ASTRO*tir* – A compact, lightweight & multi-purpose thermal infrared camera

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ABSTRACT

In this paper, we introduce ASTRO*tir*, our latest camera development, which extends Jena-Optronik's ASTRO© camera product line into the thermal infrared wavelength range. As ASTRO*tir* aims primarily at different applications on small and medium satellites, it will be a compact, lightweight and multi-purpose thermal infrared camera. Furthermore, we will expand our heritage of highly-reliable space products to support long lifetimes in geostationary and lower Earth's orbits with ASTRO*tir*. Its target mass budget of 300g is the driving requirement. To obtain a compliant design, certain design aspects need to be mastered. In this paper, we will provide details of related design trades. Additionally, we describe our conceptual design and report on the currently running bread boarding activities. We conclude by providing an overview of the ASTRO*tir* development, its schedule and milestones.

1 INTRODUCTION

Jena-Optronik GmbH (JOP) [1] has a strong heritage in the development of cameras for numerous space-based applications. So far, our focus has been on cameras working in the visible and near-infrared range of the spectrum. Our main application case for these cameras is the use as autonomous star trackers being part of a satellite's Guidance, Navigation & Control System. JOP has been very successful with these cameras –for a long time and is the world market leader in providing such sensors to satellite prime manufactures and space agencies.

Investigating the possible applications of cameras in space, one realizes that thermal or long wave infrared (IR) cameras are necessary for specific applications. One major area for several of such applications is the field of Space Situational Awareness (SSA). SSA has been gaining more and more attention over the past years especially for space objects, natural debris as well as artificial threats and disturbances such as military conflicts. Two further application fields for IR cameras are formation flying and docking. The first rendezvous and docking with a non-cooperative satellite (Intelsat 901) in geostationary orbit by Northrop Grummans MEV-1 was a key milestone for docking capabilities [2]. Furthermore, the recent years have shown that a transition from few big and multi-purpose satellites towards small, medium or even large constellations consisting of numerous small satellites is taking place. Especially for constellations, a key aspect is formation flying which usually requires relative navigation. The relative angles between the satellites can be easily provided by IR cameras as they detect the satellites reliably and independently of local lighting conditions due to their elevated temperature against the cold space background.

Based on the very successful ASTRO© product range of space proven cameras, ASTRO*tir* (tir = thermal infrared) will extend JOP's product portfolio into the thermal / long wave infrared (LWIR) wavelength range to cover all of the applications cases listed above. Following a successful ESA co-funded first evaluation, the ASTRO*tir* development project has been kicked-off in cooperation with ESA in December 2022. The project is co-funded by the GSTP Mittelstandsinitiative. The target of this project is to demonstrate TRL8 of ASTRO*tir* using an EQM.

To summarize, future applications for ASTRO*tir* are formation flying (relative navigation), approach and docking with a non-cooperative space object as well as detailed image generation of near satellite objects. Currently, no European solution for an IR camera covering the application cases and mission scenarios is available as off-the-shelf product, which further increases ASTRO*tir*'s already promising market potential. As the market demand, especially in the field of SSA, is rising further in the coming years, ASTRO*tir*'s development is performed at the right moment in time.

In this paper, we will present in section 2 the challenge we were facing in the development with respect to the target mass budget of 300g. In the end, this became the driving requirement for the ASTRO*tir* camera design. Afterwards, we describe the conceptual design of ASTRO*tir* in section 3. An important part of the development is to get hands on physical models early. This allows engineers to get to know the camera early and find the best approach for feature implementations as well as to trade design choices and decision-making. Hence, we present in section 4 our bread boarding activities we have been performing so far. Certain ASTRO*tir*'s development aspects and its schedule are presented in section 5 of this paper before we conclude in section 6.

2 CHALLENGE OF LOW MASS

The LWIR camera concept has been developed following the different mission and marketing scenarios. The aim is to develop a versatile and easy to adapt design.

An initial mass budget revealed, that beside the mechanical structural components like housing and PCB circuitry the optics with its low f-number are driving the budget depending on the image diagonal and focal length. A first design approach with a PCB circuitry following the classical approach for a radiation hard and failure tolerant space electronics was ending up with about 2kg of total mass for the camera.

The electronics concept was driven by ESCC for EEE quality and qualification levels. It utilizes power supply, SpaceWire interface (SpW), an analogue read out electronics and providing FPGA based image-processing capabilities.

The initial camera concept was based on a classical space electronics of ECSS class 1 accommodated in a squared box with 120 mm side length. It showed a total mass budget of almost 2 kg for a camera using a wide field of view (FOV) lens system, which missed by far the mass target of 300 g desired by the market. Hence, the camera concept required a major re-work, which is described in the following.

On the one hand, the approach of the electronics development has been modified. To utilize ESCC based EEE components that provide high level of integrated functionality is usually a challenging topic in space applications. In order to support the desired low mass approach, an electronics architecture that considers EEE components with high level of integrated functionality is aspired. This includes a search for detectors with higher integrated functionality and the use of components not belonging to ECSS-Q-ST-60C Class 1 or 2. The idea is to use partly EP components and to screen those, equivalent to class 1 or 2 products in order to achieve the required high reliability of the product.

Overall Electronics Architecture

The overall architecture of the LWIR camera and its general hardware breakdown is shown in Figure 1. The number of electrical interfaces are minimized in order reduce the mass of the satellite interconnecting harness with the upstreaming electronic unit as well. There are two external electrical interfaces, one power interface for the camera supply voltage and one SpW Interface for telemetry/telecommand (TM/TC) and image data provision. A regulated DC input power from upstreaming electronics units is considered for the compact design of the camera electronics.

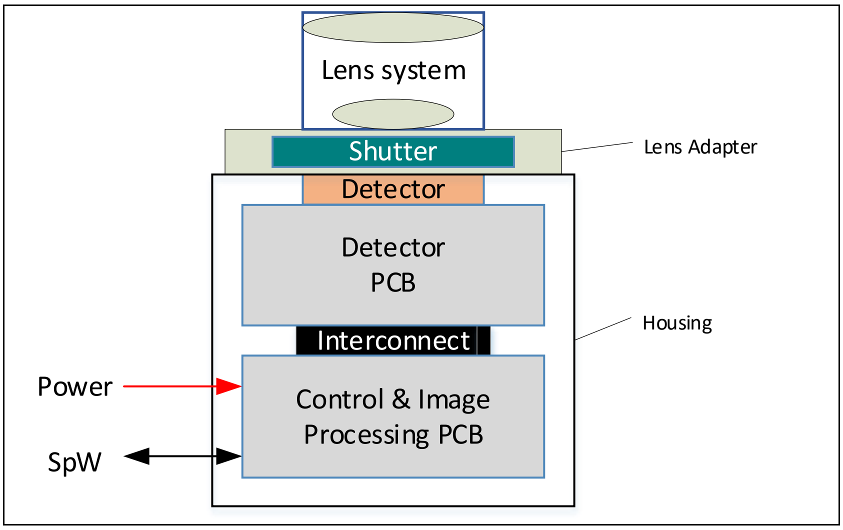


Figure 1. Schematics of the LWIR Camera

The electrical functions are partitioned onto only two small-sized printed circuit boards (PCBs):

- Detector PCB: It accommodates the detector and all the analogue circuitry that need to be placed closed to the detector interfaces;
- Control & Image Processing PCB: It accommodates the power supply generation for the detectors internal power supplies, the FPGA and its peripheral circuitry, and the SpW interface circuitry.

