the RF power required for a certain diffraction efficiency.
- The resolution is also linked with the incident angle. In order to reach the spectral accuracy required for the ALTIUS Instrument, the acceptance angle can be reduced but this would compromise the radiometric performances as the throughput is decreased. A narrower spectral resolution without influencing the SNR is thus obtained by choosing a new orientation of the cell and by increasing the transducer length.
- Finally this trade-off is bounded by the available RF power which can be made available to the system for a space mission.

The trade-off has been finalized by simulations which are providing the following theoretical behavior for key operational parameters providing the required RF signal frequency as a function of the selected wavelength and the necessary RF power at the crystal inputs in order to generate an optimum diffraction efficiency of the phase grating.

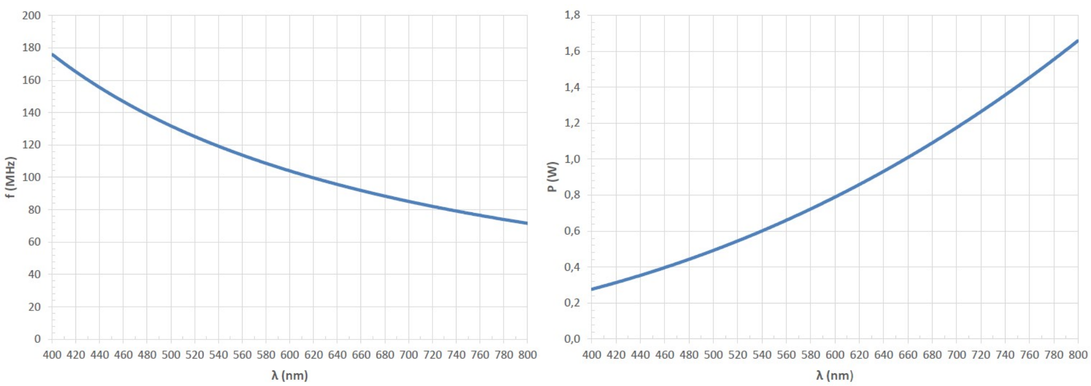

Figure 7. Predicted RF frequency and RF power to be generated at the AOTF input as a function of the desired center wavelength.

The processing of a cell of the ALTIUS required dimensions has turned out to be quite challenging and has highlighted the importance of rigorously controlled manufacturing processes, mainly in relation to potentially induced thermal stresses. Preliminary test results using the already available demonstration model have allowed to verify spectral performance as well as geometrical performance for the first and zero order of diffraction for the considered crystal geometry with a 633nm laser source.

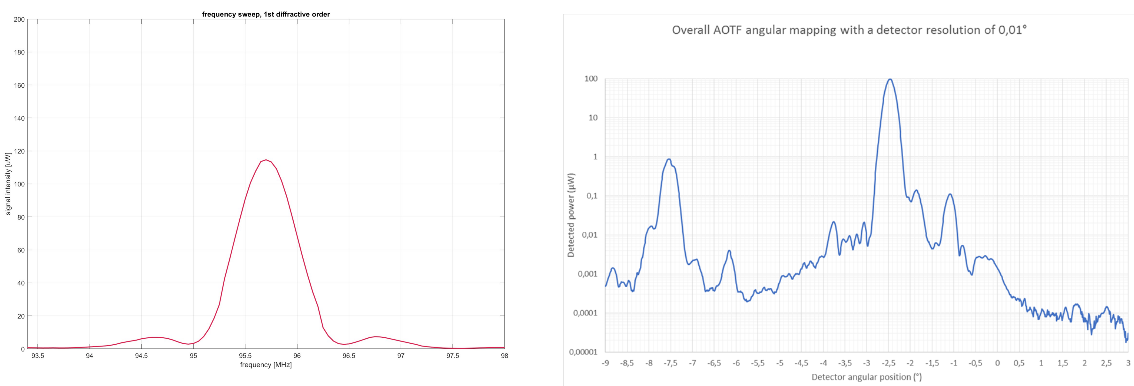

Figure 8. Measurement of the AOTF bandpass for 633nm laser emission and angular mapping of the zero and first diffracted orders exit angles at the back of the AOTF.

First test results are showing good correlation level with the simulation models (see Table 2 below) with the exception of the dissipated RF power which proves to be somewhat higher than expected.

Table 2. Comparison of measured and simulated AOTF performance parameters for a light source at 633nm

Parameter	**Predicted value**	**Measured value**
Optimal driving frequency @663 nm	*96.602 MHz*	*96.67 MHz*
Optimal driving power @663 nm	*0.9W*	*1.67W*
+1 diffracted order angle	*-2.48°*	*-2.55°*
0 order angle	*-7.49°*	*-7.57°*
Max. DE to +1 order (%)	*> 91%*	*> 85.5%*

These first test results provides a good indication about an appropriate level of performance compliance to achieve system level radiometric and spectral performance needs without the support of further system level functional adaptations.

Wire grid polarizers

In order to constrain the polarization in the correct orientation at the input of the AOTF and in an attempt to reject the straylight which is created by the order zero of the AOTF, wire grid polarizers are positioned at the front and at the back of the AOTF crystal. A wire grid polarizer consists of a fused silica substrate onto which is deposited by photolithography a dense grid of aluminium wires spaced by a distance of few hundreds of nanometers (typically 150nm). In ALTIUS such polarizer is used in a double configuration. This means that every single unit is composed of two single polarizers which are accurately aligned with each other and integrated in a mechanical housing. The quality of the alignment is constraining the performance of the selected polarization transmittance as well as the contrast ratio between the two perpendicular polarizations.

