AIRBUS ROBOTIC TELESCOPE AND SPOOK AS TEST-BED FOR SPACE-BASED SPACE SURVEILLANCE

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ABSTRACT

In June 2018 Airbus deployed the Airbus Robotic Telescope (ART), a $40\,\mathrm{cm}$ aperture telescope equipped with a CCD detector and an UBVRI filter wheel, located in Extremadura, Spain. Since 2018, the telescope has performed observations for research and within the scope of several studies for national, European and international customers. Furthermore, it has been added into the list of observatories of the Minor Planet Center (MPC) of the International Astronomical Union (IAU). The astrometric accuracy of ART has been determined for different observation scenarios during calibration campaigns and is continuously confirmed during each observation night to assess the data quality. ART operates in combination with the Special Perturbations Orbit determination and Orbit analysis toolKit (SPOOK), a versatile software framework developed at Airbus. SPOOK provides the complete set of tools necessary for an end-to-end SST cataloguing pipeline.

For the ESA SBOC Phase B2 activity, this test pipeline is employed as an important element for validation of an image processing prototype. The space-based SBOC/VISDOMS mission aims at the detection of small objects with high relative angular velocity. For the validation step, at the beginning of 2023 ART has received an upgrade with the installation of a camera with a large CMOS detector, enabling wide FOV, high sensitivity and high frame rates, similar to the one intended to be used in the SBOC flight model. In combination with the ART upgrade, image simulation capabilities have been added inside SPOOK to simulate scenarios that cannot be covered by ground-based sensors.

The paper will focus mainly on the performed upgrade on ART, the current status of the Image Simulator inside SPOOK and their applicability in the development of space-based surveillance capabilities.

Keywords: SSA; SST; Space Situational Awareness; Space-Based SSA; VISDOMS; SBOC; ART; Airbus Robotic Telescope; SPOOK; Image Simulator.

1. INTRODUCTION

Within the field of Space Situational Awareness (SSA), Airbus Defence and Space is developing technical solutions for Space Surveillance and Tracking (SST), which does also include the development of a space-based sensor. Within these activities the Airbus Robotic Telescope (ART) and the SST software suite Special Perturbations Orbit determination and Orbit analysis toolKit (SPOOK) are used for multiple aspects, ranging from generating real-world data to the simulation of complex SSA-systems. This paper provides an updated overview of ART and SPOOK with focus on their applicability in the development of space-based surveillance capabilities.

1.1. Airbus Robotic Telescope (ART)

ART (Figure 1) is a $40\,\mathrm{cm}$ aperture telescope designed for automated optical observations of space objects from Low Earth Orbits (LEO) to Geostationary Earth Orbit (GEO). The telescope is located in Extremadura (Spain), a region known for favourable weather conditions, low light pollution and low concentration of atmospheric particles. The telescope operations are handled remotely by the Airbus SSA team in Friedrichshafen with a high degree of automation.

ART was initially deployed in June 2018. At this time it was equipped with a CCD detector. In 2020, an UBVRI filter wheel was installed on it, which enables images to be taken in different wavelength ranges.

Since the commissioning of ART, it has proven its performance capabilities in multiple surveillance and tracking campaigns [1].

In addition to this performance as a ground-based telescope, ART is used as a testbed to demonstrate new detector technologies and processing algorithms intended for space-based surveillance. (see subsection 2.2).

Proc. 2nd NEO and Debris Detection Conference, Darmstadt, Germany, 24-26 January 2023, published by the ESA Space Safety Programme Office
Ed. T. Flohrer, R. Moissl, F. Schmitz (http://conference.sdo.esoc.esa.int, February 2023)

Figure 1. Airbus Robotic Telescope (ART)

1.2. SPOOK

The Space Surveillance and Tracking (SST) framework of Airbus Defence and Space in Friedrichshafen revolves around the multi-purpose software tool called SPOOK [2]. Its capabilities include the following tasks:

- End-to-end cataloguing chain (observation planning, tracklet linking, correlation, initial orbit determination (IOD) and orbit determination (OD), catalogue creation and maintenance).
- Astrometrical sensor calibrations using Global Positioning System (GPS), Galileo or International Laser Ranging Service (ILRS) objects as reference.
- Light curve generation and object characterization from optical observation data.
- Conjunction assessments, incl. probability of collision computation.

In its latest upgrade, SPOOK has received extended image simulation capabilities (see section 4).

