SHEDDING LIGHT ON SPACE DEBRIS: ADDING OBSERVABILITY TO ESA'S MASTER FOR A DARK AND QUIET SKY

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ABSTRACT

The MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) model, developed by the European Space Agency (ESA), is a critical asset in understanding the space debris environment and assessing collision risks in Earth's orbit. The event-based model takes information on all known space debris-generating events to create comprehensive snapshots of the debris population, characterizing individual objects thereof by their size, mass, and orbital parameters —key factors for evaluating collision threats.

Beyond collision risk, however, an additional perspective, increasingly important to consider, is the light pollution caused by space objects. This is a critical issue not currently addressed by MASTER, though it aligns with ESA's broader zero debris policy and international efforts such as the International Astronomical Union's Commission on Dark and Quiet Skies (IAUCPS). Brightness, an inherent property of space debris, plays a significant role in how debris affects astronomers, ground-based observations, space-based instruments, and cultural practices tied to the night sky.

This paper proposes integrating brightness, via existing data sets on the standard magnitude of objects on orbit, into the MASTER model. By correlating brightness data from global observatories with cataloged objects (e.g. via the international designator (or COSPAR-ID) or the US Satellite Catalog number), MASTER's utility is enhanced. Additionally, this paper discusses a method for estimating brightness for non-cataloged yet observed objects by utilizing orbital elements to compare the brightness data from different observatories. Besides, a mathematical model is also introduced to estimate the brightness of non-observed modeled objects, based on their size, and assumptions on shape and materials within MASTER.

The integration of brightness data into MASTER will also help address data gaps in current catalogues by fusing different data sources, providing a more complete picture of the light pollution caused by space objects. Use cases, such as the impact of the Starlink constellation on both ground- and space-based observations are discussed to highlight the need for this enhancement. Furthermore, the paper outlines how the enhancement suggested aligns with ESA's leadership in space debris mitigation and would position MASTER to contribute to global space sustainability efforts by evaluating light pollution's impact on the night sky.

Finally, this paper suggests further research into the development of a Light Pollution Score (LPS), which could serve as a future tool for quantifying the impact of space objects and constellations thereof on dark skies and informing satellite design and related policy decisions. This proposal also opens opportunities for collaborations between ESA, global observatories, and other stakeholders, further advancing the understanding of the cumulative effects of space debris on dark skies and supporting the sustainable use of outer space.

Keywords: Satellite Brightness; Space Debris Modeling; Dark and Quiet Skies; Optical Pollution; Space Sustainability

1. INTRODUCTION: THE NEED FOR BRIGHTNESS MODELING IN SPACE SUSTAINABILITY

1.1 Dark and Quiet Skies Initiative

The increasing concern over artificial light pollution in the night sky has led to global efforts to mitigate its effects, particularly through initiatives like the Dark and Quiet Skies Initiative [1]. This initiative addresses two major contributors to sky brightness: artificial light at night (ALAN) and satellite-induced brightness. While ALAN originates from ground-based lighting sources, the latter is a growing issue due to the rapid

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expansion of satellite constellations. As thousands of new satellites are launched, the cumulative brightness impact is expected to escalate, significantly affecting astronomical observations and cultural appreciation of the night sky [1].

International bodies, including the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and the International Astronomical Union (IAU), have recognized satellite brightness as a major sustainability challenge [2] . The finalization of ESA's Zero Debris Charter in 2023 and discussions within COPUOS since 2021 reflect an increasing regulatory focus on this issue. Predictions suggest that under optimal illumination conditions, over 5,000 satellites could be simultaneously visible above local horizons at key dark-sky observatories, posing a significant challenge to scientific research and environmental sustainability [3].

1.2 Growing Impact of Large Constellations

The expansion of large satellite constellations has brought economic and technological benefits, such as global broadband coverage and enhanced Earth observation capabilities. However, these advancements come with environmental costs, including increased light pollution and radio frequency interference [1]. The International Astronomical Union (IAU) has issued guidelines to mitigate the impact of satellite visibility, setting thresholds for acceptable brightness levels. For example, the IAU defines a threshold for the upper limit of artificial light at professional observatory sites to ensure true dark-sky observations. This threshold is set at <10% above the natural background at a 45° elevation [1].

From an environmental perspective, satellite brightness influences more than just astronomy. Light pollution interferes with nocturnal wildlife, affects human circadian rhythms, and disrupts traditional celestial navigation systems used by Indigenous communities. These concerns have led to increasing public advocacy for stricter satellite brightness guidelines and new regulatory mechanisms to ensure sustainable satellite operations [1].

1.3 Why Satellite Brightness Matters

Scientific studies indicate that satellite trails left in astronomical images degrade the accuracy of observational data, requiring extensive post-processing and reducing the efficiency of data collection [3]. The level of disruption depends on several factors, including:

- The size and altitude of the satellites.
- The materials and coatings used on their surfaces.
- Their orientation relative to the Sun and Earth.

Constellations such as Starlink, OneWeb, and Amazon's Kuiper have already demonstrated the large-scale impact of satellite brightness on ground-based observatories, particularly during twilight hours [4]. Astronomers estimate that without proper mitigation, future mega-constellations could leave permanent marks on observational datasets, affecting the detection of asteroids and deep-space phenomena [5].

Beyond astronomy, artificial light at night (ALAN) impacts ecosystems by disrupting migratory patterns, altering predator-prey relationships, and affecting nocturnal behavior in various species [6]. Many of these issues remain under-researched, but the need for global collaboration in developing solutions is becoming increasingly clear [7].

For many Indigenous communities around the world, the night sky holds deep cultural, spiritual, and navigational significance. Celestial bodies have been central to oral traditions, seasonal calendars, and ceremonial practices for millennia. The increasing brightness of artificial satellites threatens to disrupt these connections, erasing ancestral knowledge systems and diminishing Indigenous access to an undisturbed night sky [8].

Traditional Indigenous navigation, such as Polynesian wayfinding and Inuit star mapping, relies on an unobstructed view of the stars. Additionally, sacred ceremonies tied to celestial cycles, such as solstices and lunar phases, depend on an unpolluted night sky. As satellite constellations continue to expand, engaging Indigenous communities in space sustainability discussions is crucial to ensuring that their perspectives and rights are respected [9].

