

On the development of wide-field spectral imagers for ESA's Aurora-D mission

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ABSTRACT

Under the Space Safety Programme (S2P) and as part of the European Space Agency's D3S (Distributed Space Weather Sensor System), ESA's Space Weather Office has initiated the development of wide field auroral multi-spectral imagers to enable the observation of the Auroral Oval for operational space weather applications. The observation of the Sun's activity and its interaction with the Earth through the monitoring of the Aurora was considered to become a core element of future Space Weather monitoring systems, through the continuous observation of the corresponding Auroral emissions and of the underlying particle and geo-magnetic state conditions. A key enabling function of such observations is the ability to observe the complete Auroral Oval remotely to capture the actual status of the ionosphere and its interaction with the precipitating particles that are driven by the Space Weather conditions.

The development of the wide-field imagers was considered as enabling technology for the implementation of a novel approach using small satellites focused on Auroral Oval imaging, that would be followed by a constellation mission in a later period, enabling continuous (24/7) monitoring of the Auroral Oval. Auroral emissions are generated mostly in the far UV and visible spectral ranges. The core instrumentation of such an observational system was therefore suggested to utilise an optical spectral imager that was named Auroral Optical Spectral Imager (AOSI) and two far UV band imagers, forming the Auroral far UV Imager (AUI). The two imagers were developed in the framework of several technology developments that were started already in 2018 and further consolidated as part of the mission studies and related pre-developments. During the preparation of the Aurora Demonstration mission, several trade-offs have been conducted that finally cumulated in an imager configuration that is suitable for observations at an altitude of about 6500 km, which was baselined in the Phase B1 mission study. The required field of view of the imagers at such orbit still must cover about 50 degrees or more, which was considered as very challenging albeit not impossible.

The paper summarises the evolution of the instrument concepts in the mission context and presents the outcome and status of the instrument designs. It highlights the driving optical design aspects that come with the very wide field of view coverage for the given stringent observational conditions and present the expected imaging, spectral and radiometric performance.

Keywords: space weather, aurora, wide field of view imaging, spectral imagers

1. INTRODUCTION

Monitoring the aurora, also known as polar lights, is a critical task for space weather monitoring. Aurora can be observed remotely in the visible optical range, in the Far Ultra-Violet (FUV) and in X-ray spectral regions. Depending on the space weather conditions, the aurora has different local shapes and the Auroral Oval (AO) expands towards the equator, and further down depending on the strength of the space weather events. For strong solar storms, the AO expands therefore to low latitudes as far down as 40° or 50° North (e.g., to latitudes lower than Washington or Germany). The underlying physics and space weather related effects have been investigated for decades now and are still subject to research, although a good understanding of the basic principles is achieved by now (see e.g. [1][2][3]). The challenge for an optical instrument that shall address auroral imaging comes with the ability of the instrument to cover a large field of view while spectral resolution and purity remain important whereas angular resolution may be modest. Observation of the aurora is therefore a non-trivial task.

2. MEASUREMENT OBJECTIVES

The ESA Aurora mission has the objective to provide continuous observation of the aurora borealis and australis to monitor the impact of the solar wind and CMEs on the terrestrial system caused by the modified flow of particles inside the Earth's magnetosphere and into the ionosphere. Imaging data shall be provided of the dayside and the nightside of the AO of sufficient quality to enable the determination of the strength, dynamics, location, and extent of the auroral region. This shall be enabled by measuring FUV and visible emission lines of the aurora. The observations shall be performed with sufficient spatial resolution and short enough sampling intervals to identify the location, extent, and dynamics of geomagnetic storms. Observations shall as a goal identify geomagnetic 'local' sub-storms and monitor their development and progression. The observations shall further enable the generation of a global electron precipitation map and derive also the electron precipitation power. The evolution of the mission concept is the result of several studies that finally converged to a mission in a Medium Earth Orbit at 6500 km altitude [4].