2. SPACE BASED SURVEILLANCE

Space-based surveillance could be used to complement ground-based SSA sensors by filling existing capability gaps and by reliably providing observation data. It can provide better observation conditions in terms of availability, coverage, accuracy and timeliness due to the unique observer position and to the lack of disturbance factors such as weather conditions, atmospheric distortion and the day and night cycle. This is contrasted with technical challenges such as position uncertainty and vibrations.

The projected advantages have led to a growing interest in space-based sensors by private businesses, as well as governmental and military users [3].

ART and SPOOK offer a ground-based test facility and tailored processing algorithms and simulation capabilities to enable the efficient development of space-based sensors and are currently used in the context of a planned ESA mission (see section 2.1) as well as to develop a space-based optical sensor in the course of the European activity Sensors for Advance Usage & Reconnaissance of Outerspace situatioN (SAURON).

2.1. SBOC / VISDOMS Mission

Airbus Defence and Space develops the SBOC-instrument as part of the ”Space-Based Optical Component: Further Development of a Hosted Optical Payload, Ground Segment Preparation, and Streak Detection Algorithm Finalisation” B2 activity for ESA. SBOC is an optical payload, intended to be used as payload for the ESA VISDOMS-mission (Verification of In-Situ Debris Optical Monitoring from Space). Main goal of this mission is to improve the knowledge on the distribution of small debris in LEO, which cannot be detected by ground-based sensors. For this, the SBOC instrument combines a large field of view with a high detection performance, enabling it to detect small and faint objects with large angular speeds. The large field of view improves the coverage and allows a rough orbit determination of the detected objects. The mission shall operate on a sun-synchronous orbit, pointing towards anti-Sun direction (Figure 2). A secondary goal is the surveillance and tracking of objects in higher orbits.

The ongoing Phase B2 study is led by Airbus Defence and Space GmbH (Germany) with support by CGI UK, TOPTEC Centre from the Czech Republic and ASRO from Finland. The main goals are:

- Instrument preliminary definition including requirements consolidation and maturation of the design to achieve system SRR and PDR.
- Further development and de-risking of the on-board and on-ground image processing software.
- Development of a detection and processing chain demonstrator using simulated and real-world images and performing end-to-end tests of the image processing software.

2.2. Simulation of the End-to-End Debris Detection Pipeline

The Phase B2 SBOC study includes the development and validation of the E2E processing chain, from image acquisition to tracklet linking.

To allow characterisation of the detected small debris and to enable a coarse orbit determination of these objects SBOC uses a high image frame rate. In combination

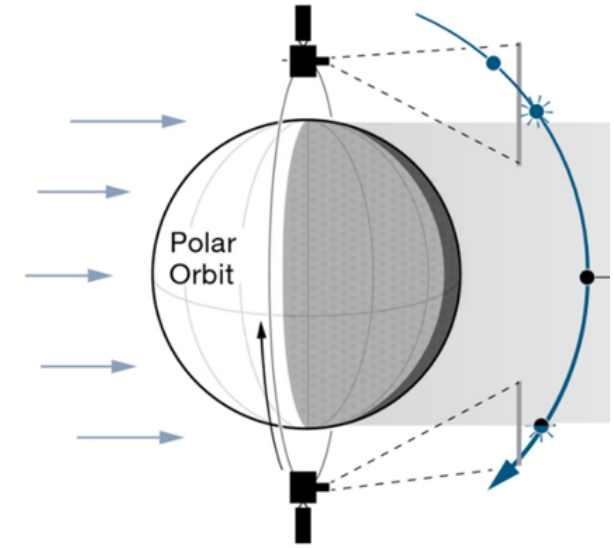

Figure 2. Typical surveillance scenario from a Sun-synchronous orbit

with the large image size, this excludes the possibility to transmit the raw image data to ground with the bandwidth available. It is therefore necessary to already perform image processing on board to reduce the amount of data, without losing any relevant information. The full pipeline is therefore split between on-board and on-ground:

- On-board:
  - Extraction of stars and regions of interest from the frame.
  - Data compression of the frame
- On-ground:
  - Data decompression of the frame.
  - Extraction of features from the regions of interests identified on-board.
  - Astrometric and Photometric reduction.
  - Tracklet Linking.

For the validation of this approach, the E2E processing chain is emulated. For the generation of raw image data two complementary solutions are used:

- The generation of real world images using ART, which will be upgraded to generate images similar to the flying model (section 3). The images will be used to challenge the processing algorithm with the complexity of real-world image content.
- Simulation of images with a newly developed software tool. Those will be used to test the impact of all relevant effects and will allow flexibility with respect to different scenarios. (section 4).

