SkySim4FGS

Sky simulator for fine guidance sensor

CONTENTS:

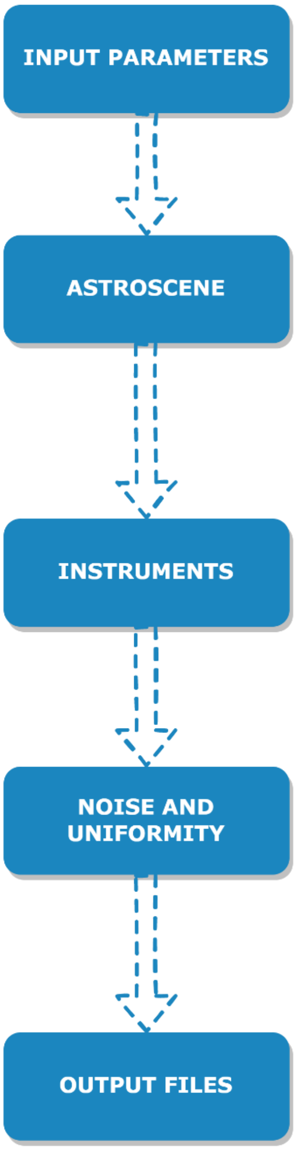
THE PURPOSE OF THE SKY SIMULATOR FOR FINE GUIDANCE SENSOR IS:

- To simulate an image of a selected part of the sky based on data from the Gaia DR2 (DR3) database and data about optics, filters and image sensor and the parameters of the sensor operation as FGS will actually see it during the mission.
- To provide the tested FGS image, which as closely as possible corresponds to the stars of the selected part of the sky with a number of noise, distortions, sensor uncertainties and a diverse background for testing its ability to correctly determine the current attitude of the satellite. For each resulting synthetic image, the FGS has available the true centres of the stars' PSFs in [RA], [Dec], and [pix], which are used to calculate the error of the star centre determination by the tested FGS software.

SYSTEM FUNCTIONALITY:

- Simulation of satellite motion and vibration and their effect on the image
- Simulation of a series of optical distortions forming PSF images of stars
- Simulation of temporary noise and spatial nonuniformity, which actually arise on the sensor
- Simulation of the background that FGS will see in the selected part of the sky
- Simulation of a series of planar objects that can occur in the field of view
- Simulation of the effect of radiation on the chip and its impact on the resulting image.
- The resulting synthetic image, which corresponds to the stars of the selected part of the sky

PROCESS DIAGRAM



- Astrometric coordinates (ra, dec) (FOV)
- FGS (satellite) Attitude (roll, yaw, pitch angular rate) and Pointing jitter noise

- Stars: photometric, astrometric parameters, uncertainties, extinction, etc
- Sky background (zodiac light, faint unresolved galaxy and stars, faint galaxy, asteroid, nebula) (diffuse area sources)