For the Aurora mission the Auroral Optical Spectral Imager (AOSI) and the Auroral far UV Imager (AUI) were baselined to monitor the auroral emissions. Many emission lines exist in the visible domain as can be seen in Figure 1. Only 4 to 6 lines are strong enough and suitable for the observations by AOSI, but other lines may be explored. However, observations in the visible spectral range are usually only possible in night conditions. AOSI is therefore conceived as a spectral line imager and used only in night conditions. AUI instead will measure the emission of several lines that are in the wavelengths range between 134 nm to 175 nm and measure the emissions of two bands. AUI is therefore conceived as spectral dual-band imager.

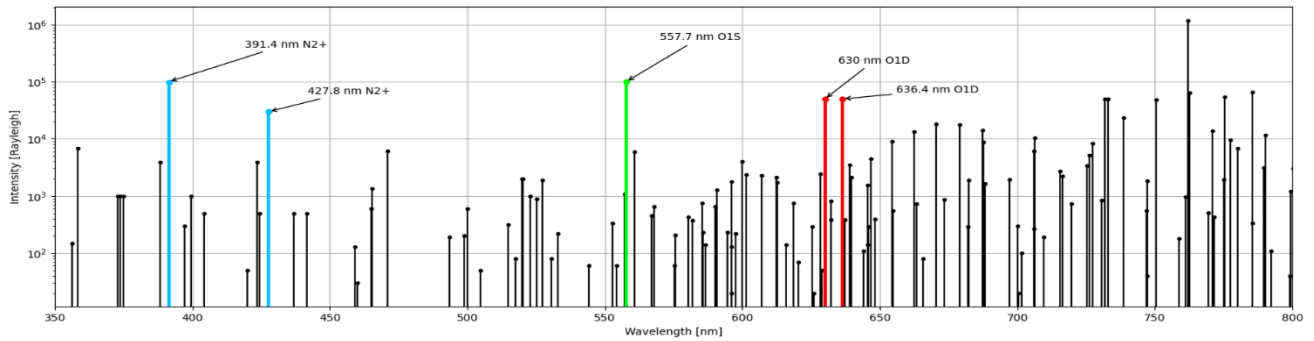


Figure 1 Auroral emission lines in the spectral range between 350 nm and 800 nm. The coloured lines are the targeted lines. The line at 760 nm may still be interesting but is currently not included in the design of AOSI.

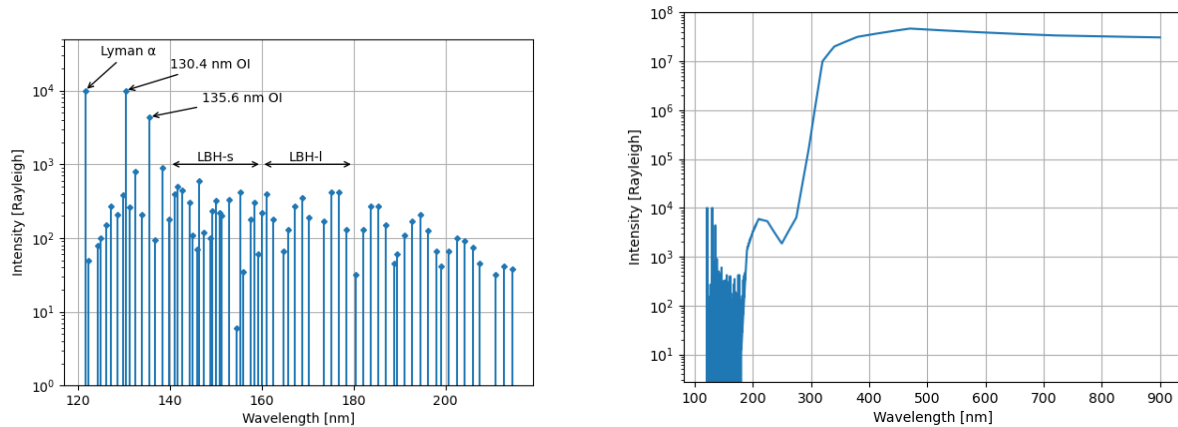


Figure 2 Far UV auroral emission lines (left) of the Lyman-Birge-Hopfield short (LBH-S) and long LBH-L (long) bands are typically used for determining electron precipitation power. The wider spectrum including the visible range illustrates the measurement challenge for AUI, since it has to suppress the visible part efficiently during day light conditions.