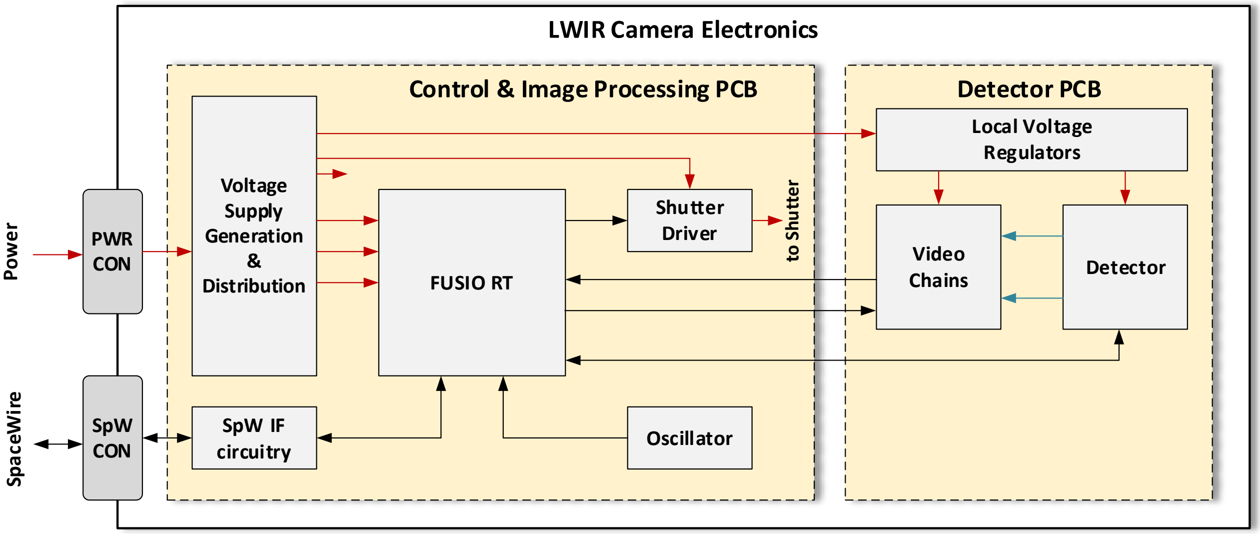


Figure 2. LWIR camera electronics scheme

The architecture of the LWIR camera electronics is shown in Figure 2. All electronics components shall fit onto two 70 mm x 70 mm PCBs to meet the goal of a compact and lightweight camera.

FPA infrared thermal detector

The detector used is an opto-electronic device sensitive to long wave infrared radiation (LWIR) based on microbolometer technology to convert infrared radiation into an electronic signal. It includes the microbolometer pixel array connected to a Read-Out Integrated Circuit (ROIC). A specific detector has been selected that provides a ROIC structure with all necessary on-chip analogue and digital functionalities to allow adjustable operation of the microbolometer array and pre-processing of the analogue output signals (e.g. gain selection, skimming). The block diagram of the detector device is shown in Figure 3.

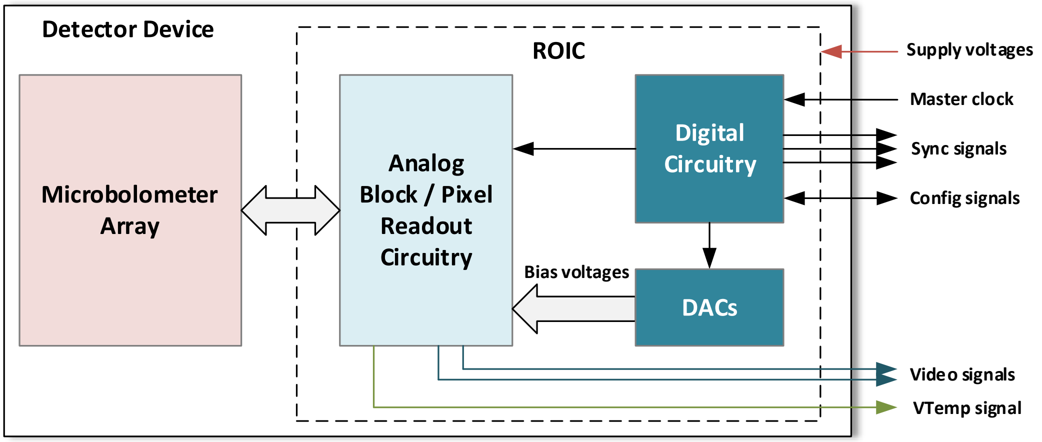


Figure 3. Detector block diagram

Detector parameters can be configured via ROIC digital interface and commanded via the camera SpW link. Configurable detector parameters are for example: windowing, gain selection, image flip, integration time adjustment and pixel bias adjustment. Pixel bias adjustment is provided by on-chip digital/analogue converters (DACs). This allows proper adjustment of the detector dynamic range depending on FPA temperature and scene dynamic. Modification of the readout gain is achieved by changing the integration capacitor in the pixel readout circuitry. This allows adaption of the detector electrical dynamic range to the analogue-to-digital converters (ADC) analogue-to-digital converters (ADC) analogue-to-digital converters (ADC) analogue-to-digital converters (ADC) analogue-to-digital converters (ADC) dynamic range. Thus, it reduces the complexity of the subsequent video chain, which should support gain switching otherwise. Furthermore, the detector includes an on-chip temperature sensor that allows FPA temperature measurement. Thanks to the supported ROIC functionalities, a small-sized FPA circuit solution is achieved. This allows flexible camera usage and proper performance adaption to the target application.

