

Satellite megaconstellations will threaten space-based astronomy

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Referee #1

(Remarks to the Author)

2025-05-07 Comments to the Authors

Questions from the editor

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A. Summary of the key results.

Four space observatories are used to probe the problem of contamination by satellite trails; they cover the relevant parameter space in terms of FoV (from tiny HST to large SPHERES), altitude (450-800km), exp.time (100-600s), pixel/resolution (0.05-5"). This covers well the case of imaging telescopes (but see the note about spectroscopy, below).

The simulation strategy adequately represents realistic observations, either by recycling actual observations (HST+ACS) or by using known information about the observatory (for the others).

The simulations are analysed, and conclusions on the effect of the (growing) population of satellites on space observatories are drawn.

The author also include in their discussion broader considerations on the impact of satellites on sustainability.

B. Originality and significance.

The effect of satellite constellations on ground-based optical and radio observations has been studied in increasing level of details. As the space observatories are embedded in the satellite population, the geometry of the problem is quite different. This paper constitutes the first attempt to characterize these effects -which are far from negligible!

C. Data & methodology

The authors describe their simulation methodology in sufficient details.

I have however a serious question about the validity of their estimate of the surface brightness of the trail. If they actually used the equation from the paper in their simulation, I am afraid this would invalidate the section on trail brightness.

Currently, the results are presented as a text paragraph. I recommend presenting them as a table, with some supporting graphs. These would allow the reader to have an overview of the results and trends, and allow the authors to focus the text on the highlights of the results and their analysis.

Currently, the metrics used to quantify the impact of satellites is the number of trail per exposure. I recommend to also compute and present the affected fraction of exposure (number of pixels under a trail / number of pixels in the exposure, or something similar). Indeed, a trail in an exposure does not ruin the exposure.

Also, the results currently focus on the 4 observatories; I would recommend also presenting and discussing generalized trends that appear from their extensive simulations. This would greatly increase the value of the paper, going from anecdotal results on 4 (representative and interesting) observatories to broader conclusions on space observatories in general.

Finally, the simulation is strictly restricted to imaging, while a large fraction of astronomical observations are performed using spectroscopy. While a similar study of the impact of spectroscopic data is probably beyond the scope of this paper, I'd recommend 1/ to include a paragraph briefly explaining the difference between the imaging and spectroscopic issues with satellites; 2/ mention which of their conclusions are also applicable to spectroscopy.

D. Appropriate use of statistics and treatment of uncertainties

The simulations presented seem rather numerically intensive. A short paragraph describing the set-up used, CPU time invested seems interesting. Also I recommend adding at least a paragraph on the number of simulation performed, the number of satellite detected, the distributions of the results, etc, so that the reader can get an idea of the uncertainties and limitations of the method.

E. Conclusions: robustness, validity, reliability

Currently, the conclusions are presented for the 4 selected examples, and there is not much information on the statistical robustness of their results.

F. Suggested improvements

Below, I give a list of generic and specific comments and suggestions.

G. References: appropriate credit to previous work?

Yes. I added a couple of very minor suggestions, but the level and quality of references are appropriate.

H. Clarity and context

I'd recommend reviewing the abstract after revising the text; I also include some suggestions for the conclusions.

Generic comments

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* The simulations focus on the number of trails per exposure. While this is a valid metrics, a trail does not ruin an exposure; it ruins the pixels under the trail. Even considering wings of the PSF, that is only a fraction of the image (of the order of 0.1 to a few % depending on the field-of-view). That fraction is useful: it quantifies the losses for surveys, and the probability that a specific target (say, a quasar) in the field be ruined by a satellite. As the simulations are done already, I'd strongly recommend to quantify the "fraction of lost pixels (or area)" as a metrics quantifying the impact of the satellites. It would also be useful to compare these values with other losses, such as the fraction of pixels lost to cosmic rays (5% for HST's ACS), or bad pixels (1-3% for ACS).

* I have a problem with the conversion from apparent mag to surface brightness -see details below. If confirmed, this would invalidate the discussion on surface brightness.

* The paper presents only a very short summary of the simulations. A more generalized presentation of the results would make the paper much more valuable, in particular to evaluate possible mitigations. The dependency of objective metrics (such as number of trail per image, and fraction of image lost) with

- zenithal distance (currently just hinted). For ground-based observations, this is a crucial parameter.

- altitude of the observatory.

- distance to the satellite. For ground-based observations, the satellites are always "far". For space observatories embedded in the constellation, they can be very near. I would be curious to see plot such as ./ distance distribution; ./ dependency of the surface brightness with distance;

- etc...

Also, additional characterization would be useful, such as what is the distribution of surface brightness and width of the trails.

Each of these -and probably others- would benefit from a plot and a short paragraph.

* the paper focuses on images:

- while a trail on an image ruins the pixels under it, it is fairly easy to spot even at low S/N. The affected region can then be masked so that it does not contaminate the data analysis. In other word, it is a (possibly major) nuisance, but it can be tackled.

- a significant fraction of scientific observations are obtained via spectroscopy, where the data partially or completely lack spatial information (except in the case of integral field spectroscopy, which can be considered as a fancy type of imaging). Therefore, there is simply no tell-tale trail to indicate a contamination. Furthermore, the exposure time for spectroscopic observations tend to be much longer than for imaging (1 to 2 orders of magnitude), increasing the number of contaminating trails (which is, in first approximation, growing linearly with the exposure time). Finally, the apparent motion of the satellite brings its surface brightness on detector to a level similar to that of the science target. So the contamination of spectroscopic observations is more complex and has the potential to be even more damaging than that of images.

I do realize that performing the same type of analysis for spectroscopic observations would be a significant endeavour. While interesting, it may be beyond the scope of this paper. If so, spectroscopy would deserve a short paragraph explaining the problem, and encouraging others to study it in more detail...

Specific comments

For each comment, I give the line in the manuscript or the section number, then copy the section of text I am commenting upon. Second line is the comment. Third line, with >, is a suggestion for possible text.

Comments marked with - are minor, no need to reply to them in detail.
Comments marked with * are substantial, and need to be addressed.

-I11. Reflections from satellites are visible to the human eye and extremely bright for professional telescopes.
Most of them are _not_ visible to the human eye, and are not that bright for pro telescopes
> can be ...

Introduction

- I37: 15000 satellites

Reference? Unless you have a better one, I'd suggest a link to Jonathan McD's page at <https://planet4589.org/space/stats/active.html>

- I46: At the current rate...

maybe more accurate:

> Should all the FCC filing result in launches, the Earth would be ... decade.

- I49: as their relative positions:

> as their apparent positions

- I51: Satellite trails contaminate the targets of science interest, generating light gradients (scattered light), and increasing the photon-noise...

Actually, these are almost secondary effects:

> Satellite trails passing over a science target can render the observation totally unusable. Even the trail misses the object, it can generate a background light gradient (scattered light) and increase the photon noise.

- I52: For new generation ground-based telescopes such as the Vera C. Rubin Observatory...

The critical factor is VRO's wide field:

> For new generation wide-field ground-based telescope such as...

- I54: it is estimated that 20% of the midnight images will present satellite ... 30-80%...
the % depend a lot on the constellation mix used in the simulation.

> fairly conservative simulation estimated that that 20% of the midnight images would present satellite...

- I56: they are mostly visible to the unaided eye at twilight during sunset and sunrise...

Actually, that is valid for the eye and any telescope:

> they are mostly visible at sunset and sunrise twilights

- I61: Dark coatings and optical blocking systems have proven to be inefficient in avoiding the presence of satellite trails [8] in astronomical imagery data...

Actually, darkSat and visorSat were never expected to prevent trails in images; that would require a much stronger darkening. The target was to get mag $> \sim 7$, to avoid naked-eye visibility and VRO saturation. I suggest to rephrase:

> 1/ only a mild decrease in the optical magnitude...

> 2/ satellites are still very bright for astronomical images...

- I64+68: missing [in references

- I74: can only be conducted through twilight and sunrise observations...

"twilight" is both morning and evening; no observations can be performed at sunrise.

> evening and morning twilights

- I78 even at midnight

You could add a ref, eg [3] or [7]

- I80: the fraction of uncontaminated night sky is at risk of becoming too small for practical science operations.

The argument is too sensationalistic; the argument would gain strength at being more quantitative. Maybe something along the line:

> the fraction of images free of satellite trails will dwindle. In particular, large-field exposures acquired during twilight are likely to be contaminated by many (tens) trails. This will have a significant impact on some science cases.

- Figure 2: Please clarify that these are illustrations for some representative observation simulations (i.e. that such simulation was not performed for all the simulated observations). It would also be useful to represent the whole field of view (possibly as a drawing rather than a full simulated image) with a box indicating the position of the zoomed detail.

Frequencies

- *** 2.1 frequencies:

I would recommend presenting the results in a tabular form rather than as text; in that way, the discussion that follows would be much easier to parse.

Lines could be -for each observatory 1/ number of trails per exp and dispersion, 2/ fraction of exposures with at least one trail;

Columns: baseline, 100 000 sat, 560 000 sat (and maybe the extreme 1M sat)

- *** 2.1 frequencies:

The number of trails is a useful metrics, but a trail affects only the pixels below it. From your calculation below, you have the width of the trail, so the number of pixels it affects can be computed, resulting in the fraction of pixels lost per exposure. This fraction is the loss for a survey observation (effectively reducing the field of view by xx%); it is also the probability that a given object of interest (say, a star with transiting planet, or a quasar) be lost under a trail.

As you already have the required data, I recommend you evaluate these fractions, and report them.

- *** I127: plot the results. The simulation should be presented also in some graphs, which would show trends and allow the reader to visualize and understand them, and extrapolate the results to other telescopes. In particular, I suggest the following plots (others may be relevant, even more relevant than these):

1/ number of trails as a function of zenithal distance. For ground-based observatories, the effect is dramatic, and I.131 suggests it is also present for space observatories.

- *** 2.1 frequencies:

The discussion could also include generalizations of the trends observed, for instance

- dependency of the number of trails with the number of satellites,

- " with the field of view

- " with the exposure time

- " with the zenithal distance

- " with the altitude of the observatory (inverse)

- others?

Brightness

- *** I169: detailed in section 3.3... See below for (potentially serious) issue with the estimate of the surface brightness. Depending on the outcome of that point, it may be necessary to re-do the analysis.

- I175: higher resolution ...

To avoid confusion, between high-resolution=smaller pixels vs larger pixels

> "better resolution" (or finer) - or - "larger resolution elements" depending on what you mean.

- I175: higher resolution leads to enhanced flux concentration, which results in increased surface brightness...

- * I181: A relatively dimmer-than-average observed brightness is expected since the trail in the Hubble exposure iedk12aoq was spatially resolved (trail width of 90 ± 20 pixels)...

Well, the object being resolved is taken care of by the first term in Eq.1. You could actually check that the predicted width of the trail matches what you predicted with Eq.1.

- * I186: case of satellites only illuminated by the full Moon...

It is really good that you quantified the effect of the illumination by the Moon, thanks.

For satellites seen from space observatory, hww, wouldn't the illumination by the Earth be much stronger than the Moon's? It is easy to imagine a geometry for which the telescope sees the side of the satellite that is not illuminated by the Sun while being illuminated by the Earth.

Methodology

- I227: Xuntian

Could you give a (very brief) justification why the HST exposure time distribution is appropriate for this observatory?

- I233: baseline population...

Excellent that you include these! Pls indicate how many objects are present in that baseline?

- * I241: methodology/1:

Do I understand well that "one simulation" consists in the following steps?

- pick an epoch

- pick a number of satellites ($100 < n < 1E6$)

- for that epoch, compute the xyz position of all satellites and the 4 observatories

- for the 4 observatories, define an observation (RA, Dec, expTime) that is compatible with their current position (avoid Earth, Moon, Sun...)

- record the satellites that are visible in each observation

If that is correct, all fine!

If not, it means I did not understand, and you may want to update the text to clarify what I did not understand.

- * I241: methodology/2:

Each simulation step is rather computationally intensive, and the number of satellites actually observed is going to be very small. Consequently, you have to iterate many, many times (in particular when there are fewer satellites) in order to get robust statistics. I'd recommend to devote a short paragraph on these computational considerations.

- I260: 3) the orientation of the reflecting surfaces to the observer

> and to the light source

- I264: minimum resolution element... seeing...

Seeing is not really relevant here (but it's OK to mention it); I'd suggest

> optical resolution of the telescope or the pixel size, whichever is larger.

- I267: assuming a random orientation between 0° to 180° with respect to the observer.

Actually, it's 2D random orientation (0-180 lat and 0-360 long)

> assuming a random orientation with respect to the observer.

- * I268: do I understand well that you pick at random a value for $4 \cdot R_{\text{sat}}^1$ in $[1, 125m^2]$? if so, this implies that the simulated cross-section distribution is rather more pessimistic than the "real" one (where most satellites are small). I realize that the simulations are done (and not cheap), but an alternative would be to assign to each satellite (I mean each constellation) a vaguely realistic cross section. Directly related, and an additional argument to assign a cross section to each satellite: monster-satellites like the BlueWalkers are dominated by their antenna, not their solar panels. Could you add a couple of

line describing the effects of your choice of size distribution?

- * I270: Eq.2 considers that the satellite is a flat disk perpendicular to the line-of-sight. In Bassa et al [27], this is justified by the fact that the satellites are seen "from below", and that their geometry from that vantage point is closer to a flat panel than to a sphere (and confirmed by the fact that this works better than a Lambertian sphere phase function). As the space observatories are embedded in the middle of the satellites, the viewing geometry is random (i.e. the satellites are not flat panels), and in particular the solar phase effect is likely to have a much stronger effect than as seen from the ground.

- * I277, Eq.3:

The $-2.5\log$ is the scaling between the surface of a static object and the surface of the trailed object, right? (do you have a ref for this equation, or is it home-brewed?).

The surface of the trail is $(\theta * \omega * t)$ [sq.arcsec]

The surface of the image of the static object is $(\pi * \theta^2 / 4)$

So the ratio should be $(4 * \omega * t) / (\pi * \theta^2)$

Did I miss something? Is this a typo? did you use this equation in the actual code?

Discussion/Mitigation

- I288: One of every four exposures obtained with Hubble Space telescope will show contamination by satellite trails.

Repeated from I.284.

> remove one occurrence.

- I301: similar tools created for ground-based telescopes [29, 30]...

You may want to add Bassa+22 <https://doi.org/10.1051/0004-6361/202142101>

where they discuss a series of representative ground-based telescopes.

- 4.1 requirements:

Publishing a list of requirements is good, but 3/ seems to be wishful thinking... While desirable, is jumping for a current precision of ~1km to few cm (i.e. over 4 orders of magnitude) feasible? This seems a challenge at the engineering level, and it may not even be feasible at the physics level. I think this 3/ deserves a feasibility comment, otherwise it affects the strength of your other demands.