The emission spectra shown in Figure 1 and Figure 2 represent typical conditions with some nominal space weather activities. The range of intensity of the line emissions is between about 100 R and 100 kR if quiet conditions and strong storms shall be covered. For the Aurora mission emphasis has been put on the ability to achieve sufficient sensitivity for quiet conditions when weak emission line intensities at the lower end of that scale must be considered. The high intensity end drives the required dynamic range of the imagers.

These key mission objectives are driving the instrument configuration, and the mission design is effectively a trade-off between the orbital constraints and the imaging performance. After several iterations of the mission concept, it became clear that wide field auroral imaging is the key to achieving the objectives and that a FoV of about 50° to 60° is desirable to enable global monitoring with a coverage of lower latitudes while maintaining reasonable angular resolution. Further mission analysis showed that whereas the far UV imager should cover the full field of view, the optical imager may be restricted to about half the FoV since it will be able only to measure the night side of the Earth anyway. To capture sufficient fine structure of the Auroral Oval and to monitor the development of sub-storms, a target of 30 km spatial sampling distance (SSD) at nadir was set. The angular resolution was expected to be commensurate with the SSD. The corresponding evolution of the baselined instrument concepts is further elaborated below.

3. INITIAL WFAI INSTRUMENT CONCEPT

For wide field of view imagers, there is a principal trade-off that can be conducted that deals with the number of modules that may be employed. AUI was based on a refractive system, which was expected to be feasible for large FOVs. Therefore, no FOV segmentation was planned and instead 3 modules were planned to cover 3 different spectral bands. AOSI on the other hand was based on a micro lens array combined with a Fabry-Perot plate that would have difficulties providing suitable performance over such large FOV. A smaller FOV configuration allows the usage of smaller detectors and is less sensitive to straylight and can become a performance enabler. A modular approach also leaves some freedom for the FOV composition i.e. by having some freedom regarding the module assembly for different applications. When AOSI was developed, the main objective was to achieve a wide field of view with about 60° even though it was not yet certain, which orbit the mission would implement and what the exact FOV configuration would be. For Aurora a Wide Field of view Auroral Imager (WFAI) was baselined in an initial study that consisted of 12 modules out of which 9 modules of each 18.8° FOV made up the visible imager (AOSI) and 3 modules were targeted to perform the far UV observations in 3 bands each with 60° FoV. For AOSI a prototype with 3 functional modules was built (see Figure 3 right). The detector for the visible and far UV light was assumed to be the same detector (HDPYX 300). More details on that concept can be found in [5].

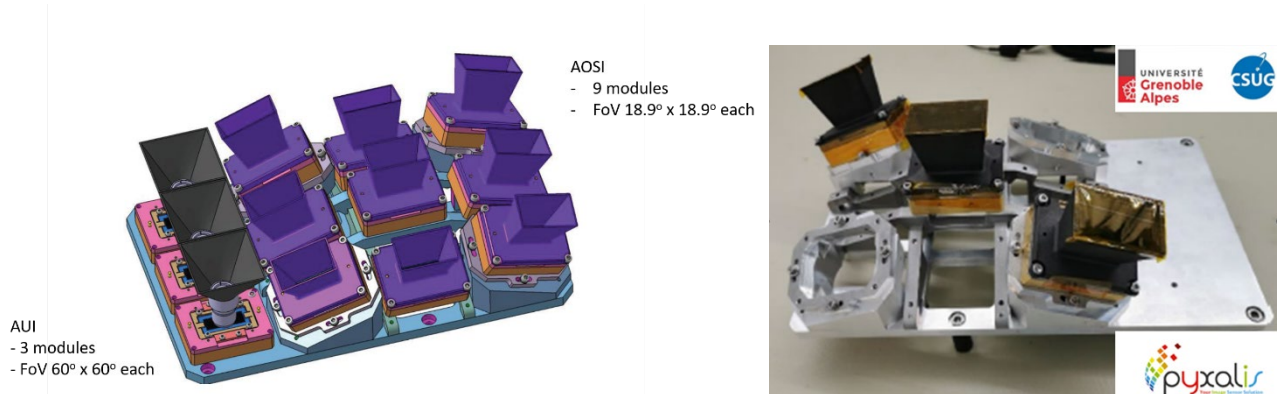


Figure 3 Initial Auroral Wide Field Imager design consisting of 3 AUI and 9 AOSI modules (left) and a prototype with 3 functional AOSI modules (right) that was realised.