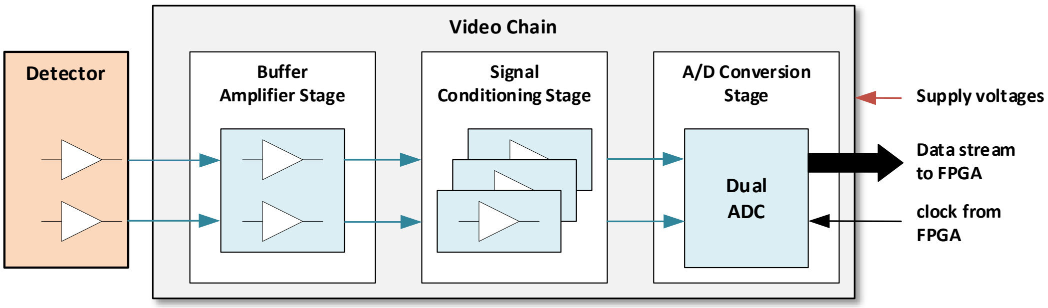


Figure 4. Video Chain Topology

Video chains

Figure 4 shows the video chain topology for analogue to digital conversion of the detector output signals. There are two video chain paths necessary, one per detector output signal. In order to reduce circuit complexity and consequently board area, a challenging selection of appropriate video processing EEE components suitable for space application is required. The selection was mainly driven by bandwidth and noise performance, package compactness (preferred dual amplifiers in one package), and low power operation (operation at low supply voltages respectively). The video chain comprises a buffer amplifier stage, a signal condition stage, and the analogue-to-digital (A/D) conversion stage. The buffer amplifier stage provides decoupling of the detector output amplifiers thereby limiting the current that needs to be provided by the video chain to the specified limits.. This avoids distortions of the detector video signals. For this stage an appropriate dual-amplifier providing small-sized package was selected. The signal conditioning stage is in charge of proper video signal adaption to the ADC input requirements and filtering for noise suppression. A dual-channel ADC device was selected, which provides two independent ADC in one package. This significantly reduces the populated board area in order to achieve the targeted compact video chain design. Moreover, the selected ADC features a nominal resolution higher than 14 bits, a very low-noise performance, a sampling rate higher than 20 Msps and an operation with low supply voltages. It is therefore well suited for application in the target LWIR camera. Thanks to the crucial selection of appropriate EEE components a video chain design with two signal paths is achieved that provides both very compact design and required video performance without impacting the detector performance.

FPGA based camera controller and image processor

To reduce the complexity, weight and cost of the electronics, the highly integrated FPGA based processing module FUSIO RT has been selected. It is responsible to fulfil all required communication, processing and control tasks required for the LWIR camera. The FUSIO RT module comprises a reprogrammable space grade SRAM based FPGA and highly reliable embedded memories: a 128 Mbit configuration memory and optional processing (2 Gbit SDRAM) and data storage memories (64 Gbit NAND Flash). These hardware functions are integrated into one single module with miniaturized package. Therefore, the selected FUSIO RT module significantly reduces board area and supports the small-sized low-mass camera approach.

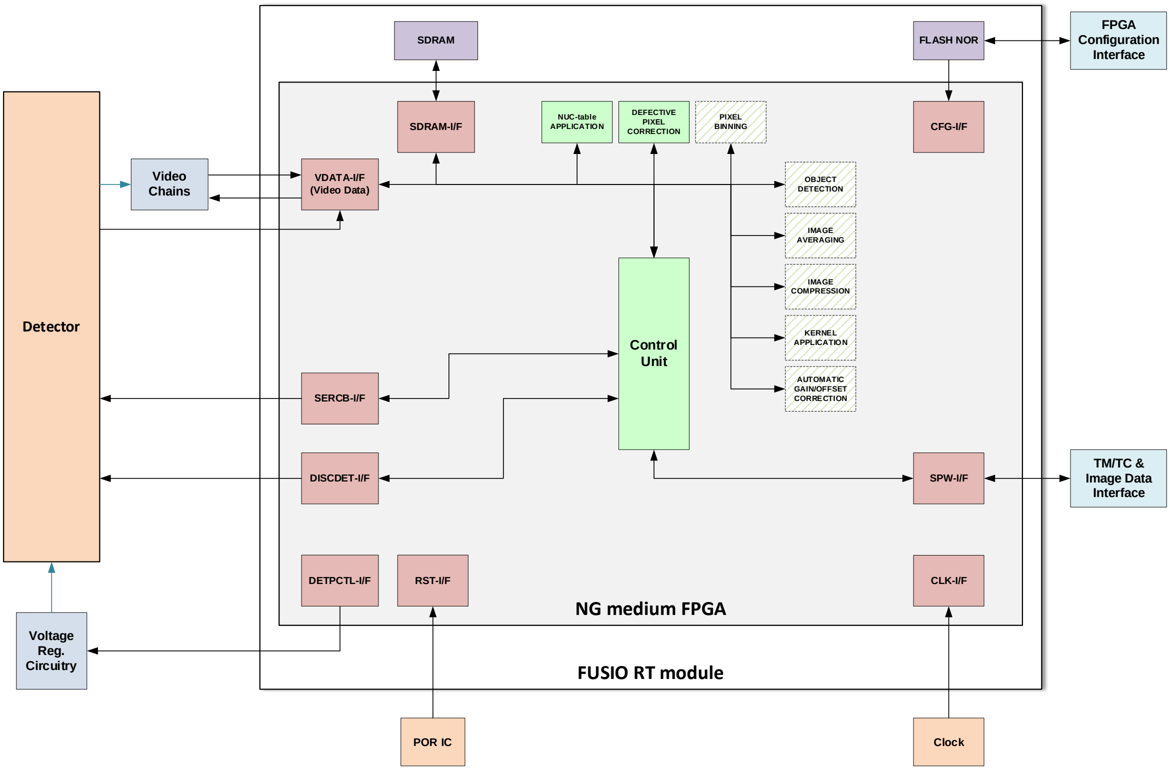


Figure 5. Block diagram of the FUSIO RT based camera control and processing architecture

The block diagram of the FUSIO RT module based camera control and processing architecture is shown in following Figure 5. A radiation hardened NG medium FPGA device, which provides sufficient gate capacity and digital signal processing resources, is embedded into the FUSIO RT module. Thanks to the FUSIO RT based architecture high flexibility and high processing performance is achieved.

SpaceWire Communication

The standardized remote memory access protocol (RMAP) is used for the TM/TC management between the LWIR camera and the upstreaming electronics unit via SpW. The RMAP provides write to and read from TM/TC memory inside the camera. The RMAP will be basically implemented in accordance to ECSS-E-ST-50-52. Some tailoring might be beneficially in order to cover specific characteristic and constraints in close cooperation with the customer. Furthermore, a proprietary streaming protocol is implemented to stream the image data to the customer. The use of a streaming protocol for the video data greatly reduces the requirements on the real-time capabilities of the satellite on-board computer (OBC) and complexity of the SpW communication in general. Unlike the RMAP protocol, the streaming protocol works asynchronously to the OBC. This means that the end user does not initiate the transmissions.

Pixel and Image Processing

Due to the implemented processing and data memory capacities of the camera electronics, not only the mandatory pixel processing algorithm but also an optional advanced image processing algorithm is provided. While mandatory algorithms are always available, a set of the optional processing algorithms will be implemented on customer demand. Image processing algorithms are implemented in dedicated processing cores.

