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The impact of SATCON recommendations on the safety and sustainability of large constellations

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ABSTRACT

The collision risk posed to satellites is a key factor when assessing the long-term sustainability of activities in space. Additionally, advocates for the preservation of dark and quiet skies have raised concerns about the impacts of large satellite constellations in Low Earth Orbit (LEO) on astronomical observations due to satellite streaks and an increase in diffuse night sky brightness from the space debris population. In response, multiple astronomy-driven working groups have been established to develop recommendations designed to reduce interference with astronomy-related uses of space. For example, the Satellite Constellations (SATCON) workshops produced recommendations which are incorporated into guidelines published by the International Astronomical Union's Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (IAU CPS). The DAMAGE computational model was used to study the effects of reducing large constellation altitudes to below 600 km on satellite conjunctions as has been recommended to reduce the impact on optical astronomy. The impact of this altitude reduction on both satellite collision risk and optical astronomy was evaluated. This study found that whilst operating satellites at lower altitudes reduces the contamination of astronomical images, the impact on collision risk for constellation satellites increases due to the reduced orbital volume within which the constellation operates. When formulating space sustainability guidelines, it will be important to consider this and other trade-offs arising from the perspectives of different users of the space environment.

1. Introduction

The Low Earth Orbit (LEO) region of space extends up to 2000 km altitude [1]. Between the years 2000 to the present day, the number of objects that have been launched into LEO has increased tenfold [2]. This increase is driven predominantly by commercial satellite constellations. As of mid-June 2025, >6928 Starlink satellites are at operational altitudes between 355 km and 572 km and 642 OneWeb satellites are operating at approximately 1200 km altitude [3,4]. Future Starlink constellation plans could see the operation of approximately 30,000 satellites between 340 km to 614 km. In addition to these constellations, further large constellations of satellites are planned for future operation at various altitude ranges in the LEO region, with >100,000 satellites proposed over the coming decades [5,6].

The potential increase in the number of satellites in LEO has raised concerns about the sustainability of the proposed activities. For example, studies have shown that an increase in the object density in orbit increases the collision risk for spacecraft operating in that region [7,2]. Collision events present a disruption in the ability of space operators to deliver services and data in space and can produce fragments that increase the collision risk for other spacecraft. As such, reducing the likelihood of collisions is a key element of space sustainability goals and guideline formulation. However, it is important to include more than just the collision risk when characterising the conditions for space sustainability. For example, an increase in the number of conjunctions associated with a higher orbital object density presents an increased burden on operators to screen conjunctions and perform risk mitigation manoeuvres. It also increases the number of manoeuvres that are performed. Performing manoeuvres can reduce the collision probability, but they also have economic consequences, can potentially shorten the lifetime of the satellite by depleting the resources onboard, and can potentially cause disruption to the service provided by the spacecraft. As such, even without collisions

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occurring, the operational burden on satellite operators to mitigate high collision risk could become unsustainable. Additionally, even if a manoeuvre is performed, the probability of a collision occurring is not reduced to zero partially due to uncertainties in the trajectories of the objects involved in a conjunction. Even if discrete collision probabilities are low, the aggregate collision probability across a large number of conjunctions can still be relatively high [8].

Astronomers are also users of space [9] whose activities are disrupted by an increase in the population of objects in orbit. Studies have shown that astronomical observations in orbit [10], on the ground [11], and across different wavelengths [12] are currently being disrupted by objects crossing the Field of View (FOV) of observations during an exposure and by an increase in noise in images as a result of reflections from the background debris population [13,14]. If the number of satellites in LEO continues to grow, the projected impact on some astronomical activities could be significant, with one study finding that 30–40 % of exposures during the first and last hours of the night for the Vera C. Rubin Observatory could be compromised [11].

In response to these sustainability concerns, various organisations have formulated guidelines to inform satellite constellation design and operations that aim to foster more sustainable behaviour in space.

The IADC is an inter-governmental committee of researchers that formulates space debris mitigation guidelines for satellite operators. Space debris mitigation is an important part of space sustainability. The IADC guidelines were formulated based on insights from studies about the evolution of the space debris environment using space debris models [1]. A thorough assessment of the impacts of these recommendations on other users and aspects important to space sustainability such as optical astronomy has not been conducted.

The International Astronomical Union's Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (IAU CPS) is another example of an international organisation of researchers formulating guidelines that encompass aspects of space sustainability. The IAU CPS recommendations [15] were formulated using insights from various workshops, including the Satellite Constellations (SATCON) workshops. In these workshops, illumination models were used to derive appropriate recommendations to reduce the impacts of satellite constellations on astronomical activities [16]. One specific recommendation produced by the SATCON workshops is that satellite constellation operators should reduce their operational altitude to below 600 km altitude wherever possible. This recommendation takes priority over reducing the number of satellites in the constellations. Whilst consideration of satellite safety constraints is mentioned, a thorough assessment of the impacts of this recommendation on satellite operators was not included.

The IADC and IAU CPS guidelines were both formulated using models that assess aspects of space sustainability from important but isolated perspectives. However, the impacts of space activities are not isolated to one type of use. When viewed more holistically, the space environment can be seen as part of a broader set of Earth systems, with connections and feedbacks spanning Earth and space [17]. This system of systems encompasses socio-economic aspects as well as physical and environmental elements. The full impacts of space activities throughout the full system are not identifiable from the analysis of one part of the system alone. As such, guidelines formulated from singular perspectives have the potential to cause unexpected and potentially unwanted consequences in the broader space system.

The importance of trade-off analysis for managing the complexities associated with multiple aspects of space sustainability has been discussed from different perspectives in recent literature [18–20]. However, existing quantitative studies that combine multiple aspects of space sustainability together predominantly focus on the combination of space debris and life cycle assessment aspects [21–23]. This study furthers the literature by providing a quantitative analysis of the trade-offs that result from changes in satellite constellation operator behaviour (specifically the changing of operational altitude) from the perspectives of both satellite operators and ground-based optical astronomers.