- I345 "open book" configuration:

This is true for very early launches. Pls fact-check the current situation: SL now operates the "open-book" configuration in an attitude that keeps the Sun in the plane of the "open-book" and/or fly "on the side" to minimize the cross-section seen from below. Here is a secondary ref <https://spaceref.com/science-and-exploration/spacex-publishes-update-on-starlink-satellite-brightness-issue/>

> pls update the text.

- I.25 (abstract), I368: We propose a series of mitigation measures that can be applied to prevent...

Actually, you do propose 3 concrete, actionable constraints on the satellite operators (with the caveat about #3, see above).

This is valuable, but they are not mitigation methods. These would be recommendations applicable to observatory operators. Just to give an obvious example: "adjust, when possible, the observation strategy to minimize the zenithal distance of the telescope", as this will dramatically reduce the number of trails.

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Referee #2

(Remarks to the Author)

This paper forecasts the impact of the increasing satellite constellation population on present and future space telescopes in low-Earth orbit (LEO). The authors correctly identify a gap in the literature, because most studies are primarily concerned with the impact of bright satellites on ground-based telescopes. To fill this gap, the authors simulate up to one million satellites with similar brightness properties as seen by Hubble today, on four LEO space telescopes: Hubble, SPHEREx (recently launched), ARRAKIS (planned c 2030), and Xuntian (planned c 2026). The paper concludes that contamination from satellites will be substantial and that additional mitigation measures are warranted to protect LEO astronomy as well as ground-based astronomy.

The paper is overall original, significant, and worthy of publication. Light pollution from an increasing population of constellation satellites is an existential threat to observational astronomy and urgently needs to be better understood to enable quantitative mitigations. The authors make necessary assumptions to simulate what images from the four space telescopes might look like, and use their results to motivate further mitigations that focus on enabling prevention, avoidance, and correction. The Figures are all visually clear and compelling, accurate given the stated assumptions, and support the paper's conclusions nicely.

Most of my suggested improvements center on two themes: (1) the large systematic uncertainty in present-day satellite

brightness models and forecasts, particularly pertaining to satellite attitude (i.e., geometric orientation relative to the observer), and (2) ensuring the published simulations enable readers to reproduce the results and use the authors' tools to investigate their own preferred suite of assumptions. The inherently huge unknowns from (1) necessitate particular care be taken to enable state-of-the-art reproducibility via (2). I also suggest a handful of additional references, and a couple of places where drawing parallels to ground-based astronomy may enhance the paper and help readers place it in context.

Major feedback

1. When describing "most mitigation efforts" (Section 1 lines 57-60), I suggest mentioning upfront how attitude, or geometrical orientation of various satellite components, can be a key darkening mitigation strategy. However, this depends strongly on satellite design and operational details, which are often proprietary and thus not possible for a third party to model.
2. I strongly suggest doing an update of Figure 1 and Table 1 — and related numbers in the text — as close to publication as feasible. Is there code available to create a new version of Figure 1? This would be an asset to the community well after the figure is finalized and published.
3. Section 2.1 clearly describes predictions for satellite trail counts as the satellite population increases over time for four space telescopes. To put this in context, and to validate some of the approximate numbers referenced in Section 1, would it be possible to add a line to Figure 3 for Rubin Observatory? More generally, I can imagine any ground- or LEO-based telescope operation team desiring a way to easily see the forecast for their telescope. If any figure were to be readily reproducible with the reader's own desired parameters and available data, it should be Figure 3.
4. For satellite brightness forecasting, there are confounding variables that can lead to huge systematic errors, and the details of these are glossed over in Section 3.3. An important one is satellite attitude, as previously mentioned. While this is listed as a factor in Section 3.3, and discussed generally in a very Starlink-specific way in Section 4.1 (lines 341-352), it is not clear how the large range from 1 - 125 m² possible reflective area affects the mean or width of the surface brightness distributions shown in Figure 4. This two-order-of-magnitude uncertainty that directly impacts brightness needs to be more clearly incorporated into the paper's quantitative analysis.
5. In a similar way, I am not convinced that 0.25 is an appropriate fixed value for satellite albedo. Tyson+24 (<https://iopscience.iop.org/article/10.3847/2041-8213/ad41e6>) describes reasonable albedos between 0.1 and 1, the latter being regularly expected for certain small pieces of debris with flat, specular surfaces. Here is another order-of-magnitude systematic uncertainty that needs to be more quantitatively considered.
6. I do not see where Fig. 4 is introduced in the text, and it appears well before Section 3.3, where modeling satellite trail brightness is described. Why is a single HST observation of a single Starlink satellite shown in this figure? Hubble has seen myriad such Starlinks before and since, see, e.g., Kruk+23 (your ref 15), and it is not immediately clear if 18 mag/arcsec² is typical or unusual for this satellite population. The entire brightness modeling scheme appears to rest on a single measurement of a single satellite.
7. Please include information related to Section 3.2 in a similar fashion as done by Lawler+21 (your ref 29) in their Figure 1 and Table 1. This will both enable readers to reproduce the satellite population simulation and verify that it is physically realistic. I note that their paper included a public GitHub repository that could be used to create a potentially more realistic simulated satellite population: <https://github.com/hannorein/megaconstellations/>. I strongly recommend a similar repository to accompany this paper, since all the Figures tell a compelling and urgent story that is rapidly changing over time.

Minor feedback

1. Satellite forecasts for all telescopes, including Rubin Observatory/LSST, depend strongly on the predicted satellite population. Thus, the cited 20% at midnight and 30-80% closer to twilight in Section 1 (lines 53-55) are very rough estimates, and I believe they assume a total satellite population of about 40,000. I suggest you add a sentence to Section 1 around line 55, e.g., "We note these estimates each assume a particular satellite population significantly smaller than the one million considered in this work." Even if the numbers are approximate, concluding there will be a large fraction of affected exposures is robust. You may wish to also cite Hu+22 (<https://iopscience.iop.org/article/10.3847/2041-8213/aca592>), which explored the regime in which proactively avoiding bright satellites may be necessary for the Rubin scheduler, and included some simulated satellite populations (<https://github.com/lsst-sims/satellite-dodging-ApJL>).
2. I suggest mentioning that specular dichromatic mirror coatings designed to reflect most incident light away from Earth are now the preferred technology by both SpaceX and Amazon (rather than dark coatings or optical blocking systems, Section 1 line 61). A relevant technical report is available here <https://www.starlink.com/public-files/BrightnessMitigationBestPracticesSatelliteOperators.pdf>. I could see this being potentially bad for space telescopes - is it?
3. I note that mitigation via adjusting spacecraft attitude could potentially preferentially darken certain satellites when they pass over specific sites on Earth, rather than in skies everywhere. I would be very interested to learn how targeted darkening for specific (lat, lon) on Earth would affect space telescopes. It is OK if this is out of scope for this paper.
4. While it is true that DTC satellites are larger and inherently brighter, some argue this is effectively offset by choosing lower orbits, because they have a lower peak brightness as seen by telescopes with large primary mirrors. As you well know, this

is because lower objects move faster and appear more out-of-focus. I suggest briefly acknowledging these complex tradeoffs in Section 1 around lines 65-69.

5. The paper cites the SATCON1 report (Walker+20) but not any of the subsequent SATCON2 reports or either of the Dark & Quiet Skies I & II reports. These might fit nicely in Section 1 around line 82. They are thankfully all indexed by ADS.

6. I note that many article titles in the References have incorrectly lowercase-preferred capitalization schemes, to the detriment of "Lsst," "spacex," "leo," "Nasa," etc.

7. Figure 1 is a lovely comprehensive view of the present and likely future situation. I noticed a typo in the Chinese constellation Qianfan (no u). I am unsure why the Qianfan numbers indicate 32 planned satellites but 90 launched? I concede it is next to impossible to keep such figures up to date!

8. I applaud the authors for considering satellites reflecting moonlight. Are the predicted trail surface brightnesses still low ($30+ \text{ mag/arcsec}^2$) for extremely bright satellites like BlueWalker3? Please cite Nandakumar+23 in addition to Mallama+23 for this satellite (<https://www.nature.com/articles/s41586-023-06672-7>).

9. Since a good deal of the paper pertains to satellite brightness forecasting, I would like to take the liberty to refer the authors to additional resources that ought to be considered and likely cited in this discussion: Privateer's Glint Evader tool (accessible via <https://wayfinder.privateer.com>), Fankhauser+23's Lumos modeling tool (<https://lumos-sat.readthedocs.io>), and CPS SatHub's SatChecker (<https://satchecker.readthedocs.io>), which does not yet include brightness predictions but will in the future.

10. In Section 3.2, line 230, the authors refer to the "Planet489 public database," but I note this is missing a "5" and that the correct citation for this wonderful resource, per the website planet4589.org/space/gcat, is as follows: A suitable short citation is 'data from GCAT (J. McDowell, planet4589.org/space/gcat)'. A full citation is: "McDowell, Jonathan C., 2020. General Catalog of Artificial Space Objects, Release 1.7.3, <https://planet4589.org/space/gcat>"

Referee #3

(Remarks to the Author)

The manuscript presents simulations of the number and brightness of low Earth orbit satellites contaminating images obtained by four space telescopes HST, SPHEREx, ARRAKIS, and Xuntian. The results indicate that space telescopes in LEO will be heavily affected by the LEO satellite constellations, especially if the full 560,000 that are planned (see FCC and ITU filings) are launched. In all cases the Chinese Xuntian telescope will be most impacted.

The work is original and builds upon a recent analysis of HST images up to 2021 (Kruk, S. et al. Nature 7, 262–268 (2023)). The methodology is communicated well, though there are some small issues which we give below.

The manuscript is suitable for publication in Nature after completion of the following comments / corrections.

Major comments:

1. The simulations only used a wavelength of 550-nm when most of the telescopes have the capacity to observe in the NIR. New calculations should be completed for the brightness of the satellite trails for key wavelengths across the different instrument and filters for each telescope.

2. The authors only used the Sun and Moon as sources of illumination. We know from ground studies that Earthshine makes significant contribution to the satellites reflective brightness as seen from the ground by an additional AB magnitude (see Fankhauser et al. 2023, AJ. 166. 59F). The simulations should include Earthshine, even if this just shows a negligible impact (similar to Moonshine).

3. The simulations were made for up to one million satellites in LEO. But the estimated /planned number is just over half a million. Either the simulations should be limited to the half million, or the text should be adjusted to state that the million used in the simulations is to estimate the scenario where more filings are submitted to the ITU over the coming years.

4. The authors cite a lot of non-peer review work and have missed a large body of previous studies in this area. For example when they discuss AST Space Mobile's Bluewalker 3 satellite in the introduction they fail to cite a ground based observing campaign published in Nature, but cite a publication from a pre-print server which has no undergone peer review. We leave individual details below in the minor comments.

Minor comments:

Abstract

Line 10: Remove all cases of 'mega' from mega-constellations. None of the currently planned constellations have one million or more satellites.

Line 11: human eye ----> un-aided eye. Human eyes can see beyond V=7 if using telescopes or binoculars.

Introduction

Line 33: Where the height is given, a citation is needed, because current TLE data (2025-05-09) shows orbital heights between 627-km to 779-km.

Line 37: for the value of 15,000 please cite source and provide date that the number was determined for readers N years from now.

Line 45: by over half a million. I have not read the manuscript that has been cited as my institution does not subscribe to Science, and a copy has not been made available on the ArXiv preprint server. Therefore, I can not confirm if reference 2, states one million artificial satellites in LEO by 2049. However, (<https://planet4589.org/space/con/conlist.html>) provides a value of 554519 satellites, which includes the Cinnamon-937 constellation and is cited by reference 2.

Line 48: Reflections are not just from the solar panels, diffuse reflection is emitted from the main chassis.

Line 49: Citations [3-5]. Missing many fundamental citations of ground based observations from 2020 to 2022. Tregloan-Reed et al. 2020 A&A. 637L. 1T, Tyson et al. 2020 AJ. 160. 226T, Horiuchi et al. 2020 ApJ. 905. 3H, Tregloan-Reed et al. 2021 A&A. 647A. 54T, Mróz et al. 2022 ApJ. 924L. 30M, Boley et al. 2022 AJ. 163.199B, Halferty et al. 2022 MNRAS 516 1502H to name a few.

Line 55: Citations [7, 8]. Unsure why Hainaut & Williams is included here as they dealt with ESO telescopes and the Vera Rubin is a U.S. NSF funded observatory.

Line 57: 'twilight during sunset and sunrise'. Should be 'twilight after and before sunset and sunrise.' During sunset and sunrise (Sun-Zenith Angle 90 to 97 degrees) the sky background is too bright to see the satellites, even with 2-m class telescopes.

Line 59 to 60. Tregloan-Reed et al. 2020 showed that the first unmitigated Starlinks were ~5.3 mag in the visible (Sloan g' passband 475.4 nm) once they were on station (i.e. at 550-km altitude). However, during orbital rise they were extremely bright at approx 2 mag.

Line 62: Citation 8 is not the only publication which dealt with Darksat.

Line 64: 7.3 in the case of Darksat 9, 10]. What about the first published peer reviewed observations of Darksat both in the optical and NIR? These early work showed that Darksat darkening treatment was only ~50% effective in the optical and 20% in the Ks band. Also the general consensus in the community was that Darksat was around magnitude 6 not 7.3 (See Tregloan-Reed et al. 2020 A&A. 637L. 1T, Tyson et al. 2020 AJ. 160. 226T, Horiuchi et al. 2020 ApJ. 905. 3H, Tregloan-Reed et al. 2021 A&A. 647A. 54T)

Line 66: solar panels --> solar panels and chassis.

Line 69: Citation 12. While Mallama's work is of good quality, citations should use peer reviewed manuscripts when available which in this case would be the 2023 Nature paper on BlueWalker 3 by the CLEOsat and the IAU CPS. Nandakumar, S., Eggl, S., Tregloan-Reed, J. et al. The high optical brightness of the BlueWalker 3 satellite. Nature 623, 938–941 (2023). <https://doi.org/10.1038/s41586-023-06672-7>.

Lines 76 to 78: But at a greater range ($r_1 - r_0$), will be fainter based on $+5\log(r_1 / r_0)$. So they will be visible for longer but will be fainter.

Line 87: 'works'. Singular as only one citation.

Results

Line 119: The average exposure time should be given here.

Lines 118 to 123: The HST results are missing from this list.

Line 124: What telescope is the value in the brackets meant for? The prior text states, ~5.5, ~33, and ~86 for SPHEREx, ARRAKIHs, and Xuntain. So which one of the three is actually ~94%. Is this value for HST? If so, is it for the 100,000 or 560,000 satellites? Consider revising text.

Line 144: 'of large sizes' to 'of cross sections $> 1\text{-m}^2$ '. If keeping 'sizes', use m^3 .

