Integrated Assessment of Satellite Optical Brightness for Preservation of Dark and Quiet Skies

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Dark and quiet skies preservation

Background

OPTICAL ASTRONOMY

Bright satellites leave streaks across images from ground-based optical telescopes, due to reflected sunlight

RADIO ASTRONOMY

Active satellites interfere with radio observations through intended and unintended emissions.

CURRENT MEGA CONSTELLATION POPULATION

10,000+ STARLINK	**600+** ONEWEB
300+ AMAZON LEO	**100+** QIANFAN GUOWANG

2019 First concern raised by astronomers, shortly after the first Starlink launches.

Dark and quiet skies preservation

Recommendations

2020–21

SATCON 1 & 2

Technical workshops

AAS & NOIRLab

2021

Dark & Quiet Skies

International conference

UNOOSA, IAU, IAC, NOIRLab, ESO

2022

IAU CPS founded

Centre for the Protection of the Dark & Quiet Skies

CONSOLIDATED TECHNICAL RECOMMENDATIONS

Guidance directed at satellite **operators** and **manufacturers** to mitigate impact at the source, iterating on satellite design and operations

Magnitude 7

Recommended brightness limit — keeping satellites faint enough to protect observations.

$$mag_V > 7 + 2.5\log_{10}\frac{r_{ORBIT}\,(km)}{550}$$

Dark and quiet skies preservation

Current regulations

Italian Space Law 2025

The authorization to exert space activities is released upon requirements compliance:

Safety of space activities across all phases and aspects, from design of the space object and its components to the management of space activities, including a specific impact-on-safety analysis and an assessment of the light and radio-electric pollution produced by space objects, plus mitigation of debris effects.

EU Space Act 2025

e-certificate release to ensure compliance of the space mission to safety requirements:

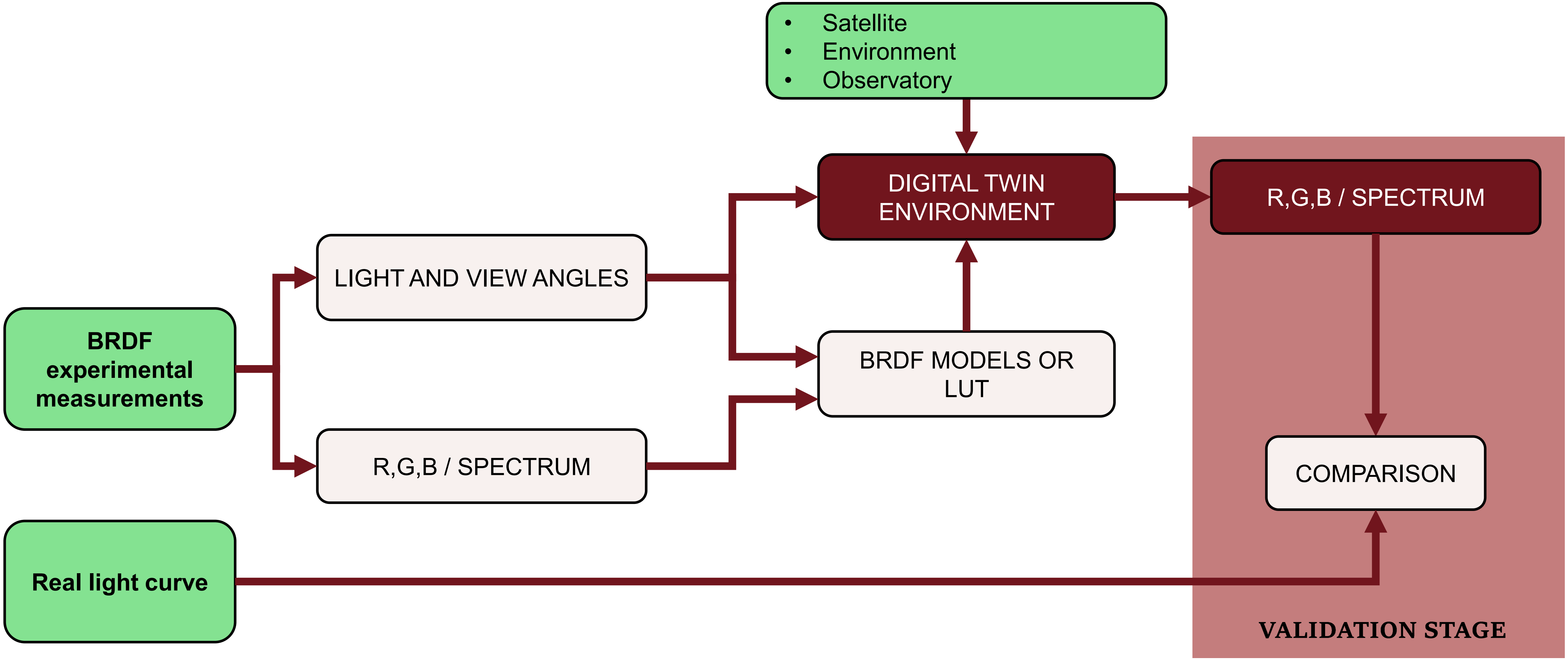
The technical requirements needed for the deployment of the e-certificate by the Agency, as well as for the dark and quiet skies, should be developed through the standardisation process. The Commission should consequently request the European standardisation organisations to develop standards in relation to such essential requirement.