Additionally, indicators of sustainability also encompass the *quality of the user experience*, as understood from the well-established literature on environmental management of outdoor spaces on Earth [24]. Through this interpretation, a system is also unsustainable if unacceptable impacts occur to the quality of use of the system. The chosen indicators to represent the impacts on specific aspects of sustainability in this study are the 'rate of collisions before manoeuvres' for impacts to spacecraft operators and the 'rate of images containing a visible satellite' for optical astronomers. Both indicators capture the quality of the respective user experience. The calculation of each of these indicators is outlined in Sections 2.2.1 and 2.2.2. These metrics were chosen as they provide equivalent metrics for quantifying a negative operational impact (i.e. a measure of 'harm') to satellite operator and optical astronomer activities respectively. Many other metrics that relate to an astronomer's perspective were produced in this study, such as average satellite magnitude, average angular velocity of satellites etc.. These were not chosen as indicators in this study because no suitably equivalent metrics from the satellite operator perspective were identified. Furthermore, indicators that represented 'harm' on an individual satellite scale rather than a full constellation scale were also considered. However, these individual satellite scale metrics were not chosen for this study due to their associated data management issues.

2. Methods

The IAU CPS report [15] recommends that satellite operators should reduce the operational altitudes of their constellations to below 600 km wherever possible to reduce their impact on optical astronomy. The goal of this simulation work was to understand if a trade-off between the indicators for satellite operators and ground-based optical astronomers exists with varying constellation altitudes.

2.1. Simulation set-up

The DAMAGE computational model is a three-dimensional physical model capable of simulating orbital populations through time [25]. References [26] and [27] describe the orbital propagator and treatment of constellation satellites in DAMAGE respectively. DAMAGE was used to simulate an active constellation of 1152 satellites operating at one of four altitudes: 1200 km, 930 km, 615 km, and 345 km. 100 Monte Carlo (MC) runs were performed for each of these four scenarios. In DAMAGE, satellite constellations are built with respect to the orbital position of an initial satellite. In each MC run, the right ascension of the ascending node and the argument of perigee of the initial satellite was randomised. Additionally, a 5 % randomness was also applied in the atmospheric model providing further variation across the MC runs. There is also an element of randomness in the determination of collisions that occur from identified conjunction events, according to the collision algorithm described in [26]. In this application of the collision algorithm, conjunctions are identified through the deterministic propagation of satellite positions. The cube algorithm [28] is only applied where a conjunction is identified, whereby the positions of the conjuncting satellites are considered to be uniformly randomly distributed within a 10 km cube. This approach allows

Table 1
Constellation design and set-up in the DAMAGE simulations.

	Altitude (km)	Number	Geometry
Active constellation configuration 1	1200 or 930 or 615 or 345	1152	Walker-star, inclination 89°, 24 planes
Active constellation configuration 2	1200 or 930 or 615 or 345	1152	Walker-delta, inclination 55°, 24 planes
Artificial background constellation	20 shells between 1200 and 345 in 45 km steps	36,000 total (1800 per shell)	Walker-star, inclination 89°, 30 planes

for the fixed mean anomaly seperation of constellation satellites to be captured appropriately. Furthermore, the specific velocities of the conjuncting satellites at the point of conjunction are used in the collision probability calculation.

The historical background population of orbital objects was not used. Instead, a persistent, artificial background constellation of 36,000 identical satellites separated across 20 uniformly distributed shells between 1200 km and 345 km was used. This represents an idealised scenario that allowed for the relationship between the satellites' operational altitude and the indicators to be extracted. In the simulations this background constellation is launched before the active constellation and persists without need for replenishment throughout the entire simulation timeframe.

Both the active and background constellation satellites had a mass of 600 kg and an operational drag cross-section of 4 sq. m. Each launch delivered 75 satellites into orbit at 300 km altitude where they then ascended to their associated operational altitude. The active constellation satellites ascended regularly through the background constellation shells during their orbit-raising phases. At the end of their 5 year operational lifetimes, active constellation satellites reduced their altitude to 20 km below their operational altitude before lowering their perigee altitude to 300 km for Post Mission Disposal (PMD). The perigee altitude was lowered by simulating low-thrust burns when the satellites were at apogee only. This eccentric disposal orbit meant that descending satellites passed less uniformly through background constellation shells during their descent. Once a target altitude of 300 km was reached, the satellites were passivated and a cross-sectional area of 30 sq. m. was adopted to rapidly remove the satellites from the simulation. This increase in cross-sectional area represents a change in the attitude and configuration of the satellites, whereby the solar panels are configured into the direction of motion to increase the atmospheric drag force acting on the satellites.

Two active constellation configurations were simulated separately in this study. By repeating the simulations for multiple constellation geometries, the dependency of the results on constellation geometry was analysed. As shown in Table 1, the active constellation was simulated in a Walker-star geometry and a Walker-delta geometry [29,30]. The satellites in the background constellation orbited in a Walker-star configuration for all cases and were only subject to the effects of the J2 orbital perturbation.