3. UPGRADES TO AIRBUS ROBOTIC TELESCOPE

In support of the SBOC activity, ART has received an upgrade in early 2023 with the installation of a new detector with a large CMOS sensor. With the new setup, the FoV of ART was nearly doubled and the sensitivity as well as astrometric performance has been further increased. The new setup is currently being commissioned and tested. This upgrade allows the generation of real-world data as close as possible to the actual flight model of SBOC.

4. IMAGE SIMULATION CAPABILITIES IN SPOOK

The Image Simulator inside SPOOK is able to generate realistic frames of passive optical systems as they would appear from a ground or space location. The simulator is highly configurable, in particular it is possible to set:

- Instrument parameters (e.g. aperture, FoV, F-number, PSF, optical distortion, transmissivity, etc.).
- Detector parameters (e.g. number of pixels, pixel physical size, type of detector, shutter type, detector noise, faulty pixels, etc.).
- Platform parameters (e.g. the vibrations due to the pointing AOCS system in case of space-based sensor).
- Scenario parameters (e.g. epoch, sensor location, pointing direction, exposure time, number of images, frame rate, number of objects crossing the FoV in each frame including their position and velocity, star catalogue, cosmics density, etc.).

4.1. Characteristics of images generated by space based sensors

Images generated by space-based sensors are typically affected by additional effects compared to images generated by ground-based systems. Some of these effects are assessed in more detail in later subsections of the papers:

- Cosmic rays (see subsection 4.6).
- Micro-vibrations due to AOCS.
- Scene rotation (if nadir pointing) of 360 degrees per orbit.
- Higher velocity of the observer compared to a ground-based one (causing a larger impact of orbital aberration).
- Objects with very high relative angular velocities (in the order of degrees per second).