The housing of the polarizers has been designed specifically such that an electrical contact is made between the housing, and the wires by pressing the grid to a soft metallic gasket. This approach present the advantage, once integrated with the AOTF as shown in Figure 6, to form a complete EMC enclosure for the AOTF assembly considering the emitted RF frequency range of operation.

Figure 9. Pictures of the wire grid polarizers integrated into their housing

Each double polarizer has been tested for WFE, reflectance and radiometric performances prior to delivery and are demonstrated to fulfill performances required for the ALTIUS. In particular, the contrast ratio is outperforming the specification of 100:1 given while transmittance is maintained within the specification illustrating the efficiency of the double wire grid approach and their alignment in the structure.

Figure 10. Transmittance of the P polarization for two samples and their respective contrast wrt S polarization

The ALTIUS pre-development activities have, once again, highlighted the crucial role played by contamination prevention techniques such as solvent cleaning and bake out to be rigorously implemented through all various hardware manufacturing and assembling steps.

RF electronics

In order to drive over the frequency range between 152MHz and 71 MHz the AOTF with the appropriate RF power input, an RF system composed of a generator and a RF amplifier has been bread-boarded based on components which could be replaced later on in the project by flight part numbers.

- The RF generator:
    - Interfaces with the CCU master channel electronics (containing the FPGA) through a backplane PCB interface using LVDS;
    - Generates a commanded frequency according to the required performance;
    - Distributes the RF signal towards the RF amplifier through a dedicated SMA—SMA coax harness.
- The RF amplifier:
    - Makes sure the impedance matching over the RF chain is adequate;
    - Amplifies the RF signal from the RF Generator to the required level for the AOTF;
    - Makes sure spurious signals and harmonics are getting filtered as required;
    - Makes sure no degradation appears of the generated signal performances at the AOTF interface;
    - Distributes the RF signal towards the AOTF through dedicated SMA—SMA coax harness.
- The AOTF including its impedance matching network represents the load to be driven.

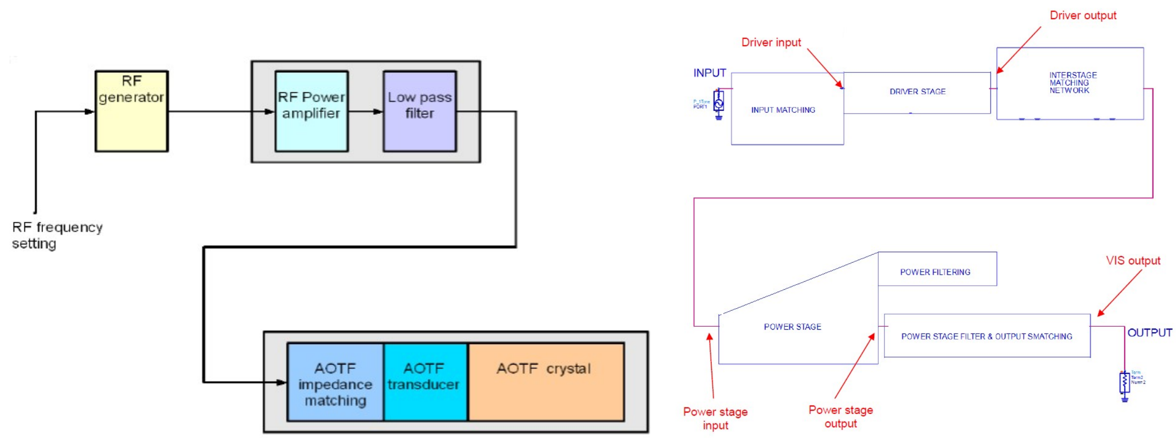

Figure 11. (Left) Block diagram of the ALTIUS RF system (right); ALTIUS RF amplifier principle

The developed RF system GSE has been tested and validated demonstrating a good level of compliance wrt the given requirements (Table 3) with few partial compliances. The design has demonstrated a good impedance matching over the chain allowing to achieve a power input at the AOTF interface which is compatible with the applicable requirements (see Figure 11) and an appropriate level of harmonics rejection.

Table 3. Main measured parameters of the RF system compared to requirements

Parameter	**Predicted value**	**Measured value**
Operability at power up	*200ms*	*Better than 150ms*
Response time	*20ms*	*Max 12ms*
Accuracy ; purity ; reproducibility	*1kHz*	*1 Hz for accuracy and purity* *0,1 Hz for reproducibility*
Long term stability (100s)	*5kHz*	*4Hz max*
Short term stability (1s)	*2kHz*	*0,3Hz max*
Unwanted spectral component level	*<-30dB*	*Max -28dB*
Power consumption of the generator	*<2.6W*	*3,1 W*
Efficiency of the amplifier	*>35% Over the band*	*Between 37% at 72MHz and 15% at 153 MHz*