The parameters and behaviours of the constellations in the simulations were as follows:

- The simulation time period extended between 1st January 2020 to the 7th January 2031. This timeframe captured the full population and part of one replenishment cycle of the active constellation. The indicators were calculated using data from the snapshot year of 2030. This snapshot year provides a worst-case scenario for the derivation of both indicators because this is the point in the constellation cycle where most satellites are in orbit (during a replenishment phase). The time of the snapshot within the snapshot year was randomised for each MC run to remove seasonal effects from the results. Further details on how the indicators were calculated follow in Sections 2.2.1 and 2.2.2.
- A propagation time-step of 5 days was used throughout the simulation period.
- The background constellation was fully populated first between 2020 and 2023, followed by the full population of the active constellation between 2023 and 2026. Launches were evenly distributed throughout each year.
- No background objects or new launches were added into the environment other than to replenish the active constellation, the satellites in which had a lifetime of 5 years. The background population satellites had lifetimes longer than the simulation period and therefore did not require replenishment during the simulation period.
- No failures, explosions or collisions were allowed to occur. This removed the introduction of additional spatial density variation due to collision fragments in the results that would obscure the indicators' dependencies on altitude. Some implications of this decision are discussed further in Section 4.
- The disposal success rate was 100 %.
- A constant 10.7 cm wavelength solar flux of $F_{10.7cm} =$ 130 and constant geomagnetic activity index of $K_p =$ 2.13 was maintained throughout the simulation period. This removed variability due to these parameters from the results.
- Satellites experience atmospheric drag at all stages of the simulation. A low-thrust propulsion system is simulated to counteract atmospheric drag at all stages of a satellite's lifetime.

Fig. 1 shows the Concept of Operations (CONOPS) for a single active constellation satellite in the 615 km operational altitude scenario. This same behaviour is repeated for each of the different simulation scenarios. The cycle of launches for new replacement satellites starts in the year 2029.

Fig. 2 shows the number of satellites belonging to the active constellation over a single MC run. Each altitude case has the same number of operational satellites at the operational altitude once the constellation is fully populated in 2027 (1152 satellites). However, once the replenishment cycle begins in 2029 to replace satellites at the end of their 5-year lifetime, the ascending and descending satellites increase the overall number of satellites in the orbital environment. For simulation cases with higher operational altitudes, satellites take longer to ascend and descend out of orbit. This produces an increase in the number of satellites in the orbital environment when a constellation is at a higher altitude, as shown in Fig. 2. The average number of satellites in orbit in the snapshot year of 2030 was extracted for each altitude case and constellation geometry. The average number for each case was very similar for both the Walker-delta and Walker-star simulations. These

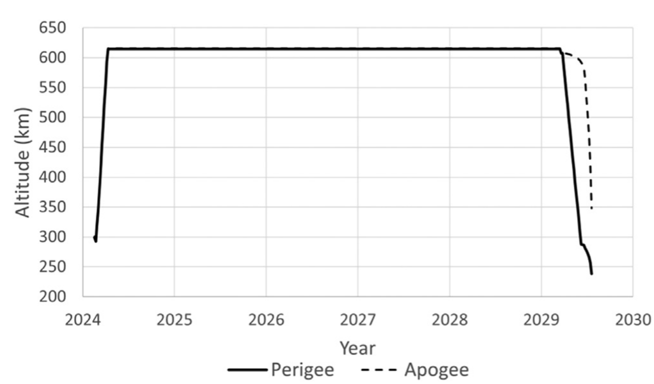

Fig. 1. CONOPS of a single active constellation satellite with an operational altitude of 615 km.

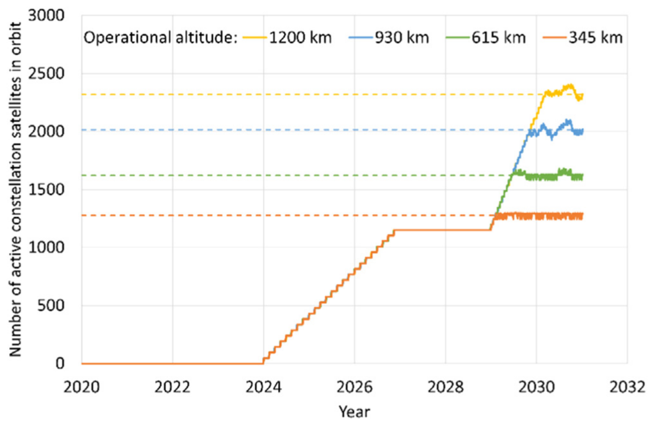

Fig. 2. Number of active constellation satellites in orbit for each altitude case of the Walker-star constellation configuration. The dotted lines show the average number of active satellites in orbit in the year 2030.

average numbers were used in Section 3 as normalisation factors to produce indicators accounting for the number of satellites in the orbital environment.

2.2. Indicator calculation

As outlined in Section 1, the indicators 'rate of collisions before manoeuvres' and 'rate of images containing a visible satellite' were chosen to measure specific consequences linked to the sustainable use of space by satellite operators and ground-based optical astronomers respectively. The methods used to calculate these indicators are outlined in Sections 2.2.1 and 2.2.2 below. Produced are two comparable indicators describing the impacts on two different users of space for the same modelled situation. With these, the impacts of altitude change on both users were analysed.

2.2.1. Rate of collisions before a manoeuvre (the collision indicators)

Only conjunctions involving satellites in the active constellation were considered and contributed to the collision indicator. This included conjunctions between satellites in the active constellation and the background constellation and conjunctions between active satellites and active satellites, where satellites are considered active until they are passivated when perigee altitude reaches 300 km.

The number of conjunctions that occur within the year 2030 per MC run was derived by deterministically propagating the satellites' positions and using the cube algorithm [28] at the point at which a conjunction was identified. As the satellites under analysis are in LEO, a cube size of 10 km was used. From this, the collision probability separated into 10 km altitude bins was produced. By combining the collision probabilities for time intervals taken at 5 day time steps with a random variation of ± 0.5 days throughout the year 2030, the collision rate across LEO throughout the year 2030 for each simulated altitude scenario was derived. The distribution of collision rate with altitude averaged across all MC runs for each constellation altitude scenario is shown in Fig. 3. With these data, an average collision rate between 200 km and 1200 km for a year was derived by summing the collision rates at each altitude. This can be interpreted as a worst-case scenario number of collisions that would be expected in a year in the absence of collision risk reduction manoeuvres. This number is the indicator '*annual total collision rate*'. Additionally, the collision rate for the operational altitude alone was also extracted. In the cases where the operational altitude fell on the boundary of a 10 km altitude bin, data from both the bin above and below the operational altitude were combined. This number is referred to as the '*annual operational altitude collision rate*' indicator. Furthermore, both were normalized by dividing by the average number of active satellites in orbit in 2030 for each altitude and constellation configuration respectively, as indicated in Fig. 2. This produced the further indicators *'annual total collision rate per satellite*' and *'annual operational altitude collision rate per satellite*'. These indicators were collected for each altitude case and for each active constellation configuration and are analysed in Sections 3 and 4.