Lines 151 to 154: This section would read better if the results from each observatory were given together, but in groups of current ($N \sim 15,000$), near future ($N \sim 100,000$), current planned ($N \sim 560,000$) and future prediction ($N \sim 1,000,000$).

Line 158: 'apparent speed' to 'apparent angular velocity'.

Line 159: '(Sun, Moon)' What about Earthshine? Recent work shows this can have a significant increase in satellite brightness when viewed from the ground (up to one AB magnitude or 2.5 times brighter: see Fankhauser et al. 2023, AJ. 166. 59F). Depending on the orientation of the observatory, Earthshine from the satellite could also be caught.

Line 160: 'area' to 'cross section'.

Line 162: The satellite's albedo should be added to this list too.

Line 170: Which bands are these numbers for? For instance HST operates in the UV, optical and NIR, SPHEREx operates 0.75 microns to 5 microns. This is important because Starlinks get brighter in the NIR (see Tregloan-Reed et al. 2021), so with the second arm of SPHEREx being in the NIR, it would be expected that Starlinks would appear brighter than for HST UV/optical images. Also should this not be in $\text{mag arcsec}^{-2} \text{ s}^{-1}$ as faster travelling satellites will appear fainter.

Line 173: ($\mu = 18.2 \pm 4.9$), Should this mean the value given on line 171 be $23 \text{ mag arcsec}^{-2}$?

Line 180: What is this value per second?

Line 188: What are the detectability levels for the telescopes?

Methodology

Line 196: Should give the HST orbital height too.

Figure 4: It is hard to see the histograms of the three telescopes under the HST. Authors should provide a stronger outline for the histograms under the HST histogram.

Figure 4: X axis label units should be mag arcsec^{-2} not mag arcsec^{-1} .

Line 208: Should define TLE as industry standard for the orbital elements used in calculating the satellite's position and velocity.

213: How many were randomly selected.

216: Are the uncertainties the 1-sigma distribution or the full range? In this format should use 540^{+530}_{-200} . If the full range can be written as 340 to 1070 seconds.

Line 218: How many random locations were chosen?

Line 222: 'orbit ARRAKIHS' to 'orbit for ARRAKIHS'

Lines 226 to 227: This should be justified. Why choose a similar distribution as the HST? Do the two telescopes have the same aperture or observe in the same passbands?

Line 237: 'randomly'. I assume a uniform distribution was used. If so, what was the mean gap between each generated number, or how many numbers were randomly selected in the range $1e2$ to $1e6$?

Line 259: I would add range here too as it has a large affect on the satellite's apparent magnitude.

Line 273 'p=0.25'. I'm not convinced that a geometric albedo of 0.25 is the best representation. Different Starlink designs have different albedo and there is quite a range in the measured effective albedo (cross-section times albedo) see Krantz et al 2023 PASP 135 095003.

Line 274: SPHEREx does not observe at this wavelength.

Line 275: $\text{mag arcsec}^{-2} \text{ s}^{-1}$ to take into account angular velocity and time illuminating the detector pixels.

Discussion

Line 291: Please give the detectability limit. Based on previous numbers from Moon illuminated satellites given earlier in the paper, we guess between 22 and 30 mag?

Line 349: Sadly this is not always true as seen by the various ground-based surveys which show a large range for the effective albedo (cross-section times albedo), indicating a range of attitudes (e.g. Krantz et al 2023 PASP 135 095003).

Referee #4

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports.

Version 1:

Reviewer comments:

Referee #1

(Remarks to the Author)

Many thanks for the detailed replies to all of my comments. All fine on my side: all my questions and doubts are addressed. The new version is even clearer and more compelling than the original.

Olivier Hainaut, ESO (ohainaut@eso.org)

Some additional comments that do not require reply:

- the revision of the surface brightness is an impressive piece of work. But indeed, it has little effect on the detectability and corresponding statistics. The Earthshine contribution is an important result -until now, it was (naively?) considered negligible.

- thank you for the new Table 1

- Thank you for Section 5.1. A typo at l.477: " the brightness of the satellite trails as a function of the distance to the satellite and the trail width (Fig. 8). " --> Fig.9.

- Fig.2: excellent idea to put the data on Zenodo.

Referee #2

(Remarks to the Author)

Thank you for incorporating significant changes into the manuscript based on comments from all the referees. Thank you especially for creating a Zenodo data repository to go along with the paper.

During the review process, two new relevant papers have come out (as preprints), which you might consider referencing: <https://arxiv.org/abs/2505.06424v1> and <https://arxiv.org/abs/2506.19092v1>. I recognize you are at the 50 reference limit/guideline for Nature, but I note this doesn't apply to Supplementary Information.

There is a typo in footnote 14 (Section 4), SatCheker -> SatChecker.

I stand by my original remarks that the paper is overall original, significant, and worthy of publication. The treatment of uncertainties appears sound, and while I do wish the authors would publish tools to enable the community to test their own preferred assumptions (e.g., effective size and albedo), I recognize this is a computationally expensive request and not strictly required for publication.

I have no further suggested revisions.

Additional Comments (no response needed):

I had not fully appreciated that the single Starlink 1619 observation is the only publicly ID'd satellite in the Hubble archive. Thank you for digging further into this and clarifying that this single data point is useful as a reality check, not as a basis for the simulated brightness distribution.

Thank you for your thorough response to the point about Starlink darkening mitigations vs actual observed brightnesses, and the extremely humbling illustration of how huge satellites can still appear bright (especially in near-IR!) even when they are not illuminated by the Sun.

Comparing forecast pixel loss fractions to Hubble's 5% cosmic ray loss fraction is a very good way to put things in perspective.

Referee #4

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports.

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Response to referee #1

Alejandro S. Borlaff, Pamela M. Marcum, Steve B. Howell

(Dated: June 20th, 2025)

Dear Referee,

Please find enclosed a revised version of our manuscript “*One million satellites in the sky: Light contamination on space telescopes*”. The authors would like to thank the detailed revision of the first version of this manuscript, which improved the results significantly. We have revised your comments carefully, marking the major changes in the manuscript using blue bold typeface. A summary of the major changes is presented below. Finally, we present a detailed answer to each of the questions and corrections prompted after the submission.

Major Changes

1. Following the suggestions from the referee review, we have performed a complete revision of the methodology to estimate the surface brightness of the satellite trails. This includes the implementation of diffuse sphere formalism [1], Earthshine, thermal emission, and satellite illumination phase angles [2], and the adoption of a realistic albedo distribution [3]. We remark that for the purposes of this paper (detectability), we found no statistically significant differences between assuming that the satellites are flat surfaces or diffuse spheres. While the updated surface brightness distribution represents a more realistic view of the satellite trail brightness, the fundamental results on our manuscript did not change. If the proposed satellite constellations become operational, virtually all images obtained with SPHEREx, *Xuntian*, and ARRAKIHS, will detect satellite trails, as well as a significant fraction of those obtained with *Hubble*.
2. The results described in Sec 2.1 are now described in a new Table (new Table 1), containing the a) average number of satellite trails detected per exposure, b) the simulated exposures with at least one trail (%), c) the area affected in arcmin², d) the fraction of field of view covered by trails (%), and e) the average trail surface brightness for Sun illuminated and non Sun illuminated satellites. This reorganization of Sec.2.1 made now the results section more clear.

3. We have included a new set of additional figures, and tables as part of the Supplementary material in a new Appendix (Sec. 5). Sec. 5.1. contains four new figures, describing the minimum observable altitude for a space telescope as a function of the limb angle (Fig. 6), the distribution of the number of trails as a function of the Earth's limb angle (Fig. 7), exposure time (Fig. 8), and the distribution of surface brightness as a function of the distance between the satellite and the observer and the trail width (Fig. 9). Sec. 5.2. contains a new table describing the layers, inclination, and altitudes of each simulated satellite layer, with a new figure (Fig. 10) with a visual representation of the latitude and longitude of each satellite for a given epoch.

Next, we will answer all the questions raised by the referee (in blue) followed by our answers in black.

Response to reviewer's general comments

1. The simulations focus on the number of trails per exposure. While this is a valid metrics, a trail does not ruin an exposure; it ruins the pixels under the trail. Even considering wings of the PSF, that is only a fraction of the image (of the order of 0.1 to a few % depending on the field-of-view). That fraction is useful: it quantifies the losses for surveys, and the probability that a specific target (say, a quasar) in the field be ruined by a satellite. As the simulations are done already, I'd strongly recommend to quantify the "fraction of lost pixels (or area)" as a metrics quantifying the impact of the satellites. It would also be useful to compare these values with other losses, such as the fraction of pixels lost to cosmic rays (5% for HST's ACS), or bad pixels (1-3% for ACS).

Answer: The referee is correct in its statement that a satellite trail does not necessarily ruin an exposure – however – their impact strongly depends on the type of science and does not only limit to cases where the physical overlap with a target. In an scenario where multiple satellite trails cross the field of view, blind surveys of transients might be extremely impacted due to the new requirement to separate artificial objects from natural sources. Masking satellite trails might not be easy, specially in non-obvious cases (i.e., dimmer satellites, debris). Another example is astrophysics of extended objects, i.e., low surface brightness astronomy, which

rely on extremely careful calibration of the sky background which in most cases require to use every single pixel available in the field of view. Extremely dim, derelict satellites and debris might not be easily identifiable as straight bright trails by automated algorithms, increasing the sky background uncertainty over time, making automatic identification algorithms to fail. Measuring the contamination of satellite trails by the fraction of pixels can be a misleading estimator of their broad impact in science.

The authors thank the referee for making the suggestion of comparing the fraction of lost pixels per area as a comparison with other well-known systematic effect: Cosmic Rays. This comparison has the advantage of communicating the impact in easy to understand manner, with a comparable quantity that astronomers can use to estimate the effect on their science. We have implemented this change in the text, as the referee suggested. We thank the referee for this extremely useful comment that enhanced the results presented in the manuscript considerably.

2. I have a problem with the conversion from apparent mag to surface brightness -see details below. If confirmed, this would invalidate the discussion on surface brightness.

Answer: We thank the referee for the careful revision of the satellite photometry section. We have revised completely this section and repeated the analysis including the suggested changes in the referee report. We describe all the changes in the items below.

3. The paper presents only a very short summary of the simulations. A more generalized presentation of the results would make the paper much more valuable, in particular to evaluate possible mitigations. The dependency of objective metrics (such as number of trail per image, and fraction of image lost) with - zenithal distance (currently just hinted). For ground-based observations, this is a crucial parameter. - altitude of the observatory. - distance to the satellite. For ground-based observations, the satellites are always "far". For space observatories embedded in the constellation, they can be very near. I would be curious to see plot such as ./ distance distribution; ./ dependency of the surface brightness with distance; - etc... Also, additional characterization would

be useful, such as what is the distribution of surface brightness and width of the trails. Each of these -and probably others- would benefit from a plot and a short paragraph.

Answer: The referee pointed out some diagnostic plots that would be indeed interesting to include as complementary material in this article. Due to the intrinsic limitations of space of the *Nature* journal, we have placed the following material as supplementary information in a new Appendix. Section 5.2 of the new version of the manuscript contains 4 new figures with the suggested material. In particular, Fig. 6 describes the minimum observable orbital altitude from a certain telescope orbit as a function of the Earth Limb avoidance angle. Figures 7 to 9 contain the distribution of: 1) Number of satellite trails as a function of the limb angle, 2) as a function of the exposure time, and 3) satellite trail surface brightness as a function of the distance from the telescope to the satellite and the width of the trail.

We included a paragraph to describe each figure, with a description of the main results and observed distributions. In short, a) the limb avoidance angle is a major factor for the observed number of trails, b) longer exposure times lead to more trails as expected, although this factor might be less important than the limb angle, and c) the surface brightness magnitude of the satellite trails seem to peak at intermediate distances (100 – 1000 km) to the observer. All these results are described carefully in the new Sec. 5.2, which is properly referenced in the main text. We thank the referee for the suggestion to include this new material.

4. * the paper focuses on images: - while a trail on an image ruins the pixels under it, it is fairly easy to spot even at low S/N. The affected region can then be masked so that it does not contaminate the data analysis. In other words, it is a (possibly major) nuisance, but it can be tackled. - a significant fraction of scientific observations are obtained via spectroscopy, where the data partially or completely lack spatial information (except in the case of integral field spectroscopy, which can be considered as a fancy type of imaging). Therefore, there is simply no tell-tale trail to indicate a contamination. Furthermore, the exposure time for spectroscopic observations tends to be much longer than for imaging (1 to 2 orders of magnitude), increasing the number of contaminating trails (which is, in first approximation, growing linearly with the

exposure time). Finally, the apparent motion of the satellite brings its surface brightness on detector to a level similar to that of the science target. So the contamination of spectroscopic observations is more complex and has the potential to be even more damaging than that of images. I do realize that performing the same type of analysis for spectroscopic observations would be a significant endeavour. While interesting, it may be beyond the scope of this paper. If so, spectroscopy would deserve a short paragraph explaining the problem, and encouraging others to study it in more detail...

Answer: We thank the referee for the suggested idea to analyze the impact of satellite trails on spectroscopic observations. In this case, a number of factors may balance the intensity of the contamination. On one hand, 1) longer exposure times make the trail surface brightness dimmer relative to the background flux, 2) spectroscopy tends to disperse the spectral energy distribution of sources and thus making their emission dimmer, including that of the satellites. On the other, as the referee mentions, 1) longer exposure times increase the number of trails, and 2) the contamination on spectroscopic observations might cover a larger fraction of the data (i.e., grism observations).

The referee is correct evaluating that the idea is worth exploring but also out of the scope of the current article, already at the very limit for *Nature*'s format. Spectroscopic simulations also require to assume a certain spectral energy distribution for the albedo for the satellites. In principle it can be approximated that the solar panels contribute for most of the emission, but the spectral albedo of the materials used by satellite operators is not publicly available to the astronomical community, making the viability of the proposed work uncertain. While the proposed endeavor is interesting and might be critical for some missions, we consider that it deserves its own publication. We have included a short description to this very important and complex problem on Sec. 4 - Discussion in the new version of the manuscript.

Response to reviewer's specific comments

1. Line 11. *Reflections from satellites are visible to the human eye and extremely bright for professional telescopes.* Most of them are not visible to the human eye, and are

not that bright for pro telescopes > can be ...

Answer: We agree with the referee. Corrected in the new version.

2. Line 37: *15000 satellites*. Reference? Unless you have a better one, I'd suggest a link to Jonathan McD's page at <https://planet4589.org/space/stats/active.html>

Answer: We thank the referee for pointing this out. Jonathan McDowell's Planet4589 database is indeed the source of this number. Modified in the new version.

3. Line 46: *At the current rate...* maybe more accurate: > Should all the FCC filing result in launches, the Earth would be ... decade.