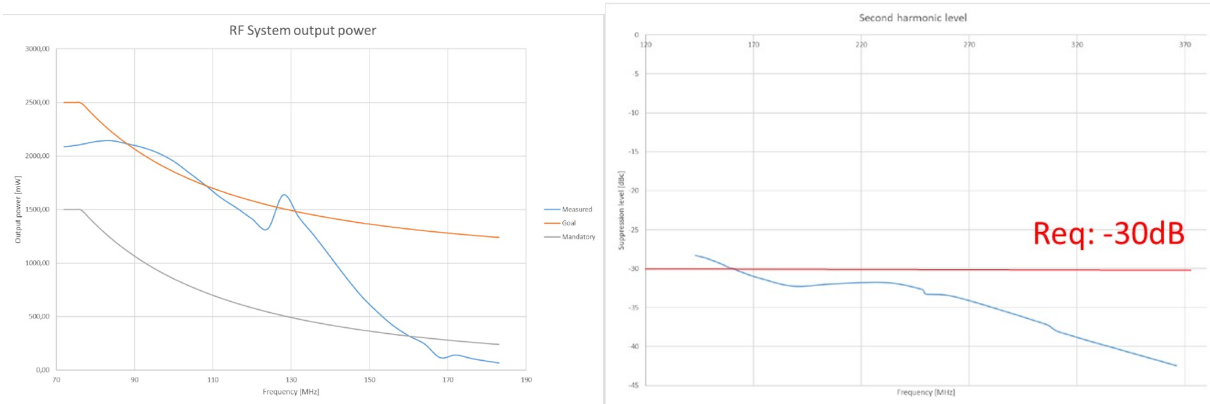

Figure 12. (Right) Emitted power at the AOTF and (left) second harmonic rejection of the RF system

Main lesson learned indicates the need for a higher required power and mass compared to the initially allocated ones, which will have to be accommodated further in the Instrument technical budgets.

3.2 UV FPI assembly stack and control electronics

For the ALTIUS Instrument, the FPI assembly is composed by a cascade of four Fabry-Pérot interferometers.

Each FPI is composed of a pair of 6.35 mm thick fused silica mirror substrates with a minimum front face flatness of λ/100 at 632.8 nm rms, on which 11 dielectric layer coatings are deposited. The recipe of the coating of each FPI mirror pair is tuned based on extensive design and analyses performed by the manufacturer in order to ensure the following main performances:

- A continuous spectral coverage between 250nm and 370nm by tuning of the piezo actuators;
- An enhanced transmittance of the FPI stack over the operational range while ensuring reduced out of band leakages;
- A bandwidth smaller than 2.5nm over the full spectral range of interest for the selected wavelength range.

Due to an extreme sensitivity of the FPI performances to deformations the selected approach to generate the mirror pairs is based on use of fully similar materials for each optical part and gluing, if necessary, using a flexible glue. The two mirrors are positioned onto a single fused silica carrier together with three piezo electro actuators. The air gap between two mirrors is in the range of a hundred of nanometers and the active tuning of the piezo actuators allow to modify selectively the air gap between the mirrors from 200 to 800nm range. The tuning of the air gap allow to select a different wavelength for constructive interference build-up. During operations the air gap distance is maintained by a close loop control thanks to the precise measure of a capacitor value is deposited onto the mirrors by lithography. Each FPI units is, therefore, totally integrated with its control electronics (as the FPI is by itself a part of the control loop of the electronics) and the efficiency of the performances are deeply related to the quality of the electronics control performances.

The lower mirror of an FPI unit is glued on the support glass with three spots. The glass surface at the glued areas is machined 0.3 mm above the surrounding area to avoid unwanted contacts between the support glass and the lower mirror, which would cause bending forces. Using this method ensures to the best extend maintainability of the air gap over the 14mm diameter clear aperture of the mirrors within 3.9nm standard deviation. This is the guarantee that spectral performances can be kept uniform over the clear apertures of one FPI unit.

The criticality of the FPI assembly performances lies within the active control and maintaining through close loop of the air gap for each unit. This air gap control shall account for each independent piezo actuator behavior depending on the identified air gap and temperature effects. It, therefore, requires a very thorough calibration approach in order to generate a full correction map where for each FPI unit the elements to be calibrated are:

- The definition of a specific air gap to be maintained for a commanded wavelength.

$$\lambda = f\,(g1;\ g2;\ g3;\ g4) \tag{1}$$

- The definition of the three piezo-electric actuators voltages to achieve a specific air gap over the complete mirror clear aperture (considering parallelism constraints) as a function of the temperature;

$$g1=f\,(Sp1(T);\ Sp2(T);\ Sp3(T)) \tag{2}$$

- The relationship between the voltage of one piezo actuator and the two others at a given temperature

$$Sp2(T)=f(Sp1(T)) \text{ and } Sp3=f'\,(Sp1(T)) \tag{3}$$

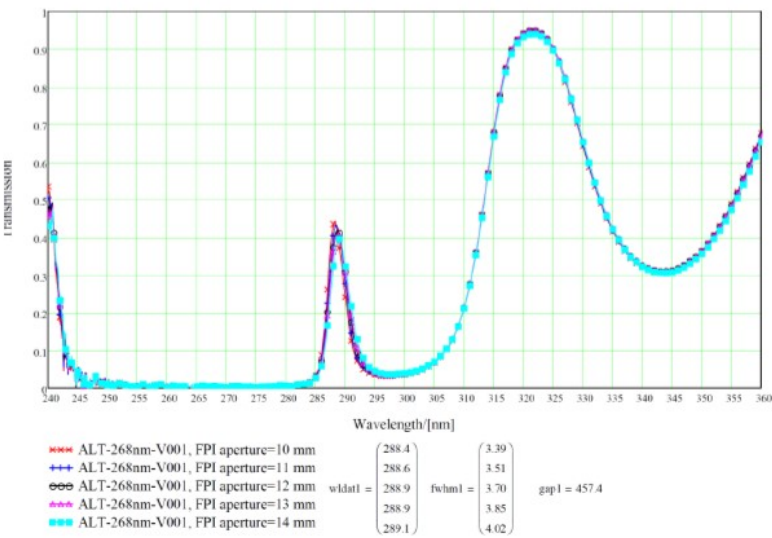

Figure 13. Measured FPI unit spectral transmittance as a function of the considered mirrors clear aperture

From a mechanical point of view, the mirrors assembly is integrated into an aluminum structure which is also carrying the proximity control electronics for the piezo actuators and air gap control capacitors. Each of the FPI unit is then integrated onto a unique baseplate which is interfaced to the optical bench of the Instrument through titanium flexures.