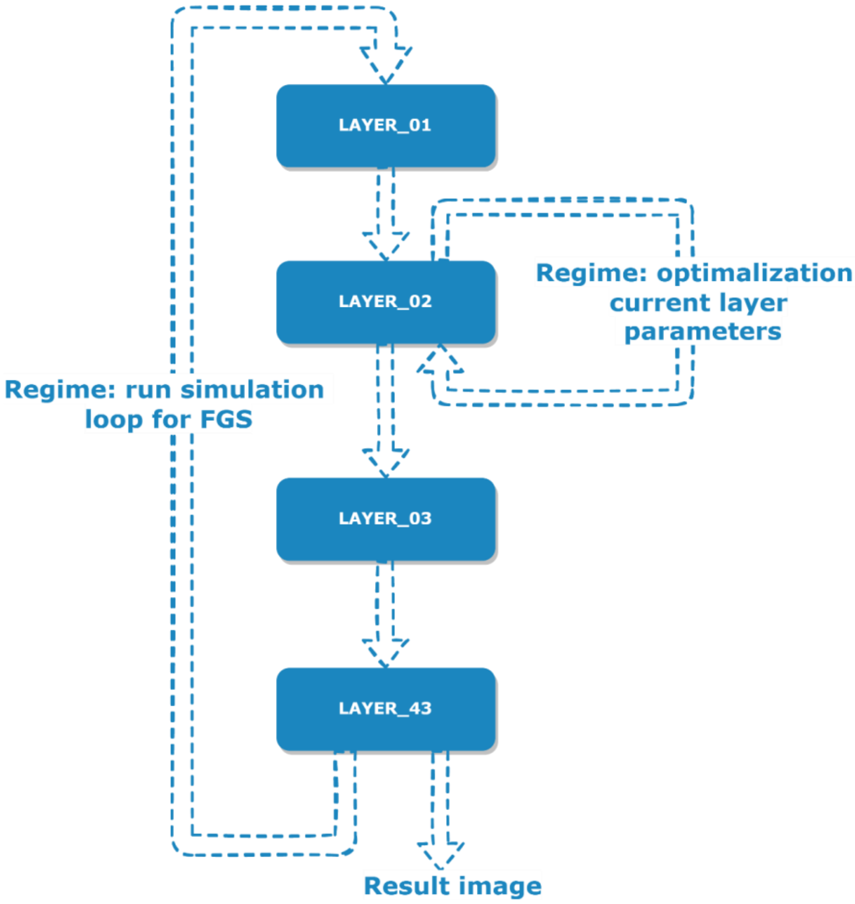
- Telescope
- Filter
- Image sensor

- Photon noise
- Radiation noise
- Sensor noises non uniformity

- TIFF image for FGS
- Files with data of parameters

SYSTEM MODES:

Sky simulation is divided into 43 procedures (Layers). Each procedure generates a partial image of specific image property. For each image processing procedure there is a dedicated HMI screen for entering parameters, visualizing result images and so on. Result of each layer (image processing procedures + HMI screen) is a partial image(s) and datafile(s).



LAYERS DESCRIPTION:

Satellite Attitude

Its uncertainty:	Position Uncertainty
Dynamic influence:	RollYawPitchAngleRate, PointingJitterNoise SmearingDueAttitudeMovement

Distortion, Aberration and PSF due optic path and wavelength

Distortion:	ImageDistortion,
Aberration:	PsfAberration, ChromaticAberration
PSF:	PsfFocusedStars, PsfOutOfFocusStars, PsfStraightLight

PSF due sensor features and wavelength

PSF:	PsfWavelengthDependent

Photometric calculation

Optic:	OpticTransmissivity
Filter:	FilterTransmissivity
Chip:	QuantumEfficiency, QuantumEfficiencyUncertainty

Noise

Star:	PhotonShotNoise
Chip:	QuantizationNoise, DarkCurrentNoise, ReadOutNoise

Non Unifomity

Chip:	DarkSignalNonUniformity, PhotoResponseNonUniformity, FringingNonUniformity,IntraPixelResponseNonUniformity

Errors on chip

Chip:	HotPixelsNonUniformity, ColdPixelsNonUniformity, BadColumnNonUniformity, TrapsNonUniformity