1.4 The Need for a Structured Observability Model

Despite the increasing recognition of satellite brightness as a sustainability issue, no formalized framework currently exists for evaluating and regulating brightness at a pre-launch stage. Operators often lack predictive tools to estimate the brightness of their satellites before deployment. Factors such as surface reflectivity, satellite orientation, and operational altitude significantly affect the visual magnitude of satellites, making post-launch mitigation difficult and expensive [1].

A structured observability model that integrates brightness predictions into space sustainability assessments is needed. Current models, such as ESA's MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) model, are well-suited for debris risk assessments but do not yet incorporate brightness metrics. By extending MASTER to include brightness information, satellite operators and regulators would gain access to an estimating predictive tool that allows them to assess brightness impacts in advance and implement mitigation strategies where necessary.

Additionally, ESA has studied optical pollution from GEO satellites, as most regulatory efforts have focused on LEO constellations. Incorporating brightness modeling into MASTER could expand its application beyond LEO, enabling improved mitigation strategies for satellites at various altitudes.

2. THE MASTER MODEL AND ITS ROLE IN SUSTAINABILITY

2.1 Background on MASTER

The MASTER model, developed by the European Space Agency (ESA), has been a critical tool for assessing space debris risks for over 30 years [4]. It provides a detailed database of space debris generating events, degradation effects releasing additional space debris objects, estimates of where those objects are released, evolution of their trajectories and the assessment of object flux (which serves as a primary factor in the evaluation of collision risk) on target missions. MASTER is widely used, among others by:

- Mission planners to assess satellite collision probabilities.
- Engineers to design shielding solutions for spacecraft.
- Researchers to study long-term space debris evolution.

The latest update to MASTER (August 2024) primarily includes a detailed population upgrade for new breakup events that occurred between 2016 (last reference epoch) and 2024, as well as updates on known historic events. Besides breakup modelling, the MASTER population is also built on an event database consisting of:

- Solid rocket motor (SRM) firings, contributing slag and dust particles.
- Nuclear reactor core ejections and leakage events, releasing sodium-potassium (NaK) coolant droplets.
- Launch- and mission-related objects, which include spent rocket bodies and inactive satellites.

2.2 Limitations of MASTER (It Does Not Yet Model Brightness)

While MASTER provides robust data on debris populations, their distribution in near Earth orbits and associated flux estimates (for past, present and future epochs) on target missions, it lacks brightness modeling capabilities [4]. The model characterizes objects primarily by their size, mass, and orbital parameters, but it does not account for:

- Material reflectivity and albedo (which influence visual brightness).
- Surface coatings and their aging characteristics (which can reduce or amplify brightness).
- Phase angle variations (which change brightness depending on observer location).

Without these parameters, MASTER cannot currently evaluate how satellites contribute to light pollution or how debris objects might interfere with ground-based astronomical observations [10]. Additionally, IAU guidelines recommend limiting satellite brightness to 7.0 Vmag + 2.5 × log(SatAltitude/550 km), which MASTER does not yet account for [1]

2.3 How This Work Extends MASTER for Brightness Modeling

To address this limitation, this study proposes an extension to MASTER that integrates satellite brightness modeling by incorporating:

- Astronomical magnitude estimates for all cataloged objects .
- Material composition and shape parameters to refine brightness estimates.
- A framework for fusing observational brightness data with MASTER's existing population models.

This enhancement will enable MASTER to serve not only as a tool to support collision risk assessments, but also as a source for satellite brightness impact assessments. By integrating satellite photometry data from global surveys, MASTER can refine its brightness assessments with every population update.

By bridging the gap between orbital debris modeling and brightness impact assessments, MASTER will contribute to a more holistic approach to sustainable space operations. As satellite constellations continue to grow, ensuring that brightness impacts are understood, well estimated, and mitigated in advance will be crucial to preserving dark skies for both scientific and cultural purposes [11].

3. METHODOLOGY

3.1. Extending MASTER to capture observability characteristics

The MASTER population consists of distinct population snapshots, capturing the state of all modelled objects in the space environment. For the historic population snapshots, quarterly population files are generated until the reference epoch. The latest reference epoch in MASTER-8 is August 2024. Future projections are generated via ESA's Debris Environment Long-Term Analysis (DELTA) tool and then cast into annual snapshots. Those population snapshots can be downloaded for free via ESA's Space Debris User Portal (SDUP).

On the user side, the MASTER population snapshots present themselves via so called *probability density* maps. Those maps are used by the MASTER software to sample objects representative of the environment at the user's requested epoch and orbital region to produce flux estimates. The probability density maps are, however, only the final step in the population generation process of MASTER. In the following, we discuss rather along the first steps in that process where individual source models generate simulated objects and their properties. This is the inflection point to augment MASTER's current population generation with additional object characteristics that would enable brightness assessments.

The Program for Orbital Environment Modeling (POEM) implements all the individual source models and generates the first population snapshots. For instance, a cloud of slag and dust particles as a result of a solid rocket motor firing at a distinct date and time. For each simulated object, an entry is created in the so-called *sim file*. Each sim file entry adheres to the following format:

```
AABCCCCDDDDDDD E F.FFFFFFFF G.GGGGGGGG H.HHHHHHHH IIII.IIyI JJJJJJ.J K.KKKK LLL.LL MMM.MM NNN.NN OOO.OO
```

The individual columns in this fixed format file are explained in the Table 1 (with standard Fortran format descriptors):

Table 1: POEM sim file format description

Column element	Description
AABCC CCCDD DDDD D	Unique object designator, encoding various information described separately in Table 2
E	Quality indicator, format I1. Can be either statistical (=1), mixed (=2), or deterministic (=3). *Statistical* means that object information comes from the model only, *deterministic* means that object properties are known from observed objects (e.g. as part of the TLE catalogue), and *mixed* means an object has both modelled and estimated (from observed quantities) characteristics.
F.FFFFF FFF	Representation factor, format E10.4. Collects objects of very similar properties under one representative data entry.
G.GGG GGGG G	Mass in kg, format E10.4.
H.HHH HHHH H	Characteristic length (or diameter) in meters, format E10.4.
IIII.III	Mass-to-area-ratio (m/A) in kilograms per square meter, format F8.3
JJJJJJ.J	Semi-major axis in kilometers, format F8.1
K.KKK K	Eccentricity, format F6.4
LLL.LL	Inclination in degrees, format F6.2
MMM. MM	Right ascension of the ascending node in degrees, format F6.2
NNN.N N	Argument of perigee in degrees, format F6.2
OOO.O O	Mean anomaly in degrees, format F6.2

The first element in the data file, the unique object designator, encodes additional information which appears to be useful to support also the incorporation of the information on the optical properties of an object. The designator can be further broken down into the elements as described in Table 2.