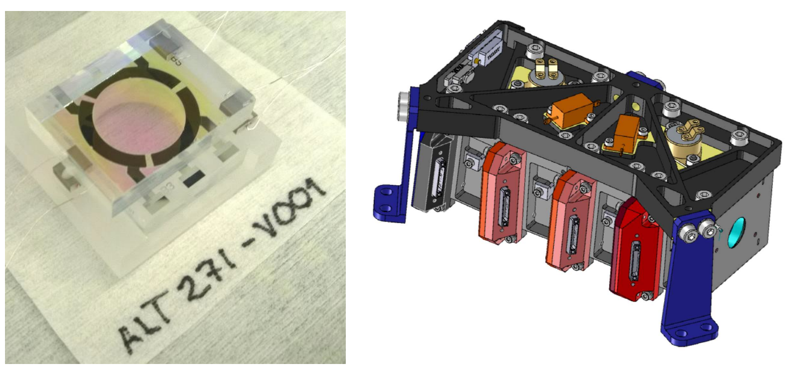

Figure 14. FPI unit mirrors assembly and design of the overall FPI assembly integrated

The FPI assembly development has been validated in a step by step manner based on the manufacturing and testing of two prototype models and an EQM model, increasing the complexity of the commanded system in an incremental way. The processing of the ALTIUS FPI prototypes and EQM has highlighted the importance of rigorously controlled manufacturing processes, mainly in relation to potential coating issues.

Spectral and radiometric tests were already performed on the prototype demonstrators in a successful manner and will soon be performed on the EQM. The effectiveness of the active control could already be demonstrated through spectral and radiometric testing of the FPI assembly in stand-alone considering the FWHM of the selected spectral band achieved after calibration (black curve in Figure 15) compared to the open loop performances (red curve in Figure 15). These tests have been demonstrating the criticality of the bandpass of the control electronics to be appropriate in order to ensure appropriate optical performances (spectral bandpass and throughput) from the µs to the minute timeframe.

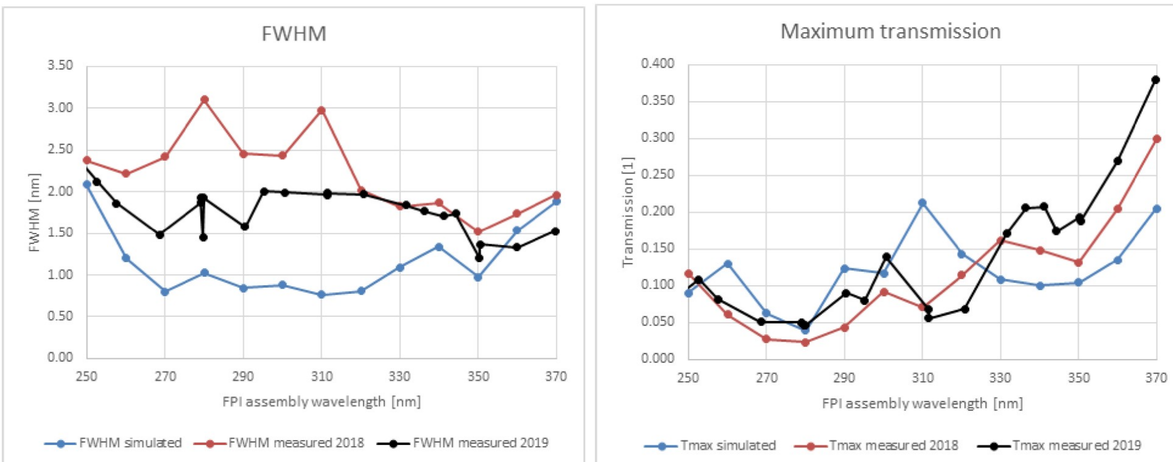

Figure 15. Achieved FWHM and transmittance for the complete FPI assembly (simulated in blue, open loop in red, closed loop after calibration in black)

3.3 Development and qualification of UV filters and coatings

The spectral and radiometric performances of the UV Channel will be achieved end-to-end by combining the performance of the Fabry-Pérot assembly and the performances of a bandpass filter which will be positioned in front of the assembly. The flight filter shall have an optimum transmittance in the UV operational band between 250nm and 370 nm while ensuring a high optical density in the VIS and SWIR range up to 1200nm in order to block out of band straylight which could be detected by the Instrument. The development of a filter coating precursor was made by Balzers GmbH based on deposition by PARMS process onto a fuse silica substrate. To reach specified performance the coating design is divided on both faces of the substrate. Face one coating defines the pass-band and the blocking range until 700 nm and is composed of 386 layers HfO_2/SiO_2 while face two coating defines the blocking from about 700 nm to 1000 nm and is composed of 318 layers of the same materials. For each layer, the typical layer thickness ranges between 10 nm and 100 nm.