ESA - Space debris mitigation requirements

Dark and quiet skies referenced multiple times.

Data driven approach to brightness evaluation

BRDF measurements driving materials reproduction and brightness simulation.



What is needed

Input and resources required

DIGITAL TWIN SIMULATION ENVIRONMENT

SATELLITE

3D model: geometry & mesh

Orbit: ephemeris

Attitude: orientation (quaternion)

ENVIRONMENT

Solar spectrum: irradiance @ 1AU

Sun position: DE440 ephemeris

Atmosphere: optical depth

OBSERVATORY

Quantum efficiency: sensor response

Filter: Employed filter

Window transmission: sensor additional transmittance

Observer position

Observatory hardware: gain, resolution, diameter, focal length

Materials BRDF

Per-material bidirectional reflectance distribution functions

Wavelength-dependent reflectance for every surface material

EXPERIMENTAL STAGE PERFORMED IN LABORATORY FACILITY

BRDF extraction pipeline

From measurements acquisition to implementation within digital twin

1 Acquisition of raw measurements in different spectral bands

- Both camera (RGB) and spectrometer (VIS) applicable

2 Measurements calibration with reflectance standard, BRDF extraction

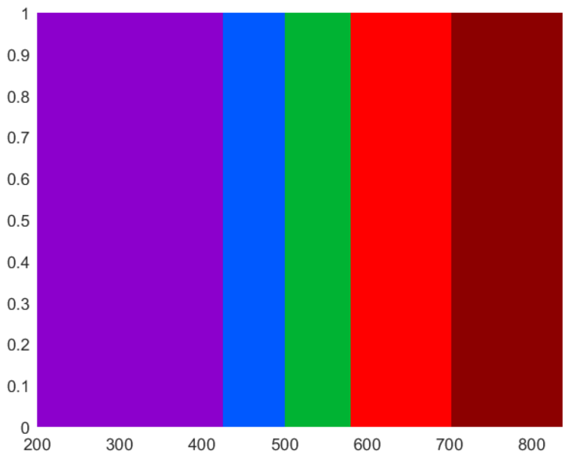
- Calibrated against pure white reflectance standard

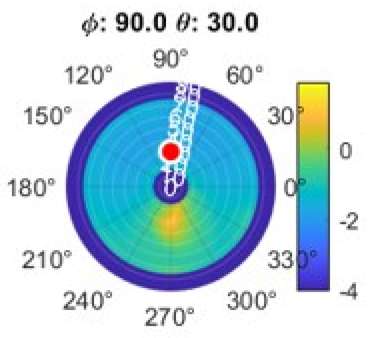
3 Polar maps to observe the reflectance behaviour of different materials

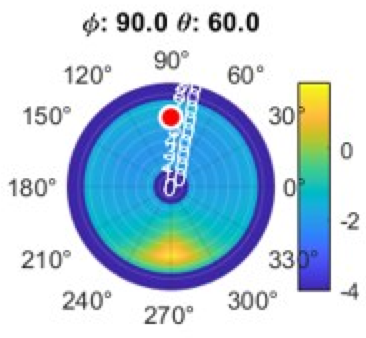
- «Human readable» output and characterization