One idea that does not involve breaking changes in the current sim format is to use the sub-source type to encode information on the modelled material, which itself is linked to a (to be designed) lookup file mapping the reflective properties. For instance, in [12], a list of combined materials and shapes was suggested for breakup fragments, such as metal_angledrod, metal_grain, cfrp_needle, plastic_bent, or white_paint_flake.

Table 2: POEM sim file unique object designator format description

Designator element	Description
AA	Source type, format I2. Currently entails: explosion (=0), collision (=1), launch- and mission-related objects (LMRO, =2), sodium-potassium (NaK) droplets (=3), solid rocket motor slag (=4) and dust (=5), paint flakes (=6), ejecta (=7), and multi-layer insulation (MLI) breakup fragments (=9).
B	Sub-source type, format I1. Currently used only for three source types, otherwise it is just zero: If source is LMRO: Payload (=1) Rocket body (=2) Mission (=3) Constellation (=4) West-Ford-Needle Cluster (=5) If source is NaK: Core ejection droplets (=1) Leakage droplets (=2) If source is ejecta: Cone ejecta (=1) Spallation ejecta (=2)
CCCCC	Event identifier, format I5. For instance, the sequential event number for the list of breakup events in MASTER. For continuous sources, like paint flakes, it entails the year of the release.
DDDDDDD	Object identifier per event, format I7. Can be a sequential counter, e.g. for collision and explosion breakups. For catalogued objects, it may reference a catalogue identifier (such as the US Satellite Catalog Number, also known as “NORAD ID”, or ESA's DISCOS ID).

However, the list of materials and shapes may grow substantially and would ultimately require an expansion of the currently single integer sub-source type. In addition, the sub-source type is already in use for another purpose with certain source types, like the categorisation into payloads, rocket bodies, etc., for the launch- and mission-related source type.

Moreover, for observed objects where astrometric and photometric data has been collected, it could be beneficial to augment the current three dynamic and geometrical object properties (mass, diameter, m/A) with optical quantities. It is therefore suggested to expand the sim file format as follows:

1. An additional column to encode material and shape information
2. An additional column to collect knowledge from brightness measurements

The additional Columns will contain information about the magnitude value, the source of the magnitude, as well as standard deviation from the mean of the Dataset.

3.2. Data Sources, modelling and Integration

Astronomers characterize the brightness of celestial objects using the magnitude system, which is a logarithmic scale referenced to the star Vega. This system quantifies brightness based on the amount of flux received by an observer. Direct measurement yields the apparent magnitude, which describes how bright an object appears from Earth. Alternatively, an existing approach to model the apparent magnitude m is the following is described in equation (1)

$$m = -2.5\log_{10}(F) + C \qquad (1)$$

where C is a calibration constant dependent on the reference source and F the Flux of light emitted by the source. Since the measured flux is affected by factors such as the distance to the object, its intrinsic luminosity, and the wavelength of observation, a second parameter is introduced: the absolute magnitude m_{abs}. This value represents the brightness an object would have if observed from a standardized distance of 10 parsecs (pc), allowing a direct comparison between different objects independent of their actual locations [13].

The classification of satellites based on their magnitude follows a similar methodology. The apparent magnitude quantifies the observed brightness of an artificial satellite from a given vantage point, while the absolute magnitude provides a standardized measure of brightness, enabling direct comparison between different satellites under identical observational conditions.

The magnitude of an object is influenced by several factors, making it challenging to model with high precision. The most fundamental approach to magnitude estimation is the direct measurement of an object’s brightness relative to the reference star Vega, which has an apparent magnitude of $m_{Vega} = 0$ in the V-band. However, unlike stellar objects, whose brightness is primarily defined by their intrinsic luminosity, the brightness of a non-luminous, reflective object depends on several additional parameters such as:

- Distance to the observer h, affecting the inverse square law of brightness.
- Geometrical cross-section A, as projected onto the observer's line of sight.
- Surface reflectance properties (albedo ρ and material composition).
- Attitude (orientation) of the object, determining the incident and reflected light angles.
- Wavelength dependency, as different materials exhibit spectral variations in reflectivity.
- Phase angle φ defined as the angle between the Sun, the object, and the observer.

The phase angle plays a particularly important role in determining the reflection characteristics. For satellites in low Earth orbit (LEO) and geostationary orbit (GEO), this leads to the well-documented effect of satellites becoming highly visible during dusk and dawn [14].

Visual Magnitudes of resident Space Objetcs (RSOs) are expressed in reference to the sun's magnitude m_{sun} of -26.7 and the ratio of reflected light from the sun towards the observer according to equation (2)

$$m_{app} - m_{sun} = -2.5\log_{10}\left(\frac{F_{app}}{F_{sun}}\right) \quad (2)$$

With the Flux emitted by the sun F_{sun}.

The Flux that is received by the Observer itself is a function of the light emitted by the sun and is expressed in (3)

$$F_{app} = \omega \cdot \rho \cdot F(\varphi) \cdot F_{sun} \quad (3)$$

Where ρ referes to the Albedo as a function of material and surface properties, ω to the geometric scaling factor, which is a function of the Objects Cross section scaled to the square of the distance to the Obser R, $\omega = \frac{A}{R^2}$ and $F(\varphi)$ to the phase function. The latter describes the angular dependant reflectance of an object based on the scattering behaviour and its geometry [13].