Due to specific heat treatments used for layers oxidation, the transmittance for the coating is increased significantly in the range between 250nm and 370nm while showing excellent blocking up to 1000 nm. For flight hardware it will then be necessary to extend of the current filter blocking up to 1200nm by tuning further the second face of the filter coating.

The bandpass filter went through extensive qualification campaign in line with the ALTIUS environmental loads as defined in the **Table 4** and has demonstrated full qualification as well as excellent ageing performances and thermal performance stability.

Table 4. Tests performed on bandpass filter

Test	Method	#1	#2	#3	#4	#5	#6
Performance	Spectral measurements	X	X	X	X	X	X
Adhesion	ISO 9211-4-02-01	X					
Cleanabiltiy	IPA and acetone	X					
Abrasion	ISO 9211-4 -02-01	X					
Humidity	24H 90%rH 40-50°C as per ECSS	X			X	X	
TVC	5 cycles -40°C to +40°C at 5eE^{-5} mbar		X		X	X	
TC	20 cycles -40°C to +40°C		X		X	X	
Radiation	10 MeV of 2,0E^{10}/cm^2			X	X	X	
Roughness	White light interferometry		X				
UV lifetime	1350 kWh/m2 over 4 days	X	X	X	X		
Fluorescence			X				
Adhesion	ISO 9211-4 -02-01	X	X	X	X	X	

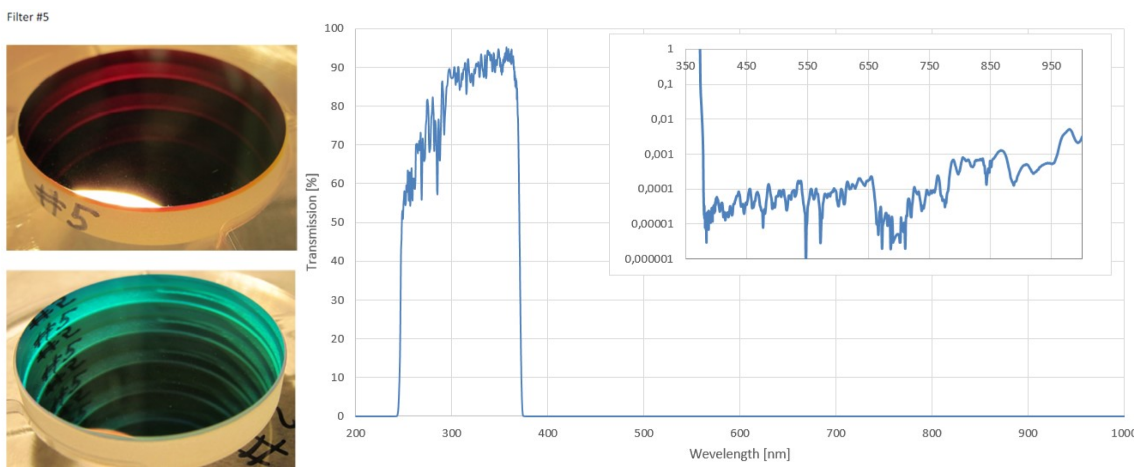

Figure 16. View of bandpass filter and spectral performances

UV Channel system level reflections

In consideration of what tested and observed throughout the pre-developments, the following challenges have been identified at system level for the ALTIUS UV Channel based on preliminary anticipated performance results: a) the difficulty to achieve the initially targeted throughput requirements; b) the difficulty to reach the required system level SNR; c) the difficulty to achieve the required out of band high blocking optical density; d) the difficulty to limit the overall level of straylight. Future project activities will focus on resolving the above identified challenges in the most effective manner for the ALTIUS Mission.

3.4 CMOS sensors and control electronics

The detector used in the UV and VIS channels of the ALTIUS Instrument is a backside illuminated CIS115. This detector has been initially designed and developed to be radiation hard by Teledyne E2V. Testing of front side sensor precursor and early backside models were done by Open University as illustrated in [03] and [04]. A quite extensive trade-off among various possible detectors candidates for ALTIUS has brought to the choice of these off-the-shelf detectors which has led to a considerable programmatic benefit to the ALTIUS project whilst offering a very good technical compromise wrt the choice of a dedicated detector development.

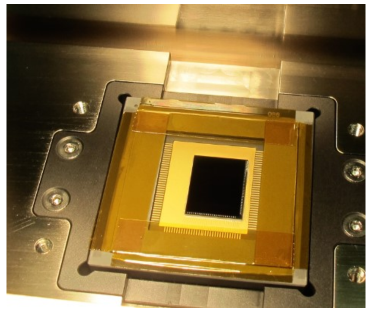

Figure 17. VIS CIS115 CMOS sensor

This detector is natively 7µm pitch 2000x1504 pixel arrays operating at 6.2Mpix/s readout rate, which has been designed for operation in both the UV and the VIS spectral range. This device has been selected for the ALTIUS as it presents a low dark current of 20e-/s at room temperature and a reasonable readout noise of 6e- RMS compatible with the radiometric requirements made for both VIS and UV channels.

In order to maintain performances over the mission, specific care was taken to the cleanliness of the devices,. As such both UV and VIS sensors models were tested through a sequence of wipe test and XPS verification which has been demonstrating a level of contamination at delivery below detection limit of 20ng/cm² for the procured flight sensors.

Also particular attention was paid in the ALTIUS flight hardware selection in the screening of the selected devices such that would they present a minimum number of bad pixels and bad pixel clusters in line with the scientific requirements.