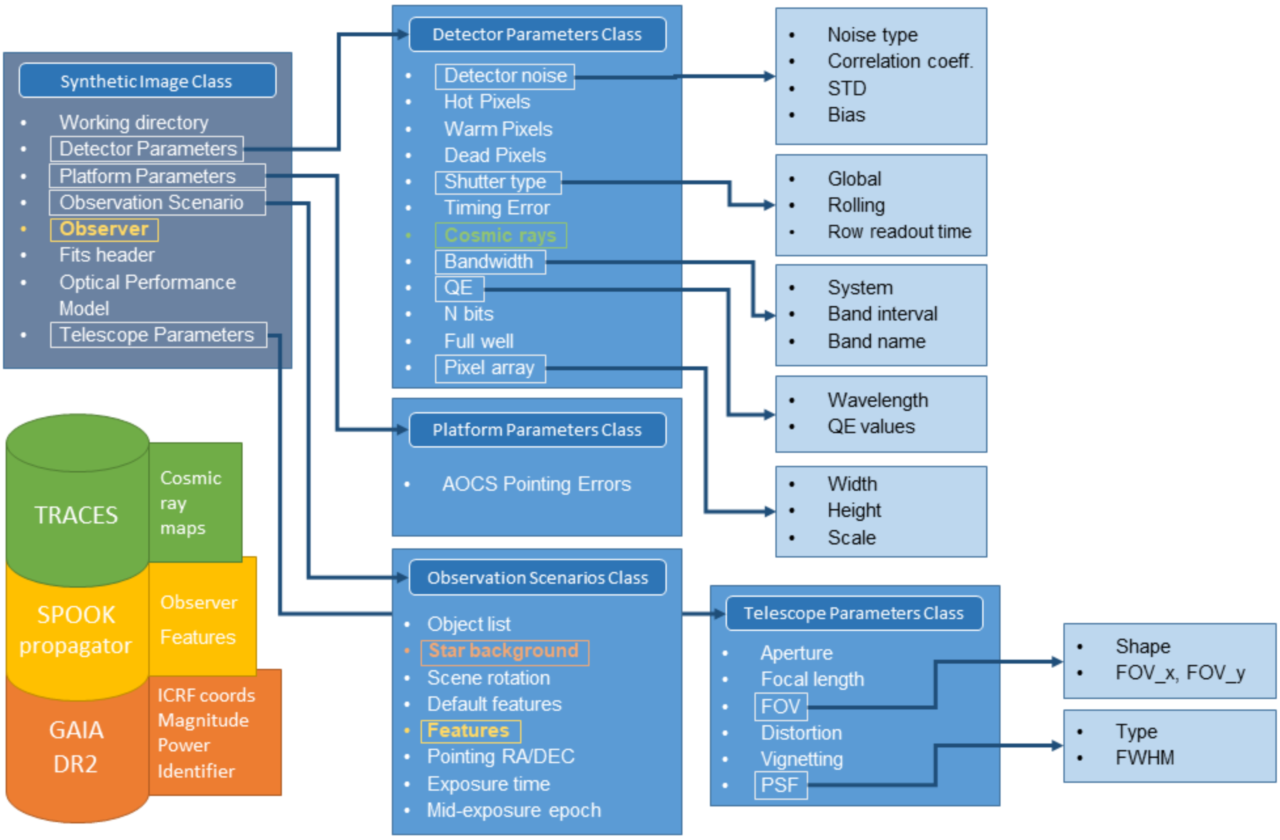

Figure 3. Class organization for the Image Simulator.

There are some effects that occur only on-ground and they are not affecting space-based images.

- Atmospheric refraction (see subsection 4.7).
- Clouds.

Some other effects occur independently on the sensor position:

- Detector related effects, like shot noise, readout noise, hot pixels, etc. (see subsection 4.8).
- Time offset due to the shutter (relevant in case of rolling shutter, see subsection 4.5).
- Time delay due to a bad synchronization of the GPS receiver.
- Annual aberration.
- Binning.
- Windowing.
- Optical distortion.
- Vignetting.

4.2. Architecture

The Image Simulator is fully written in Python and can be run as a standalone tool. However, some functionalities utilize modules pertaining to the SPOOK core. These include:

- Measurement simulator, to identify if and when a simulated object is crossing the FoV at any time during the simulation period.
- Photometry functions, to identify the optical properties of a simulated object when crossing the FoV (in particular magnitude and SNR).
- Orbit propagator, to propagate the orbit of the simulated targets and observer for the full simulation period (if space-based sensor).
- WGS84 functions, to calculate the exact position of the observer on the Earth surface at any time given latitude, longitude and altitude (if ground-based sensor).

The current class organization chart of the Image Simulator is shown in Figure 3.

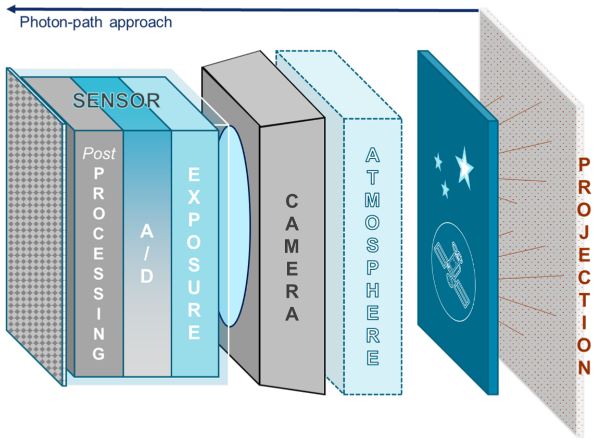

Figure 4. Block representation of the modelling principle for the Image Simulator

Effects are modelled sequentially and digitally reconstructed to mimic the physical phenomena as they occur in real life:

1. The model utilizes a Gnomonic projection to represent the features.
2. Data on brightness/position of object is collected and corrected in the right reference frame, brightness calculations and background noise models are applied.
3. Atmospheric effects are applied (Scintillation and Refraction).
4. Observation errors/defects are corrected, such as pointing errors, parallax and relative motion.
5. During the exposure phase, vignetting and cosmic ray maps are applied, along with signal-dependent noises (see subsection 3.7).
6. After the A/D conversion, readout noise and reset noise are applied.
7. Finally, binning is performed and potential time tag errors are applied.

Figure 4 shows graphically these phases.

4.3. Star generation

The Star generation constitutes one of the critical parts that has a large impact on the final performance. In fact, in one of the steps of the E2E Processing chain (see subsection 2.2), the image is astrometrically solved only if a minimum number of stars is correctly identified inside the image (this is necessary to compensate the effect of optical distortion and small pointing misalignment). In this way the position of each object other than stars is calculated with respect of the position of the identified stars in the image.

Moreover, the stars should be simulated in the image not only in the right position, but also with the correct brightness, in order to perform photometric calibration.

The catalogue used for the star generation is the GAIA DR2 catalog, released in 2018 and based on data collected for 22 months between 2014 and 2016. This catalogue includes almost 1.7 billion of sources, most of which are stars with known astrometrical coordinates and magnitude [4].