Including the phase functions for Lambertian and specular scattering *F1* and *F2* with a dimensionless mixing coefficient β, the magnitude of the Satellite is determined according to (4)

$$m_{std} = m_{sun} - 2.5\log_{10}\Big(A \cdot \rho \cdot \big(\beta \cdot F_1(\varphi) + (1-\beta) \cdot F_2(\varphi)\big)\Big) + 5\log_{10}(h) \quad (4)$$

For Earth-orbiting objects, an additional Earthshine correction can be introduced for high phase angles $\varphi > 120°$ where sunlight scattered from Earth's atmosphere and surface significantly enhances satellite brightness. However, for low phase angles (i.e., RSOs in direct sunlight), studies suggest that Earthshine has negligible impact and can be omitted in magnitude calculations [15], [16].

Table 3: Brightness as Pollution

Satellite Brightness (Magnitude)	**Description**	**Visibility**	**Impact on Light Pollution**
0 to -4	Extremely bright	Visible even during twilight or daytime	Significant contribution to light pollution, very bright in the night sky
+1 to +3	Bright	Easily visible to the naked eye	Noticeable impact on light pollution, visible at night with minimal effort
+4 to +6	Moderate	Visible in dark conditions, harder to see in urban areas	Moderate impact, visible mainly in rural dark sky areas
+6 and higher	Faint	Only visible through telescopes	Minimal impact, unlikely to affect naked-eye observations of the night sky

Table 3 gives a proposed relative interpretation of the magnitude scale for observers when considering satellite brightness. Satellites with lower magnitudes, i.e. values close to 0 or negative appear brighter, particularly during twilight periods when they remain illuminated by the Sun. In contrast, satellites with higher magnitudes are generally too faint to be observed without telescopic instrumentation, though their cumulative effect on diffuse sky brightness remains a subject of study, especially with the expansion of mega constellations. To mitigate these impacts, efforts focus on reducing satellite reflectivity, optimizing orbital altitudes, and coordinating observation schedules to minimize interference, emphasizing the need for a systematic characterization of satellite brightness distributions to safeguard ground-based astronomical observations [17].

Brightness Model: To integrate brightness data of RSOs, this work proposes a combined approach that incorporates both photometric database measurements and with an analytical reflectivity-based brightness model to account for objects not included in observational datasets. The MMT-9 photometry database, which contains standard magnitude data for 12,753 objects, serves as the primary reference for direct observational data, while the reflectivity model enables the estimation of brightness for RSOs that are not included in existing datasets. The absolute magnitude is estimated by assuming Lambertian scattering, incorporating the object's phase angle and attitude, and normalizing observations to a standardized distance of 1000 km with a fixed phase angle of 90°. The calculated magnitudes are then validated against MMT-9 observations by cross-referencing the NORAD ID.

Table 4: Key Data Sources for Observability Module

Data Source	Type	Use in the Model
MMT-9 Photometry	Standard Magnitude standard deviation for V-Band observations	Including Brightness Data to MASTER Calibrating satellite brightness
DISCOS Database	Object Characteristics	Calculate Brightness according to a diffusive scattering model

Role of the MMT-9 Database:The MMT-9 photometry database provides real-time satellite brightness measurements in magnitudes, enabling detailed visibility modeling from Earth. The observatory's nine 71 mm f/1.2 lenses operate in the visible spectrum, calibrating satellite magnitudes against V-band field stars. Object identification is achieved through correlation with publicly available TLE data, allowing precise orbital association. This approach enables the unique classification of 100–400 satellite crossings per night, establishing MMT-9 as a key resource for continuous photometric monitoring of artificial objects in Earth's orbit.

By incorporating these magnitude values, it becomes possible to predict which satellites will be bright enough to contribute to light pollution and when they will be most visible in different regions. Additionally, time-dependent brightness variations are tracked, accounting for changes in a satellite's orbital position, reflectivity, and solar illumination conditions. This data enables the refinement of observability models, incorporating temporary brightness fluctuations, such as satellite flares caused by specific satellite orientations.

To develop an accurate satellite observability model, several essential data fields from the MMT-9 database are utilized:

ID: The NORAD-ID serves as a unique identifier assigned to each satellite, facilitating cross-referencing with other databases and ensuring precise tracking of orbital trajectories.

Name: The satellite's designated name or identifier (e.g., STARLINK-5432, GLOBALSTAR M004), allowing categorization based on operational status, constellation membership, and mission type.

Standard Magnitude (Std. Mag): A fundamental parameter in the photometric characterization of Earth-orbiting objects, standard magnitude represents the apparent brightness of a satellite as observed from a reference distance of 1000 km, positioned outside the Earth's penumbra, with a corresponding phase angle of 90°. This standardized measure facilitates comparative brightness analysis across different orbital objects. Observed satellites are correlated with their respective orbital elements using publicly available Two-Line Element (TLE) sets from CelesTrak, ensuring precise association between photometric observations and known trajectories [18], [19].

Brightness Estimation from DISCOS Data: To further expand the Brightness Catalogue within MASTER, this extension integrates estimated magnitude values derived from a defined brightness model. The foundation for this approach is established through ESA's Database and Information System Characterizing Objects in Space (DISCOS), which serves as a comprehensive repository of orbital and physical properties for over 39,000 trackable objects but also including simulated debris and fragments that remain within the observable size range.

DISCOS provides a detailed characterization of space objects, encompassing parameters such as size, shape, and mass, while also offering critical metadata regarding launch events and orbital parameters. As such, it constitutes a fundamental tool for analyzing the near-Earth environment and assessing the properties of artificial objects in space. The most relevant parameters utilized in this study are:

satno: The satellite number (NORAD-ID), uniquely assigned to each tracked object, enabling direct comparison of data across different datasets.

Name: Identifies the object and facilitates categorization, particularly in distinguishing debris from operational spacecraft.

dim1, dim2, dim3: Object dimensions, depending on the assigned shape model. These parameters describe length, height, depth, or diameter, as applicable.

Shape: The estimated geometric representation of the object. As space objects typically hold complex geometries, this parameter approximates their structure using a combination of simple shapes, such as spheres, cylinders, cones, panels, and nozzles.

Span: The largest dimension of an object, corresponding to its maximum cross-sectional dimension. This parameter directly influences the amount of light scattered towards Earth and thus its apparent brightness.

Semi-major axis *(semi_major_axis_km)*: Defines the orbital distance of the object relative to Earth's center, accounting for the planet's radius. This parameter is essential for classifying satellites according to their orbital regime (LEO, MEO, GEO) [20].