Answer: We thank the referee for the suggestion, which was included in the new version of the manuscript.

4. Line 49: *as their relative positions:* > as their apparent positions

Answer: Corrected in the new version.

5. Line 51: *Satellite trails contaminate the targets of science interest, generating light gradients (scattered light), and increasing the photon-noise...* Actually, these are almost secondary effects: > Satellite trails passing over a science target can render the observation totally unusable. Even the trail misses the object, it can generate a background light gradient (scattered light) and increase the photon noise.

Answer: The authors thank the referee for the text suggestion. Included in the new version.

6. Line 52: *For new generation ground-based telescopes such as the Vera C. Rubin Observatory...* The critical factor is VRO's wide field: > For new generation wide-field ground-based telescope such as...

Answer: We agree. Modified in the new version.

7. Line 54: *it is estimated that 20% of the midnight images will present satellite ... 30-80%...* the % depend a lot on the constellation mix used in the simulation. > fairly conservative simulation estimated that that 20% of the midnight images would present satellite...

Answer: We agree that those predictions are conservative. We modified the text to emphasize it.

8. Line 56: *they are mostly visible to the unaided eye at twilight during sunset and sunrise...* Actually, that is valid for the eye and any telescope: > they are mostly visible at sunset and sunrise twilights

Answer: Thanks for this correction, we included it in the text.

9. Line 61: *Dark coatings and optical blocking systems have proven to be inefficient in avoiding the presence of satellite trails [8] in astronomical imagery data...* Actually, darkSat and visorSat were never expected to prevent trails in images; that would require a much stronger darkening. The target was to get mag $>\sim 7$, to avoid naked-eye visibility and VRO saturation. I suggest to rephrase: > 1/ only a mild decrease in the optical magnitude... > 2/ satellites are still very bright for astronomical images...

Answer: We agree with the referee that the goal of Darksat or VisorSat was not the complete removal of reflected light at the levels required for non-detection by professional telescopes. However, we consider that it is important to emphasize this fact, as multiple media reports claim that these prototypes are the solution to satellite light contamination. We have rephrased this sentence to include the correction suggested by the referee in the new version of the manuscript.

10. Line 64+68: missing [in references

Answer: Corrected in the new version.

11. Line 74: *can only be conducted through twilight and sunrise observations...* "twilight" is both morning and evening; no observations can be performed at sunrise. > evening and morning twilights

Answer: Thanks for this correction. Modified in the new version.

12. Line 78: *even at midnight*. You could add a ref, eg [3] or [7]

Answer: We thank the referee for the suggestion. We added the references to the sentence.

13. Line 80: *the fraction of uncontaminated night sky is at risk of becoming too small for practical science operations..* The argument is too sensationalistic; the argument would gain strength at being more quantitative. Maybe something along the line: > the fraction of images free of satellite trails will dwindle. In particular, large-field exposures acquired during twilight are likely to be contaminated by many (tens) trails. This will have a significant impact on some science cases.

Answer: We agree with the referee. We made a revision of the sentence emphasizing the rise in the number of affected exposures, avoiding repetition of the information described previously in the paragraph.

14. Figure 2: Please clarify that these are illustrations for some representative observation simulations (i.e. that such simulation was not performed for all the simulated observations). It would also be useful to represent the whole field of view (possibly as a drawing rather than a full simulated image) with a box indicating the position of the zoomed detail.

Answer: The figures are representative simulations meant to illustrate the effect in the images. Full image simulations were not rendered for each one of the 3000 simulations per telescope. We modified the caption in Figure 2 to specify that the panels represent affected sections from the total simulated exposure. Due to the size of the images – specially for *Xuntian* – it is impractical to represent the full field-of-view in the panels in the main text. We attached them as additional figures to the referee report (see Figs. 1,2,3, and4), and as part of the Supplementary material. Following the suggestion of the referee we made the full figures available as additional material in a Zenodo repository, with the databases containing the properties of the satellite trails (doi:10.5281/zenodo.15707680). The

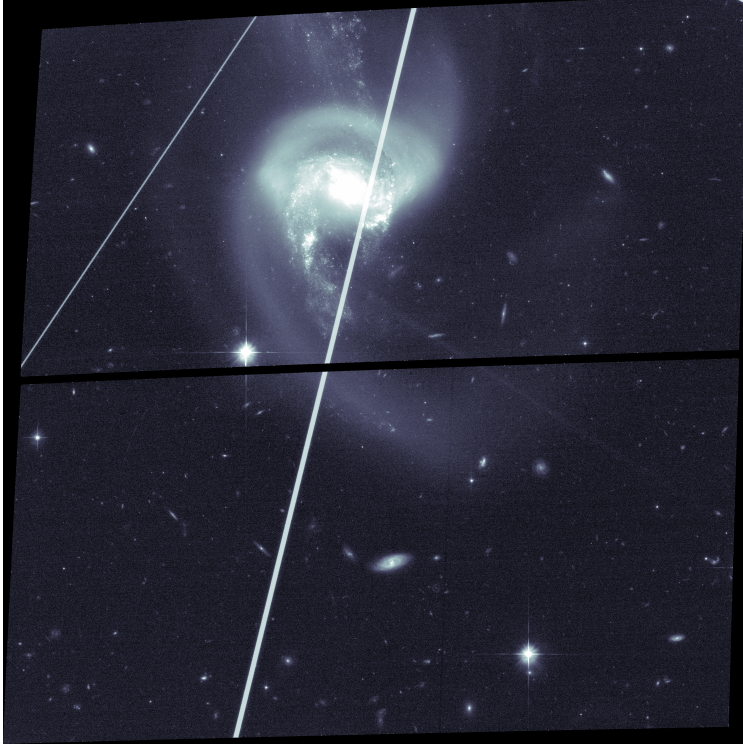


FIG. 1. Example of contaminated *Hubble* space telescope exposure simulation. The satellite trails were generated by simulating the orbits of $N = 560,000$ satellites. *Exposure properties*: Right ascension and declination: $(\alpha = 179.1625^\circ, \delta = +55.1656^\circ)$. Limb angle: 31.63° . Exposure time: 1309 s. Background: jbhq01020. PID: 12170.

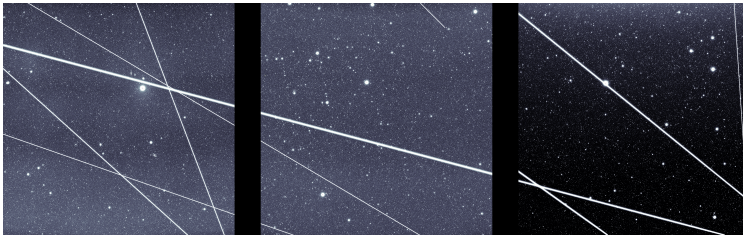


FIG. 2. Example of contaminated *SPHEREx* exposure simulation. The satellite trails were generated by simulating the orbits of $N = 560,000$ satellites. *Exposure properties*: Right ascension and declination: $(\alpha = 179.2857^\circ, \delta = -42.6098^\circ)$. Limb angle: 106.08° . Exposure time: 112.5 s.

repository is current accessible through request until the manuscript is released by *Nature*.

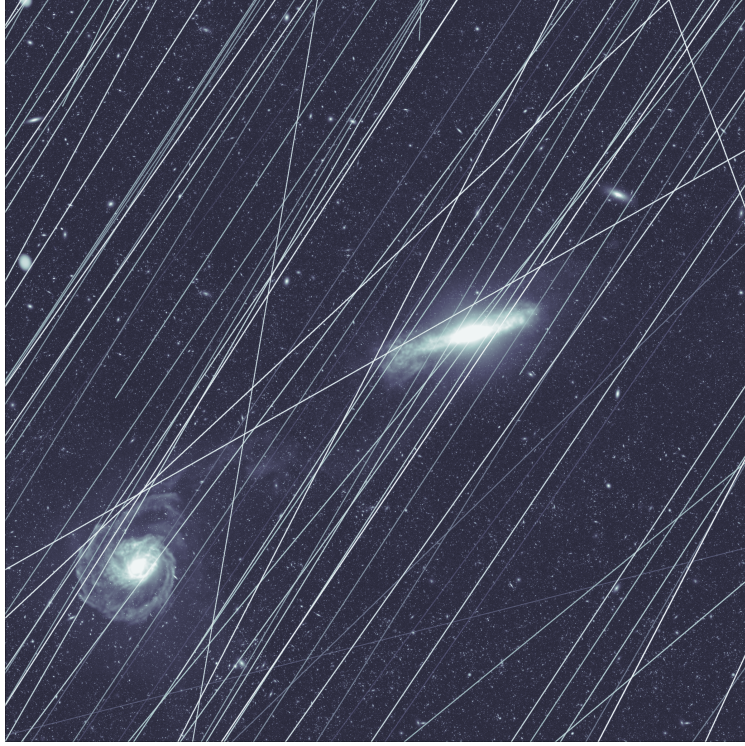


FIG. 3. Example of contaminated *ARRAKIHS* Space Telescope exposure simulation. The satellite trails were generated by simulating the orbits of $N = 100,000$ satellites. *Exposure properties:* Right ascension and declination: ($\alpha = 249.7058^\circ$, $\delta = -52.0297^\circ$). Limb angle: 25.94° . Exposure time: 600 s.

15. Section - 2.1 Frequencies: I would recommend presenting the results in a tabular form rather than as text; in that way, the discussion that follows would be much easier to parse. Lines could be -for each observatory 1/ number of trails per exp and dispersion, 2/ fraction of exposures with at least one trail; Columns: baseline, 100 000 sat, 560 000 sat (and maybe the extreme 1M sat)

Answer: We thank the referee for this very important comment. In the new version, Section 2 has been modified to include a new table (now Table 1) with five main properties of the simulated satellite trail population: 1) Average number of trails per exposure, 2) % exposures with at least one trail, 3) angular area affected, and 4) fraction of field of view (FOV) affected by the trails, and 5) trail surface brightness under different illumination conditions. This new table helps to improve the clarity of the results and enhances comparison between different

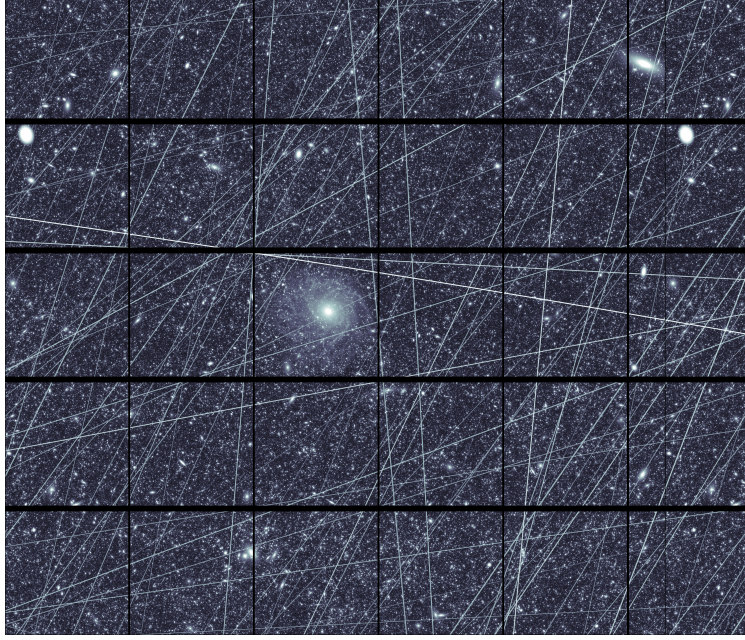


FIG. 4. Example of contaminated *Xuntian* Space Telescope exposure simulation. The satellite trails were generated by simulating the orbits of $N = 560,000$ satellites. *Exposure properties:* Right ascension and declination: ($\alpha = 274.8913^\circ$, $\delta = +55.8733^\circ$). Limb angle: 30.70° . Exposure time: 510 s.

telescopes.

16. Section - 2.1 Frequencies: The number of trails is a useful metrics, but a trail affects only the pixels below it. From your calculation below, you have the width of the trail, so the number of pixels it affects can be computed, resulting in the fraction of pixels lost per exposure. This fraction is the loss for a survey observation (effectively reducing the field of view by xx%); it is also the probability that a given object of interest (say, a star with transiting planet, or a quasar) be lost under a trail. As you already have the required data, I recommend you evaluate these fractions, and report them.

Answer: We agree with the referee on this issue. Following their advice, we included one row on new Table 1, containing the fraction of the field of view directly affected by the satellite trails. However, we remark that the area is a sub-optimal estimator of the total impact of satellite trails for science. Observations of ex-

tended objects might occupy more than 50% of the field of view on the telescope, or even the entire field, inevitably contaminating areas of interest. Some scientific cases require accurate photometry for multiple sources and/or regions of the sky (i.e., low surface brightness astronomy) across the entire field of view. Automatic trail masking methods (<https://acstools.readthedocs.io/en/latest/satdet.html>) can fail or misidentify trails when their brightness is comparable to the astronomical sources, affecting the analysis of large area surveys, highly increasing the cost and processing effort to account for them. In some cases, crossings between two or more trails in different consecutive exposures might even appear as unresolved sources in the final mosaics if the number of exposures is low ($N \sim 2 - 3$). Our results show that if the planned constellations are completed, *Xuntian* and ARRAKIHs will have $2.46^{+0.28}_{-0.28}\%$ and $12.2^{+3.7}_{-3.8}\%$ of the field of view contaminated by trails, while for *Hubble* and SPHEREx the fractions are lower $0.92^{+0.20}_{-0.20}\%$ and $0.41^{+0.02}_{-0.02}\%$. These fractions duplicate at one million satellite population levels, and demonstrate that the effect can be comparable or even higher than the effect of Cosmic Rays. We have included the fraction of the field-of-view as an estimator, together with the number of trails and fraction of contaminated exposures in the new Table 1.

17. - Line 127: Plot the results. The simulation should be presented also in some graphs, which would show trends and allow the reader to visualize and understand them, and extrapolate the results to other telescopes. In particular, I suggest the following plots (others may be relevant, even more relevant than these): 1/ number of trails as a function of zenithal distance. For ground-based observatories, the effect is dramatic, and l.131 suggests it is also present for space observatories.

Answer: We thank again the referee for this comment. Our results do show that lower limb angles present higher levels of trail contamination, as expected. We have included the requested material in the new Appendix 5.2 of the manuscript.

18. - Line 127: - *** 2.1 frequencies: The discussion could also include generalizations of the trends observed, for instance a) dependency of the number of trails with the number of satellites, b) with the field of view, c) with the exposure time, d) with the

zenithal distance, e) with the altitude of the observatory (inverse) - others?.

Answer: Fig. 6 to 9 of the new version of the manuscript contain most of the trends suggested by the referee. We acknowledge that simulating the number of trails as a function of the field of view and altitude of the observatory is not immediately achievable with the adopted simulation strategy, since – in practice – mapping each point on that parameter space requires to simulate an entirely different observatory.