The WCS module inside Astropy in Python allows to convert right ascension and declination into pixel coordinates. The energy received from each star is then computed based on its magnitude, its temperature and the optical properties of the telescope. Finally a 2D gaussian spread function is used to spread the energy into the nearby pixels starting from the computed pixel coordinates. Special attention is paid to the non-sidereal observations, where the pointing direction is changing, and so the stars do not appear as point-like. For this particular case, more advanced models are used.

4.4. Feature generation

The features re-use most of the functionalities of the star generation (in particular the WCS module for the conversion between astrometrical coordinates and pixel coordinates and the function to compute and spread the energy in the pixel matrix).

But some extra issues arise:

- In a space-to-space observation, the distance of the object can be very small (in the order of km), and its distance (and consequently its relative angular velocity and brightness) can change not only between one image and the following, but also inside the same image during the exposure time. That might create object streaks that are curved and/or with non-uniform brightness (see Figure 5).
- In case of a rolling shutter, this affects the position of the objects in the image, so this effect must be compensated. This effect is described in more details in subsection 4.5.

These two effects are currently taken into account in the Image Simulator.

4.5. Rolling Shutter

The shutter is the component of a camera through which the lens aperture of a camera is opened to make the light

Figure 5. Example of curved streak with a 40% variation of brightness over the exposure.

enter. That allows to customize the exposure time of the image.

Two types of shutter exist in optical detectors:

- Global Shutter, where all the rows are exposed for the same exposure time simultaneously.
- Rolling Shutter, where each row is exposed for the same exposure time, but at different times as the readout sweeps through the sensor.

Figure 6 shows the full readout process for the two types of shutter.

The Rolling Shutter is the type that causes more issues.

In case of Rolling Shutter, the position of the streak in the image is not the one expected at the "recorded" time of the image, but with a time offset depending on the row number (the first and the last row have respectively the most negative and the most positive time offset). Since a streak typically covers more than one row (in case of fast objects it might be hundreds or thousands of rows), the time offset might change significantly between the start and the end of the streak, and this effect is taken into account in the simulator.

Figure 7 shows an example. The two frames represent the same scenario, the one on the left with global shutter and the one on the right with with rolling shutter. The epoch of the global shutter image (same for each row) is equal to the epoch of the middle row of the rolling shutter image (so the rows above have an earlier epoch and the rows below have a later epoch). Seven streaks can be identified in each of the two images:

- The three horizontal streaks (No.1, No.2 and No.3) are not affected in terms of length (since they do not cover more rows), but they are affected in terms of position (in the global shutter case they are aligned, in the rolling shutter they are skewed).

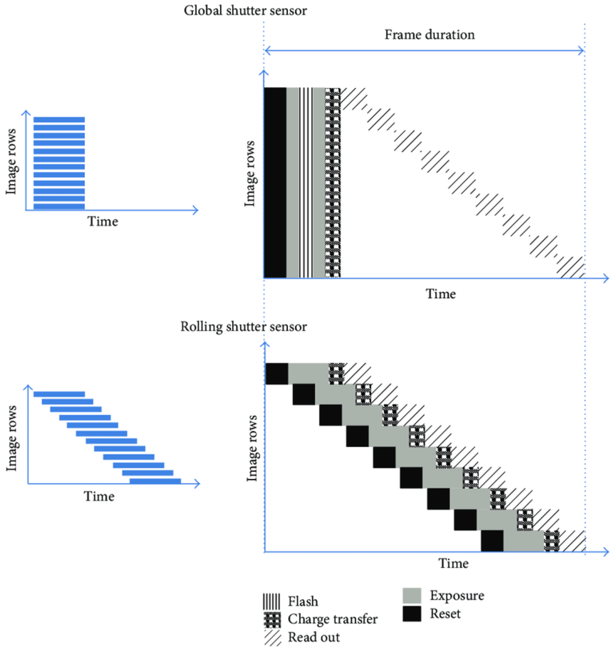

Figure 6. Readout timing for rolling and global shutter, with readout on the y axis and time on the x axis [5].

- The two inclined streaks (No.4 and No.5) are affected both in terms of position and length (streak No.5 is affected more because it spans more rows).
- The two vertical streaks (No.6 and No.7) are the ones that are affected more, since they have only vertical component of the velocity. The curious fact is that, since the two vertical streaks are moving in opposite direction (streak No.6 is moving downwards, streak No.7 is moving upwards), streak No.6 gets stretched and streak No.7 gets shortened in such a way that with rolling shutter the two streaks are aligned and look exactly the same. Even though in any case from a single image (even with global shutter) it is not possible to identify in which direction a streak is moving, in the rolling shutter case it is not possible even to compute the velocity magnitude. Only having more consecutive frames with the same object allows to identify in which direction the streak is moving and consequently to compute the correct velocity.