4. CONCEPT ITERATION OF THE WIDE FIELD AURORAL IMAGERS

Further development of WFAI revealed that there was no good reason to maintain a single instrument. WFAI was therefore further decomposed and AUI and AOSI went their own development path with different prime contractors.

AUI design iteration

During the Aurora mission preparations, the AUI design was further elaborated, and the instrument development was combined with a technology development activity that had the objective to demonstrate the curving of detectors. The curving was expected to be beneficial since it would reduce the number of lenses that were necessary to achieve the expected imaging performance. Due to the transmission losses of the far UV light in the available lens materials (e.g. CaF or MgF), it is essential to reduce the total thickness of the lens material. One more essential critical point for AUI is the suppression of the visible light from the Sun illumination of the Earth that is required to allow measurements also under day conditions. The development of suitable transmission filters [6] was expected to suppress the visible light sufficiently so that the concept AUI was maintained with the assumption that 3 or 4 such filters (lens coatings) would need to be realized to achieve sufficient suppression. However, the loss of transmission in a single filter appeared to be significant (of the order of 90% loss) so that the final throughput of the instrument was very limited. Compensation of the loss of throughput by increasing the aperture of the imager was not possible since the lens material would increase too much when the aperture was increased. Effectively, such far UV imager cannot have a lens diameter much larger than 1 cm without losing too much transmission. In this configuration the refractive far UV concept did not match the sensitivity requirements of the Aurora mission. For that reason, the refractive instrument concept was abandoned.

Since the result was anticipated, ESA had looked into the possibility of developing a reflective concept as alternative. Based on a general review of compact far UV camera concepts by Spann [7] and some more elaboration and parametric analysis of some suitable designs made by Unick [8] it appeared to be feasible to employ a 4-mirror reflective design for AUI that would have enough throughput such that the radiometric sensitivity could potentially be achieved. An optical design was therefore derived by ESA together with an outline of a first instrument concept.