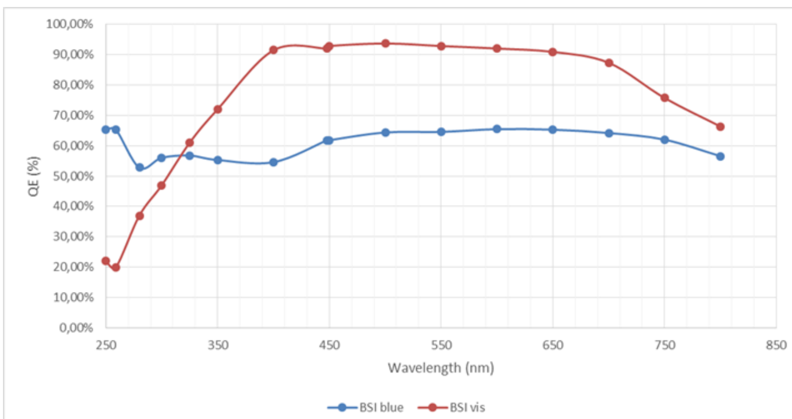

Figure 18. QExFF of the two versions of the CIS115 for UV and VIS enhanced versions

The CIS115 sensor was initially implemented in the JANUS Instrument onboard the JUICE Mission and in this scope was LAT tested and performance tested [05] in its visible range version in line with ESCC9020 standard. For the ALTIUS it was, therefore, necessary to perform delta testing of the VIS version while the UV version was going through a dedicated LAT testing sequence. This verification included ALTIUS vibration and shock level, which are well above the specification of the standard. The LAT testing has been recently passed in a successful manner ensuring that the VIS and UV sensors can withstand the quite severe vibration and shock loads which are currently defined for the ALTIUS Instrument.

Control electronics

A key part of the development was to ensure that the selected CMOS could be driven in an appropriate manner for the ALTIUS Mission needs. The CIS 115 is a rolling shutter while the ALTIUS scientists were initially anticipating the implementation of a global shutter approach. In order to ensure reducing the delay between rows acquisition start and still maintain an appropriate minimum integration time for each rows, an adequate clocking scenario has been put in place for the Instrument and validated through testing.

To host the detector onto the optical bench, a dedicated Focal Plane Assembly (FPA) board, fully representative of the flight hardware design has been developed. This FPA PCB contains the serializer/deserializer necessary for clocking the CIS115 and the 16 bits ADCs which are interfacing the four analog outputs of the sensor to the control electronics. The main drivers for the PCB design is the extremely small volume into which the components have to be fit, combined with the fact that this same design approach shall be fully reusable for each channel configuration.

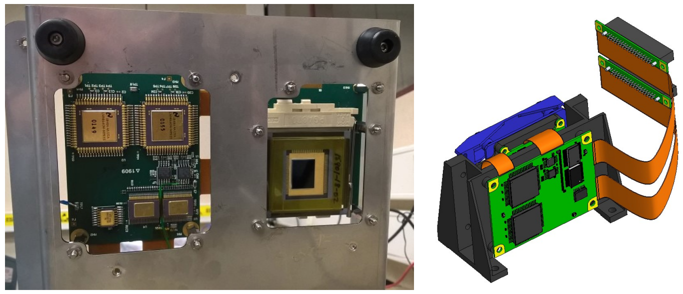

Figure 19. FPA proximity electronics and its integration into the focal plane assembly

The FPA PCB is connected though dedicated interfaces to an FPGA integrated in the CCU master PCB. This master PCB is playing the role of channel coordination by:

- Interfacing the FPA PCB allowing clocking detectors, streamlining and processing image data
- Interfacing with S/C data and TM/TC through spacewire interfaces
- Interfacing with mechanisms control PCB
- Interfacing with Spectral filters control PCB (either FPI controller in the UV or RF system in the VIS and SWIR) and providing corrected commands for spectral acquisition accuracy.

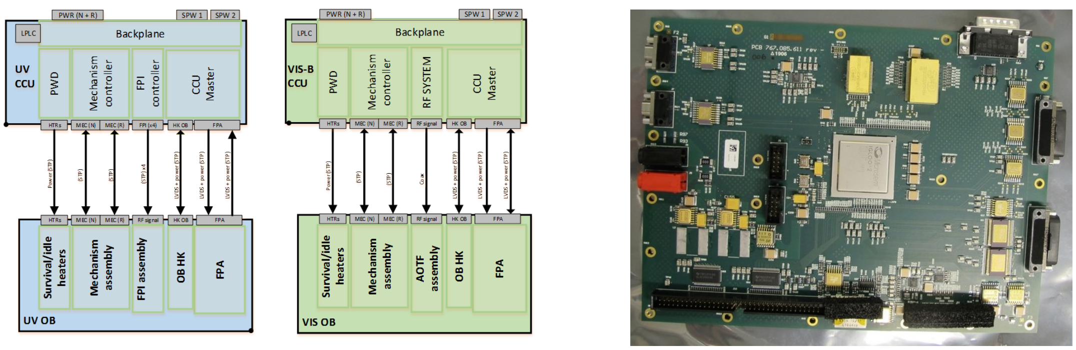

Figure 20. (Left) Architecture of the CCU control electronics for the VIS and UV channel; (right) CCU master electronics PCB precursor

The Precursor of the CCU master PCB has been developed based on an IGLOO2 reprogrammable FPGA from Microsemi, which is representative of the RTG4 flight FPGA selected for the purpose of the project. It demonstrates the overall video path from raw data acquisition, bad pixel correction, image windowing and pixel binning to packetization through CCSDS standard protocol.