The following pixel processing algorithms are implemented:

- Defective Pixel Correction
- Non-Uniformity Correction.

These mandatory algorithms have to be implemented in order to provide thermal infrared image with sufficient SNR for machine vision and visual application.

Additionally, there are two more algorithms available for the user of the ASTRO*tir* camera.

- Pixel binning
- Region-of-Interest (ROI) selection (for data rate reduction if necessary)

Optional processing algorithms, which offer advanced image processing functionality for anticipated application scenarios of the LWIR camera, are for example:

- (Repeated) Arbitrary Kernel Application (This functionality can be used to implement pre-processing steps, which are part of a more complex algorithm, e.g. applying a filter for edge detection)
- Image Averaging
- Lossless Image Compression
- Automatic Gain/Offset Scaling

These advanced image processing functionalities are configurable and can be completely bypassed.

Optical lens configuration

As mentioned earlier our development goal was to reduce the mass to a few hundred grams.

We considered different detector sizes and its implications on the lens design and especially on its mass. Preliminary optical designs have been developed and a total lens mass (lenses + Mounts) has been estimated, see Figure 6. Larger image diagonals or image circles driving the optics diameter and therefore the mass. Small detector diagonals can be realised with smaller lenses for the same FOV but they do have the drawback of a lower resolution. Refractive IR optics tend to have a higher mass compared to optics for the visible wavelength range, due to the high density of IR glasses/materials. Germanium with 5.3 g/cm³ and the chalcogenide glasses IG2/IG4 (~4.4 g/cm³) are at the top end of optical material densities. The low F# in the order of 1 to 1.5, typical for IR lenses, further demand larger optics diameters, increasing the lens mass even further. Additionally, the need of a larger back focus distance to allow the installation of mechanical shutter also result in an increase of lens diameter which result in a quadratic mass growth with the diagonal of the detector.

Figure 6 shows the estimated total lens masses for different detector diagonals considered. The right hand side of Figure 6 offers a clear favourable configuration w.r.t. to the resolution per solid angle of the optics. It shows that wide angle optics tend to be more lightweight even for SXGA resolution with 12 µm pixel pitch than those with narrow field of view. The camera design limits the image circle to 10 mm in combination with an extended detector size of 1280 x 1024 pixels to minimize the optics mass and therefore the total camera mass. This approach visualized in Figure 7 allows using flexible image formats (quadratic, rectangular or even round) and provide less limitations on the total mass requirements for future applications.

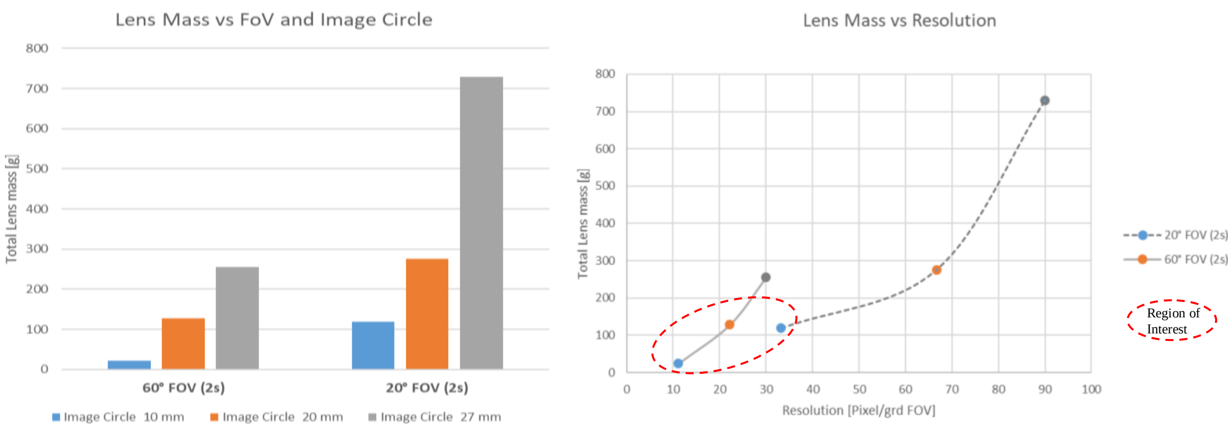
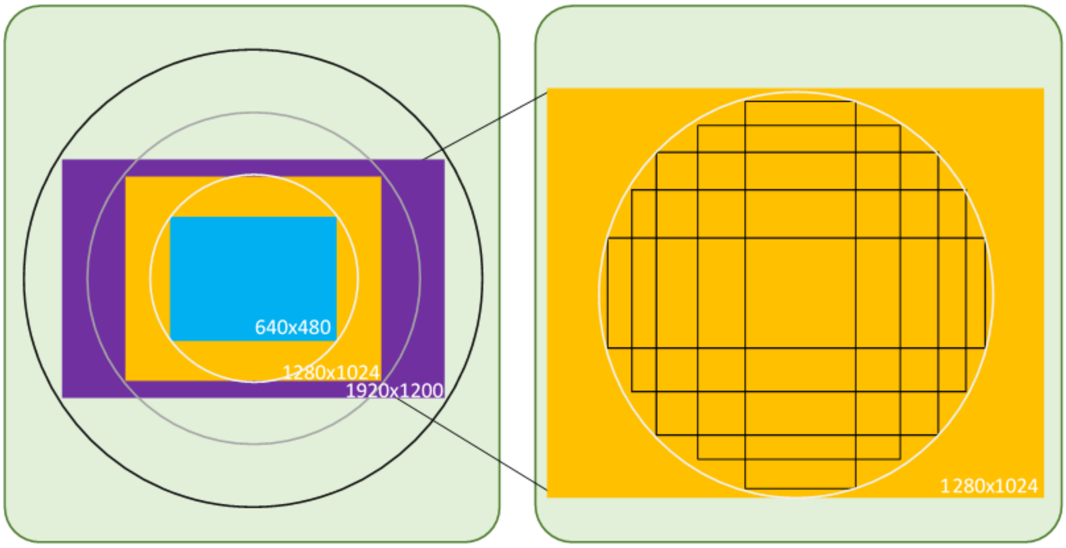


Figure 6. Total lens mass (Optics + Mounts) for different Field of views and different detector diagonals

In general, small lens systems with a small image size can be used with larger detectors to maximise information or to implement variable image formats. One of the biggest advantages of such a configuration is that the detector does not need to be aligned w.r.t. the line of sight (LOS). This alignment and/or configuration can be performed electronically after the final assembly during the optical test of the camera. The considerations and design decisions sketched in Figure 7 lead to a very compact camera design shown in Figure 8. The optical head has a quadratic layout with 80 mm length in X- and Y-direction. The total height varies from 52 mm with the wide angle 60° FOV lens to 76 mm with a 20° narrow FOV lens.



a) Schematics of different Detector vs. Imaging Size of the Optics. A small lens systems can work with larger detectors to obtain the same image information as with a small detector.

b) Ideas of a variable image formats. A small lens systems with a small Image size can be used with larger detectors to maximise information or to use variable image formats.