Sky background

Background:	ZodiacalLight, FaintUnresolvedStarsAndGalaxies

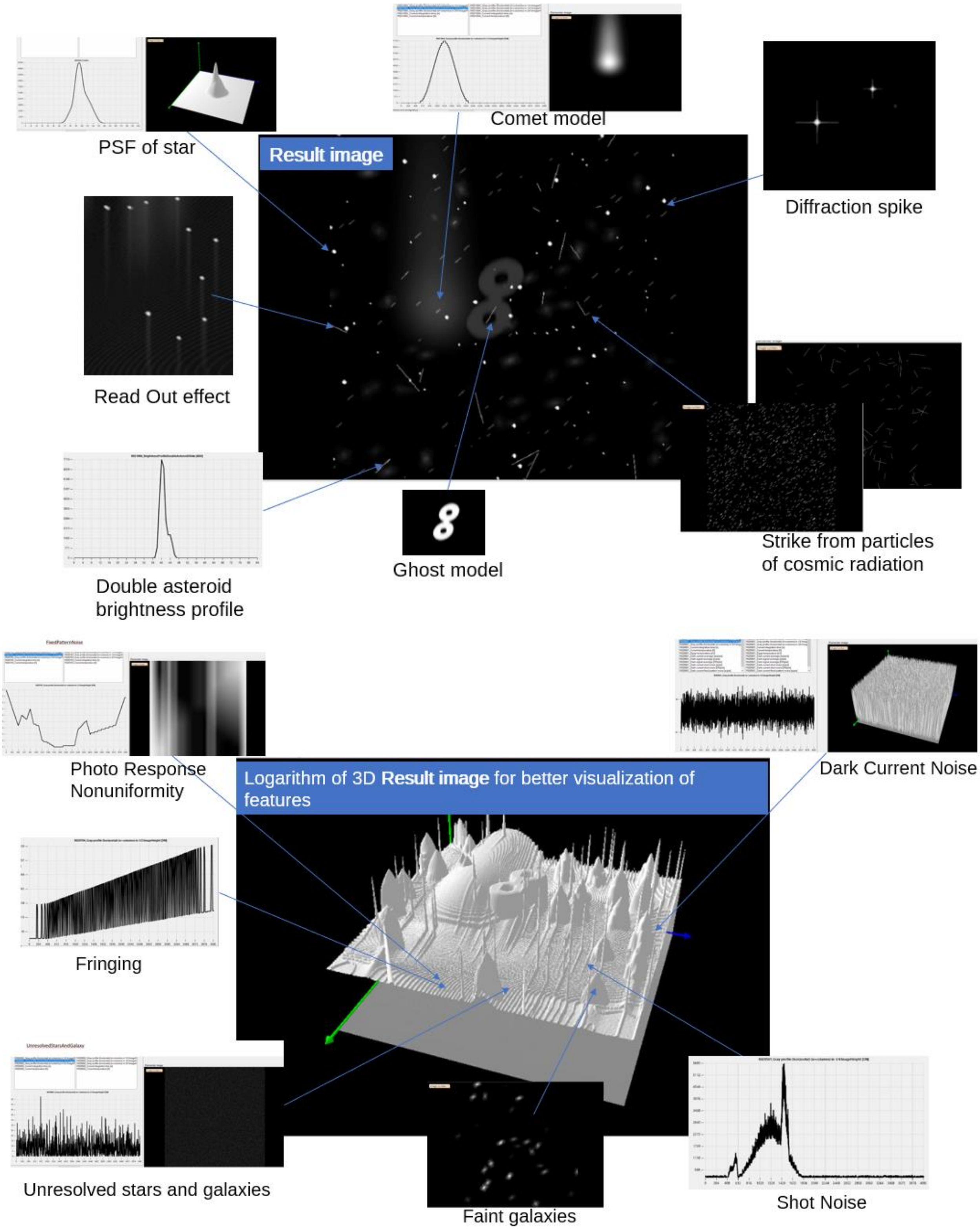
Area objects background

Area objects:	Ghost, FaintGalaxyAreaObjects, NebulaAreaObject, RingNebulaAreaObject, CometAreaObject, AreaObjectUserDefined

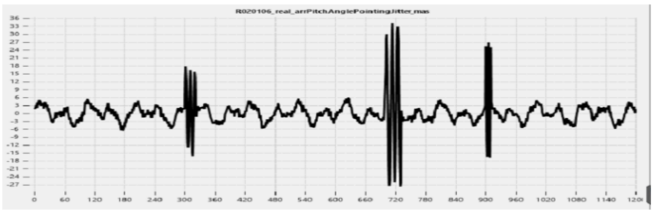
NonArea objects

Points, lines objects:	Asteroid, DoubleAsteroid
Eclipse:	TemporaryStarDisappearance

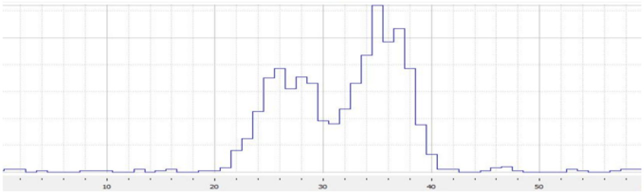
OUTPUT IMAGE EXAMPLES:



Pointing jitter equivalent angle noise



Effect of splitting center of star PSF due jitter

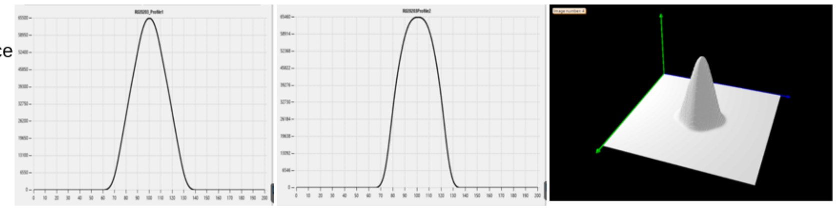


Psf Focused Star

wavelength, position dependence

parameters of optic

Validation against measured brightness profiles of PSF stars on Hubble images

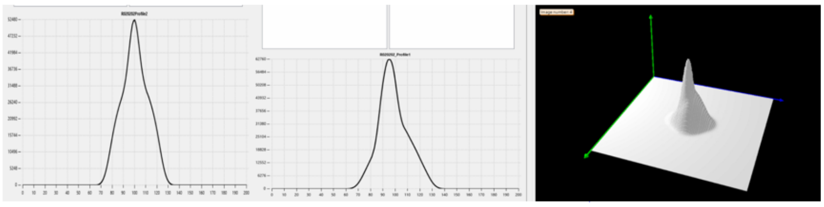


Psf Aberration

wavelength, position dependence

parameters of optic

Validation against measured brightness profiles of PSF stars on Hubble images

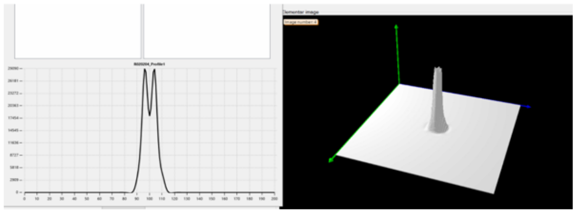


Psf Out Of Focus Star

wavelength, position dependence

parameters of optic

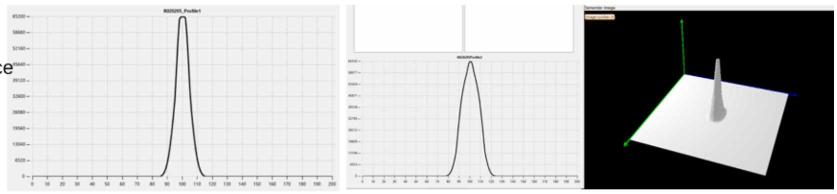
Validation against measured brightness profiles of PSF stars on Hubble images