The testing and debugging of the electronics is currently still ongoing and a few unwanted behaviors have been corrected:

- The electrical testing of the CCU mater precursor was completed and considered suitable for interface testing with the FPA PCB;
- There were initially issues with the sensor supplies / biases due to ambiguities of the datasheet which have been solved after integration of the FPA PCB with CCU master;
- After tuning several Firmware and hardware parameters, first check of sensor linearity and full electronics noise was identified to be good enough to proceed with first light:
  - Dark image, integration time 0-1 rows: noise is about 3.2 LSB while expectation was < 4.0 LSB
  - Linearity / full utilization ADC range: ADC full range is 0-16383, dark level of sensor has been placed at approx. 1000, saturation knee of sensor output around 14000-15000.

However, the first light test performed recently in July 2019 with the sensor shows a row patterning which is currently under investigation.

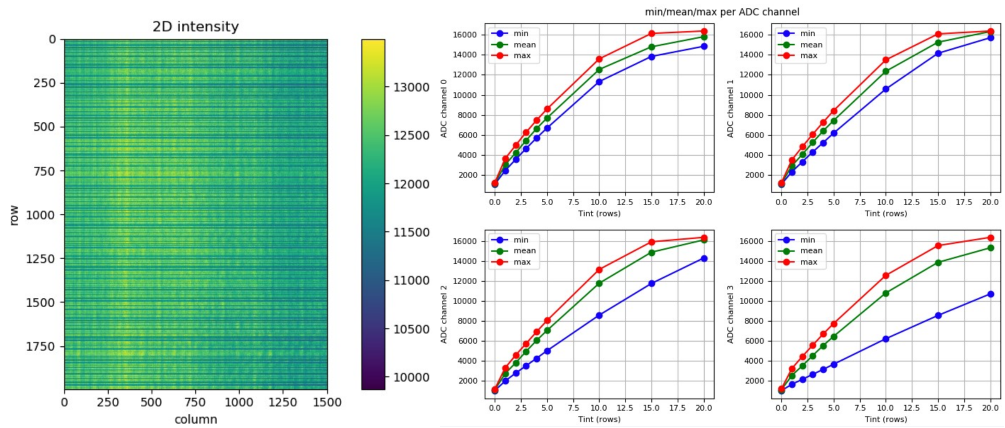

Figure 21. CIS115 first light 2D array and quick linearity test

3.5 Mechanism development

The main mechanism concept is based on a motor block which shall actuate a mechanism arm which is either integrating a ND filter (for the VIS and SWIR channels) or a combination of a ND filter and a mirror (for the UV channel). In each channel the same mechanism design is used in a different orientation such that it can achieve the required actuations and position relevant optical elements within the optical path. Ultimate scope of the ALTIUS mechanisms demonstration model is to answer the following key questions:

- Is the selected design capable to survive the launch environment while ensuring limited outgassing in the vicinity of optical elements;
- Is the considered design robust enough to ensure a total of about 64000 actuations considering ECSS guidelines for margin of safety;
- Is the tolerances achieved by the mechanism compatible with the optical tolerances to maintain pointing and radiometric performances:
    - relative displacement in X and Y: ±0,1mm between center of the folding mirror and center of the optical beam striking the mirror;
    - relative displacement in Z: ±0,25mm between center of the folding mirror and center of the optical beam;
    - angular error: ±0,1° (TBC) between the folding mirror normal and the 45° nominal position.

A thorough design trade-off considering various approaches wrt lubrication, motorization, direct or indirect drive has been concluded by the selection of a Stepper motor encapsulating a wet lubricant Braycote 601 which is connected in direct drive. The mechanism accuracy is granted thanks to a combination of step counting and accurate hard stop position while the locking during launch is granted on the mechanism arm thanks to a resettable pin puller which is interfacing to a balanced mechanism arm. At any time the mechanism status and position is getting controlled thanks to fully redundant reed switches which are getting activated depending on the arm position.

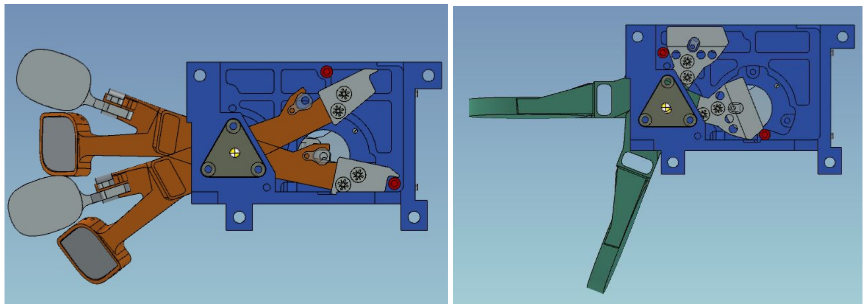

Figure 22. Design of the UV and VIS/SWIR mechanisms of the ALTIUS

The mechanism demonstration model is currently completing environmental qualification as pre-cursor to the AOTF and FPI EQM's which will soon follow.