2.2.2. Rate of images containing a visible satellite (the visibility indicators)

Only satellites in the active constellation were considered in the derivation of this optical astronomy indicator. To calculate the brightness of the satellite from the ground, a reflectance function approximating Starlink satellites was assumed for all satellites [11], where the albedo was assumed to be 0.25. This is a simple approximation that does not include specific attitude modelling that would realistically contribute to the brightness of individual space-

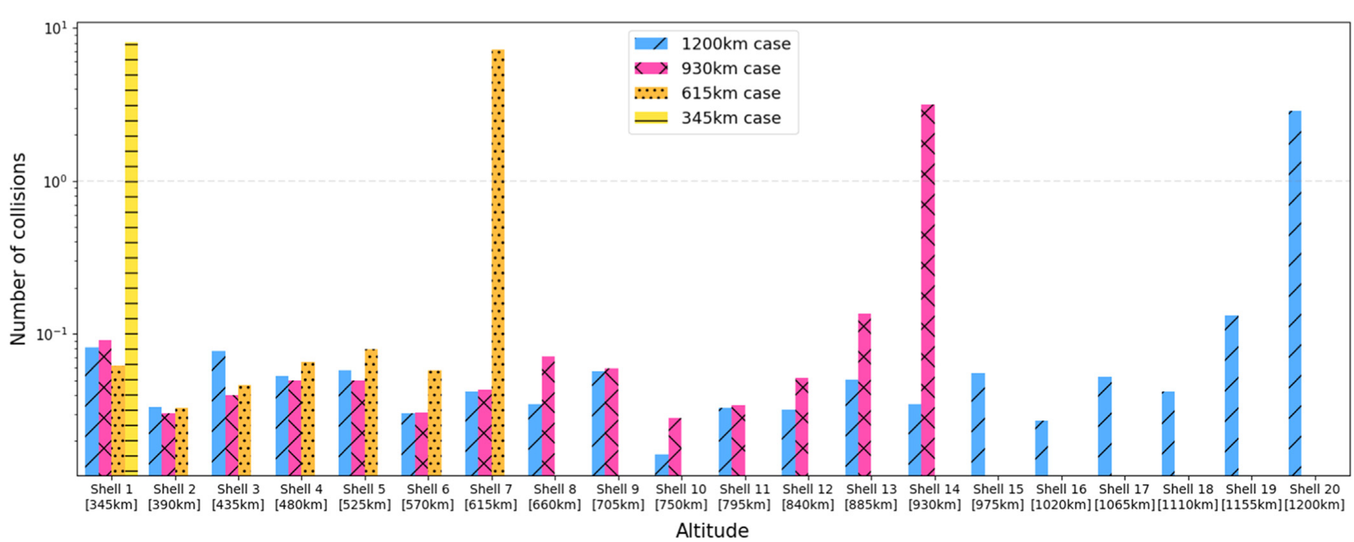

Fig. 3. Bar graph of the average collision rate at each 10 km constellation shell altitude bin across 100 MC runs for each of the altitude cases for the Walker-star simulations. Yellow bars with horizontal lines indicate the results for the 345 km case, orange dotted bars for the 615 km case, pink bars with crosses for the 930 km case and blue bars with diagonal lines for the 1200 km case results.