4.6. Cosmic Rays

In case of images acquired by a space-based sensor, one relevant effect is due to the cosmic rays.

Cosmic rays are high-energy particles (typically protons or atomic nuclei) that travel through space at nearly the speed of light. These particles (similarly to photons) when hit the detector can excite the electrons in the pixels and "generate" single bright pixels or short tracks. These phenomena are recreated within the model through the

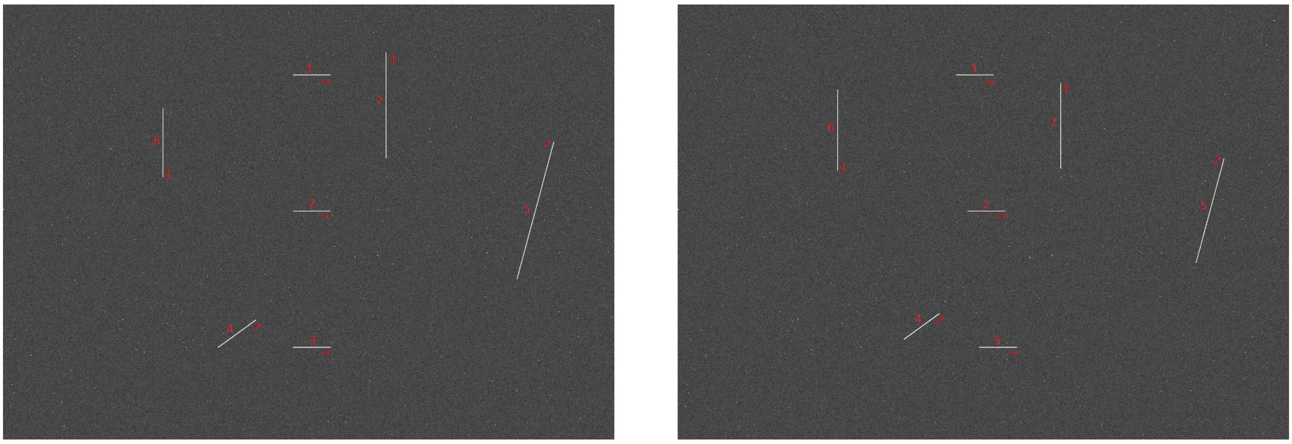

Figure 7. Synthetic images, global shutter (on the left) vs rolling shutter (on the right). The arrows indicate the direction of each streak.

Bethe-Bloch theory of energy loss for charged particles, to simulate the voltage offset during A/D conversion.

The position of these bright pixels or short tracks is not predictable, and they can be easily mistaken for real objects.

If the density of these false positives is low enough, they can be filtered out in post-processing. However, there are specific regions around the Earth where the density of cosmic rays is much higher than the average (for example the South Atlantic Anomaly SAA).

The use of a few mm copper or aluminium shielding on the detector can prevent these effects from degrading the results. Figure 8 shows the results using the TRACES software (developed inside Airbus) for cosmics map generation. The software uses the information about the cosmic density, the pixel physical size, the full image size, the thickness of the shielding and other intrinsic sensor properties (Quantum efficiency, Dynamic range, Full-well capacity, Readout noise, Maximum voltage).

Those maps are then overlapped to the original image generated by the Image Simulator to generate the final image.

4.7. Optical-related effects

A variety of tangible effects originate from the optical system. For ground-based observers, the atmosphere constitutes one of the greatest sources of error.

Atmospheric refraction exhibits a behaviour described by the well-known Snell's Law, where incoming light from an external object encounters air of gradually increasing density. As the density increases, so does the index of refraction - causing the light to bend as a function of height. To a ground observer, the object of interest will be shifted depending on the zenith offset and distance of the object. Thin shell or plane parallel models -although crude- can quite accurately model the refraction, and results from [6] show that the effects on LEO and MEO objects are quite relevant.

Scintillation instead exhibits a random behaviour akin to noise. It is characterised as a combination of the absorption, scattering and seeing phenomena caused by the atmosphere, and results in a variation of apparent magnitude from a ground-based observer. The distribution of photons bombarding the pixel wells can be modelled via Poisson distribution, and it's entirely signal-dependent.