The model developed in this study follows the assumption that objects exhibit diffusive reflection, thereby neglecting attitude-dependent variations in brightness. The brightness values are normalized to the standard magnitude, which, as stated above, assumes an observer-object distance of 1000 km and a phase angle of 90°.

Furthermore, rather than representing objects as a composition of multiple geometric primitives, as indicated in the shape column, they are approximated as a single characteristic shape, either spherical, cylindrical, or tumbling plate. This simplification facilitates an initial implementation within the database, providing a structured foundation for further refinement.

Future studies may extend this approach by incorporating satellite-specific models, particularly through the integration of a Bidirectional Reflectance Distribution Function (BRDF). Such an extension would enable a more accurate representation of material-dependent reflectance properties, including attitude-dependent scattering effects.

The developed model follows the estimation process, displaced in Fig. XX, which is s initiated by obtaining the current population from the DISCOS database, which provides information about the orbit, shape, mass, and size of an object.

This enables the assignment of one of the introduced fundamental shapes by extracting shape information from the corresponding column in the database. In cases where the shape is undefined, the width-to-height ratio is used to determine whether an object is more accurately described as a sphere or cylinder. Debris and simulated objects without an assigned shape or span are assumed to be spherical by default, with a default cross-section of 10 cm.

The information about shape and span is further utilized to calculate the cross-sectional area, which is a key parameter in determining the amount of scattered light.

As introduced previously, a scattering-model-specific phase function is used to estimate the magnitude of an object based on the illumination angle. For the standard magnitude, this angle is set to 90°. To neglect the attitude of an object, the mixing coefficient of diffuse and specular scattering is set to 1, ensuring that the phase function relies solely on the diffuse component. The three main shapes are modeled accordingly as described in Table 5. The different phase functions are plotted depending on the phase angle, to show the influence of an object's illumination based on its original shape. This provides an understanding that the change of the illumination angle has a lower effect on the on spherical objects compared to plate-like objects and is visualised in Figure 1.

Table 5: Phase functions for diffusive light scattering of different common geometries [21]

sphere	$F_{sphere,diff}(\varphi) = \frac{2}{3\pi^2}\left((\pi - \varphi)\cos(\varphi) + \sin(\varphi)\right)$
cylinder	$F_{cylinder,diff}(\varphi) = \frac{\cos^2\left(\frac{\varphi}{2}\right)}{4}$
flat plate (tumbling)	$F_{plate,tumb}(\varphi) = \frac{1}{\pi}(1 - \cos(\pi - \varphi))$

Since the relative position of an Observer to the RSO effects the observed magnitude, the precise consideration of elongation angles for plate angle is more crucial compared to the consideration for spherical objects. This influences the normalised standard magnitude values which are derived from the observed magnitude distributions and estimated based on adequate models.

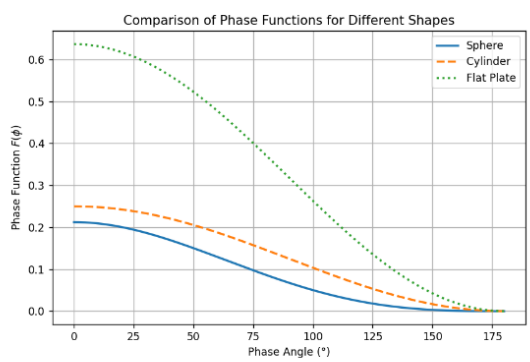

Figure 1: Phase function modelled for spherical, cylinder and tumbling flat plates Objects visualize the effect the shape of an object has on the factor with which the light gets reflected towards the Observer.

The third component in modeling the visibility of an object is its material-specific reflectivity, which determines the albedo assigned to a given surface. This value is typically derived from experimental measurements, which, to date, have been conducted exclusively under terrestrial conditions. However, long-term exposure to space radiation alters surface properties, potentially affecting both albedo and, consequently, the observed magnitude of an object. A comprehensive database of reflectivity changes due to space weathering effects remains an open research topic.

In this work, the material-specific albedo range is introduced based on findings from the COLA study. Each material is assigned a unique one-digit identifier, which may be incorporated into the future MASTER simulation ID to facilitate automated material classification in orbital population models. The MASTER ID, consisting of 14 digits, includes a designated material identifier, as exemplified Section 3.1.

Incorporating Brightness Data into MASTER: Following this development, the Brightness Data extension can be included in Master based on the following steps:

1. Add a brightness module to the MASTER tool, which will pull Std. Mag (Standard Magnitude) data from satellite tracking sources such as MMT-9. This module will store brightness values for all tracked satellites and constellations.

2. Use Data from DISCOS to estimate the brightness of an Object accordingly t an appropriate Magnitude estimation Model, which respects the Shape, Albedo, phase angle and distance to the Observer

3. Introduce the specific character B of the Simulation ID from MASTER to refer to the specific Material of the Object, which is linked to a characteristic Light scattering Value. This is used to estimate the amount of light that will reach the observer. In the introduced Model this refers to the mean albedo, calculated with the albedo range, given in the materials file [12].

4. Modify the existing debris catalog in MASTER to include optical properties like brightness, surface reflectivity (albedo), and satellite orientation, allowing for the prediction of light pollution in addition to debris risks. Additionally, the Database will be extended with an identification Column to refer to the origin of the Value, whether it is a result of the Model or if it was estimated through an observation.

These steps are visualised in the Flowchart, pictured in Figure 2 to visualize the extraction and integration procedure.

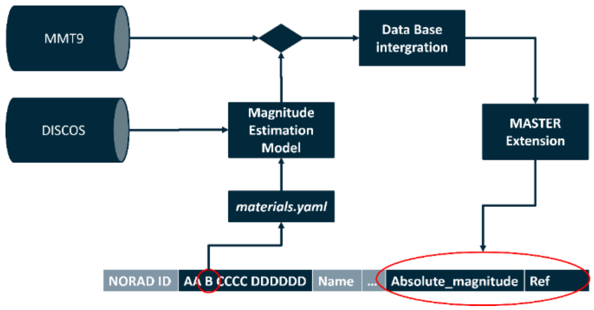

Figure 2: Implementation of computed and extracted Data to the MASTER Population, by incorporating material specific characteristics from the simulation ID, obtained from the MASTER Tool

3.3. Calibration and Validation

The Model is calibrated by estimating the correlation between the model-based brightness calculation and the observed standard Magnitude extracted from the MMT9 Database, for objects which fit the assumed simplification of a diffusive sphere. These Objects exist in form of Calibration spheres, which were launched in the 1960s by NASA to perform radiometric and photometric analysis of space objects [22]. The analysis is performed for Lincoln Spheres 1 and 4, with NORAD IDs 1361 and 5398, as well as for Calsphere 1, Calsphere 2, and Calsphere 4(A), with NORAD IDs 900, 902, and 1520.