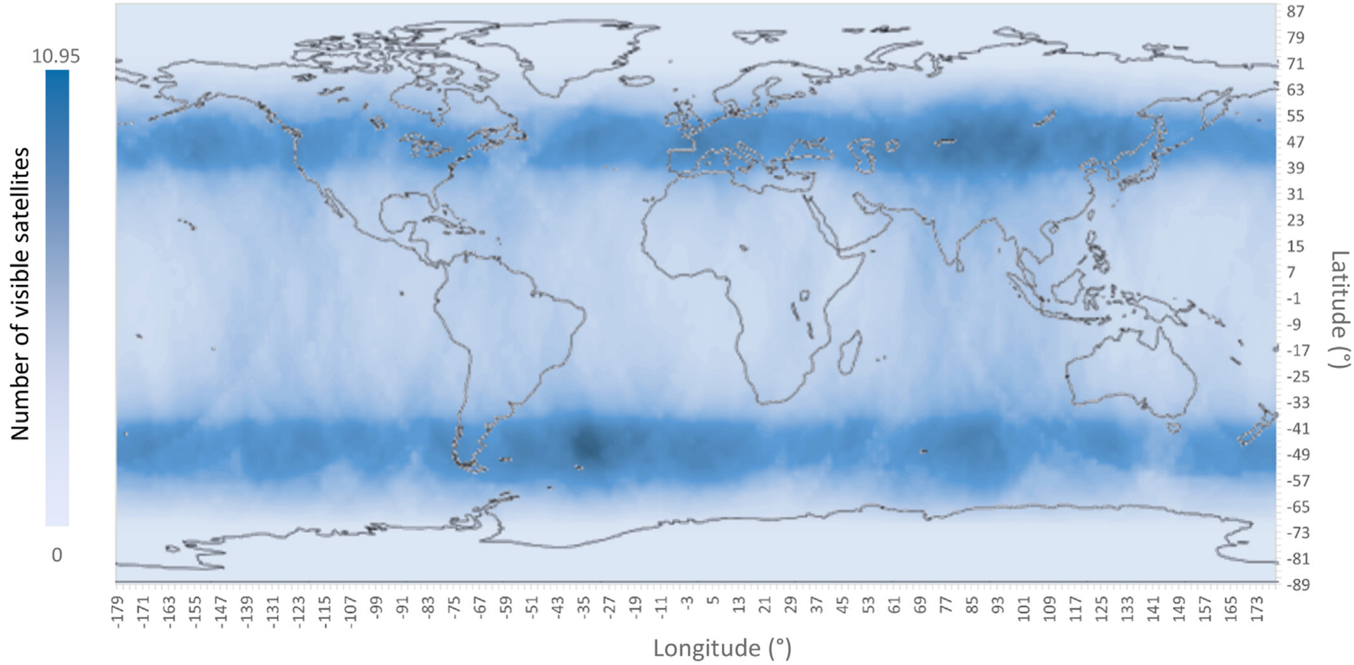

Fig. 4. Graph of the of the average number of visible satellites from each 2° latitude-longitude grid from 100 MC runs of the Walker-delta constellation configuration at 615 km operational altitude. The color gradient indicates the number of visible satellites from that location with darker blue representing more visible satellites.

craft. However, [11] shows that this function can well-approximate direct photometric measurements of Starlink satellites.

Earth's surface was split into latitude-longitude grid cells of size 2 degrees. Each grid cell was then divided into smaller sections corresponding to 1 m diameter telescopes each with a FOV of 6 degrees. This meant that each 2° latitude-longitude grid cell was divided further into 900 smaller grids that represented 6° FOV 'images' in the simulation.

A satellite was considered visible if it was brighter than magnitude 6.5 and could be seen from a grid cell within an elevation of 10 degrees above the horizon when the Sun was at least 12 degrees below the horizon. It was assumed that any visible satellite contained within the FOV of an image would be considered disruptive. This assessment was performed for each grid cell.

Additionally, only the instantaneous locations of the satellites were considered; no trails associated with an image exposure time were generated. As a result, this methodology will tend to underestimate the number of images at each location containing a visible satellite. The average number of satellites from 100 MC runs visible from each latitude-longitude grid for the Walker-delta constellation geometry is shown in Fig. 4. This figure shows an example of the 615 km altitude case only.

By considering each of the 900 images per latitude-longitude grid cell, the number of images containing a visible satellite per grid cell was produced. By considering only the images in night-time observing conditions (taken as when the Sun was at least 12 degrees below the horizon), the spatially averaged number of night-time images that were affected by satellites in the instantaneous moment of the snapshot was calculated. Only one snapshot taken at a randomised time in the snapshot year was generated. By combining visibility snapshots across all MC runs and dividing by the number of MC runs, the time-averaged number of affected night-time images in a year was calculated. By dividing the number of affected images by the total number of global night-time images, an average rate of affected images in a year was produced. This rate was then multiplied by the number of seconds in a year to give the annual visibility indicator representing the '*annual image contamination rate*'. A second variation of this indicator normalised by dividing by the average number of satellites in orbit in the year 2030 was also produced which represents the '*annual image contamination rate per satellite*'. As with the collision indicators, these visibility indicators can also be interpreted as an average expected number of 6° FOV night-time images from any location on Earth containing a visible satellite in a year.

3. Results and analysis

As described in Section 2, comparable indicators describing the consequences of changing constellation altitudes from the perspectives of satellite operators and ground-based optical astronomers were derived from each simulation scenario.

3.1. Simulation outputs

The change in the values of these indicators with respect to the altitude of the constellations shows the consequences of changing constellation altitude from the perspectives of both users. The indicators and their relationship to altitude, calculated as described in Section 2, are shown in Figs. 5, 6 and Table 2 in Appendix A. These results show that a trade-off in the indicators for astronomers and satellite operators occurs when the maximum operational altitude of the satellite constellation is lowered. These opposing trends are resolvable in indicators presented as annual indicators, annual per satellite indicators, when analysing all altitudes including and below the maximum operational altitude and when analysing the operational altitude alone. These trends are also consistent and observable for both active constellation configurations. Each aspect is discussed in more detail in the sub-sections to follow. The errors in Fig. 5 are the standard deviation of the mean taken from the results of 100 MC runs and therefore represent the distribution across all MC runs. As a result, they appear large in Fig. 5, but the trend was consistently observable across every MC run.

3.1.1. Total and operational altitude collision indicators

Each collision indicator was derived from data taken across altitude bins within the whole LEO region under analysis (the 'total'