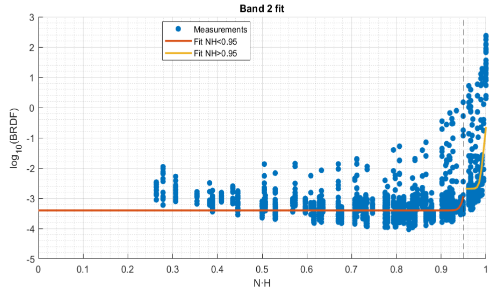
4 Fit with analytical models and derivation of LUT for usage in digital twin

- Usage in digital twin environment



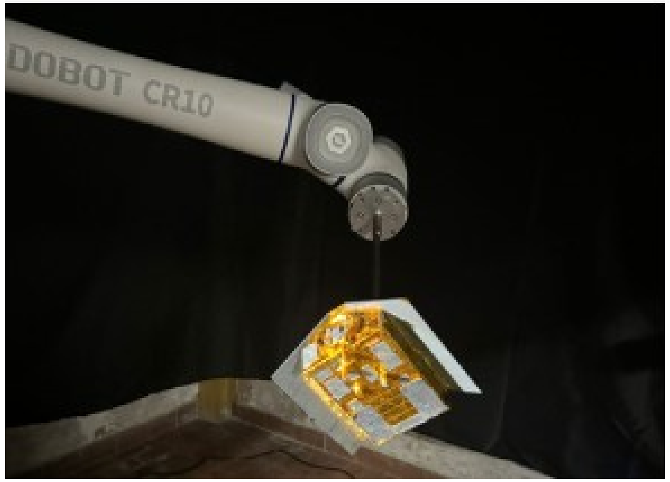






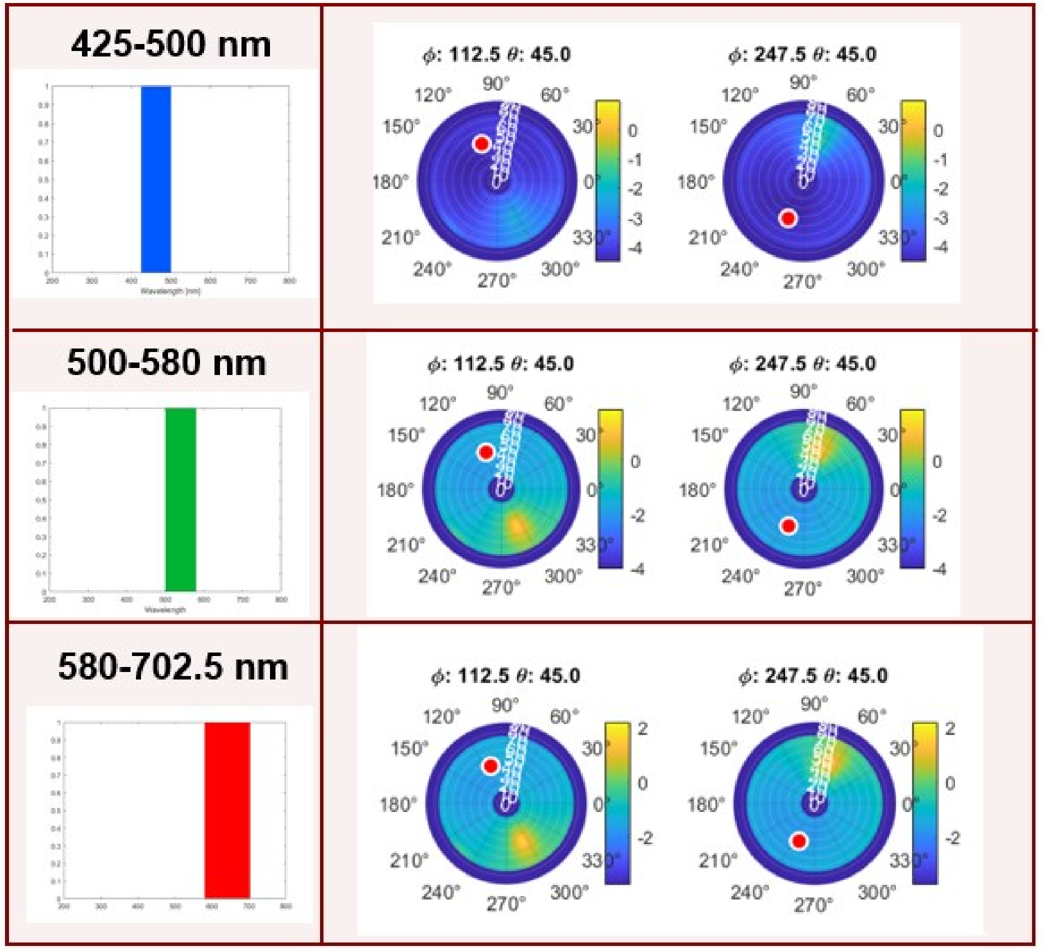
BRDF laboratory facility

Two autonomous robotic arms replicating several illumination/viewing conditions



BRDF spectral measurements

MLI - Standard workflow using spectrometer

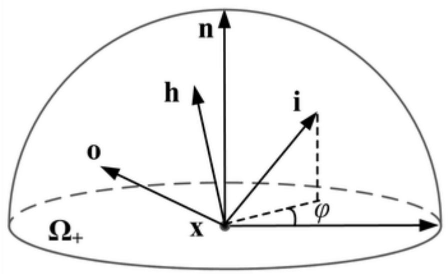


- Polar maps show the specular behaviour of MLI with a diffusive contribution
- Reflectance increases overall in the green and red band correctly reproducing the material appearance