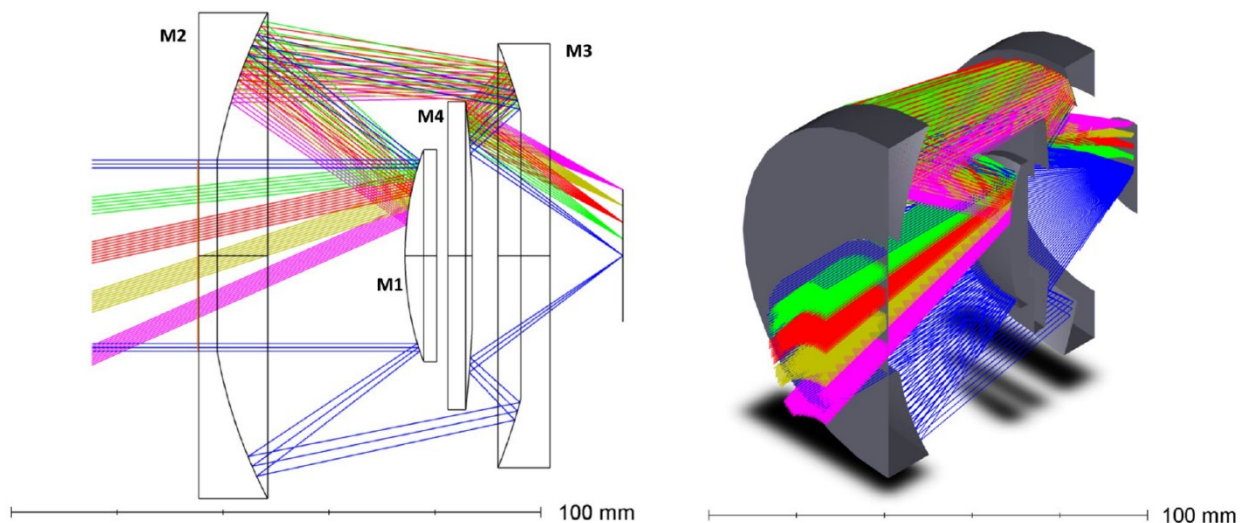


Figure 4 Initial 4-mirror design concept of AUI. The left image shows a layout of the optical design and right one a 3D illustration. The focal plane was planned to be located well behind the M3 mirror.

The optical performance of the design was tested across the FOV analytically and showed to be acceptable or even slightly better than expected. The optical throughput of such imager is between 15% and 20% and the effective aperture was expected to be at least between 15 and 20 mm with an acceptable vignetting. Further optimisations were performed that showed the feasibility of an even larger aperture diameters across the field. The angular resolution of such imager may even allow to target nadir spatial sampling and angular resolution corresponding to about 10 km.

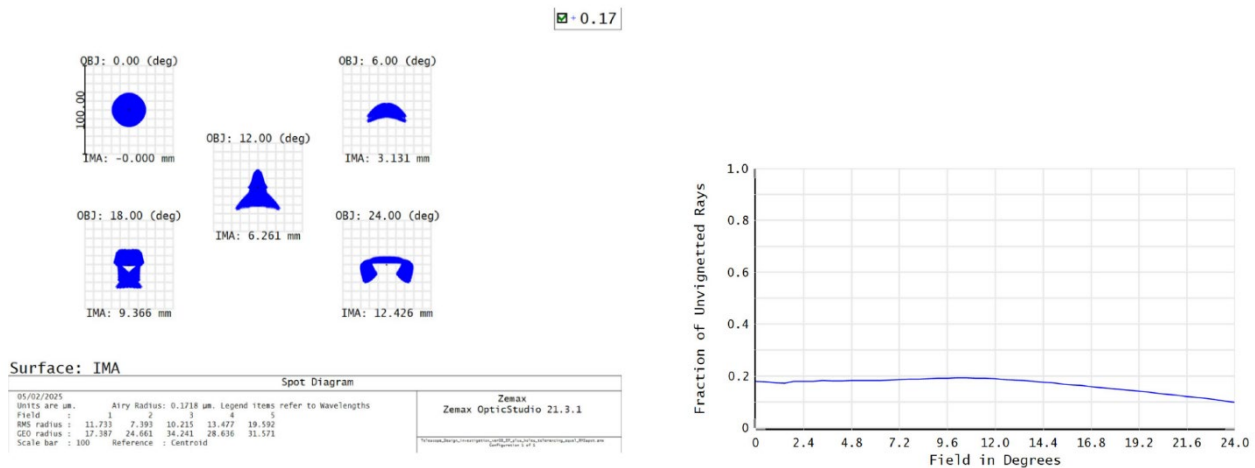


Figure 5 RMS spot sizes of the 4-mirror design across a FOV of $\pm 24^\circ$. The variation of the optical throughput (vignetting) is shown on the right figure.

The remaining key element for AUI was the required filter concept (visible light suppression) that would transmit the wanted signal and suppress the unwanted visible light. Fortunately, the SMILE mission was progressing in parallel for which a bandpass coating was developed [9] that was very similar to the filters that are required for Aurora. The reflectivity of such coatings can be up to 85% but depend on the angle of incidence. Since the angles vary significantly across the beam path as can be seen in Figure 4, an average transmission of about 60% may be expected but some variation across the FOV is unavoidable. Calculations of the coating / filter performance were performed to get a first feeling on the expected reflectivity for larger variations of the incidence angle. More detailed modelling of the response is required in future.