Figure 7. Schematics of image size and format w.r.t. detector diagonal

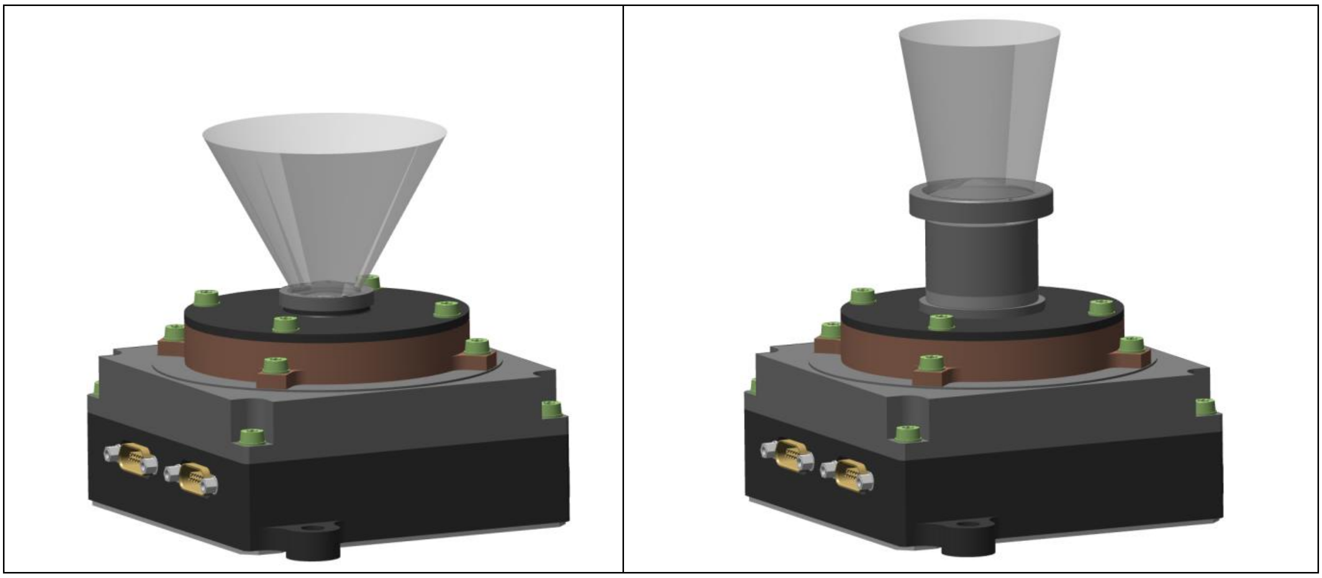


Figure 8. ASTRO*tir* camera with 10mm detector diagonal used with wide (left) and narrow (right) field of view optics

The camera’s mass budget is now compatible with market demands, which demands for small and midsize satellites lightweight cameras with less than half of a kilogram, see Table 1. The optics mass is ranging from 10 to 16 percent depending on the chosen angle of view. With less than a kilogram stereo metric flight configurations with two cameras can be realised.

Table 1: Mass budget of ASTRO*tir*

Component	Estimates Masses Wide FOV 60°	Estimates Masses Narrow FOV 20°
unit	g	g
Mechanics Box	170	170
PCBs	120	120
Bits and pieces	20	20
Optics	30	60
Total mass	**340**	**370**

3 ASTROTIR CONCEPTUAL DESIGN

Low mass and high performance are key features driving the conceptual design shown in Figure 9. Furthermore, the aim of that project is to develop a camera, which is capable in providing LWIR pre-processed imagery for easy usage and minimizing spacecraft or ground processing activities. The camera shall have a low power consumption target of less than 7W. Additionally it shall have a high thermal resolution of 50 mK and a MRTD (minimum resolvable temperature difference) of about 1 K for high lateral frequencies. It will have a modular design allowing the use of lenses with different focal length and different field of view. Even though low mass has driven the conceptual design mostly, those other important parameters cannot be neglected, leading to design decisions and affecting mechanical and assembly, integration and test sequences.

A goal of the design approach is to avoid alignments as much as possible. LOS adaptation will be realised purely electronically. This is a big advantage w.r.t. assembly and testing schedule. As mentioned above, this is achieved by the use of an oversized detector. Despite of all lateral tolerances of the optical active area w.r.t. the mechanical packaging, the assembly will be done without any alignment simply as “plug and play” assembly.

Figure 9. ASTRO*tir* product rendering. It has a quadratic layout with 80mm length in X- and Y-direction.

The configuration of the LWIR camera is variable not only in terms of the selected field of view. The customer may decide whether the camera needs a sun illumination protection shutter or not, see Figure 10. As the microbolometer performance is affected from sun irradiation. Pixels illuminated by the sun light degrade in performance for up to several months. In order to avoid this, the possibility to equip der LWIR Camera with a state-of-the-art opto-mechanical shutter device is given. If the mission perspectives are met with traces of the sun burned into the detector matrix the camera can be used without. Depending on the profile of the mission it is possible that the sun never illuminates the detector or only for short periods of time per pixel. Details have to be assessed and to discussed with the customer.

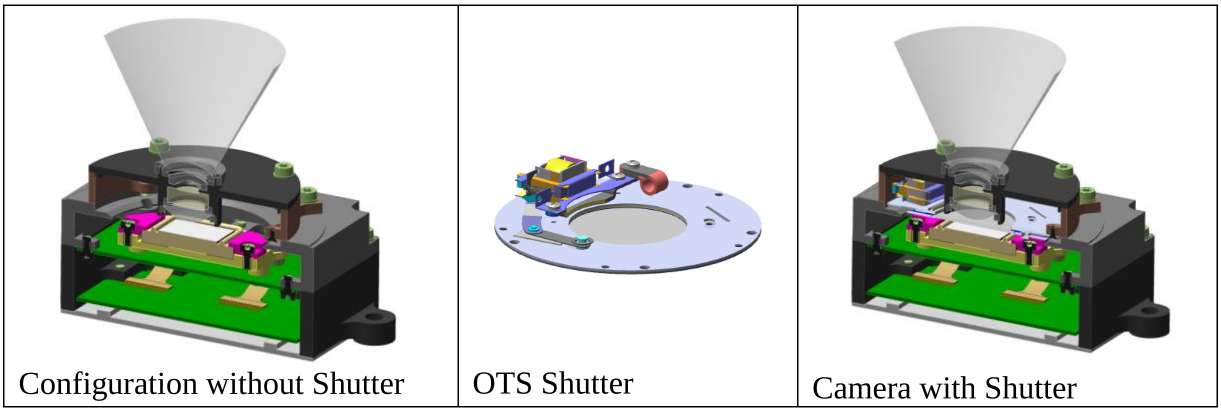

Configuration without Shutter
OTS Shutter
Camera with Shutter

Figure 10. LWIR Camera Shutter configurations

The selected shutter is a vacuum ready of the shelf assembly and has been flown twice in a similar configuration in the past. On ground lifetime testing revealed an operation of 6 million opening and closing cycles. The shutter is open by default without an electrical current through the voice coil actuator. It can be commanded using the SpW interface via TC.