The model achieves a Pearson R coefficient of 0.9885 between measured and estimated absolute magnitudes, confirming its applicability for diffusive spherical objects. A further visualization compares the brightness distribution based on MMT9 and DISCOS data. Two significant observations emerge from this analysis:

1.) Objects in the MMT9 dataset are fairly distributed around a mean magnitude of 8.57, while objects from the DISCOS database are centered around a magnitude of 10.5. This indicates that the estimated magnitudes are systematically fainter by a factor of 1.93 compared to the observed values.

2.) The model-based magnitude remains consistently fainter by a factor of 1.93 across the entire dataset. Applying this calibration factor results in the distribution represented in Fig. XX.

As visualized in Figure 3, two characteristics of the magnitude estimation are considered in the analysis: the linearity between modeled and real-world data, expressed for the dataset using the Pearson coefficient r, and the distribution of the magnitude values.

The Pearson coefficient is estimated by comparing the measured magnitude from MMT9 with the estimated magnitude from the model, based on the assumptions described in the previous chapters. This coefficient expresses the similarity between the expected and estimated values, as well as the trend within the dataset. The positive coefficient of r=0.9885 demonstrates the applicability of the developed model for objects with a known shape and reflectivity, supporting the validity of the model.

Additionally, the distribution of the magnitudes from both the modeled (blue) and measured (red) data is visualized. This further illustrates that, in both cases, only small deviations between the real-world and modeled data are observed for the Calibration Spheres.

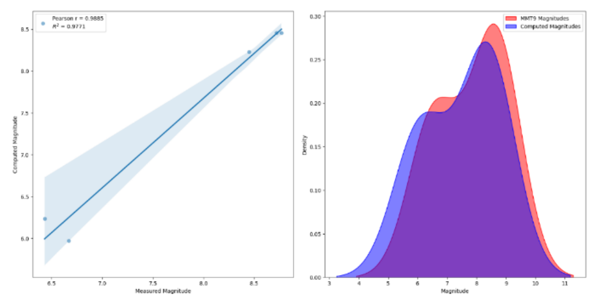

Figure 3: Pearson Correlation of measured and estimated Magnitude for the same Objects from the DISCOS and MMT9 Database show a Pearson r correlation of 0.9885 for the Calibration spheres. Left: Model bases Magnitude estimation and measured Magnitude for the same object shown in a scatter plot. Right: Kernel Density Estimation of the Magnitude Distribution of modelled and measured standard Magnitude values

The expansion of the magnitude estimation model to the entire dataset reveals a significantly lower correlation between measured and estimated magnitudes. This may result from unknown material properties, as well as the simplified model, which assumes spherical, cylindrical, and plate-like objects with a diffuse reflectivity of 0.2.

The low Pearson coefficient of r=0.2023 reflects the weak correlation between the measured and

estimated magnitudes of an object. This is a direct consequence of the linearity between the model and real-world data in the comparison. Most notably, MMT9 provides a magnitude distribution with a mean value of m=6.72m, whereas the modeled data exhibits two peaks: one between m=−2 and m=0 and second one between m=0 and m=4. In contrast, the measured magnitudes reveal a single peak between m=3 and m=7m, indicating that the majority of the observed RSOs have a faint appearance, as the limit of observability to the naked eye is at m=6 . The modeled magnitudes tend to be lower, meaning that the estimation leads to a conservative assessment of brightness values.

This concentration of the magnitudes is a direct result of the low dispersion of the span width of the Objects in the region of the peaks. For the first peak between m=−2 and m=0 of the computed magnitudes it is observed that purely spherical Objects are encountered, with a mean span with of 28.89m and an interquartile range of 0. This concentration of Objects with the same span-width offers one explanation to the large number of Objects with the same magnitude range. The second peak is as well a result of the low interquartile range of IQR = 0 for the span of the catalogued objects. Since the mean span is with 4.02m a factor of 0.139 lower than for the first peak, the object appears fainter and therefore the magnitude value increases. This time spherical and cylindrical objects are considered in the brightness estimation.

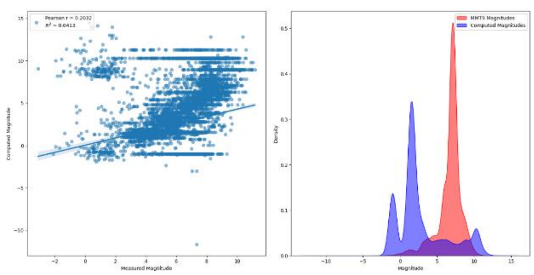

Figure 4: The Pearson correlation between the measured and estimated magnitudes for the same objects from the DISCOS and MMT9 databases shows a Pearson correlation 0.2032. Left: Modelled Magnitude vs. Measured Magnitude per object visualizes the significant range differences between the measured and computed magnitudes for Objects with arbitrary shapes. ***Right:*** *A Kernel Density Estimation (KDE) of the magnitude distribution for modeled and measured standard magnitude values illustrates the shifted distribution between measured and computed magnitudes.*

However, excluding large satellite constellations such as the 7,951 Starlink and 656 OneWeb satellites from the analysis increases the correlation between the modeled and observed magnitudes. This is due to the significant deviation of Constellation satellites from the spherical assumption and their strong influence on the obtained data, as they do not exhibit purely diffusive reflection.

From the correlation parameter, it is possible to derive a linearity between the observed and modeled magnitudes, resulting in a Pearson coefficient of r=0.5268. This finding highlights the need to consider large constellations separately from other satellites and debris objects, an issue that will also be addressed in CONCLUSION AND FUTURE WORK section.