Psf Wavelength Dependent

wavelength, position dependence
parameters of sensor charge diffusion

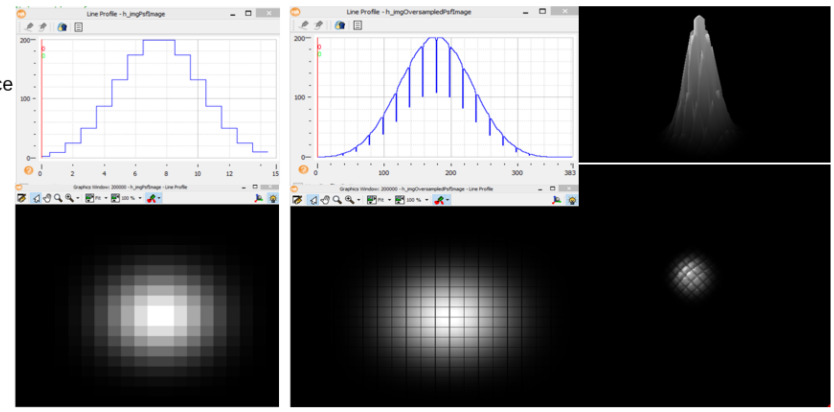
Validation against theoretical models from scientific articles



semifinished
Psf Inter Pixel Variation Dependent

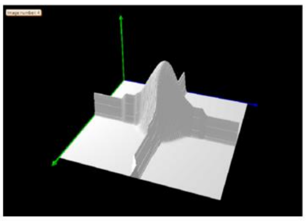
wavelength, position dependence
parameters of sensor pixel response nonuniformity

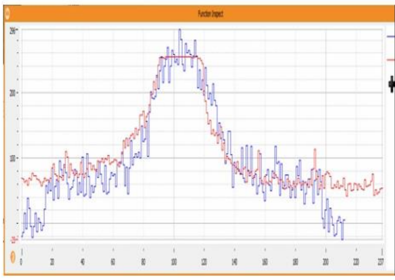
Validation against theoretical models from scientific articles

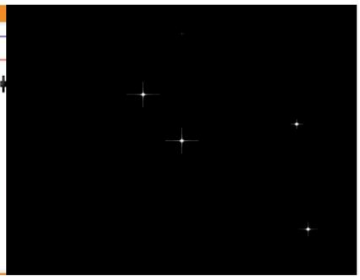


DiffractionSpike (StraightLight)

Validation against real HST image brightness profile of star with straight light effect (Red-HST, Blue-model)

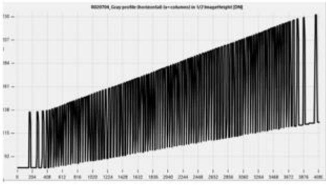


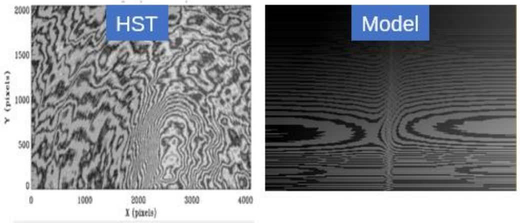




Fringing Nonuniformity

Validation against measured brightness profiles on Hubble images





Dark Signal Nonuniformity

Validation against theoretical models from scientific articles

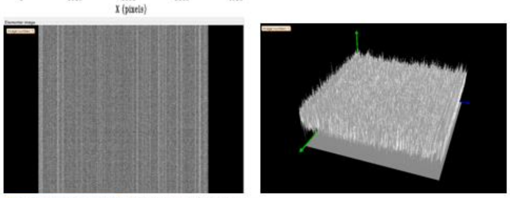
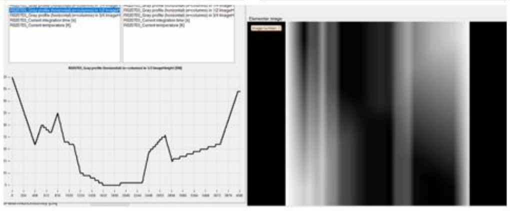