By means of this shutter, the detector can be protected against “sun burn”, when the camera is pointing towards the sun. Another purpose of the shutter is to allow making a one point non uniformity correction of the pixels. Since there is a variation of the pixel response to thermal infrared radiation a correction of this effect needs to be performed with the image data. This can be done on ground for different FPA temperatures by means of two uniform blackbody scenes at different temperatures idealy being as much as possible located at both ends of the observation intervall. Fore each pixel a set of coefficients will be calculated and made available to the FPGA. The FPGA can therefore correct all pixel with individual gain and offset values for each FPA temperature.

Since the space environment is expected to vary the detector response due to aging effects, those coefficients may change over the mission lifetime. In order to compensate those effects the shutter may be used to correct at least varying offset data by providing a kind of dark image for the actual

FPA temperature.
The design will be based on passive thermal heat dissipation towards the S/C mechnical interface, see Figure 11. Heat generated mainly by the FPGA, power regulator and the detector will be transferred towards the housing down to the spacecraft interface at the bottom. Heat pathes are the PCBs for the EEE components mounted directly to the PCB. The detector will conduct its heat of less than half a Watt directly into the aluminium housing, since the mechanical fixation of the detector does show the lowest thermal resistance when compared to the electrical connection to the PCB. In order to ease the handling during AIT the detector will be mounted with two connector sockets to the PCB. Qualification of these connector sockets has to be considered and is one of the contributions to the small and lightweight concept of the camera.

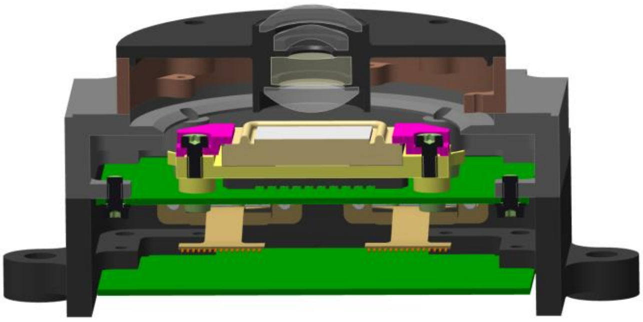


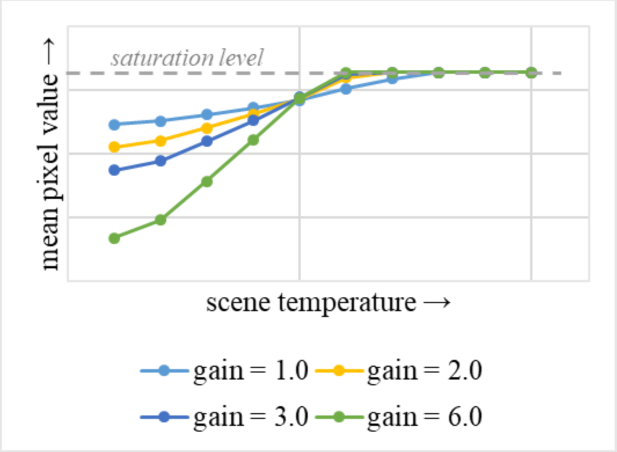
Figure 11. Detector assembly to LWIR camera assembly

4 ASTROtir BREADBOARD

The major motivation for the breadboard activity is to get to know the most essential hardware, its detector, early as well as to learn more about the behaviour of a thermal camera in general. The breadboard is available much earlier than any other hardware model used in the development program because it uses commercial proximity and readout electronics to drive the detector and produce image data. This allows focusing onto the specific detector behaviour under various environmental conditions and detector configurations states. A dedicated test program has been created and is currently being carried out, which allows an objective and comprehensive analysis of the detector behaviour in a reproducible manner and controlled environment. The breadboard uses as detector the same uncooled microbolometer array that is used in the ASTRO*tir* design. Besides this detector, the breadboard is composed of a commercial proximity board with USB interface, a commercial lens and a 3D-printed housing, see Figure 12. The commercial proximity board allows a simple operation of the breadboard with a PC and digital controls. The commercial lens uses optical elements made out of germanium, has an f-number of f/1.2 and an effective focal length of 7.5 mm. The structure of the breadboard is provided by a 3D-printed housing, which holds all individual components in place. Using a dedicated software the detectors behaviour and performance can be manipulated easily. Variable parameters of the detector are e.g. the gate voltages, the integration time and the integration capacity. The acquired images can be further processed in order to evaluate the characteristics of camera performance.

Figure 12. Photo of the ASTRO*tir* breadboard. Within the 3D-printed housing, one can see the commercial lens in the front as well as a shutter mechanism slightly behind and above the lens.

In the breadboard test program, various tests are carried out to determine the best camera operating point for the camera system. This includes the determination of the best dynamic range with respect the temperatures occurring in the intended application cases. By changing the various tuneable parameters of the microbolometer array, the detector characteristics can be adapted. The following figures represent measured data clearly showing the influence of the different electronic detector parameters that change the detector characteristics.



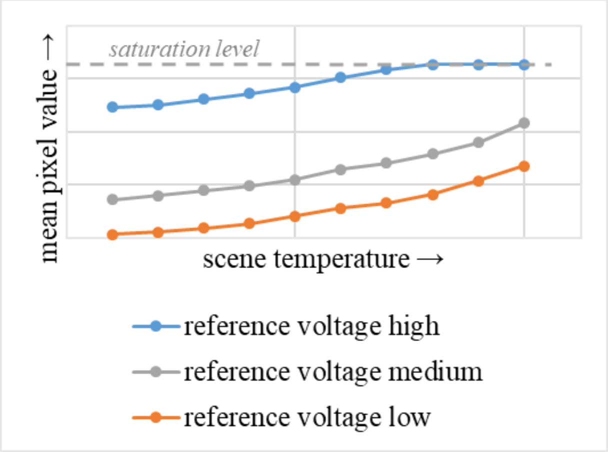


Figure 13. Detector response vs. scene temperature for different gain parameters

Figure 14. Detector response vs. scene temperature for different reference voltages

Figure 13 represents the detector response (the mean pixel value is calculated as a measure of the detector response) versus different scene temperatures, where each trace is determined with another detector parameter set. For each trace, one specific parameter is varied. The sensitivity of the detector is determined by integration capacity used, which is a variable detector parameter. Thus, the resulting variable gain is reflected in the different slope of the measurement curves. Hence, the saturation level is reached at different scene temperatures and the dynamic range is expanded or limited. As Figure 14 shows, tuning the reference voltages has an impact on the offset of the measurement curves. In consequence, using a higher reference voltage will also lead to faster saturation.