As previously, the distribution of the Magnitude in form of a Kernel Density Estimation provides insides in the Data from Measured and Computed Magnitude. The exclusion of Starlink and OneWeb Satellites shifts the distribution of both Datasets to a similar range from m = -3.2 to m = 15. While Measured Magnitudes are distributed.

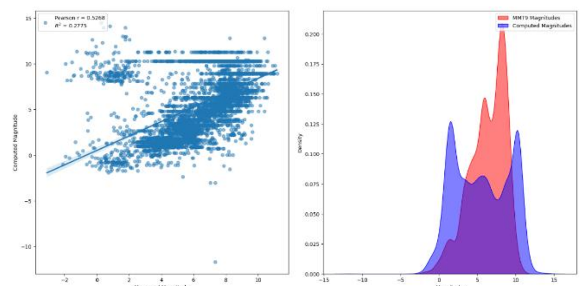

Figure 5: Pearson Correlation of measured and estimated Magnitude for the same Objects from the DISCOS and MMT9 Database show a Pearson r correlation of 0.0.5268 for the Dataset excluding OneWeb and Starlink Satellites. Left: Model bases Magnitude estimation and measured Magnitude for the same object shown in a scatter plot visualize the difference in magnitudes between measured and computed magnitudes. Right: Kernel Density Estimation of the Magnitude Distribution of modelled and measured standard Magnitude values show that the modelled and measured Data appear in the same magnitude range

4. RESULTS AND DISCUSSION

4.1. Broader Implications for Space Sustainability

Sustainable Orbital Management: The integration of brightness-aware modeling into MASTER enhances its role as a sustainability-focused space debris model, extending its utility beyond collision risk assessment to include the optical impact of satellites on the night sky. While current space traffic management practices primarily focus on debris mitigation and collision avoidance, the addition of brightness data introduces a new dimension of sustainability, ensuring that satellite deployments do not contribute excessively to sky brightness pollution.

A brightness-optimized approach to satellite design and constellation management is essential to balancing the growth of satellite infrastructure with the preservation of dark skies. By integrating brightness estimates, MASTER can identify orbital regimes where deployments should be optimized to reduce the cumulative brightness effect on astronomical observations. In addition to hardware-based mitigation strategies such as low-reflectivity coatings, brightness-aware modeling can help inform deployment strategies, including adjusting constellation altitudes, phasing, and spacing to minimize the cumulative impact of satellites on dark skies.

This work aligns with broader sustainability efforts such as Space Footprint aimed at promoting environmentally responsible space operations while maintaining the functionality of satellite constellations. As more space-faring nations and private entities participate in satellite launches, ensuring that the sustainability of space operations includes optical pollution considerations is crucial.

Policy Alignment with ESA's Zero Debris Initiative: ESA's Zero Debris policy aims to minimize the accumulation of space debris through responsible mission planning, post-mission disposal, and compliance with mitigation guidelines. While its primary focus is on debris mitigation, the policy also acknowledges the unintended optical emissions of satellites and their impact on ground-based astronomy. Integrating brightness-aware modeling into MASTER aligns with these efforts by providing a standardized framework for assessing satellite brightness and supporting mitigation strategies.

This enhancement also aligns with global efforts such as the International Astronomical Union's Commission on Dark and Quiet Skies (IAUCPS), which works to address the increasing impact of large satellite constellations on astronomy. By incorporating brightness modeling, MASTER could serve as a regulatory tool, providing a standardized method for evaluating the brightness impact of proposed satellite missions during licensing and approval processes.

Additionally, including brightness data in MASTER promotes greater transparency in space operations, allowing policymakers to assess the cumulative impact of satellite constellations on ground-based astronomy and night sky visibility. Such data could also support international regulatory discussions, helping shape future policy recommendations for sustainable satellite operations.

Informing Future Satellite Design & Operations: The findings of this study can directly contribute to best practices in the satellite industry for reducing satellite brightness. By incorporating pre-launch brightness impact assessments, operators can proactively implement design modifications that minimize sky brightness pollution, ensuring that satellites remain functional while reducing their visual impact. Potential mitigation strategies include:

- Low-reflectivity coatings and surface treatments that reduce unintended light reflections.
- Shading and shielding technologies that control the intensity of reflected sunlight.
- Optimized satellite orientation strategies to minimize brightness spikes.

Regulatory bodies could use MASTER's brightness model to establish threshold limits for satellite visibility, setting guidelines for constellation operators to mitigate their impact. Additionally, the introduction of a Light Pollution Score (LPS) could provide a quantitative framework for assessing the brightness impact of space objects and ensuring compliance with sustainability policies.

This work also presents opportunities for collaboration between:

- ESA, commercial satellite operators, and international space agencies to integrate brightness mitigation strategies into satellite design.
- Ground-based observatories and astronomical institutions to refine observational datasets.
- Regulatory bodies and policymakers to establish best practices for maintaining dark and quiet skies in space governance.

By fostering these collaborations, MASTER's brightness-aware modeling can contribute to a more sustainable approach to space development, ensuring that scientific, cultural, and environmental concerns are addressed as satellite deployments continue to expand.

Considerations for Space-Based Observatories: While ground-based observatories face the most immediate challenges from satellite brightness, space-based telescopes conducting wide-field astronomical surveys could also benefit from predictive brightness modeling. Instruments such as the Roman Space Telescope, Euclid, and James Webb Space Telescope (JWST) may encounter increased interference as satellite populations grow.

MASTER's brightness modeling could be extended to predict satellite passages through space-based telescopes' fields of view, allowing for strategic scheduling of observations to minimize the impact of bright satellite trails. This addition would ensure that both ground-based and space-based astronomical instruments can continue producing high-quality scientific data despite the increasing number of active satellites.

Cultural and Public Interest in Dark Skies: The preservation of dark skies extends beyond scientific and regulatory concerns; it is also a matter of cultural heritage and public interest. For centuries, the night sky has played a significant role in cultural traditions, celestial navigation, and Indigenous astronomy. With increasing light pollution from satellites, public awareness and engagement in dark sky preservation efforts are growing.

By quantifying brightness contributions from satellites, MASTER's modeling capabilities could support public outreach initiatives explaining the impact of artificial satellites on the night sky.

- Collaborations with cultural and Indigenous astronomy programs to understand and mitigate satellite impacts on traditional skywatching practices.
- Astrophotography and amateur astronomy communities, providing tools to predict and minimize interference from bright satellites.