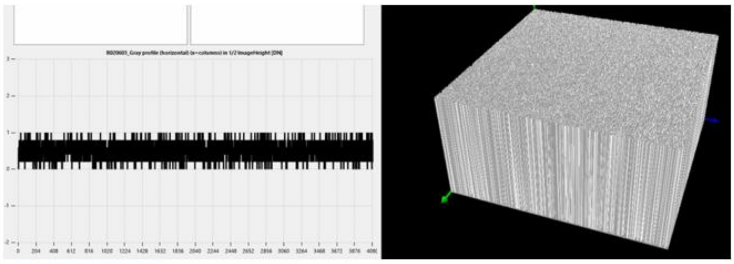
Photo Response Nonuniformity

Validation against theoretical models from scientific articles



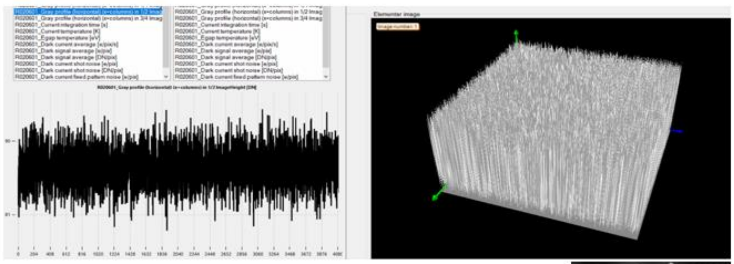
Sensor Quantization Noise

Validation against theoretical models from scientific articles



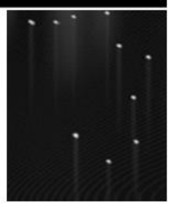
Dark Current Noise

Validation against theoretical models from scientific articles



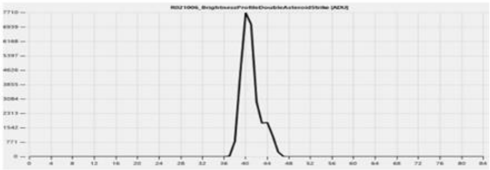
Read Out Effect

Validation against measured brightness profiles on Hubble images



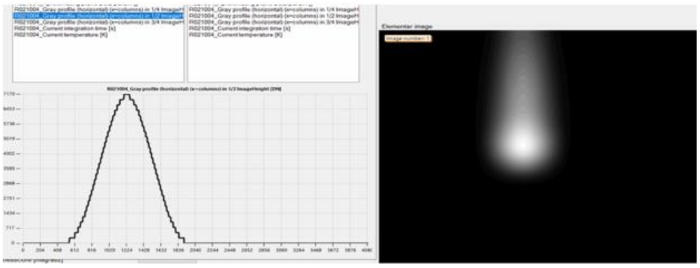
Double Asteroid brightness profile

Validation against real HST image brightness profile of asteroid



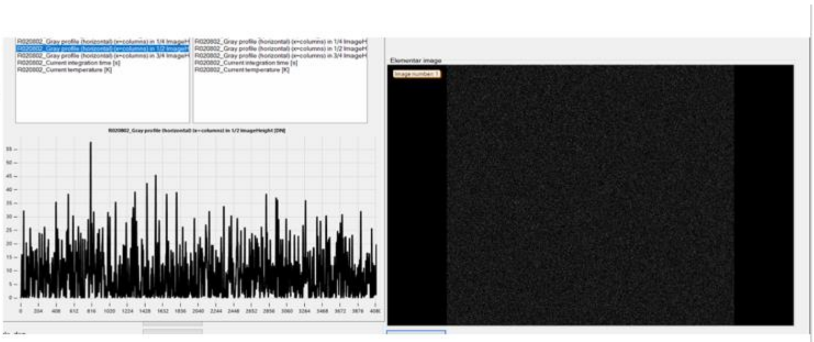
Comet

Validation of shape brightness profile against real HST image brightness profile of comet