As a key characteristic of thermal imagers, the thermal resolution is investigated by determining the noise-equivalent differential temperature (NEDT) and the MRTD. A further influence to the detector behaviour and performance is determined by the FPA temperature. As the detector heats up during operation, a static situation is reached only after a certain time of active operation of the camera. Until then, the FPA temperature is changing, which leads to different effects. Such FPA temperature variations will most likely occur during the cameras operation in orbit as well. Hence, we plan to perform extended tests with respect to the detector behaviour with changing FPA temperature.

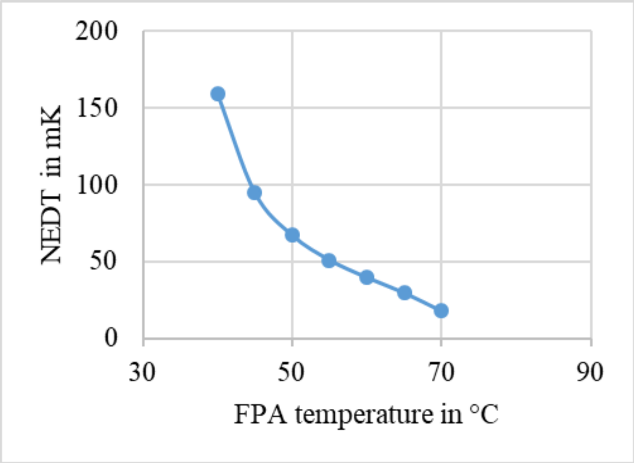


Figure 15. Noise equivalent differential temperature vs. detector temperature

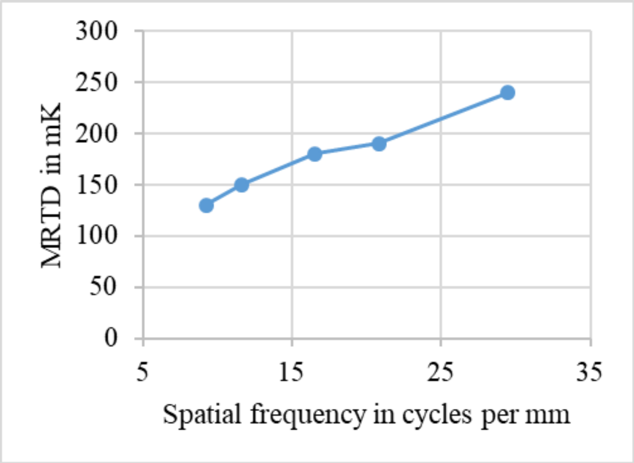


Figure 16. Minimum resolvable temperature difference vs. spatial frequency

First results of already conducted tests are shown in Figure 15 and Figure 16. It should be mentioned that the data originate from partially approximated and interpolated measurement points. Nevertheless, it is evident that the performance with respect to the thermal resolution is highly dependent on the FPA temperature. Because of the limitation of the resolution by the sensor pixel size, the MRTD is influenced by the object size.

The various breadboard tests are also used to develop an adequate algorithm for calibrating the LWIR camera. For a successful calibration, it is necessary to correct the non-uniformity, defect pixels and the dependence of the camera temperature itself. This calibration process shall ensure that high performance images with low noise and a high thermal resolution can be acquired. Figure 17 to Figure 20 illustrate the difference between the raw image of a homogenous scene and a USAF-1951 test pattern (left) and the corresponding calibrated images (right). It is obvious that the raw images have significantly worse image quality than the images corrected using the NUC due to the superposition of the so-called fixed pattern noise. Calculating the spatial noise (2-dimensional standard deviation of the pixel values) of the homogenous scenes and applying a NUC reduces the noise from 1604 DN to 57 DN (DN = digital number, a total bit depth of 16 bit leading to DN = [0…65535]). Looking at the images of the USAF test pattern, one even subjectively perceives an immense improvement in contrast, image quality and thermal resolution. This punched test pattern is used to determine the spatial and thermal resolution power such as MRTD.

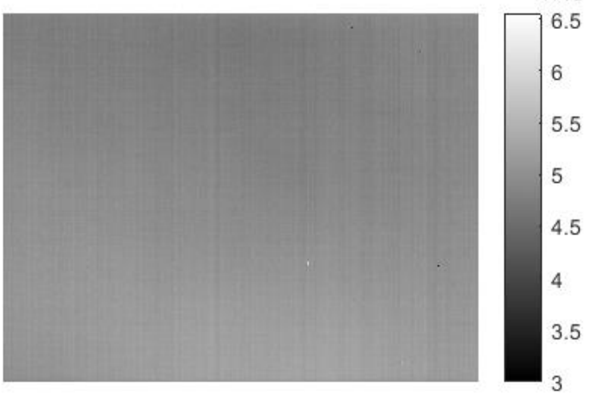


Figure 17. Homogeneous scene before NUC (spatial noise equals 1604 LSB)

Figure 18. Homogeneous scene after NUC (spatial noise equals 57 LSB)

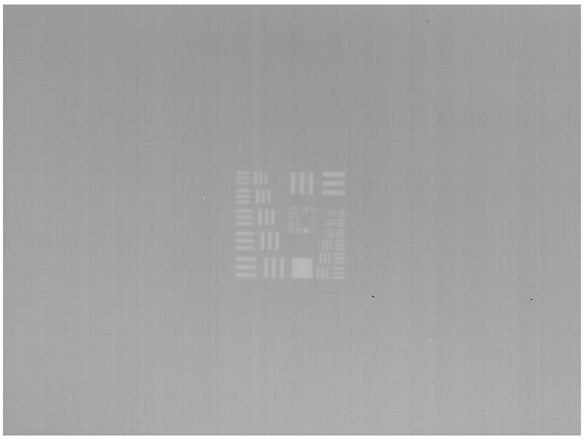


Figure 19. Image of USAF test pattern before NUC

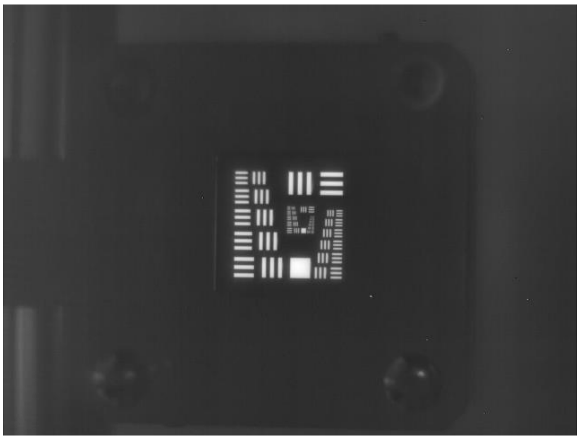


Figure 20. Image of USAF test pattern after NUC

Figure 21 shows a thermal image of a 3D-printed model of the International Space Station attached to a flange with threaded rods. Its main body consists of polyamide, the solar panels are made of carbon fibre. The image shows how different materials reflect different temperatures. In addition, temperature gradients are also visible on the respective parts, so that test object can still be interpreted as a 3-dimensional object. The great advantage of thermal cameras is that artificial objects in space can be detected even without light in the visual range, since they usually emit thermal radiation at a temperature significantly higher than the cosmological background radiation equal to about 3°K.