Ensuring that space remains a shared, observable environment for both scientific discovery and cultural appreciation is a key component of long-term sustainability efforts. MASTER's ability to provide data-driven insights into sky brightness trends makes it a valuable resource for fostering discussions around the environmental, cultural, and scientific importance of dark and quiet skies.

4.2. Addressing Technical Challenges

To ensure the maintenance of consistent data across different databases like MMT9 and DISCOS, the objects are linked through their NORAD ID. Validation, it was shown that the estimated magnitude based on models for light scattering and material properties differs significantly from observed magnitudes, even though a strong overlap between simple geometric objects with known albedo was provided. This highlights the need for sophisticated models that account for the advanced and complex shapes that satellites have in reality.

As a first iteration, the model was expanded to include, in addition to spheres, other shapes such as cylinders and tumbling flat plates to account for the non-sphericity of objects. This led to the implementation of a calibration factor of 1.93 when validating the model against the measurements obtained by MMT9, in order to achieve a high correlation between measured and computed magnitude values.

As visualized in the validation chapter, the model-based magnitude estimation shows a significant deviation from the measured magnitude from MMT9. This reveals a crucial fact: purely model-based magnitude estimation cannot be used to predict the magnitude an RSO will have, as it depends on the observer's position. Instead, the database will be constructed from both measured and estimated values. RSOs existing in both databases, MMT9 and DISCOS, will be assigned the measured magnitude from MMT9. Since DISCOS contains a larger population of space objects, 48,042 objects in the database will obtain a computed magnitude value.

To highlight this, two additional columns are introduced to the database: "ref," indicating whether a value was modeled or obtained from MMT9 as a reference, and "std_dev," which provides the standard deviation. Objects with similar shape and surface properties, such as debris, show a standard deviation of $\sigma = 3.21$ with an interquartile range of 0, meaning we consider a high uniformity of the Data. This is also true for modelled Objects, as they appear with a high uniformity, due to the generalized assumptions, that cluster Objects in groups of Shapes, Albedo and spans, which lead to reduced variety in the resulting magnitude Data, compared to the Data from MMT9, which is visualised in Figure 6. However, computed values generally don't achieve such a concentration around the mean value of the magnitude, therefore the Data is more spread out. The Data measured by MMT9 show a consistent measurement, as the mean value of the standard deviation is $\sigma = 0.67$

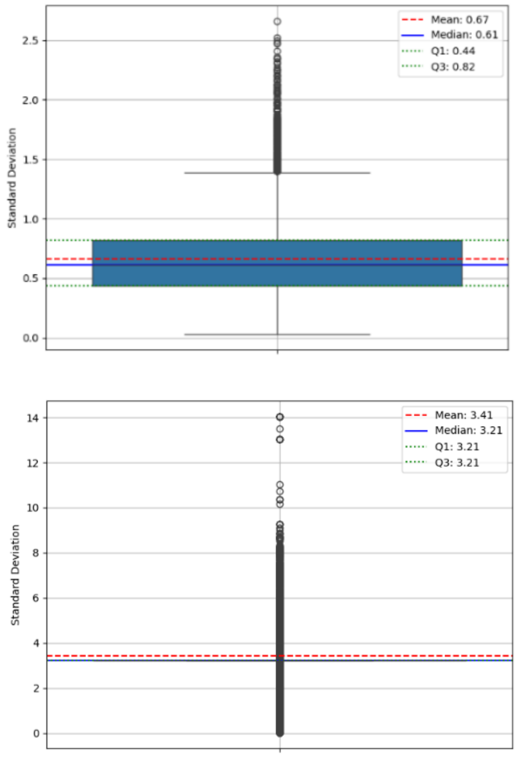

Figure 6: Standard Deviation of the measured Data (top) and the computed magnitude values (bottom), based on the assigned Albedo, shape and span.

The Standard Deviation of the Constellation Satellites This underlines the necessity of considering constellation satellites separately, as their impact on the database cannot be compared to the effect a singular satellite has on the distribution. This is due to the high similarity in the design of individual satellites within a constellation.

5. CONCLUSION AND FUTURE WORK

Integrating observability metrics into MASTER helps quantify satellite brightness, supporting design, mission planning, and compliance with zero-debris requirements.

Magnitude in the V-band spectrum provides fundamental insights into an object's shape and material. It depends on the scattering model as well as object-specific factors like attitude, material, and geometry. With an appropriate phase function, measured brightness can be used to estimate these properties through model backpropagation. Small changes in material or orientation significantly impact observed magnitude, highlighting the impact the design of a Satellite has on its Magnitude.

As the estimated magnitude depends on a characteristic scattering model, this study shows that the current approach to estimating an object's magnitude based on its given features differs significantly from the measured brightness of objects with more complex geometries. This highlights the need for more accurate modeling and the development of sophisticated methods to predict expected magnitude before launch. The proposed standard magnitude can serve as a baseline to quantify brightness and establish guidelines to minimize its impact.

The model developed in this study assumes that objects behave as purely diffusive surfaces, neglecting attitude dependency. It normalizes brightness values to the standard magnitude, which is defined for an observer-RSO distance of 1000 km and a phase angle of 90°. Instead of modeling objects as a combination of geometric components, they are represented as single shapes, either spherical, cylindrical, or flat plates, to facilitate the initial database implementation. This simplification allows for a first integration of brightness estimation into MASTER while maintaining computational efficiency.

In this paper, an initial implementation of a brightness estimation model based on RSO-specific characteristics is introduced to provide magnitude values for MASTER. The proposed model can be further refined into a more advanced version by developing more complex brightness scattering models, such as bidirectional reflectance distribution functions (BRDFs), to improve correlation for non-spherical objects.

By providing an initial implementation of a basic model, this work enables future studies to refine and adapt it to specific needs. It also allows for the customization of material properties, including albedo adjustments and the assignment of materials to the MASTER SIM ID.

Future adjustments may include a magnitude profile that better accounts for brightness variations based on an object's elevation angle. In addition to the fixed observer distance of 1000 km, this would incorporate minimum and maximum values to create a more realistic magnitude curve. This approach would also allow the database to reflect object tumbling more accurately.

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