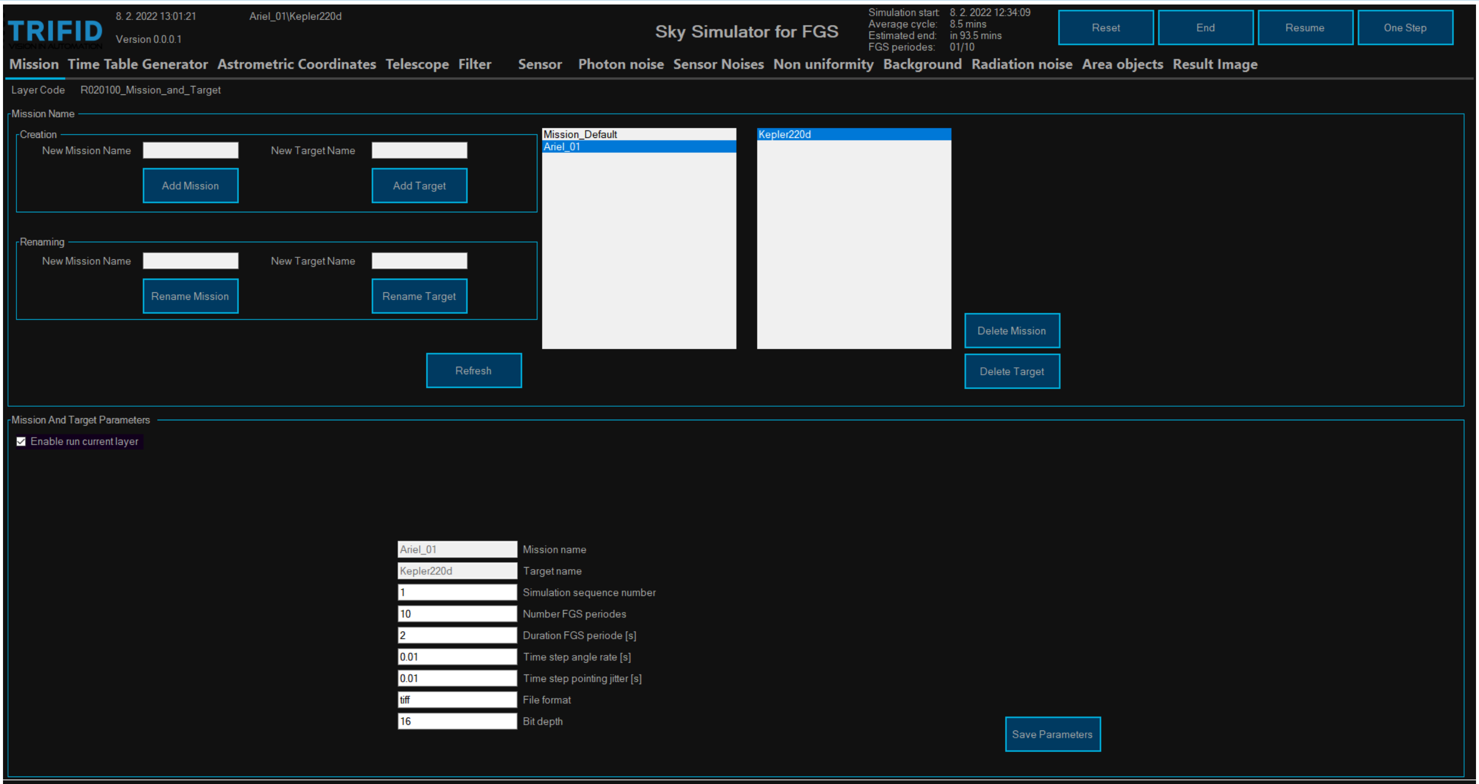


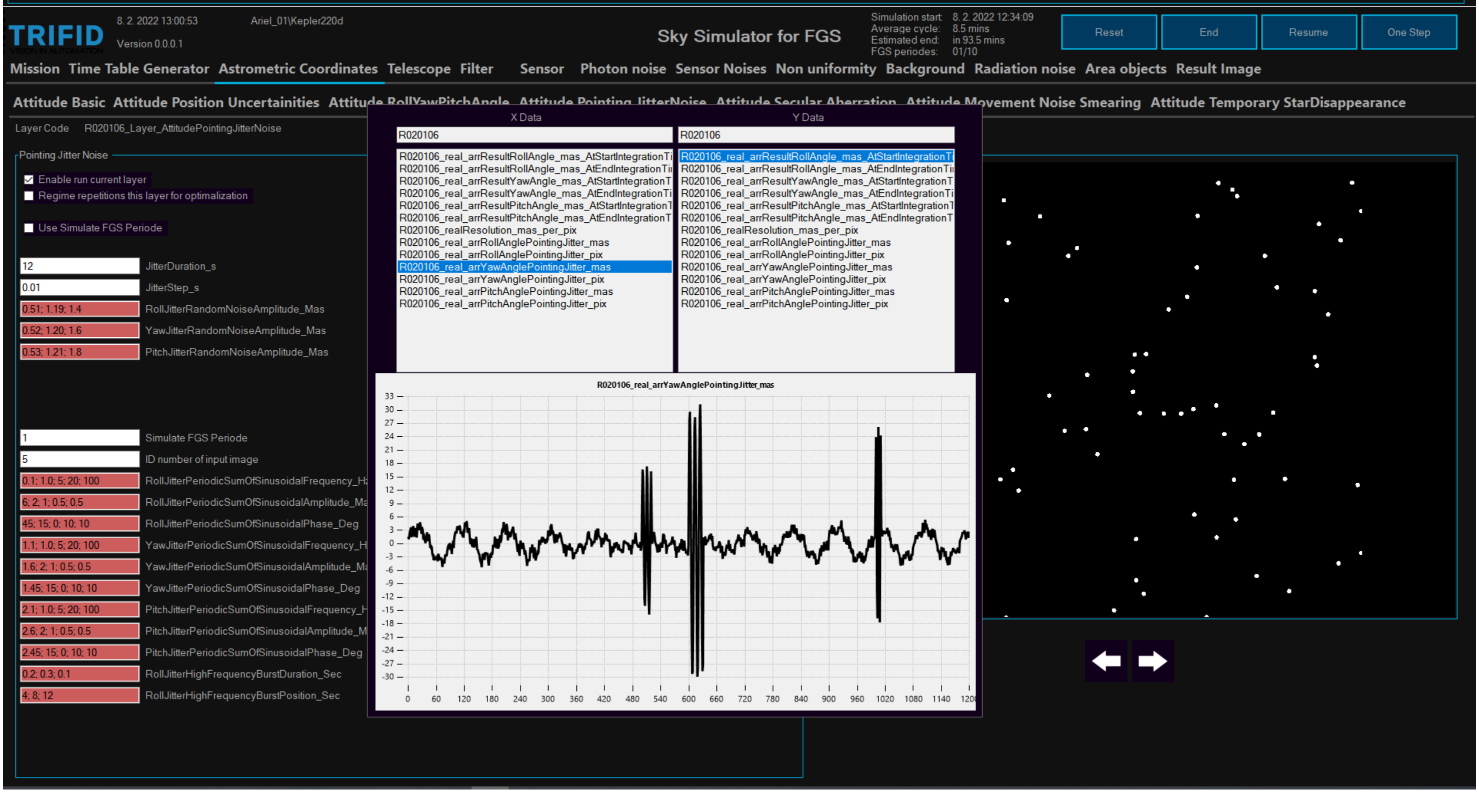
Unresolved Stars And Galaxy

Validation of shape brightness profile against real HST image brightness profile of background



HMI PAGE EXAMPLE:





CURRENT CAPABILITIES AND FUTURE VISION

- ## SkySim4FGS

  The basic configuration simulates the Fine Guidance Sensor view from the L2 region. It uses the Gaia DR3 astrometric and photometric database, covering stars in the magnitude range from +3 mag to +20 mag. Due to the large distance from Earth, modelling of satellites and space debris is not required.

- ## SkySim4SpaceSST (in cooperation with Astros, expected February 2027)

  The extended configuration builds on the basic setup by adding a simulation of a space-based SST camera. It includes optical effects, the natural space environment (Earth limb, Moon, planets, zodiacal light), orbital positioning, communication with Astros databases, and modelling of satellites and space debris.

  The result is a synthetic image of a star field with added images of registered satellites and space debris, as observed by the SST camera at a selected orbital position and time. For this purpose, a unified star database in Gaia DR3 format is prepared, combining Gaia stars with bright stars from the Hipparcos/Tycho catalogues, covering a magnitude range from −1.46 mag to +20 mag.

- ## SkySim4EarthSST (in cooperation with Astros, expected February 2027)

  Adds simulation of ground-based SST systems, including ground cameras, telescope optics, atmospheric effects (e.g. seeing, refraction, light pollution), and modelling of satellites and space debris. The result is a synthetic image of a star field with added images of registered satellites and space debris, including atmospheric effects, as observed by a selected ground-based SST telescope at a given time.

- **SkySim4STR (expected end of 2027)**
  Focused on Star Tracker simulation, including onboard Gaia-based star catalogues, optical modelling, orbital positioning, environmental effects, and integration with external databases.