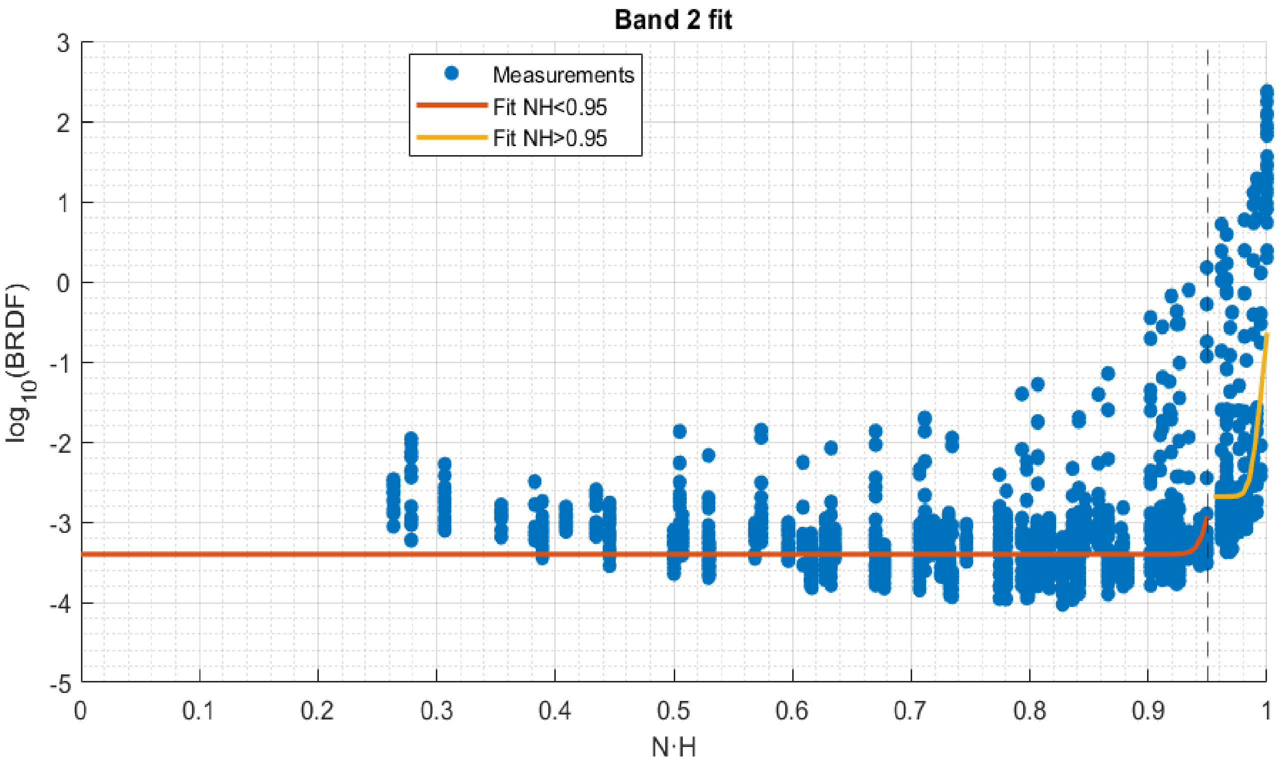
BRDF spectral measurements fitting

MLI - Measurements fitting to the analytical Blinn-Phong model

- BRDF analytical models are functions heavily dependent on the N·H product, with H as the half vector
- Rotating H around N (changing L and V azimuths) returns the same product
- Fitting can be split in two areas based on N·H to better modeling the specular region
- Physical behaviour not enforced



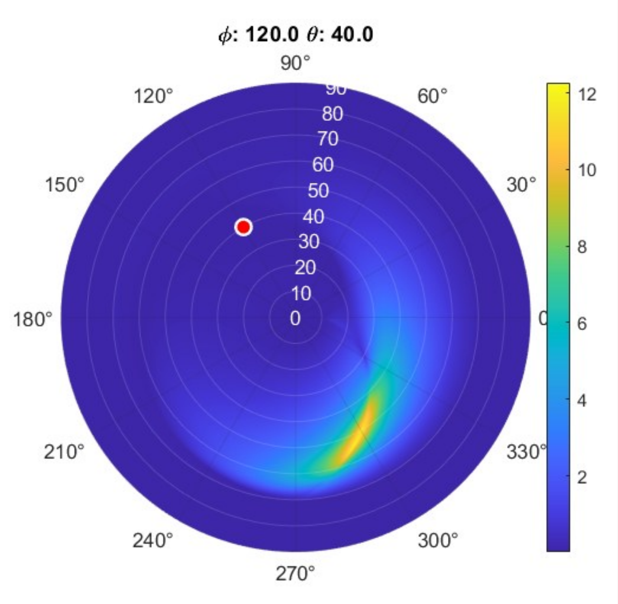
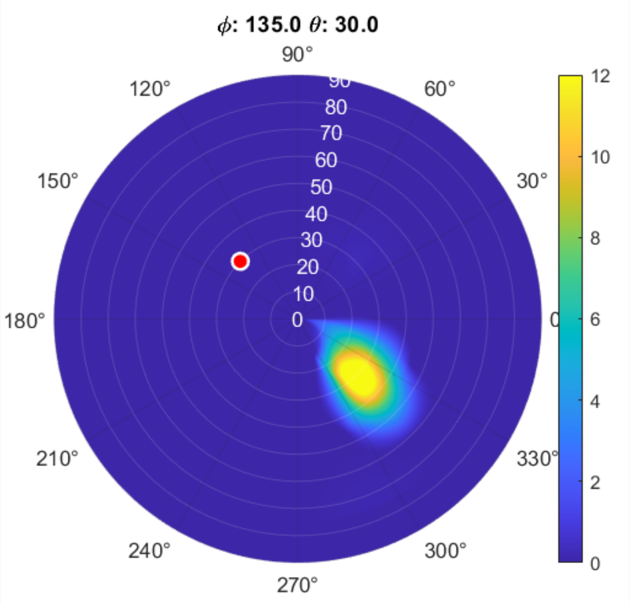
$$BRDF = \frac{K_D}{\pi} + K_S \frac{n+2}{2\pi} \cos(\vartheta_H)^n$$



BRDF measurements

Lookup table (LUT)

A LUT enables the **direct utilisation of BRDF measurements within digital environments**, bypassing the need for an analytical model. LUTs are built based on a 4D tensor traceable to the geometrical configuration of the measurements acquisition. Each entry corresponds to an illumination and viewing direction, returning the corresponding measurement. 4D interpolation is required for missing points