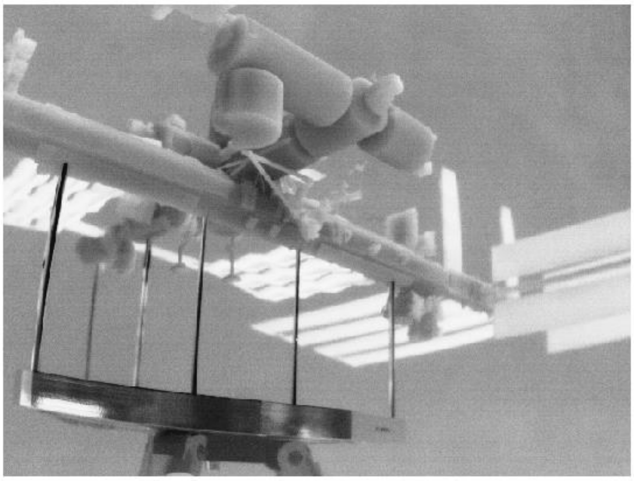


Figure 21. Thermal image of a 3D-printed model of the International Space Station

5 ASTROTIR DEVELOPMENT ASPECTS AND SCHEDULE

A major goal for the ASTRO*tir* development is to finish the development within 36 months. This has two main reasons. First, as application cases for ASTRO*tir* already exist, market demand increases and no European of the shelf solution of a compact, lightweight and high reliable thermal infrared camera is available, an early market entry holds the opportunity for a good market population, leading to increased sales. The second reason for a short development time is given by the co-funding scheme, which supports only 36 months activities separated in three 12 months long funding periods. Each period needs to be finished successfully before the funding for the next period is released.

In consequence of the project duration aspect, we tailored the established processes for instrument developments to our needs. One might say that this shows aspects of the so-called “New Space approach”. However, as long as different definition for this terminology are used it always has to be explained, what in particular is meant by it. One aspect we focussed on is to get hands on experience with critical hardware early. Hence, we started very early with our bread boarding program described in Section 4. Furthermore, we combined early hardware availability with a further goal, which is to minimize configurations by using the same design for the EM and the EQM. As a result, our EM activity starts with the assembly and integration slightly after the design phase ends. This is visible in the development overview presented in Figure 22. Procurement activities for the EM start as early as possible during the design phase to optimize the overall project duration. The EM campaign focusses on learning the assembly, integration and commissioning of the ASTRO*tir* camera and ends with functional tests. These tests act not only as a first indication for the camera performance and behaviour but also act as a quality gate for our ground support equipment, related software and scripts to perform such tests. Furthermore, we use the EM to finalize our procedures for the tests, the assembly, the integration and the commissioning steps. Once the EM campaign ends the EQM campaign starts. We expect to have slight adaptations in the EQM campaign compared the EM campaign .This might be related to design aspects but also cover the assembly, integration, commissioning of the EQM, which lead to adaptations of procedures, software or the ground support equipment. Hence, a certain adaptation time is foreseen in between the EM campaign finish and the EQM assembly and integration start. The EQM campaign will mirror the EM campaign but will be extended by an environmental test program acting as qualification program for the design. The qualification program includes the following tests: vibration, shock, thermal vacuum and EMC and ESD with performance test at the beginning, end and in-between the environmental tests.

The full timeline of the ASTRO*tir* development is presented in Figure 22. The development started late in 2022 and the design phase will end in Q2 of 2024. Overall, the development foresees an EM and an EQM mentioned above. The EQM will be used to reach TRL 8 in 2025. In consequence, FM production can start end of 2025. We expect to have a lead-time below 12 months for FMs in a batch of up to 12 units. Hence, FMs in this baseline option can be delivered by end of 2026. One can even imagine an even earlier FM production running in parallel to the EQM campaign with several weeks offset. This approach carries more risk than the baseline option but will lead to much earlier FM delivery dates. It has the potential to save several month in the first FM delivery date, which will be early in 2026 in this case.

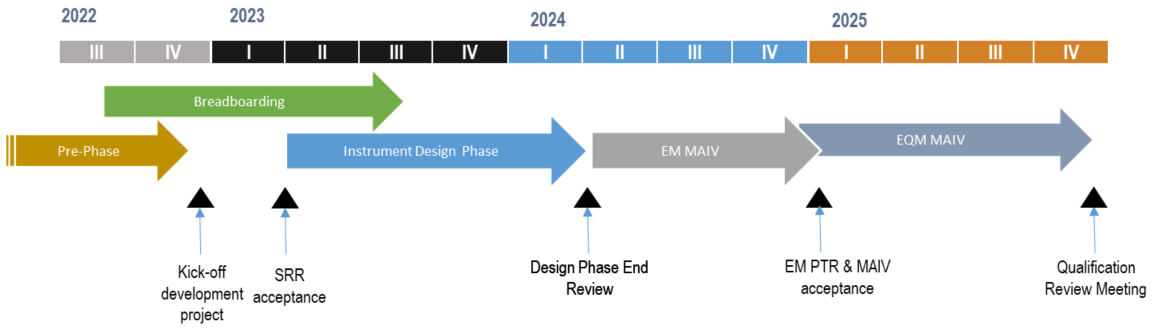


Figure 22. Development overview of the ASTRO*tir* thermal infrared camera

6 SUMMARY AND CONCLUSION

In conclusion, we have presented a conceptual design, certain challenges we already mastered, our essential bread boarding activities and relevant development aspects for our new thermal infrared camera ASTRO*tir*, which will extend Jena-Optronik's ASTRO$^{©}$ camera product line beyond the visible wavelength range. Furthermore, with ASTRO*tir* a unique European compact and lightweight thermal camera multi-purpose solution with long lifetimes in the harsh space environment will be available for the first time.

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7 REFERENCES

[1] Jena-Optronik website: www.jena-optronik.de

[2] Matt Pyrak, Joseph Anderson, "Performance of Northrop Grumman's Mission Extension Vehicle (MEV) RPO imagers at GEO," Proc. SPIE 12115, Autonomous Systems: Sensors, Processing and Security for Ground, Air, Sea and Space Vehicles and Infrastructure 2022, 121150A (6 June 2022); https://doi.org/10.1117/12.2631524