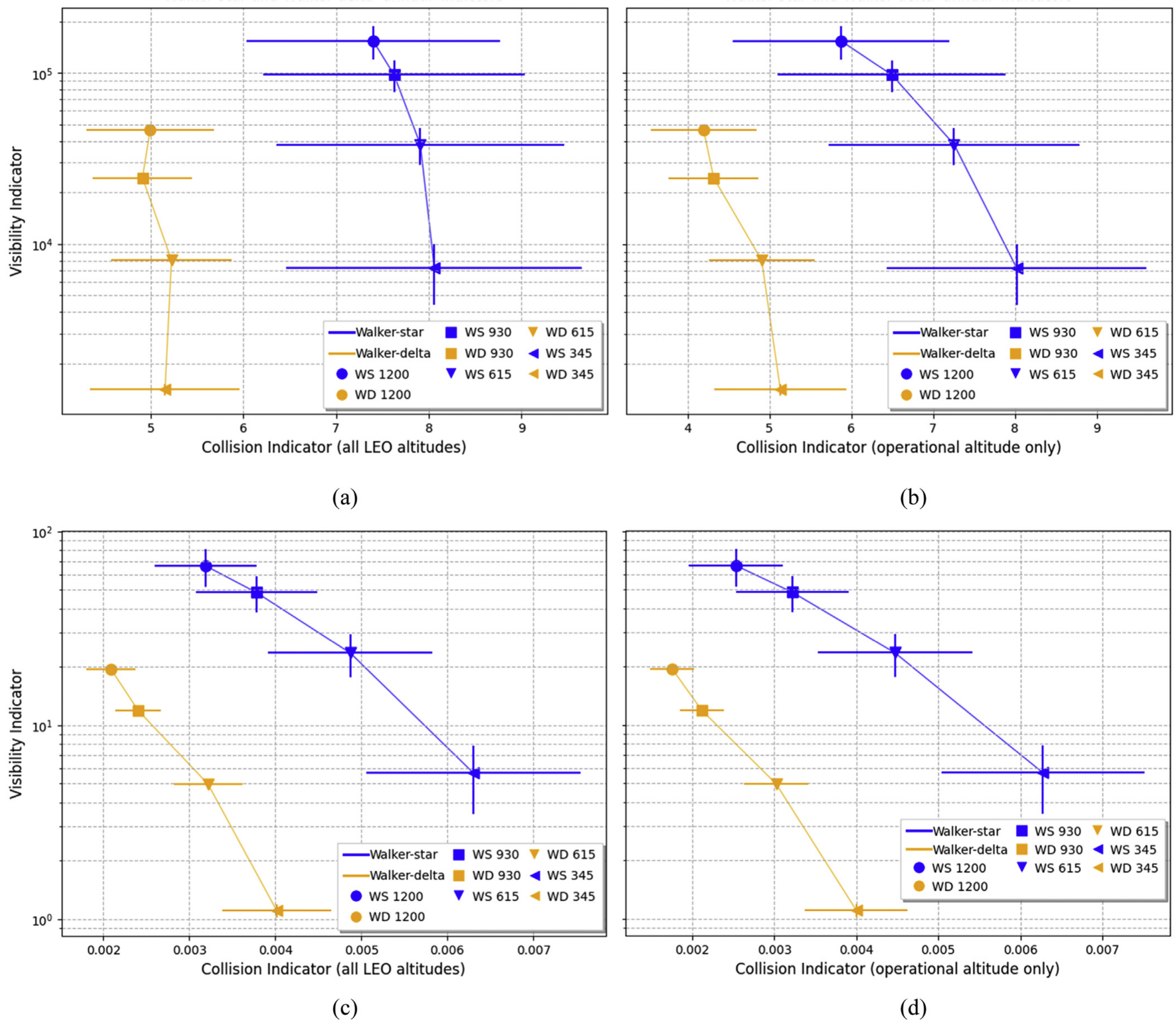

Fig. 5. Plots of the visibility and collision indicators plotted against each other for each of the altitude cases. Blue values are from the Walker-star simulations and orange are from the Walker-delta simulations. Circles show the results from the 1200 km simulations, squares show the results from the 930 km simulations, downwards-pointing triangles show the results from the 615 km simulations and left-pointing triangles show the results from the 345 km simulations. (a) ‘Annual’ visibility and collision indicators across all altitudes transitioned by the active constellation satellites. (b) ‘Annual’ visibility and collision indicators from the operational altitude only. (c) ‘Annual per satellite’ visibility and collision indicators across all altitudes transitioned by the active constellation satellites. (d) ‘Annual per satellite’ visibility and collision indicators from the operational altitude only.

collision indicators), and also separately for the operational altitude alone (the ‘operational’ altitude collision indicators). These results are presented in Fig. 5 and Table 2. The effect of altitude change is most strongly observed through analysis of the operational altitude collision indicators, as shown in Fig. 6. This is because the probability of collision is many orders of magnitude higher in the operational altitude bins than at all other altitudes transitioned by ascending and descending satellites. The effect of altitude change is still observed in the total collision indicators. However, because these indicators include the contributions of ascending and descending satellites, the strength of the relationship is diluted by the noise introduced by the satellites at varied altitudes.

3.1.2. Walker-star and Walker-delta configurations

Two constellation geometries were analysed in these simulations: 1) Walker-star configuration with an inclination of 89 degrees and 2) Walker-delta configuration with an inclination of 55 degrees.

The inclination of a constellation orbit determines the number of visible satellites at all latitudes. This relationship is highly non-linear, with locations with the highest density of visible satellites occurring at latitudes close to the inclination of the constellation satellites. This can be seen in the visibility map presented in Fig. 4. The Walker-star simulations produced the highest density of visible satellites in images at polar latitudes, whereas the Walker-delta configuration produced high densities of visible satellites at around ± 55 degrees latitude. This meant that for the visibility indicators calculated for the Walker-star configuration, contributions from visible satellites at very high-latitude locations dominated. This is notable because the majority of large, professional ground-based optical observatories are located within ± 50 degrees latitude. As such, the average image contamination rate de-