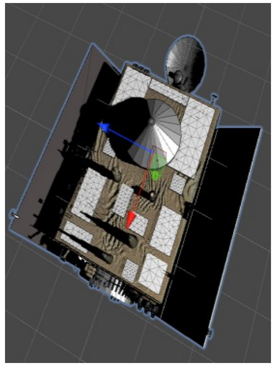
INTERPOLATED MAP via LOOKUP TABLE	CLOSEST NEIGHBOUR IN DATASET
	

Validation approach

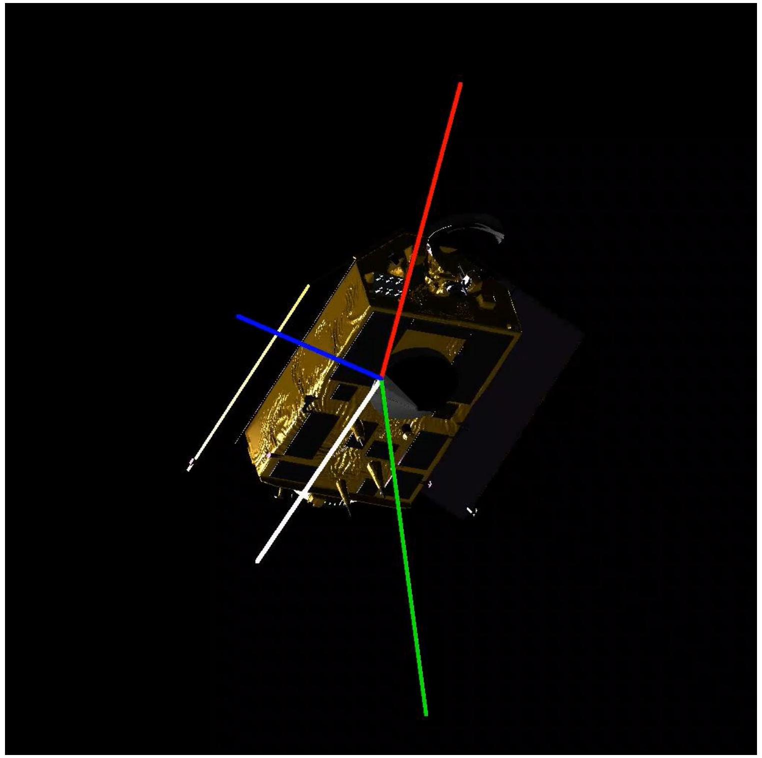
Rendering using BRDF measurements and comparison between real and simulated light curves

VALIDATION CAMPAIGN

- Sentinel 6A used as reference target
- Comparison of real and simulated light curves given attitude ephemeris and materials
- Real light curves obtained in different filters using the observatory SCUDO

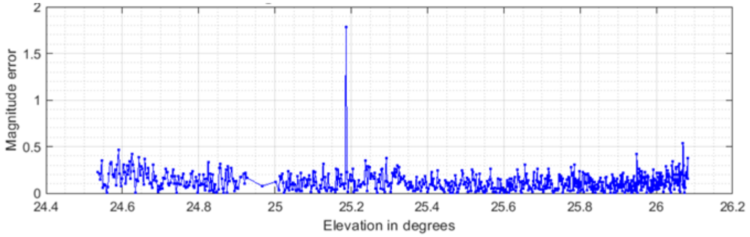



RENDERING OF SENTINEL 6A



MAGNITUDE ERROR

Sloan g



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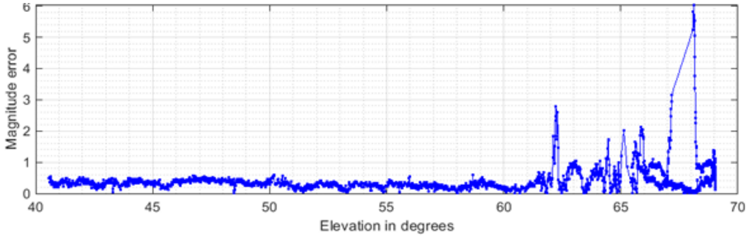

Conclusions

Data driven approach to optical brightness simulation

- The data driven approach has been validated by comparing real light curves with simulated ones, using materials properties extracted within the laboratory facility.
- Validation campaign featured observations in different photometric filters, testing the software capabailities in the full visible spectrum
- The median error in different filters is around 0.5 magnitudes, enabling the validation of a reliable tool for magnitude estimation

Thanks for you attention!

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