In our simulations, each exposure is generated based on a survey plan, which is defined by the accessible areas of the sky that will remain visible for all the exposure time. At the same time, the three dimensional location of the telescope at every moment is defined by the TLE of the observatory. If the altitude is modified, the entire survey plan must be redefined, since the original region of the sky to be observed may not be visible. However, since we are mapping different ranges of exposure time, limb angle, distance from the satellite to the observer, we are able to explore the variation of the number of detected trails and surface brightness as a function of these parameters.

On first approximation, under similar conditions, the number of trails per unit time is a function of the square root of the field of view. In practice, different telescopes present different observational strategies (i.e., SPHEREx strict zenith angle), to which we intended to abide by, aiming to focus on providing an as-realistic-as-possible forecast of the the potential effects of satellite trail contamination on space telescopes. We agree with the referee that – while it is out of the scope of this first paper – generalizing the results to a user-defined telescope would be a very interesting resource for the astronomical community, and we will pursue it on a forthcoming paper.

19. Line 169: detailed in section 3.3... See below for (potentially serious) issue with the estimate of the surface brightness. Depending on the outcome of that point, it may be necessary to re-do the analysis.

Answer: We thank the referee for the careful revision of the surface brightness estimation. A complete revision and reanalysis of the section was completed for the new version. We detail the changes in the revised manuscript below.

20. Line 175 *higher resolution* To avoid confusion, between high-resolution=smaller pixels vs larger pixels > "better resolution" (or finer) - or - "larger resolution elements" depending on what you mean. higher resolution leads to enhanced flux concentration, which results in increased surface brightness...

Answer: Thanks to the referee for this clarification. In this sentence, we meant higher (finer) spatial resolution in the sense of pixels with smaller angular area in the sky. We corrected the sentence to be more clear in the new version.

21. Line 181: *A relatively dimmer-than-average observed brightness is expected since the trail in the Hubble exposure iedk12aoq was spatially resolved (trail width of 90 ± 20 pixels)....* Well, the object being resolved is taken care of by the first term in Eq.1. You could actually check that the predicted width of the trail matches what you predicted with Eq.1.

Answer: The referee prompted a careful revision of the discussion on *Starlink* 1619. First, the updated brightness estimations for the trails reveal the average surface brightness of the satellite trails can be relatively dimmer. The main reason for this change with respect to the previous version is that Earthshine (see next comment) can be a significant contributor to the trail surface brightness, making some previously-undetectable-trails detectable. As a consequence, the surface brightness of *Starlink* 1619 is now compatible with the expected distribution in Fig. 4 of the new version of the manuscript.

Second, as the referee suggests, we have further information that can help to evaluate whether the simulated surface brightness distribution is realistic or not. *Starlink* 1619 belongs to the first generation of *Starlink* satellites, with a total solar panel area of $\sim 26 \text{ m}^2$. Taking into account a random inclination of the solar panel surface to the observer, we can expect a cross-sectional radius of $2.36^{+0.41}_{-0.96}$.

If the trail width is 7.9 arcsec, we can use Eq. 1 in the reviewed Sec. 3.3 to determine the distance between *Hubble* and the satellite, $d_{\text{sat}} = 88.9^{+7.9}_{-16.2}$ km. Comparing the surface brightness distribution of satellites as a function of the distance (see Sec. 5.1, Fig. 9 in the Supplementary material), we can confirm that the observed brightness is indeed compatible with the simulated distribution for *Hubble*, supporting the realism of our simulations. We included these new results on Sec. 2.2.

22. Line 186: *case of satellites only illuminated by the full Moon.... It is really good that you quantified the effect of the illumination by the Moon, thanks. For satellites seen from space observatory, hww, wouldn't the illumination by the Earth be much stronger than the Moon's? It is easy to imagine a geometry for which the telescope sees the side of the satellite that is not illuminated by the Sun while being illuminated by the Earth.*

Answer: The referee is correct, Earthshine is a non-negligible emission for satellite trails. In the new version of the manuscript, we have introduced several new terms for the brightness contribution, including Earthshine and thermal emission. We provide more details below.

23. Line 227: *Xuntian. Could you give a (very brief) justification why the HST exposure time distribution is appropriate for this observatory?*

Answer: The choice of a similar exposure time distribution as *Hubble* for *Xuntian* is based on two factors: 1) *Xuntian* will orbit at a similar altitude as *Hubble* Space Telescope. Most exposures obtained from equatorial Low Earth Orbit telescopes are upper limited by a) visibility during the orbit, and b) cosmic rays. At $h \simeq 450$ km, *Xuntian* will have ~ 46 minutes per orbit for most targets vs. *Hubble's* 55 minutes per orbit [4], and potentially a similar cosmic-ray rate. 2) *Hubble* and *Xuntian* have similar apertures (2 m vs. 2.4 m) and spatial resolutions ($\sim 0.05''$ vs. $\sim 0.073''$), meaning that they will achieve relatively similar sensitivities in the same exposure time. Following the advice of the referee, we have included a short sentence in the manuscript to clarify this choice.

24. Line 233: *baseline population....* Excellent that you include these! Pls indicate how many objects are present in that baseline?

Answer: The total number of satellites included in the baseline population is 8544 objects. We authors thank the referee for pointing this omission. We have specified this number in Sec. 3.2 Satellite constellations orbit on the new version of the manuscript.

25. Line 241: Methodology/1: Do I understand well that "one simulation" consists in the following steps? - pick an epoch - pick a number of satellites ($100 < n < 1E6$) - for that epoch, compute the xyz position of all satellites and the 4 observatories - for the 4 observatories, define an observation (RA, Dec, expTime) that is compatible with their current position (avoid Earth, Moon, Sun...) - record the satellites that are visible in each observation If that is correct, all fine! If not, it means I did not understand, and you may want to update the text to clarify what I did not understand.

Answer: The steps described by the referee are indeed correct.

26. Line 241: Methodology/2: . Each simulation step is rather computationally intensive, and the number of satellites actually observed is going to be very small. Consequently, you have to iterate many, many times (in particular when there are fewer satellites) in order to get robust statistics. I'd recommend to devote a short paragraph on these computational considerations.

Answer: We generated a total of 3000 exposures per telescope, containing a variable number of satellites between 100 and 10^6 . The full analysis of each one of the 12,000 simulations takes 1.5 CPU hours, adding to a total of 750 days of combined CPU time. Due to the tight page limits of the Nature's format, we decided to omit this piece of information from the main manuscript.

27. Line 260: . 3) the orientation of the reflecting surfaces to the observer > and to the light source

Answer: Corrected in the new version of the manuscript.

28. Line 264: *minimum resolution element... seeing....* Seeing is not really relevant here (but it's OK to mention it); I'd suggest $>$ optical resolution of the telescope or the pixel size, whichever is larger.

Answer: We modified the sentence following the suggestion by the referee.

29. Line 267: *assuming a random orientation between 0° to 180° with respect to the observer..* Actually, it's 2D random orientation (0-180 lat and 0-360 long) $>$ assuming a random orientation with respect to the observer.

Answer: This is correct. We modified this sentence in the new version.

30. Line 268: *do I understand well that you pick at random a value for $4 \cdot R_{\text{sat}}^1$ in $[1, 125 \text{m}^2]$?* if so, this implies that the simulated cross-section distribution is rather more pessimistic than the "real" one (where most satellites are small). I realize that the simulations are done (and not cheap), but an alternative would be to assign to each satellite (I mean each constellation) a vaguely realistic cross section. Directly related, and an additional argument to assign a cross section to each satellite: monster-satellites like the BlueWalkers are dominated by their antenna, not their solar panels. Could you add a couple of line describing the effects of your choice of size distribution?

Answer: The referee points to a very important question. The cross-section of the satellites is a major factor to estimate their brightness that cannot be directly addressed with the currently available information from the operators. Most companies do not provide the dimensions of their spacecraft taking into account their deployed solar panels. As a consequence, we based our ranges in the population of the major launching operators in the present. The cross section of the OneWeb satellites is 2.7 m^2 ($N = 660$, 4.4% of the total population). For Starlink v.1 ($N = 4714$, 31.4%) the cross section is 26 m^2 , while a total of $N = 4289$, (28.6%) have an area at the peak of the assumed distribution, 125 m^2 . The referee is correct pointing out that a uniform distribution of areas between $[1 - 125 \text{ m}^2]$ does not completely represent the complexity of dimensions of the current satellite population, but we consider that the assumed distributions are sufficiently realistic for the purpose of the current manuscript – assessing the detectability or

not of the trails – if we consider the newer generations of satellites. In fact, constellations with even larger satellites are being planned (i.e., orbital data centers) with sizes up to 3600 m^2 [5][6].

31. Line 270: . Eq.2 considers that the satellite is a flat disk perpendicular to the line-of-sight. In Bassa et al [27], this is justified by the fact that the satellites are seen "from below", and that their geometry from that vantage point is closer to a flat panel than to a sphere (and confirmed by the fact that this works better than a Lambertian sphere phase function). As the space observatories are embedded in the middle of the satellites, the viewing geometry is random (i.e. the satellites are not flat panels), and in particular the solar phase effect is likely to have a much stronger effect than as seen from the ground.

Answer: In our simulations, the effective cross-section of the satellites is scaled accordingly to the given angle on each satellite. The referee is correct pointing out that in the real case, the relative orientation between source - satellite - observer can affect the observed surface brightness of the trail. This is visible in some particular cases of "variable" satellites, where their surface brightness fluctuates along the trail, suggesting that they are tumbling (see Fig.5). It is important to remark that 1) most satellites maintain a similar brightness across a single trail, and that 2) the approximation is valid for the main purpose of this article, which is forecasting the frequency of trails for different telescopes. In future works we will explore accurate trail modeling of the satellites taking into account real surface orientations.

32. Line 277, Eq.3: . The $-2.5\log$ is the scaling between the surface of a static object and the surface of the trailed object, right? (do you have a ref for this equation, or is it home-brewed?). The surface of the trail is $(\theta * \omega * t) [\text{sq.arcsec}]$. The surface of the image of the static object is $(\pi * \theta^2 / 4)$. So the ratio should be $(4 * \omega * t) / (\pi * \theta)$ Did I miss something? Is this a typo? did you use this equation in the actual code?

Answer: Following this and the previous comments of the referee, we have done a deep revision of the Sec 3.3 photometric analysis for the satellite trails, both in



FIG. 5. Observation of a fluctuating surface brightness satellite trail obtained with *Hubble* Space Telescope (ACS/WFC F606W, j6mf421oq, Proposal ID: 9433).

terms of manuscript and actual code. We agree with the referee that in the previous version, the presentation of the satellite brightness in terms of magnitudes was not entirely clear and might lead to confusion. For reference, we based our methodology on the following works:

- Trail width and apparent surface brightness [1, 7]
- Reflected and thermal flux from LEO satellites: [2].

In response to the referees question, to estimate the surface brightness of a satellite trail, first we must estimate the apparent magnitude of the satellite (as if it was static over the detector) and then disperse the flux over the trail area (surface brightness). To make the equations more clear, we have redefined the total satellite flux in terms of spectral flux density ($\text{W m}^{-2} \text{Hz}^{-1}$) instead of magnitudes.

The total energy received from a satellite per pixel is essentially the flux (F_{sat}) multiplied by the time that the satellite spends on a single pixel (t_{eff}). Then to obtain the surface brightness (Σ_{sat} , $\text{W m}^{-2} \text{Hz}^{-1}$ per arcsec^2) one must divide

that product by the area of the trail (A_{trail}) and the total exposure time (t_{exp}). Finally, to transform from surface brightness flux in $\text{W m}^{-2} \text{Hz}^{-1}$ per arcsec^2 to surface brightness magnitudes (mag arcsec^{-2} , AB system) we just use:

$$\mu_{\text{sat}} = -2.5 \log_{10}(\Sigma_{\text{sat}}) - 56.1. \quad (1)$$

We detailed this process step by step in the new revised Sec. 3.3. We thank the referee for bringing this potential confusion to our attention.

33. Line 288: . One of every four exposures obtained with Hubble Space telescope will show contamination by satellite trails. Repeated from l.284. > remove one occurrence.

Answer: Corrected in the new version. We removed the first occurrence.

34. Line 301: *similar tools created for ground-based telescopes [29, 30]....* You may want to add Bassa+22 <https://doi.org/10.1051/0004-6361/202142101> where they discuss a series of representative ground-based telescopes.

Answer: We thank the referee for the suggestion. We added Bassa+22 in this sentence in the new version of the manuscript.

35. Section 4.1 - Requirements: Publishing a list of requirements is good, but 3/ seems to be wishful thinking... While desirable, is jumping for a current precision of 1km to few cm (i.e. over 4 orders of magnitude) feasible? This seems a challenge at the engineering level, and it may not even be feasible at the physics level. I think this 3/ deserves a feasibility comment, otherwise it affects the strength of your other demands.

Answer: Orbit determination at precisions of cm for specific objects has been achieved. One example of such efforts is the Doppler Orbitography by Radiopositioning Integrated on Satellite (DORIS, <https://earth.esa.int/eogateway/instruments/doris/description>), a CNES-led mission that achieved precisions down to 1 cm. It is important to note that for the example in the discussion, we used the pixel scale of the highest resolution telescope available in LEO (Hubble). Identification of trails might be feasible with less orbital precision than the optimal conditions.

36. - Line 345: *"open book" configuration*. This is true for very early launches. Pls fact-check the current situation: SL now operates the "open-book" configuration in an attitude that keeps the Sun in the plane of the "open-book" and/or fly "on the side" to minimize the cross-section seen from below. Here is a secondary ref <https://spaceref.com/science-and-exploration/spacex-publishes-update-on-starlink-satellite-attitude/> > pls update the text.

Answer: We agree with the referee. The attitude of the satellites is adapted over the launch-to-operations stage. The public SpaceX document <https://www.starlink.com/public-files/BrightnessMitigationBestPracticesSatelliteOperators.pdf> provides some insight about the different attitude profiles for Starlink satellites. We have modified the text to include this reference and make the sentence clearer.

37. Line 25 (abstract), Line 368: *We propose a series of mitigation measures that can be applied to prevent....* Actually, you do propose 3 concrete, actionable constraints on the satellite operators (with the caveat about #3, see above). This is valuable, but they are not mitigation methods. These would be recommendations applicable to observatory operators. Just to give an obvious example: "adjust, when possible, the observation strategy to minimize the zenithal distance of the telescope", as this will dramatically reduce the number of trails.

Answer: We agree with the referee. Mitigation methods do not fully represent some items, such as the availability of live information about the attitude of the satellites. We modified the abstract to use the expression "actions" instead of mitigation measures, in an effort to include the actionable items described in the discussion. We thank the referee for bringing this point to our attention.