Although the suppression of four reflective filters is already good, it is not sufficient for the application. Former missions have therefore employed image intensifiers that are not sensitive to visible light by using photo cathodes that are not sensitive to photons in the far UV range mostly. The implementation of image intensifiers on the other hand is complicated, since the units are complex and require a high-voltage supply. Additionally, the dynamic range is limited and the gain setting sophisticated if a large dynamic range is required. Key element to avoid the image intensifier is the ability of further suppressing the visible light by about 5 orders of magnitude by another filter that would be similar to the suppression of an image intensifier. Since the transmissive filters that were foreseen for the refractive AUI concept are providing a very similar suppression function as the image intensifier, it was suggested to implement such transmission filter on AUI on a substrate that would be implemented in the optical path. Similarly, as for the reflective filters, the response depends on the incidence angle of the rays and since the variation of the angle is large as can be seen in Figure 4, a suitable position must be found where the variation of the incidence angle is smallest. One suitable position is between M2 and M3 but with the disadvantage that the filter area would be large. As the etendue is constant there might be other locations with smaller areas (e.g. in front of the detector) that may be considered but that would however come with some transmission loss. Further optimizations are required in future.

The detector of AUI was a crucial element for design considerations. The initial development of AUI was also based on the HDPYX 300 as for AOSI. The detector has a format of 2800 x 1088 pixels. For a FoV of about 55° with an SSD of 30 km at nadir corresponding to about 0.25° , the number of pixels is not large (about 250x250). With the prospect of going down to 10 km SSD a 1 Mpixel detector is more than sufficient. However, for the given optical design the image area is about $25 \times 25 \text{ mm}^2$ and it is not possible to reduce it assuming realistic optical parameters. That means for an SSD of 30 km, the number of pixels to be binned is about 10x10, and for 10 km 3x3. The accumulation of the read noise is significant but can be tolerated. It is noted that detectors with larger pixel pitch would be more suitable but hardly exist. HDPYX was discarded since its size was smaller than the required image area. Another reason was that the far UV sensitivity was not considered sufficient, and an enhancement would require technology development. For the given design a detector with a format of 2x2 Mpixels and 10 μm pixel pitch was indicated. The CIS120 detector from Te2V was identified therefore as a suitable candidate for AUI. Te2V has further investigated the far UV response of this type of detector, and it was concluded that the expected quantum efficiency of about 40% would be sufficient to meet the radiometric requirement of the Aurora mission. Since its performance and qualification status for space applications were also at the right level and

since it was also available with a Peltier cooling package, it was selected as a baseline. The degradation of the detector dark current due to gamma-rays and heavy ions is significant and needs to be considered for the end-of-life performance calculation.

ESA has developed a performance model for the imagers of the Aurora mission to forecast the expected performance and to verify if the mission requirement would be met [10]. The calculated instrument response looks quite promising as can be seen in Figure 6 where the response of the LBH-L module is shown.

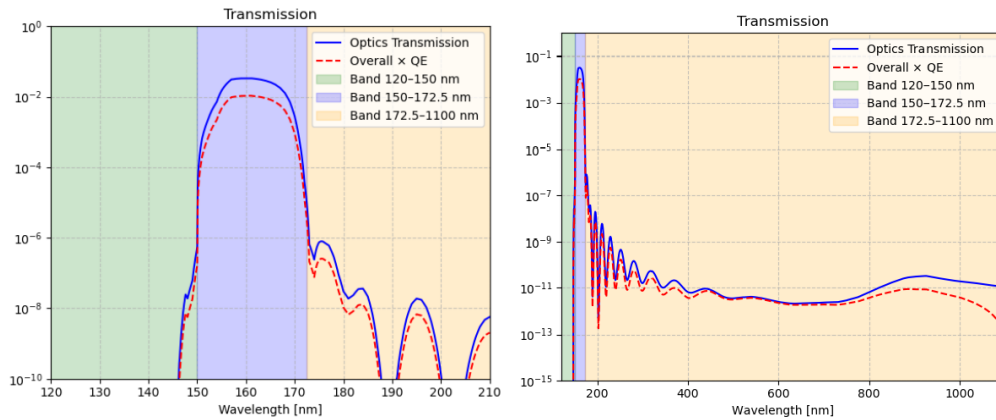


Figure 6 AUI response functions for 18° angle of incidence for the LBH-L module that target the spectral range from 150 nm to 172.5 nm. The linear plot (left) shows the band response and the logarithmic plot (right) the very good suppression of the visible light.