  The simulated synthetic images will contain a star field with modelled radiation effects and optical path effects, including stray light, halo, ghost reflections, surface contamination, veiling glare, etc. There is also the possibility to include images of registered satellites and space debris, as observed by an SST camera at a selected position and time in Earth orbit.

- **SkySim4FGS_Easy**
  A simplified version of the basic mode using faster algorithms, suitable for lightweight applications such as CubeSats.

- **Easy Variants**
  All future modules will also be available in simplified “Easy” versions for faster simulations.

FUTURE ENHANCEMENTS

SkySimTrifid will evolve to provide higher realism and easier integration with customer systems. Key development directions include:

- **Machine learning optimisation**
  Automatic tuning of simulation parameters (PSF, noise, non-uniformity) to match specific FGS, SST or Star Tracker systems, reducing manual calibration effort.

- ## Use of real calibration data

  Integration of user, or manufacturer-provided data (Flat Field, Dark, Bias images) to accurately reproduce sensor-specific behaviour and fixed-pattern effects.

- ## Advanced sensor modelling

  Improved modelling of non-uniformities (DSNU, PRNU, FPN, fringing, intra-pixel response) and their dependence on temperature and exposure time.

- ## High-fidelity optical modelling

  Enhanced simulation of PSF, distortion, and motion blur will be based on the analysis of real images provided by operators of the modelled camera systems.

- ## Validation with real space data

  Comparison with images from space telescopes to ensure realistic simulation outputs.

- ## Extended applications

  Support will be extended to include Star Tracker testing, satellite docking scenarios, CubeSat swarms, and advanced space debris simulations. Future development will also focus on simulating camera imagery in satellite docking scenarios, generating synthetic images for satellites with laser inter-satellite communication, simulating camera views in proximity to space debris, and modelling optical system degradation due to micrometeoroid erosion.