Another family of displacement phenomena, known as "parallactic displacements", are often associated with the geometry and relative speeds between the observer and the object of interest. Effects like annual and diurnal/orbital aberrations can be very relevant and therefore are taken into account in the Image Simulator, whereas effects like stellar parallax and gravitational lens have a negligible impact.

Other effects may be intrinsic to the telescope apparatus: some are caused by a geometrical obstruction of the light when entering the aperture, or by defects within the components themselves. For narrower apertures vignetting is particularly problematic, causing a gradient in signal acquisition along the edges of the active pixels grid.

4.8. Detector-related effects

A significant range of additional effects are characterized by the type of detector installed, with noise distributions differing between CCD and CMOS (Complementary Metal-Oxide Semiconductor) sensors. In the case of CMOS sensors, the voltage sampling takes place directly on the individual pixel, so sensitivity and charge conversion differs significantly from CCD systems. Further differences may be caused by illumination type (front and back) and voltage timing patterns.

For the purposes of the project, a representative noise

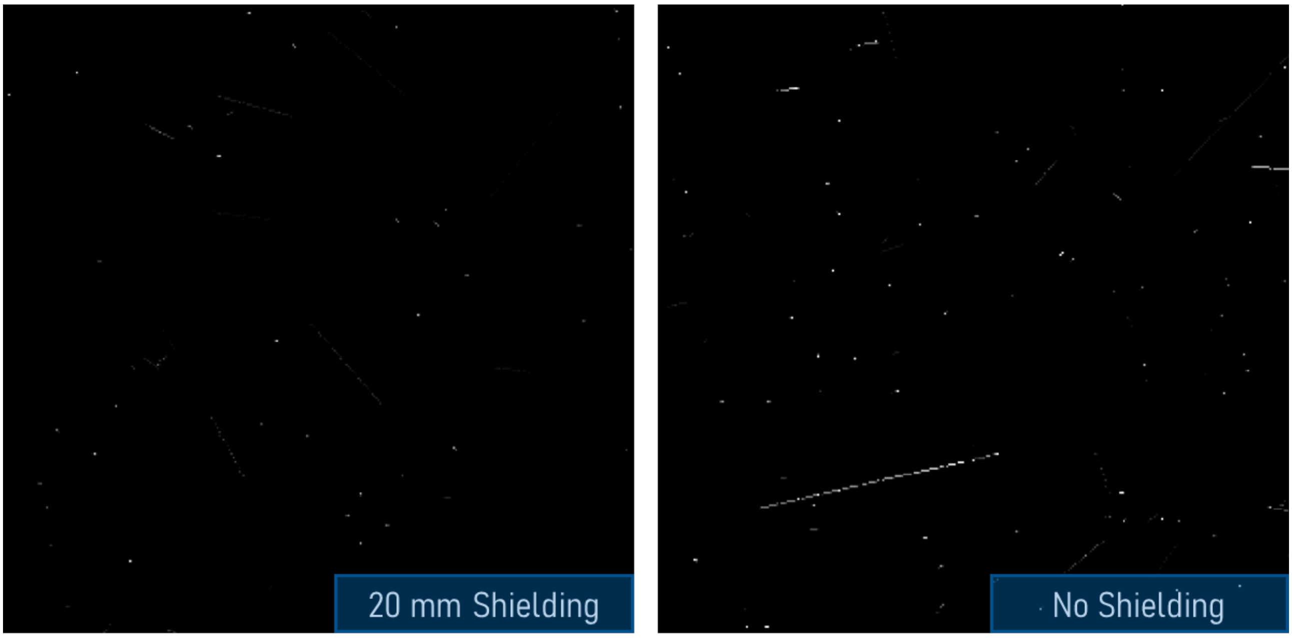

Figure 8. Generated cosmics maps using TRACES under intense flux conditions inside the SAA

model is being developed to simulate a variety of effects. It is useful to distinguish these effects based on time and signal dependency:

- Shot Noise is a signal dependent phenomena, it exists due to the random fluctuation of photons and causes spatial and temporal randomness. This noise can be modelled as a Poisson Distribution.
- Readout Circuit Noise represents the fluctuations in the signal processing chain, which cause a bias in the A/D conversion. This type of noise is entirely independent from the signal [7].
- Reset Noise, similarly, is also a signal independent process. It arises from a time dependent uncertainty of charges when pixels are individually reset. Its effect is larger on low light conditions [8].
- Dark Current Noise, also known as ”Thermal Noise”, is caused by thermal energy within the silicon lattice of the sensor. For uncooled systems and long exposure times, the electrons generated via this process are caught up in the electron well and can significantly affect the signal.