For the LBH-L module the achieved suppression is expected to be in the range of about 10%, which means that the unwanted light compared to the nominal light in the target band is small enough even under the most extreme measurement conditions (weak Aurora). The module targeting the Oxygen and LBH-S band performs even slightly better since its nominal band is located further towards the far UV and less affected by the visible light and would likely achieve suppression levels of about 1%. Performance modelling is usually performed for the worst-case condition, and it is predicted that the signal to noise ratio is about 3 in these conditions for an integration time of 1 minute. Achieving an SNR of 3 over the mission lifetime requires cooling of the detector down to about -10°C.

AOSI design iteration

After the pre-development activity with the 9x9 modules design was completed, a review took place and a redesign exercise was initiated. It was suggested to reduce the number of modules thereby easing the readout scheme by using a larger (Pyxalis GIGAPYX) detector which had better prospects for future implementation and more synergy with other space-related developments. The number of modules went down to 4 (2x2) as can be seen in Figure 7. Further analysis at mission level revealed that the power consumption and required satellite resources of AOSI with 4 modules would still be significant. It was further concluded that only two modules would typically provide useful data since the other two would observe mostly the sun illuminated part of the Earth. The observational strategy was subsequently further optimized and it was decided to reduce the number of modules to 2. This configuration was further elaborated.

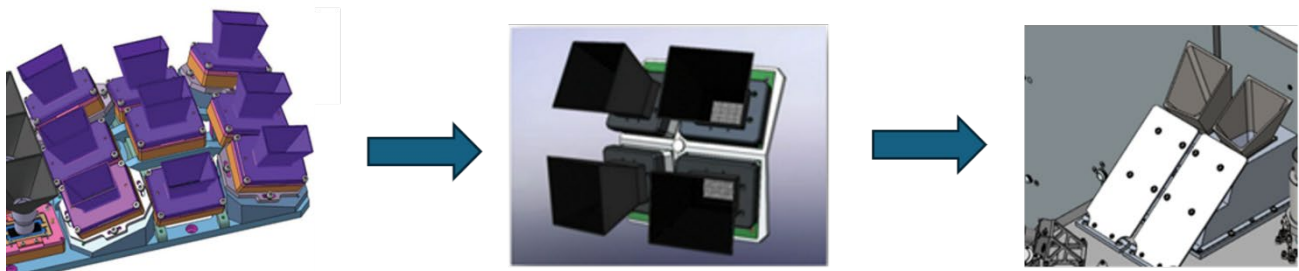


Figure 7 Illustration of the evolution of the module configuration of AOSI from 2017 until 2025.

The initial prototyping of AOSI has shown that the manufacturing and assembly accuracy of the components is challenging and that the performance of the spectrometer was difficult to maintain over the complete (detector) area of the spectrometer. During the Phase A/B1 ESA has therefore initiated a pre-development of the AOSI concept that was based on the GIGAPYX detector with a closer monitoring of the assembly process and involved uncertainties. The testing of the prototype was rather comprehensive and included some straylight tests and an investigation of the stability of the spectral performance under various environmental conditions such as temperature dependence and real light conditions by mimicking background sources expected during observations (moon). The development further matured and analysed the processing scheme of AOSI, which was not straight forward since it involved a Fourier transformation or alike methods to derive the spectrum from the Fabry Perot interferometer. Several algorithms were investigated and a least square method was identified as suitable, although the processing requires still a significant amount of processing time in the data processing unit. Although all the anticipated difficulties of the spectrometer appeared to be no showstoppers, there was one major drawback of the interferometer concept identified that was affecting mainly the duty cycle of the instrument, which was the inability to cope with the moon background. Although the spectral resolution is well below 1% and the background rejection is in principle very good, the detector of the instrument reaches its limit of handling the signal already at low background (moonlight) levels. A trade-off that was then conducted that took all aspects into account concluded that a concept based on linear variable filters would be better suited since the spectral resolution would still be sufficient to reject the background while the complexity and processing demand of the instrument would be reduced significantly. Therefore, the baseline concept was changed to an LVF based concept (see e.g. [12]). The actual impact of the design change on the thermo-mechanical design was limited since the change was mainly the replacement of the Fabry-Perot plate by the LVF.