[1] E. M. Vallerie, Investigation of photometric data received from an artificial satellite, DTIC (1963).

- [2] T. Horiuchi, H. Hanayama, and M. Ohishi, Simultaneous Multicolor Observations of Starlink’s Darksat by the Murikabushi Telescope with MITSuME, *Astrophys. J.* **905**, 3 (2020).
- [3] J. A. Tyson, A. Snyder, D. Polin, M. L. Rawls, and Ž. Ivezić, Expected impact of glints from space debris in the lsst, *Astrophys. J.* **966**, L38 (2024).
- [4] [https://hst-docs.stsci.edu/hsp/past-hst-proposal-opportunities/
the-hubble-space-telescope-primer-for-cycle-27/hst-cycle-27-primer-orbit-calculation-examp](https://hst-docs.stsci.edu/hsp/past-hst-proposal-opportunities/the-hubble-space-telescope-primer-for-cycle-27/hst-cycle-27-primer-orbit-calculation-examp)
- [5] <https://patents.justia.com/patent/20250108938>.
- [6] <https://www.thalesaleniaspace.com/en/news/ascend-new-alternative-terrestrial-datacenters>.
- [7] C. G. Bassa, O. R. Hainaut, and D. Galadí-Enríquez, Analytical simulations of the effect of satellite constellations on optical and near-infrared observations, **657**, A75 (2022).

Response to referee #2

Alejandro S. Borlaff, Pamela M. Marcum, Steve B. Howell

(Dated: June 20th, 2025)

Remarks to the Author

This paper forecasts the impact of the increasing satellite constellation population on present and future space telescopes in low-Earth orbit (LEO). The authors correctly identify a gap in the literature, because most studies are primarily concerned with the impact of bright satellites on ground-based telescopes. To fill this gap, the authors simulate up to one million satellites with similar brightness properties as seen by Hubble today, on four LEO space telescopes: Hubble, SPHEREx (recently launched), ARRAKIHS (planned c 2030), and Xuntian (planned c 2026). The paper concludes that contamination from satellites will be substantial and that additional mitigation measures are warranted to protect LEO astronomy as well as ground-based astronomy.

The paper is overall original, significant, and worthy of publication. Light pollution from an increasing population of constellation satellites is an existential threat to observational astronomy and urgently needs to be better understood to enable quantitative mitigations. The authors make necessary assumptions to simulate what images from the four space telescopes might look like, and use their results to motivate further mitigations that focus on enabling prevention, avoidance, and correction. The Figures are all visually clear and compelling, accurate given the stated assumptions, and support the paper's conclusions nicely.

Most of my suggested improvements center on two themes: (1) the large systematic uncertainty in present-day satellite brightness models and forecasts, particularly pertaining to satellite attitude (i.e., geometric orientation relative to the observer), and (2) ensuring the published simulations enable readers to reproduce the results and use the authors' tools to investigate their own preferred suite of assumptions. The inherently huge unknowns from (1) necessitate particular care be taken to enable state-of-the-art reproducibility via (2). I also suggest a handful of additional references, and a couple of places where drawing parallels to ground-based astronomy may enhance the paper and help readers place it in context.

Dear Referee,

Please find enclosed a revised version of our manuscript “*One million satellites in the sky: Light contamination on space telescopes*”. The authors would like to thank the detailed revision of the first version of this manuscript, which improved the results significantly. We have revised your comments carefully, marking the changes in the manuscript using **bold blue typeface**. A summary of the major changes in the new version is presented below. Finally, we present a detailed answer to each of the questions and corrections prompted after the submission.

Major Changes

1. Following the suggestions from the referee review, we have performed a complete revision of the methodology to estimate the surface brightness of the satellite trails. This includes the implementation of diffuse sphere formalism [1], Earthshine, thermal emission, and satellite illumination phase angles [2], and the adoption of a realistic albedo distribution [3]. We remark that for the purposes of this paper (detectability), we found no statistically significant differences between assuming that the satellites are flat surfaces or diffuse spheres. While the updated surface brightness distribution represents a more realistic view of the satellite trail brightness, the fundamental results on our manuscript did not change. If the proposed satellite constellations become operational, virtually all images obtained with SPHEREx, *Xuntian*, and ARRAKIHS, will detect satellite trails, as well as a significant fraction of those obtained with *Hubble*.
2. The results described in Sec 2.1 are now described in a new Table (new Table 1), containing the a) average number of satellite trails detected per exposure, b) the simulated exposures with at least one trail (%), c) the area affected in arcmin², d) the fraction of field of view covered by trails (%), and e) the average trail surface brightness for Sun illuminated and non Sun illuminated satellites. This reorganization of Sec.2.1 made now the results section more clear.
3. We have included a set of additional figures, and tables as part of the Supplementary material in a new Appendix (Sec. 5). Sec. 5.1. contains four new figures, describing the minimum observable altitude for a space telescope as a function of the limb angle (Fig. 6), the distribution of the number of trails as a function of the Earth’s limb

angle (Fig. 7), exposure time (Fig. 8), and the distribution of surface brightness as a function of the distance between the satellite and the observer and the trail width (Fig. 9). Sec. 5.2. contains a new table describing the layers, inclination, and altitudes of each simulated satellite layer, with a new figure (Fig. 10) with a visual representation of the latitude and longitude of each satellite for a given epoch.

Next, we will answer all the questions raised by the referee (in blue) followed by our answers in black.

Response to reviewer’s major comments

1. When describing “most mitigation efforts” (Section 1 lines 57-60), I suggest mentioning upfront how attitude, or geometrical orientation of various satellite components, can be a key darkening mitigation strategy. However, this depends strongly on satellite design and operational details, which are often proprietary and thus not possible for a third party to model.

Answer: We thank the referee for this important comment. We have included a mention to attitude and design factors in the introduction of the manuscript. We agree that this are critical factors, and we discuss them extensively in Sec. 4, including some updated references to Starlink mitigation techniques.

2. I strongly suggest doing an update of Figure 1 and Table 1 — and related numbers in the text — as close to publication as feasible. Is there code available to create a new version of Figure 1? This would be an asset to the community well after the figure is finalized and published.

Answer: We have updated Figure 1 and Table 2 to the most up to date information available about the planned constellations. The suggestion of creating a live code that can update the figure automatically with new announcements is extremely interesting. Currently, the article version of Figure 1 is generated based on a local database manually reviewed and retrieved from Planet4589 public database planet4589.org, but we will take under consideration generating a linked website able to generate updated versions in the future. We thank the referee for this suggestion.

3. Section 2.1 clearly describes predictions for satellite trail counts as the satellite population increases over time for four space telescopes. To put this in context, and to validate some of the approximate numbers referenced in Section 1, would it be possible to add a line to Figure 3 for Rubin Observatory? More generally, I can imagine any ground- or LEO-based telescope operation team desiring a way to easily see the forecast for their telescope. If any figure were to be readily reproducible with the reader's own desired parameters and available data, it should be Figure 3.

Answer: Currently, our simulations can only simulate LEO orbiting observers (defined with a particular Two Element Orbit), and do not consider ground-based effects like seeing or atmospheric extinction. While the referee raises a particularly interesting question to explore in forthcoming publication, our intention with this article is to focus on the impact of satellite constellations on Low Earth Orbit space observatories, poorly covered in the literature until now, in contrast with the case of ground-based observatories, like the Rubin Observatory. Note that the simulations generated for this work took over 18,000 hours of equivalent CPU time, and they must be repeated for any change in orbit altitude, field of view, or observing plan. Generalizing the simulations for the use of any ground or LEO telescope operation team is certainly out of the scope of the current effort, but we deeply thank the referee for this suggestion, that we will consider for a future publication.

4. For satellite brightness forecasting, there are confounding variables that can lead to huge systematic errors, and the details of these are glossed over in Section 3.3. An important one is satellite attitude, as previously mentioned. While this is listed as a factor in Section 3.3, and discussed generally in a very Starlink-specific way in Section 4.1 (lines 341-352), it is not clear how the large range from 1 - 125 m² possible reflective area affects the mean or width of the surface brightness distributions shown in Figure 4. This two-order-of-magnitude uncertainty that directly impacts brightness needs to be more clearly incorporated into the paper's quantitative analysis.

Answer: Our results incorporate the uncertainty in trail surface brightness by assuming a random physical area between 1 – 125 m² for each one of the 10⁶ simulated

satellites, by including them in a Monte Carlo fashion. This is, each satellite simulation assumes a different configuration (i.e., size, albedo) within its probability distribution, thus incorporating their uncertainties to the observables. We agree with the referee that physical area, combined with attitude/orientation, and reflectance are the most important contributors to the uncertainties in the prediction of surface brightness. However, none of these parameters are publicly accessible for the astronomical community for each satellite. As a consequence, the only way to forecast the effect of future satellite constellations is to assume representative ranges based on the best current knowledge of the satellite population properties. We discuss the need for more information from satellite operators in Sec. 4 of the manuscript.

5. In a similar way, I am not convinced that 0.25 is an appropriate fixed value for satellite albedo. Tyson+24 (<https://iopscience.iop.org/article/10.3847/2041-8213/ad41e6>) describes reasonable albedos between 0.1 and 1, the latter being regularly expected for certain small pieces of debris with flat, specular surfaces. Here is another order-of-magnitude systematic uncertainty that needs to be more quantitatively considered.

Answer: We acknowledge that the fixed albedo $p = 0.25$ does not account for the whole range in reflectivity for satellites. Horiuchi et al. 2023, PASJ 75 584, reports optical and NIR albedos between 0.1 and 0.47 for Starlink satellites, while as the referee mentions, Tyson et al. 2024 ApJL V966, 2, assumes albedos between 0.1 and 1. It is important to remark that the objective of the current manuscript is not to accurately simulate the actual surface brightness of individual satellites, but to assess the number and frequency of trails that will be detectable to space telescopes. Following the advice of the referee, and in order to account for the broad range of uncertainties in the satellites albedo, we modified the fixed albedo to a random uniform distribution between 0.1 and 0.5, following the reported values in the literature. The new albedo distribution reflects in a more realistic way the variability on surface brightness in the simulated trails, but it does not change the main result: the vast majority of the satellite trails will be detectable for the considered telescopes. We have included an detailed

explanation on Sec. 3.3 in the new version of the manuscript. We thank the referee for bringing this issue to our attention.

6. I do not see where Fig. 4 is introduced in the text, and it appears well before Section 3.3, where modeling satellite trail brightness is described. Why is a single HST observation of a single Starlink satellite shown in this figure? Hubble has seen myriad such Starlinks before and since, see, e.g., Kruk+23 (your ref 15), and it is not immediately clear if 18 mag/arcsec² is typical or unusual for this satellite population. The entire brightness modeling scheme appears to rest on a single measurement of a single satellite.

Answer: We thank the referee for spotting the omission of a direct reference to Fig. 4 in the original manuscript. We corrected it in the new version.

The referee points also to a very important question not directly addressed in the manuscript. While Kruk et al. (2023) did provide an extended list of satellite trails observed in *Hubble* images, the authors did not attempt to identify the satellites that generated them. Kruk et al. (2023) analyzed images from 2002 to 2021, undoubtedly including multiple trails from non-Starlink satellites. The trail of Starlink-1619 on November 2nd, 2020 identified by J. McDowell on *Hubble* WFC3/UVIS ([iedk12aoq](#)) is – to the best of our knowledge – the only positive identification of an artificial satellite on a *Hubble* image. Part of the cause for this limitation is the lack of an open archive of orbital solutions for satellites with sufficient precision. As a consequence, [iedk12aoq](#) is the only source available until now to verify that the photometry of the simulated trails is realistic. This fact remarks three of the major requests of the astronomical community, 1) the need of open databases for satellite streaks, 2) identifications of the satellite streaks with the spacecraft, and 3) precise orbital solutions for all satellites of interest.

As the referee suggests, we have further information that can help to evaluate whether the simulated surface brightness distribution is realistic or not. *Starlink* 1619 belongs to the first generation of *Starlink* satellites, with a total solar panel

area of $\sim 26 \text{ m}^2$. Taking into account a random inclination of the solar panel surface to the observer, we can expect a cross-sectional radius of $2.36^{+0.41}_{-0.96}$. If the trail width is 7.9 arcsec, we can use Eq. 1 in the reviewed Sec. 3.3 to determine the distance between *Hubble* and the satellite, $d_{\text{sat}} = 88.9^{+7.9}_{-16.2} \text{ km}$. Comparing the surface brightness distribution of satellites as a function of the distance (see Sec. 5.1, Fig. 9 in the Supplementary material), we can confirm that the observed brightness is indeed compatible with the simulated distribution for *Hubble*, supporting the realism of our simulations. We included these new results on Sec. 2.2.

We would like to remark that the surface brightness of our simulated sources does not depend on the observations of Starlink-1619, since they are modeled independently. In addition, we point out that the surface brightness estimation of the satellite trails has been extensively reviewed, including changes to the albedo distribution, Earthshine, thermal emission, and phase angles, resulting in a more realistic distribution of the surface brightness at the observed wavelength. As a consequence, the discussed Starlink observations now are fully compatible (1σ) with the simulated brightness distribution, including its estimated distance to the telescope. We deeply thank the referee for prompting this analysis which reinforced the results of the manuscript.

7. Please include information related to Section 3.2 in a similar fashion as done by Lawler+21 (your ref 29) in their Figure 1 and Table 1. This will both enable readers to reproduce the satellite population simulation and verify that it is physically realistic. I note that their paper included a public GitHub repository that could be used to create a potentially more realistic simulated satellite population: <https://github.com/hannorein/megaconstellations/>. I strongly recommend a similar repository to accompany this paper, since all the Figures tell a compelling and urgent story that is rapidly changing over time.