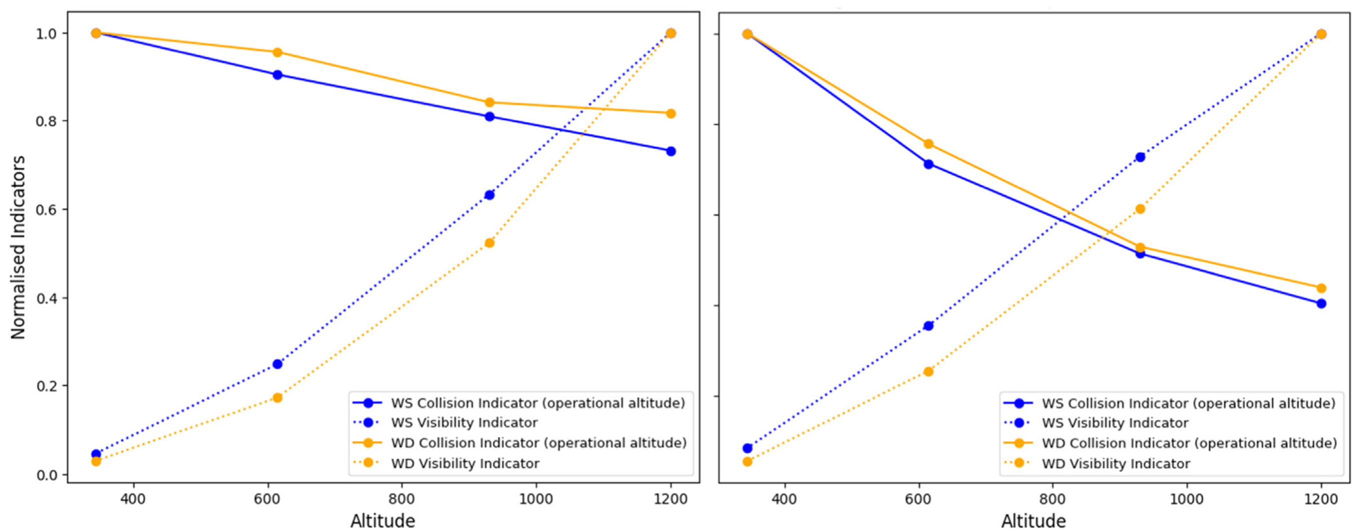

Fig. 6. Plots of the relative change in the visibility and collision indicators with altitude for both the Walker-star and Walker-delta configurations. (Left) Plots of the 'annual' indicators with altitude. (Right) Plots of the 'annual per satellite' indicators with altitude.

rived from these simulations for observatories in these latitude regions is likely overestimated for the Walker-star simulations.

However, the visibility indicators produced from the simulations of the Walker-delta configuration are likely more representative of the image contamination rates experienced at latitudes currently containing many major professional ground-based observatories. They are also more similar to those that would be captured for the current Starlink constellation [31].

The differing satellite constellation configurations also have an impact on the collision indicators. The background population remains in a Walker-star configuration for simulations involving both versions of the active constellation configuration. This creates an additional offset for the Walker-delta satellite constellation simulations that affects the number of conjunctions, and therefore the collision indicator, compared to the Walker-star simulations.

The observable differences in the results between the Walker-star and Walker-delta simulations show that satellite constellation design affects the severity of impact for ground-based optical astronomers and LEO satellite constellation operators. This study included the variation in indicators across different constellation designs to demonstrate that the opposing trends between the chosen optical astronomer and satellite operator indicators are not an artefact of one specific constellation design.

3.1.3. Annual and annual per satellite indicators

As identified previously in Fig. 2, despite having the same number of operational satellites in each altitude case, there are higher average numbers of satellites in the LEO environment in 2030 for the higher altitude cases. This is due to satellites taking longer to ascend to and descend from higher operational altitudes during the replenishment phase. As such, indicators can be derived from a whole constellation perspective (the 'annual' indicators) and from a 'per satellite' perspective (the 'annual per satellite' indicators), where the 'per satellite' indicators are normalised for the average number of satellites in orbit for the snapshot year. One expectation may be that a higher collision rate would be expected in the higher altitude cases due to there being more satellites in orbit. However, both the annual and annual per satellite indicators show conflicting trends in the visibility and collision indicators as the operational altitude of the active constellation decreases. The constellation-level indicator particularly highlights that despite almost double the number of satellites occupying the LEO region in the 1200 km scenario than the 345 km scenario, the collision indicator is still higher for the lower altitude scenario.

4. *Discussion*

4.1. General discussion

The results presented in Section 3 show that, when assessing the indicators outlined in Section 2, lowering the maximum operational altitude of satellite constellations has conflicting impacts for ground-based optical astronomy and satellite constellation operators. Lowering the maximum operational altitude produces conditions where the likelihood of an active satellite interfering with a ground-based optical image decreases, but the likelihood of an active satellite experiencing a conjunction with another object increases. Most current proposed frameworks used to formulate space sustainability guidelines tend to characterise sustainability from the highly limited, often singular perspective of one type of space user. This study illustrates how existing approaches need to be adapted to assess multiple perspectives at once so that the trade-offs resulting from recommendations can be better understood. In doing so, new insights into the sustainability of activities in space can be revealed. By using approaches that can assess the sustainability of actions from multiple perspectives at once, the robustness of sustainability recommendations in a holistic, systems-level context can be improved. This could be achieved through the adaption of existing models (a limited example of which was demonstrated in this study) or through the creation of new models.

The objective of this work was to demonstrate the existence of one conflicting trade-off between user needs resulting from modelling techniques limited to a singular perspective. The simple model scenarios used in this study were employed to assess the trends in indicators as a result of the altitude change alone. The point of trade-off where the indicators for different users cross in Fig. 6 is not intended to be interpreted as an appropriate compromise. Using the point of trade-off alone is not a robust method for defining sustainability in the space system; instead, users should be consulted directly and their perspectives on the acceptable conditions in the system should be incorporated into sustainability guidelines.

Furthermore, when analysing the results in Fig. 5, it can be seen that the impacts on astronomy for the Walker-star configuration are much larger than for the Walker-delta configuration. Some recent papers investigating parameters for defining an 'orbital' or 'LEO carrying capacity' for use in space sustainability guidelines focus heavily on recommendations about constellation design [32,33]. However, none of these papers assess the impacts of these designs on users other than generalised satellite constellation operators. As the results in this study show that different constellation designs have different impacts on different users, this is a further example of how models analysing limited perspectives could produce unwanted consequences from the diverse perspectives of multiple types of users.