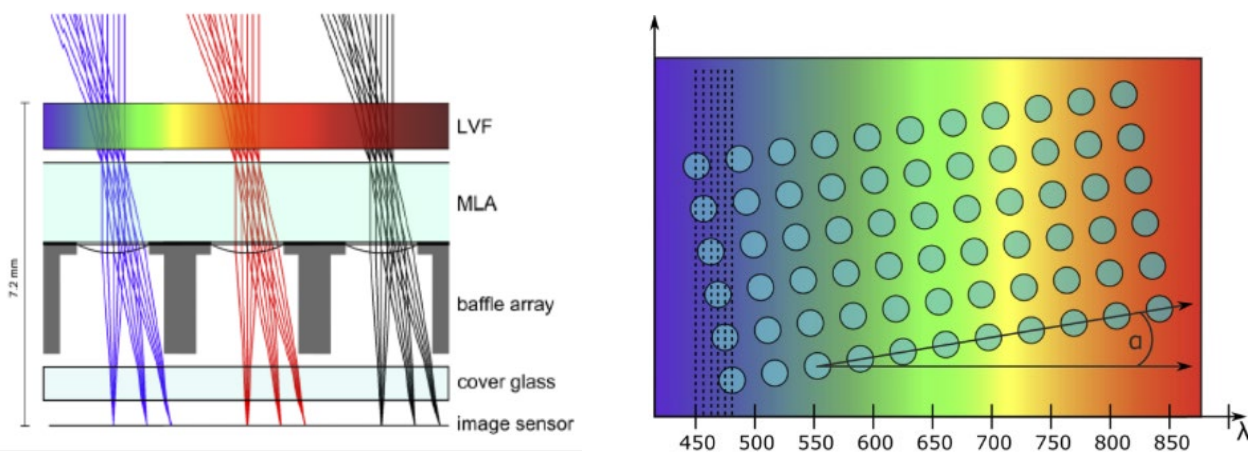


Figure 8 Linear Variable Filter concept (left) and configuration of the micro-lens array on the filter (right).

Performance calculations show that the expected signal collected by the multiple micro-lenses that are in the range of interest of the emission lines will provide sufficient radiometric performance and moonlight rejection capability such that the instrument duty cycle is not severely affected. Auroral emission can be measured also in quiet space weather conditions and weak aurora. An instrument prototype of the AOSI Multispectral Module is currently under development, and first results are expected soon.

SUMMARY AND CONCLUSION

This paper has summarised the development of the Auroral Imagers that took place over the last decade. It can be seen that the development of instrumentation for new space applications is a complex task and requires continuous iteration of the mission objective, the satellite and mission configuration and the instrument design aspects and their performance modelling. As a result of the developments that have taken place, it may be concluded that monitoring of the aurora with

small satellites and small instrumentation is possible, but it requires a very thorough implementation that takes all the aspects of the mission into account. The key instrument parameters are summarized in

Table 1 Key performance figures of the Auroral Imagers.

Parameter	AOSI	AUI	Comment
Spectral range	350 – 700 nm	130 – 145 nm (Module 1) 150 – 175 nm (Module 2)	Multiple apertures / wavelengths used for AOSI
Number of modules	2	2	
FoV	27.5° x 54°	50°	
Spatial sampling distance	30 km	30 km (10 km)	
Binning	2x2	10x10 (3x3)	
Angular resolution	0.25° to 0.5°	0.1° to 0.3°	Variation across the FoV
Effective aperture diameter	~1 mm	~20 mm	Multiple apertures used for AOSI
Focal length	1.9 mm	24 mm	

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