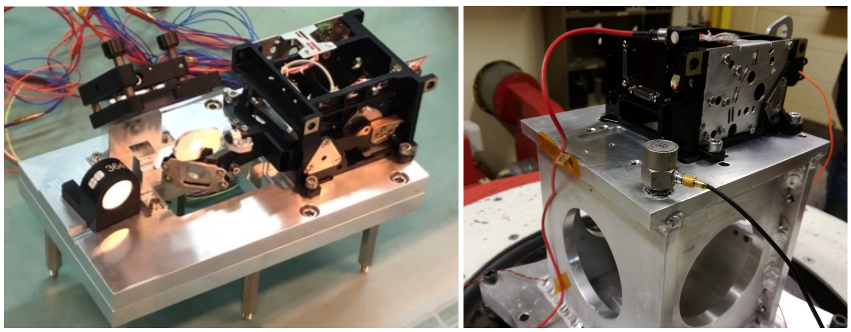

Figure 23. Mechanism demonstration model integrated in the thermal test bench (left) and in preparation for vibration test (right)

The mechanisms went nominally through thermal vacuum testing in non-operation conditions between -40°C to +40°C, operational testing (including stalling torque testing) between -30°C and +40°C; vibration test sine and random. It present currently still stable positioning and angular performances in line with the requirements.

Table 5. Sine vibration test levels

Orientation	Freq (Hz)	Load
In plane	5	20g
In plane	125	40g
Out of plane	5	20g
Out of plane	125	30g

Table 6. Random vibration test levels

Freq (Hz)	PSD (g^2/Hz) (18.5gRMS equivalent) in all direction
20	0.05
150	0.8
300	0.8
400	0.2
900	0.2
2000	0.001

Shock testing of the ALTIUS mechanism demonstration model is currently under preparation. At the end of shock testing sequence a lifetime test is planned where the mechanism is going to be actuated 209000 times considering one actuation every five seconds over a total test duration of two weeks. This testing shall validate the overall performances and demonstrate that the mechanism is capable of performing over the complete mission duration.

3.6 Bread-boarding of full VIS Channel

In order to validate end to end the functionality and preliminary performance of the ALTIUS VIS Channel, a breadboard based on commercial optics, replicating to the closest the optical parameters of the VIS channel but integrating the elements described above (i.e. AOTF, RF system, Detector and control electronics) has been developed in OIP. This breadboard will support verification of the planned instrument functional architecture but also verification of instrument calibration approach. These tests are planned for the last quarter of 2019.

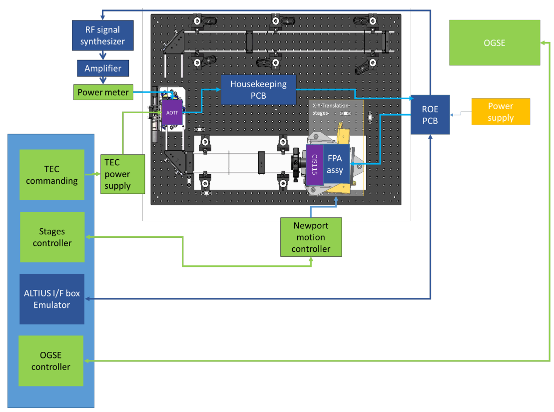

Figure 24. ALTIUS VIS Channel Breadboard concept design

From the preliminary test results obtained through single system contributors individual testing (and described in the previous sections of this paper), it is anticipated that the breadboard verification will allow to bridge the gap towards refinement of the geometric, radiometric and spectral VIS Channel performances foreseen for the ALTIUS Instrument. The foreseen bread-board will also support further refinement of the calibration approach of the Instrument. Finally, it will support the identification of needs for specific on ground data processing ensuring that suitable on ground correction algorithms will be further deployed in the next phase of development.

4. CONCLUSIONS

This paper has provided a snapshot of the ALTIUS pre-development activities and results obtained as of today. This activity has given a substantial contribution in clarifying major risks associated to the ALTIUS Instrument development (e.g. manufacturing processes control, cleanliness, etc.) and has brought into light some of the major technological challenges still to be resolved in the future project phases (e.g. straylight issues, other radiometric and spectral non-compliances, etc.). In spite of the difficulties faced along the manufacturing and testing of the bread-boarded critical elements, the obtained preliminary results are currently showing performances converging more and more towards the ALTIUS needs. Additionally, needs for system level adaptations to maintain performance requirement at the mission side have been identified and will be further implemented in the frame of the future project phases. Last but not least, the already executed testing activities have paved the way towards a smoother qualification campaign of the ALTIUS Instrument most critical elements.

ESA and OIP N.V. wish to thank all subcontractors and partners involved in these pre-development activities, VTT Finland for the FPI assembly and electronics, Gooch & Housego for the AOTF development, BIRA-IASB for the RF electronics, Teledyne e2V for the CMOS sensor testing and QinetiQ Space N.V. for the activities on the ALTIUS mechanism. Special thanks goes to the BIRA-IASB ALTIUS Scientists Team for their valuable contribution to the Instrument pre-development activities.

REFERENCES

[1] Mannila, R., Näsilä, A., Viherkanto, K., Holmlund, C., Näkki, I., "Spectral imager based on Fabry-Perot interferometer for Aalto-1 nanosatellite", Proc. SPIE 8870, 887002 (2013)

[2] E. Dekemper et al. "Tunable acousto-optic spectral imager for atmospheric composition measurements in the visible spectral domain", App. Opt.,Vol.51,6259-6267(2012)

[3] M. Soman, K. Stefanov, D. Weatherill, A. Holland, J. Gow and M. Leese, "Non-linear responsivity characterisation of a CMOS Active Pixel Sensor for high resolution imaging of the Jovian system", JINST, Vol.10, C02012 (2015)

[4] M. R. Soman, E. A. H. Allanwood, A. D. Holland, G. P. Winstone, J. P. D. Gow, K. Stefanov, and M. Leese "Proton irradiation of the CIS115 for the JUICE mission", Proc. SPIE 9602, (2015)