Other systemic effects, such as ”Amp-Glow”, that have been historically associated with aging amplifier circuitry in CCD sensors, are of a completely different nature in CMOS: in this system Amp-Glow arises when the integrated support circuits generate heat or emit near-infrared light. Since in recent days this effect has become less of a concern for higher-end systems, the effects are not currently modelled within the Image Simulator.

Defective pixels are also a topic of concern, both when discussing the effects of cosmic rays and manufacturing processes. Dead, warm and hot pixels can all be labelled as such, and their distribution and concentration vary depending on the characteristics of the individual sensor [9].

Finally, some systems provide immediate binning as a pre-processing solution to preserve storage space. The image is compressed by extrapolating a representative value from a ”bin”, such as a small window size for a number of pixels. This value can be obtained by either selecting the mean, median or weighted average, and the type of approach used can have a relevant effect on streak representation.

4.9. Test and Validation of the generated images within the pipeline

A direct way that contributes to the validation process of the Image Simulator is to start from a real image from ART (for which all the sensor and observation scenario properties are known) and recreate the same scenario using the simulator.

The results are very promising. Using as reference an image of a GPS tracking in 2021, the two images (the real and the simulated one) look almost indistinguishable (see figure 9).

However, the visual inspection is not sufficient, and more sophisticated techniques should be used to properly validate the Image Simulator:

- On the global scale, some statistic similarities measures can be used to compare the real and the simulated image (similar to the visual inspection, but

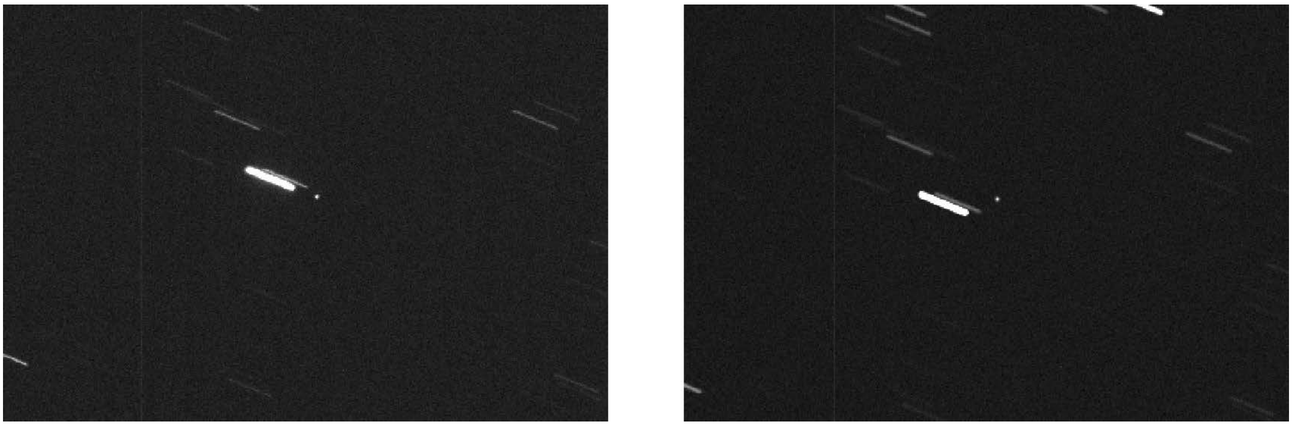

Figure 9. Tracking of a GPS satellite. Image taken from ART (on the left) and fully simulated using the Image Simulator (on the right). The two images are zoomed to show more clearly the object in the middle.

with a quantitative index). A proposed approach consists in a histogram comparison metric.

- On a local scale, the images can be processed using some Image Processing software in order to extract astrometric and photometric quantities for the objects in the images. These quantities are then compared to each other and to the ground truth provided as input to the Image Simulator.

These steps are still on-going and will be developed in the next months, as part of the test plan for SBOC.

Moreover, some effects cannot be directly validated, because of lack of real images with space-based effects.

5. CONCLUSION

For the development of future space based sensors realistic test and validation data is necessary to assess the expected performance as well as to develop the necessary hardware and the data processing pipeline.

For this, Airbus Defence and Space has upgraded its ground-based sensor capabilities (ART) as well as the image simulation capabilities of its in-house SSA/SST tool SPOOK. With the new upgrades it is possible to generate synthetic and real-world data as close as possible to the ones produced by space based sensors. The current developments directly benefits the on-going development of the SBOC instrument and will enable further developments in the domain of Space-Based SSA.

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