To further the previous point, some examples of studies considering more than one perspective in the approach to quantifying metrics for space sustainability exist, particularly when combining life cycle assessments with debris and collision-related impacts [21–23]. However, whilst other perspectives such as those of optical astronomy are sometimes qualitatively mentioned, the majority of current orbital carrying capacity-related papers focus solely on the perspective of satellite operators by assessing debris population growth and collision risk in orbit, without the inclusion of other sustainability perspectives quantitatively in their analyses [34–41]. As stated previously, it is possible that unintended negative consequences may arise counter to space sustainability goals if metrics for space sustainability are derived without consideration of the diverse perspectives of different space users.

4.2. Further work and considerations

The scope of this work was limited to assessing the consequences of lowering the maximum operational altitude of an active satellite constellation on ground-based optical astronomy and a constellation operator alone according to the indicators defined in Section 2. In reality, there are many other aspects to consider, both with regard to other users, socio-economic and Earth-systems, as well as other indicators to consider for the specific users in this study.

Additionally, this study was limited to considering images with instantaneous exposure times for derivation of the astronomy indicators. Therefore, this study was unable to assess the impact of satellite trails associated with extending the exposure time of an image. A fixed FOV of 6 degrees was also used in this study. Given that the impacts on astronomy scale with increasing image FOV size and exposure time, the astronomy indicators in this study likely provide an underestimation of the impacts on larger, professional optical observatories.

Furthermore, the use of the cube method to derive conjunction statistics is more limited than high-fidelity conjunction assessments and may not capture as accurate statistics regarding the number of conjunctions in a simulation. However, the cube algorithm is suitable for capturing an approximation of the conjunction statistics, making it suitable for resolving trends in the data, as was intended in this study. Nonetheless, a high-fidelity conjunction assessment may provide a more accurate representation of the realistic collision statistics for these simulations.

Finally, two large simplifications were made to remove the introduction of additional spatial density variations in the simulations: 1) a uniform background population of satellites was used to replace the realistic background population of objects for the computation of collision statistics in this study and 2) no failures, collisions or explosions were allowed to occur. This approximation was necessary to resolve the relationship between altitude change and the identified indicators. Therefore, if future studies intended to produce indicators with more physically meaningful absolute values to assess the effects of changing the operational altitude of satellite constellations, the historical background population could be used and sources of debris generation allowed in the simulations.

5. Conclusions

This study showed that a trade-off in the impacts on different space users can arise if sustainability recommendations are not informed by multiple perspectives of space sustainability. The results showed that lowering the altitude of satellite constellations has some negative impacts on the sustainability of space from the perspective of satellite operators that were not specifically included in the formulation of the SATCON recommendations. This does not mean that lowering the altitude of satellite constellations is not in the interest of space sustainability, nor does it mean that the collision risk created as a result of lowering the altitude is unacceptable for satellite operators. However, these results highlight that a robust assessment of space sustainability should consider the multiple and varied perspectives from all uses and exploration of space.

The results in this paper show that more collaborative and holistic modelling techniques and assessments are required to formulate more robust space sustainability guidelines and recommendations. These models should be capable of defining and assessing space sustainability from the perspective of a diverse set of users and sub-systems to ensure that recommended activities do not create unintentional consequences. This could be achieved either through the adaption of existing models or through the creation of new collaborative models.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Megan Perks is a PhD student at the University of Southampton, UK, and also a member of the UK Space Agency delegation to the Inter-Agency Space Debris Coordination Committee. She receives funding from EPSRC and a University of Southampton Anthony Wright PhD Studentship to fund her PhD. Hugh Lewis is a Professor of Astronautics at the University of Southampton, UK. He is a also a member of the UK Space Agency delegation to the Inter-Agency Space Debris Coordination Committee. Nina Vaidya is an Assistant Professor in Astronautics and Spacecraft Engineering. There are no other interests to declare.

CRediT authorship contribution statement

Megan E. Perks: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Hugh G. Lewis:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Nina Vaidya:** Writing – review & editing.

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Appendix A

Indicators produced from the DAMAGE simulations as described in Section 2. The 'total' collision indicators combine data from across all altitudes in each simulation case. The 'operational' collision indicators combine data from the operational altitude only. All values are quoted at 3 dp.

Walker-star (89°)												
Altitude (km)	Collision indicators								Visibility indicators			
	Annual				Annual per satellite				Annual		Annual per satellite	
	Total	Standard Deviation	Operational	Standard Deviation	Total	Standard Deviation	Operational	Standard Deviation	Total	Standard Deviation	Total	Standard Deviation
1200	7.399	2.733	5.876	2.648	0.003	0.001	0.003	0.001	153,940.650	68,417.221	66.363	29.494
930	7.625	2.827	6.496	2.780	0.004	0.001	0.003	0.001	97,416.407	40,833.142	48.313	20.251
615	7.909	3.099	7.257	3.057	0.005	0.002	0.004	0.002	38,202.206	18,813.399	23.534	11.590
345	8.060	3.189	8.025	3.173	0.006	0.002	0.006	0.002	7227.105	5592.782	5.652	4.374

Walker-delta (55°)												
Altitude (km)	Collision indicators								Visibility indicators			
	Annual				Annual per satellite				Annual		Annual per satellite	
	Total	Standard Deviation	Operational	Standard Deviation	Total	Standard Deviation	Operational	Standard Deviation	Total	Standard Deviation	Total	Standard Deviation
1200	4.995	1.377	4.197	1.291	0.002	0.001	0.002	0.001	46,592.453	4721.600	20.086	2.035
930	4.912	1.068	4.320	1.095	0.002	0.001	0.002	0.001	24,368.372	2566.814	12.085	1.273
615	5.224	1.295	4.907	1.283	0.003	0.001	0.003	0.001	8043.793	976.709	4.955	0.602
345	5.155	1.613	5.134	1.610	0.004	0.001	0.004	0.001	1416.663	214.207	1.108	0.168

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