APPLICATION AREAS AND USERS

SkySim4FGS

Designed for companies developing or operating Fine Guidance Sensors (FGS).

The simulator generates highly parameterised synthetic images representing real space conditions, enabling testing and validation of pointing algorithms. It includes realistic disturbances such as radiation effects, satellite motion, and noise.

Also supports validation of integrated FGS systems by supplying simulated inputs to verify performance, noise filtering, and correct star recognition.

Uses Gaia DR3 star catalogue (3–20 mag).

SkySim4SST

Intended for companies developing software for tracking and characterisation of satellites and space debris, as well as for detection of new, unregistered objects.

Supports both space-based and ground-based SST systems. The simulator generates images of a given field of view, including stars, Moon, planets, Earth limb, and known objects. It incorporates realistic environmental and instrumental effects such as stray light, sensor noise, thermal effects, and camera motion.

By comparing synthetic and real images, users can identify unknown objects.

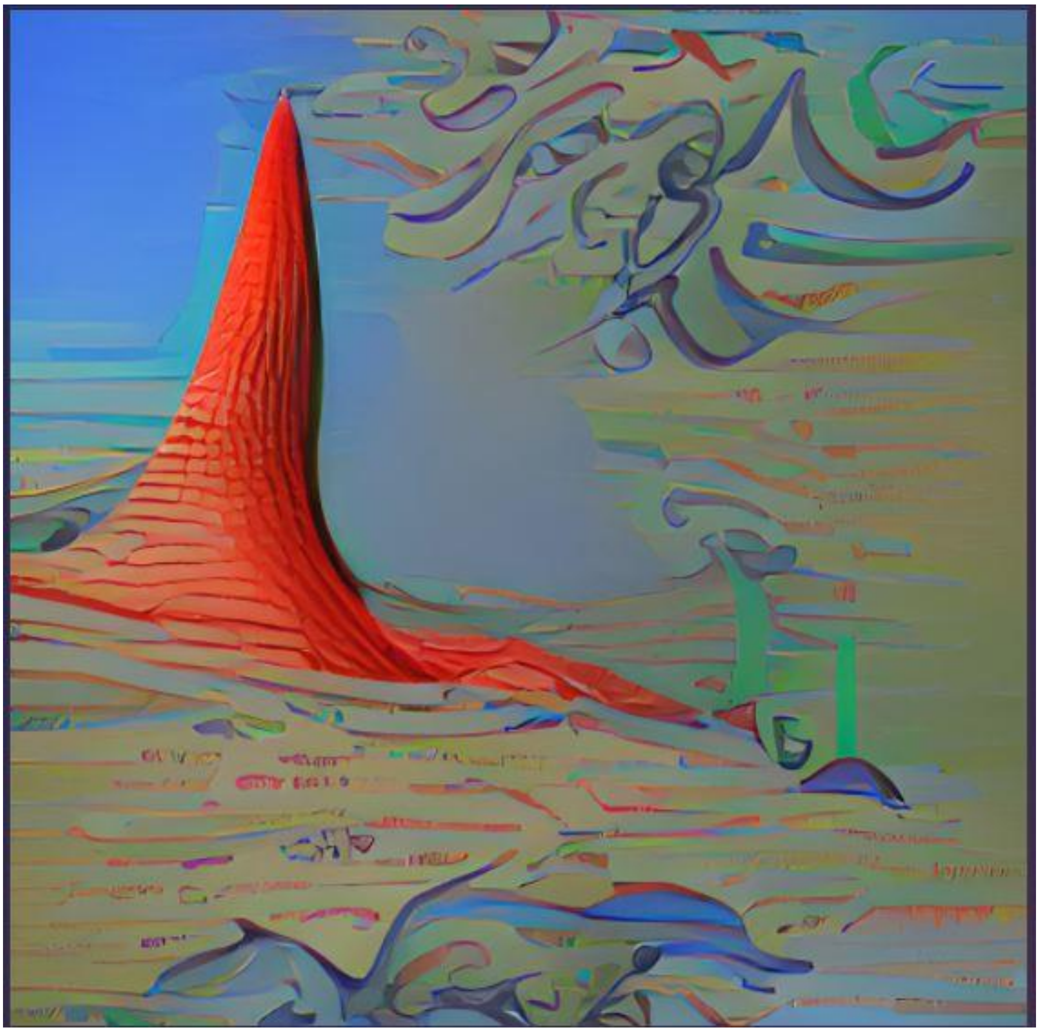
Uses Gaia DR3/DR4 and Hipparcos/Tycho catalogues (−1.46 to 20 mag).

SkySim4STR

Designed for manufacturers and users of Star Trackers (STR).

Provides large datasets of synthetic star field images for software development, including realistic sensor noise, optical effects, and non-uniformities.

Also enables validation of integrated STR systems by simulating real observation conditions and verifying correct attitude determination and star identification.



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