Answer: We have included a new figure and a table in the manuscript following this suggestion. Table 4 of the new version of the manuscript contains the number of satellites (N_{sat}), inclination (i), and orbit altitude (h) for each layer of each constellation. Figure A.1. (also attached here as Fig. 1) represents the projected

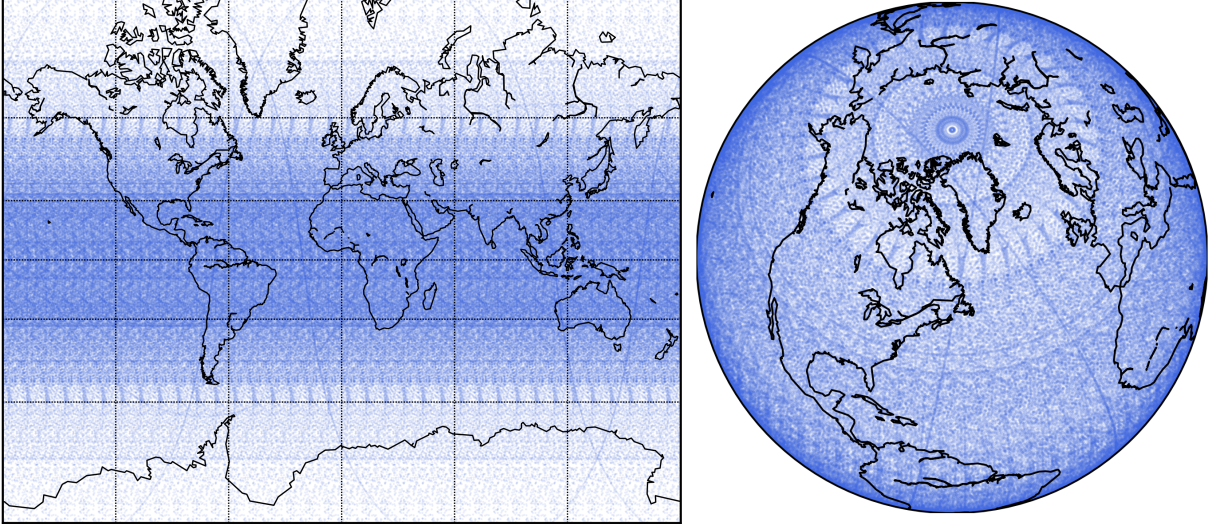


FIG. 1. Distribution of the complete set of simulated constellations described in Table 1 on the main manuscript (557,794 satellites), projected over the entire globe (left, Mercator projection) and over the North Atlantic (right panel, orthographic projection). Each blue point represents one satellite. Most telecommunication satellite constellations avoid polar orbits, resulting in a reduced number of satellites at very high or very low latitudes.

distribution of satellites over the Earth in two projections (Mercator and orthographic).

Following the suggestion of the referee we created a Zenodo repository with the databases containing the properties of the satellite trails ([doi:10.5281/zenodo.15707680](https://doi.org/10.5281/zenodo.15707680)) to facilitate further analyses by the community. The repository is current accessible through request until the manuscript is released by *Nature*.

Response to reviewer's minor comments

1. Satellite forecasts for all telescopes, including Rubin Observatory/LSST, depend strongly on the predicted satellite population. Thus, the cited 20% at midnight and 30-80% closer to twilight in Section 1 (lines 53-55) are very rough estimates, and I believe they assume a total satellite population of about 40,000. I suggest you add a sentence to Section 1 around line 55, e.g., “We note these estimates each assume a particular satellite population significantly smaller than the one mil-

lion considered in this work.” Even if the numbers are approximate, concluding there will be a large fraction of affected exposures is robust. You may wish to also cite Hu+22 (<https://iopscience.iop.org/article/10.3847/2041-8213/aca592>), which explored the regime in which proactively avoiding bright satellites may be necessary for the Rubin scheduler, and included some simulated satellite populations (<https://github.com/lsst-sims/satellite-dodging-ApJL>).

Answer: The referee is bringing up an important point. Previous works regarding the contamination levels due to satellite trails have been assuming satellite population levels from the project announced in 2020 (i.e., Starlink, OneWeb) which only comprise satellite populations in the order of $\sim 10,000$. Following the advice of the referee we have modified the last sentence of the paragraph as requested. We found the reference to Hu+22 remarkably appropriate for the second item in Sec. 4.2., regarding satellite avoidance operations on telescopes. We thank the referee for this addition to the manuscript.

2. I suggest mentioning that specular dichromatic mirror coatings designed to reflect most incident light away from Earth are now the preferred technology by both SpaceX and Amazon (rather than dark coatings or optical blocking systems, Section 1 line 61). A relevant technical report is available here <https://www.starlink.com/public-files/BrightnessMitigationBestPracticesSatelliteOperators.pdf>. I could see this being potentially bad for space telescopes - is it?

Answer: The authors thank the referee for this useful resource. Based on the bidirectional reflectance function (BRDF) in the figure present in page 5 from the SpaceX *Starlink* document, *Gen2* dielectric mirrors would reduce the reflectivity *at all angles*, emitting less light than the *Gen1* at all directions, and even less than the carbon nanotube paint (darkest paint reference). If confirmed, this would be certainly an interesting method to reduce brightness.

However, even in this best case scenario, the reduction in brightness only represents a change 1/10 in flux, which in magnitudes it translates to 2.5 magnitudes dimmer. With an expected surface brightness of $\sim 18 - 22$ mag arcsec $^{-2}$, most resulting trails would be still far brighter than many astronomical sources

of interest, including the Zodiacal light. It is important to remark that *Gen2* satellites are a 5 times larger than their predecessors, potentially compensating the reported reduction in brightness. This hypothesis is, in fact, supported by ground-based observations.

In Fig. 2 of the present document, we represent the apparent optical magnitude of *Starlink* trails vs. their NORAD Catalog Number, obtained through the IAU CPS Satellite Constellation Observation Repository (SCORE) [4]. The NORAD Catalog Number is a sequential ID assigned as a function of the launch date and thus, it is representative of the satellite model. The apparent magnitude of the Starlink satellites has indeed become brighter ($p < 10^{-5}$, Spearman correlation test) with increasing models and thus with time, contradicting the conclusions of the *SpaceX* technical report attached.

3. I note that mitigation via adjusting spacecraft attitude could potentially preferentially darken certain satellites when they pass over specific sites on Earth, rather than in skies everywhere. I would be very interested to learn how targeted darkening for specific (lat, lon) on Earth would affect space telescopes. It is OK if this is out of scope for this paper.

Answer: We agree with the referee, this is certainly an important point to explore.

Analyzing the affects of changes in the attitude requires the use of more complex simulations than those presented in this manuscript. In particular, future simulations with access to realistic attitude distributions and bidirectional reflectance functions could attempt to predict the impact of directed darkening on space telescopes. While this is an interesting endeavor, our manuscript is focused on reporting a realistic forecast for satellite trails on LEO space telescopes based on the available information made public from the industry operators. We appreciate the recommendation to explore this factor in a forthcoming paper.

4. While it is true that DTC satellites are larger and inherently brighter, some argue this is effectively offset by choosing lower orbits, because they have a lower peak brightness as seen by telescopes with large primary mirrors. As you well know, this

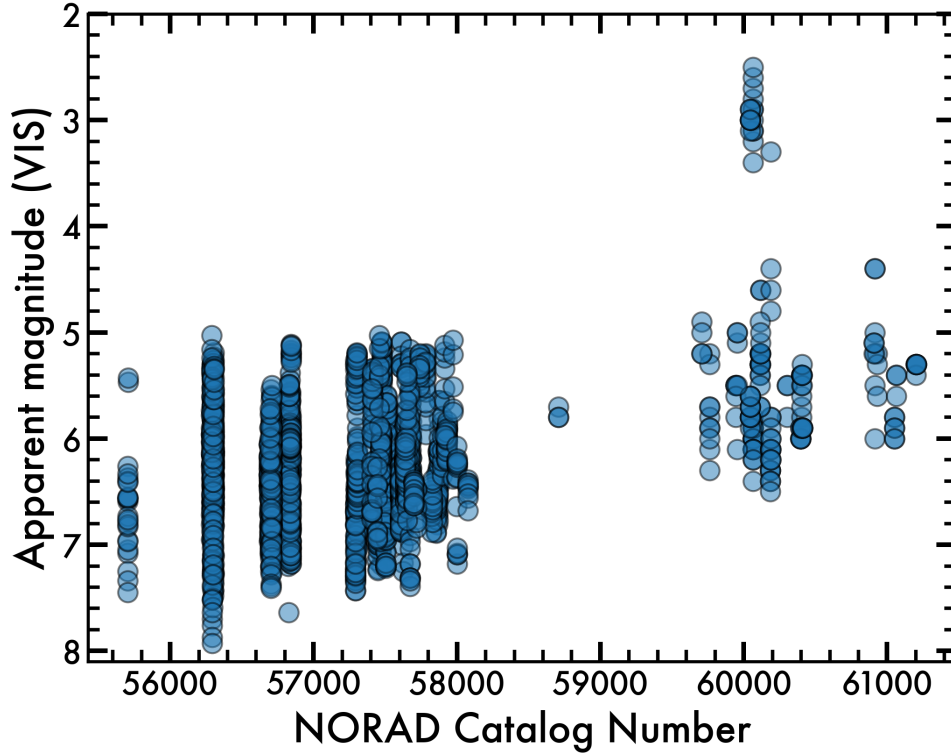


FIG. 2. Apparent magnitude of Starlink satellites as a function of their associated NORAD Catalog Number. Dataset obtained through the IAU CPS Satellite Constellation Observation Repository (SCORE). Observing filter: Clear (optical). Instrument: Mini-MegaTORTORA (MMT-9) wide-field monitoring system [5].

is because lower objects move faster and appear more out-of-focus. I suggest briefly acknowledging these complex tradeoffs in Section 1 around lines 65-69.

Answer: We modified the requested sentence to address the relatively lower orbit for Starlink DTC satellites, as requested.

5. The paper cites the SATCON1 report (Walker+20) but not any of the subsequent SATCON2 reports or either of the Dark & Quiet Skies I & II reports. These might fit nicely in Section 1 around line 82. They are thankfully all indexed by ADS.

Answer: We thank the referee for the recommendation. The suggested references were added at the requested paragraph.

6. I note that many article titles in the References have incorrectly lowercase-preferred capitalization schemes, to the detriment of “Lsst,” “spacex,” “leo,” “Nasa,” etc.

Answer: We have corrected this typo on the new version of the bibliography. We found that it was caused by the BibTeX interpreter used to store and generate the literature records on the LaTeX file.

7. Figure 1 is a lovely comprehensive view of the present and likely future situation. I noticed a typo in the Chinese constellation Qianfan (no u). I am unsure why the Qianfan numbers indicate 32 planned satellites but 90 launched? I concede it is next to impossible to keep such figures up to date!

Answer: We thank the referee for spotting the typo, which has been corrected in the new version of the figure. Regarding Qianfan, we acknowledge the discrepancy from the official plans and the actual number of launches as reported by Planet4589. We remark that as a cautionary criteria, we simulate the planned number of satellites intended to be part of the constellation, since some of them might be decaying or disposed (13 out of 90 are marked as failed/decaying, <https://planet4589.org/space/con/qf/stats.html>).

8. I applaud the authors for considering satellites reflecting moonlight. Are the predicted trail surface brightnesses still low ($30+ \text{ mag/arcsec}^2$) for extremely bright satellites like BlueWalker3? Please cite Nandakumar+23 in addition to Mallama+23 for this satellite (<https://www.nature.com/articles/s41586-023-06672-7>).

Answer: As described in the summary, we have performed a deep revision of the satellite photometry in the new version of the manuscript. The new analysis includes a series of additional effects non-accounted for in the previous version like Earthshine or thermal emission. By accounting for these factors, some satellites not illuminated directly by the Sun can still be detectable by a LEO telescope.

Following the suggestion of the referee, we have attached to this report an additional version of current Fig. 4 (Fig. 3 of this document) with the expected surface brightness energy distribution of large satellites ($A_{\text{sat}} > 100 \text{ m}^2$) without

Sun-illumination. The new results show that large satellites like BlueWalker3 can be detectable for *Xuntian*, ARRAKIHS, and *Hubble* Space Telescope at surface brightness magnitudes brighter than 25 mag arcsec² in the optical range. Importantly, the surface brightness remains the same in near-infrared, since it is dominated by the thermal black-body emission from the satellite. Note that the vast majority of the simulated satellites visible to SPHEREx were illuminated by the Sun due to its terminator aligned Sun-synchronous polar orbit.

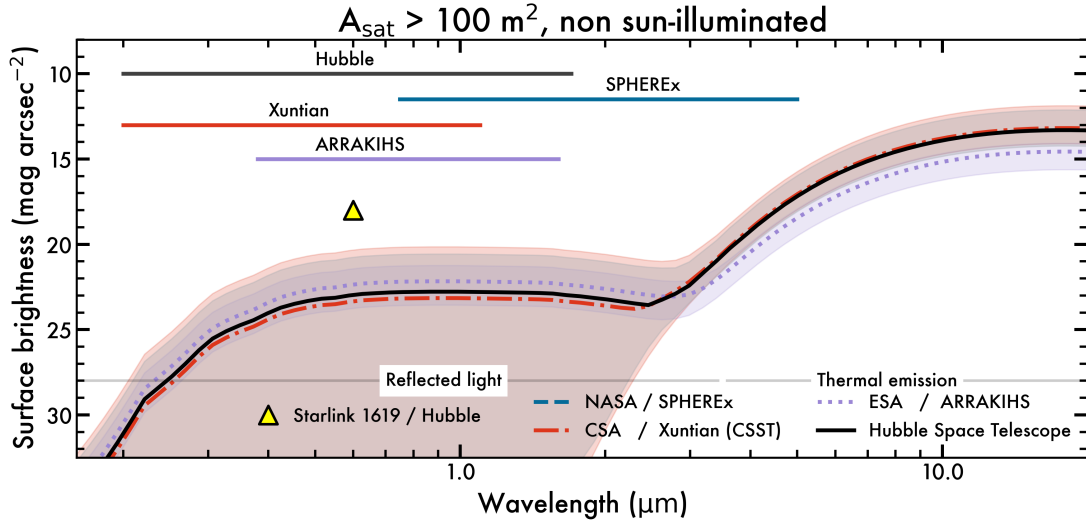


FIG. 3. .

9. Since a good deal of the paper pertains to satellite brightness forecasting, I would like to take the liberty to refer the authors to additional resources that ought to be considered and likely cited in this discussion: Privateer's Glint Evader tool (accessible via <https://wayfinder.privateer.com>), Fankhauser+23's Lumos modeling tool (<https://lumos-sat.readthedocs.io>), and CPS SatHub's SatChecker (<https://satchecker.readthedocs.io>), which does not yet include brightness predictions but will in the future.

Answer: We thank the referee for the suggested references. We included Fankhauser+23 and Lumos in Sec. 3.3, and SatChecker in the second paragraph of Sec 4, along with other modelling resources cited in the manuscript.

10. In Section 3.2, line 230, the authors refer to the “Planet489 public database,” but I note this is missing a “5” and that the correct citation for this wonderful resource, per the website planet4589.org/space/gcat, is as follows: A suitable short citation is ‘data from GCAT (J. McDowell, planet4589.org/space/gcat)’. A full citation is: “McDowell, Jonathan C., 2020. General Catalog of Artificial Space Objects, Release 1.7.3, <https://planet4589.org/space/gcat>

Answer: We thank the referee for bringing this important omission to our attention. Planet4589 has been an outstanding resource, critical to this research. We have corrected the typo in the new version, and included a proper citation in the bibliography, as suggested.

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- [1] E. M. Vallerie, Investigation of photometric data received from an artificial satellite, DTIC (1963).
- [2] T. Horiuchi, H. Hanayama, and M. Ohishi, Simultaneous Multicolor Observations of Starlink’s Darksat by the Murikabushi Telescope with MITSuME, *Astrophys. J.* **905**, 3 (2020).
- [3] J. A. Tyson, A. Snyder, D. Polin, M. L. Rawls, and Ž. Ivezić, Expected impact of glints from space debris in the lsst, *Astrophys. J.* **966**, L38 (2024).
- [4] <https://score.cps.iau.org/search>.
- [5] S. Karpov and G. Beskin, Mini-megatortora photometric survey of the northern sky, in *Astronomy at the Epoch of Multimessenger Studies* (2022) pp. 156–156.



Nature submission: ID: 2025-04-08231

Dr. Alejandro S. Borlaff - NASA Ames Research Center
Moffett Field Air Base - N245-6, 94035. CA, USA.

Original title:

One million satellites in the sky: Light contamination on space telescopes

August 22th, 2025

Dear Editor,

We submit the reviewed manuscript for its final editor revision. In this letter, we answer point-by-point to all the requests from the editorial office (Sec. 1), and the referees (Sec. 2). We would like to appreciate the work of the editorial office during the revision process. It is a true privilege to be in position to publish our research at *Nature*. On behalf of all the coauthors, thank you very much.

As an additional note, NASA Communications Office (OCOMM) would like to coordinate with *Nature's* editorial office for a potential press release at the time of publication. Our point of contact on NASA OCOMM is Aaron McKinnon (aaron.mckinnon@nasa.gov).

Below, we detail all the answers from the editor **in blue**, followed by our answers in black font.

1. Editor's comments

8th August 2025

Dear Dr Borlaff,

Your manuscript, "One million satellites in the sky: Light contamination on space telescopes", has now been seen by our referees, whose comments are attached below. In the light of their advice I am delighted to say that we can in principle offer to publish it. First, however, we will need you to revise your paper to address the points made by the referees, and to make some editorial changes to your paper so that it is as brief as possible and complies with our Guide to Authors (<https://www.nature.com/nature/for-authors>).

We thank the editor for their careful revision and detailed checklist for the final version of our manuscript. In this document we detail all the changes and checks performed for this final stage re-submission.

You will see that the reviewers caught several typos in the text, as well as tables and figures that are never cited. In addition, the article needs major reformatting to conform to the Nature style. We ask you to review the formatting guidelines below, including word/character limits for the title, abstract, main body and methods sections. Please also consider which figures and tables are best suited for Methods (as Extended Data objects) vs Supplementary Information; the latter is ideal for larger tables, but will not be typeset in the Nature style. I am happy to discuss this reformatting via a video call if you would find this helpful; please drop me an email if you'd like to schedule this.

We have corrected all the comments made by the referees below, and corrected several missing references to elements in the paper, including figures and tables, which have been corrected in the new version of the manuscript.

While I appreciate that the formatting guidelines below are extensive, reading and implementing them carefully at this stage is crucial to avoid delays further down the production pipeline.

We have addressed all the required changes as best as possible. If any further changes are required by the editorial office we will process them as soon as possible.

This journal strongly supports public availability of data and custom code. Please place the data and code used in your paper into a public data repository, or alternatively, present the data as Supplementary Information. If data and code can only be shared on request, please explain why in your data Availability Statement, and also in the correspondence with your editor. Please note that for some data types, deposition in a public repository is mandatory; more information on our data deposition policies and available repositories appears below.

If you need help with our data sharing policies or finding a suitable data repository, you should consider:

- Contacting Springer Nature's Research Data [Helpdesk](#) for advice. The helpdesk provides free advice on research data policies of funders, institutions and journals and on finding research data repositories.
- Finding a suitable [data repository](#) for your data from our recommended repository list. Where they are available, community specific repositories are preferred. Unstructured repositories are suitable alternatives if no structured public repositories exist.

Following the suggestions of the referees we created a Zenodo repository with the databases containing the properties of the individual satellite trails as well as the total statistics for the population of trails per observatory ([10.5281/zenodo.15707680](https://doi.org/10.5281/zenodo.15707680)) to facilitate further analyses by the community. The repository is currently accessible through request until the manuscript is released by Nature and it is referenced in the manuscript.

Regarding software, our manuscript does not use any software that has not been previously reported in a published research paper. Our work is based on an already published, open-source software named Skyfield. Skyfield (Rhodes 2019, 2019ascl.soft07024R) is a Python based software that computes positions for the stars, planets, and satellites in orbit around the Earth. Skyfield accepts Two Line Element datasets that define the position of satellites and telescopes, and allows to estimate the position on the satellites in the sky from the point of view of the telescope. This software is fully documented in its website (<https://rhodesmill.org/skyfield/>), their source code fully available (<https://github.com/skyfielders/python-skyfield/>) and it was published in the Astrophysics Source Code Library in 2019 (<http://ascl.net/1907.024>). The author of this software is not a collaborator or associate of our team, and they were not involved in the creation of the submitted manuscript.

TRANSPARENT PEER REVIEW: Nature uses a transparent peer review system for original research manuscripts. We encourage increased transparency in peer review by publishing the reviewer comments, author rebuttal letters and editorial decision letters. Such peer review material is made available as a supplementary peer review file.

Please note: we allow redactions to authors' rebuttal and reviewer comments in the interest of confidentiality. If you are concerned about the release of confidential data, please let us know specifically what information you would like to have removed. Please note that we cannot incorporate redactions for any other reasons. Reviewer names will be published in the peer review files if the reviewer signed the comments to authors, or if reviewers explicitly agree to release their name. For more information, please refer to our [FAQ page](#).

We agree with Nature's transparent peer review system.

ORCID: **IMPORTANT:** All authors identified as 'corresponding author' on the manuscript must have an ORCID associated with their Nature account before submitting the final version of the manuscript. While non-corresponding authors do not have to link their ORCIDs, they are encouraged to do so. Please note that it will NOT be possible to add/modify ORCIDs at the proof stage. Thus, if they wish to have their

ORCID added to the paper they must follow the above procedure prior to acceptance. If you have any issues attaching an ORCID identifier to your MTS account, please contact the [Platform Support Helpdesk](#).

The only corresponding author in this manuscript (Alejandro S. Borlaff) has his ORCID ID associated with their *Nature* account [[0000-0003-3249-4431](#)]

LENGTH: The main text should be no more than ~2000 words and 4 modest display items; 1 display equivalent to ~250 words and refers to both figures and tables. Keep in mind that important technical details that are not central to the main message of the paper can be moved into the Methods section or, if necessary, a Supplementary Information section (see below).

The current version of the manuscript follows the Editor's recommendation of submitting it as a Long (8-page) Article. Our current version of the manuscript complies with the limits for number of words in the main text and number of display items.

TITLES: Titles cannot exceed 75 characters (including spaces); they must not contain punctuation.

Thank you for this correction. Following the suggestions from our co-authors and the editor, we decided that the new title of our manuscript will be:

Satellite megaconstellations will threaten space-based astronomy

which is within the limits and specifications for *Nature*. We hope that the change is acceptable.

SUMMARY PARAGRAPH: All *Nature* papers begin with a fully referenced paragraph, typically no longer than 200 words, aimed at readers in other disciplines. This paragraph starts with a 2- to 3-sentence, basic introduction to the field; continues with a 1-sentence statement of the main findings starting 'Here we show' or an equivalent phrase; and finally, concludes with 2 to 3 sentences putting the main findings into general context so it is clear how the results described in the paper have moved the field forward. A downloadable, annotated example is available at <https://www.nature.com/nature/for-authors/formatting-guide>. In some cases it may be necessary to exceed this limit in order to explain complex material for readers in other fields – in such cases, summary paragraphs can be up to 230 words in length. The extra length, however, is for introduction and context, and not for additional technical information.

The summary paragraph (abstract) complies with *Nature*'s guidelines. Its current length is 199 words. We used the annotated example as a support material.

MAIN TEXT: Further introductory material in the main text of the paper should not be necessary. Any discussion at the end of the paper should also be brief, and not repeat what is already written in the initial summary paragraph. Subheadings of up to 40 characters (including spaces) may be used to separate sections of the paper if this aids navigation. Nested subheadings are not permitted.

The current version of the manuscript contains 3184 words in the main text and 5 display items. This is within the limits for a 8-page long article (<4300 words of text and, additionally, 5-6 modest display items). We reviewed and made sure to avoid repeated information across the manuscript. All the subheadings comply with the 40 character limit. No nested subheadings were applied.

METHODS: At the end of the main text document (after the main figure legends), there should be a section entitled "Methods", which provides a more detailed discussion of the additional methodological information that would allow other researchers to replicate the results (we define "Methods" quite broadly, so this is not limited to details of experimental protocols – supplementary discussion and analysis can also be included). The Methods section will not appear in the print version but will be fully copy-edited and appear online in the full-text HTML and PDF versions.

The Methods section should be written as concisely as possible but should contain all elements necessary to allow interpretation and reproduction of the results. If there are additional references in the Methods section, their numbering should continue from the last reference in the main paper, and the list should follow the Methods section. If the methods require chemical structures, figures or tables, these should be supplied as Extended Data (see below). The section can be up to ~3000 words long and include up to ten Extended Data items.

For mathematically complex methods, or methods that require an unusually large number of figures or tables (beyond what can be accommodated as Extended Data), the entire Methods section should instead be supplied as a separate Supplementary Information.

We have reorganized the distribution of the manuscript according to the Nature formatting guide. In particular:

- Main text and Methods are now strictly separated.
- All Main text figures appear at the end of Main text, before Methods.
- Figure 5, previously part of Methods, has been moved to Extended Data as requested.

- Supplementary information, which previously contained a single paragraph with the DOI of Hubble Space Telescope observations, has been merged into Extended Data as requested.

Note: Subheadings in Extended Data are for organizational purposes only, not intended to be displayed in the formatted manuscript if the Nature format does not allow it to.

REFERENCES: As a guideline, most papers should need no more than 50 references in the main text; additional references can be cited in (and listed after) the Methods section, as detailed above.

Our manuscript complies with the limits for references as required. The main text contains exactly 50 references. Methods adds two more references, included at the end of the list, as requested.

MAIN TEXT STATEMENTS: We require authors to provide a detailed Author Contribution statement immediately after the acknowledgements; the specific contributions of each author must be listed. It is also a condition of publication that authors include an Author Information statement indicating how to access information regarding reprints and permissions, stating whether or not there is a financial or non-financial competing interest, and naming the author to whom correspondence and requests for materials should be addressed. Please ensure that this section is included in the manuscript file after the Methods (but before the Extended Data legends) - it will not appear in the print version but will appear online in the full-text HTML and PDF versions. For details of "end note" style and an example see <https://www.nature.com/nature/for-authors/formatting-guide>.

These requested statements are included in this version of the manuscript.

DATA AVAILABILITY STATEMENT: All Nature papers must now include a separate Data Availability Statement (DAS) after the Methods section (and any associated Methods references), and before the Extended Data legends. A detailed document outlining the data availability policy, containing various DAS examples that authors may use or modify can be found at: <https://www.nature.com/documents/nr-data-availability-statements-data-citations.pdf>.

The submitted version of the manuscript contains the requested Data Availability Statement.

For all studies using custom code or a mathematical algorithm deemed central to the conclusions, a statement must be included under the heading "Code availability", indicating whether and how the code or algorithm can be accessed, including any restrictions to access. This does not apply to standard data reduction or processing

software (which should be named), but it does apply to anything that has been modelled. More information can be found at <https://www.nature.com/authors/policies/availability.html#code>.

The submitted version of the manuscript contains the requested Code Availability Statement.

Nature's preferred approach to sharing research data is via public repositories (<http://www.nature.com/authors/policies/availability.html#data>), but when this is not possible a DAS should include, at a minimum, a statement confirming that all relevant data are available from the authors and/or are included with the manuscript (e.g. as source data or Supplementary Information). The statement must list which data are included (e.g. by figure panels and data types) and mention any restrictions on availability. If a dataset generated or analysed during the study is publicly available and already has a unique Digital Object Identifier (DOI), we strongly encourage authors to include this in the reference list and to cite the dataset in the Methods. Certain statements that previously would be found in the Author Information section (e.g. accession numbers for any newly determined sequences, structures, microarray or zoobank data; project IDs for MG-RAST data; accession numbers for X-ray crystallographic coordinates and structure factor files, or comparable NMR or cryoEM data) should now be included only in the DAS.

Following the suggestion of the referees and the editor we created a Zenodo repository with the databases containing the properties of the satellite trails (10.5281/zenodo.15707680) to facilitate further analysis by the community. The Zenodo DOI is specified in the DAS as requested.

FIGURE LEGENDS: These should be listed sequentially after the references in the main text and not in the figures files. Each legend should begin with a brief title for the whole figure and continue with a short description of each panel and the symbols used. Any error bars in the figures must be defined (for example, s.d., s.e.m.) and the value of n indicated; see <https://www.nature.com/nature/for-authors/formatting-guide> for further explanation.

The Figure legends are displayed as requested in the current version of the manuscript.

DISPLAY ITEMS: We ask that you take stock of all the data that have been generated throughout the review process and ensure that only the data most central to the conclusions are presented in the main figures. Figures should be comprehensible to readers in other or related disciplines, and assist their understanding of the paper. We encourage authors who are describing complex processes to include a schematic of the main finding as part of the Extended Data to aid readers unfamiliar with the immediate discipline. Figures should be as small and simple as is compatible with

clarity. All panels of a figure should be logically connected; each panel of a multipart figure should be sized so that the whole figure can be reduced by the same amount and reproduced on the printed page at the smallest size at which essential details are visible. For guidance, Nature's standard figure sizes are 89 mm (one column), 120 mm (one and a half columns), or exceptionally 183 mm (two columns) wide; the full depth of a Nature page is 247 mm. All panels of figures should be presented on a single page and assembled into a rectangular shape for publication; please indicate any essential alignments (parts horizontal, vertical, spacings of stereo pairs, etc.). Tables should be prepared using the Table menu in Microsoft Word.

We agree with the conditions for the display items. We are providing the manuscript in LaTeX format, which allows to automatically resize each image to the required size. Each individual figure file has been uploaded with the TeX file, for processing. All our figures are currently formatted to be displayed in two columns wide or one at a half columns. Please let us know if that is not advisable for some of them, and we will adapt as requested.

THIRD PARTY RIGHTS: You must provide proof that you have secured permission to use any third party materials that appear in any part of your manuscript, including extended data and supplementary information. Please fill out a [Third Party Rights Table](#), and upload this to our manuscript tracking system with the final version of your manuscript. Third party materials include any figures, tables, images, videos or text boxes that are reproductions or adaptations of items that have previously been published elsewhere and/or are owned by a third party. This includes pictures taken by professional photographers, maps and images downloaded from the internet. You will need to obtain the right to use each of these items before your paper can be accepted for publication. You will also need to give proper attribution to the copyright holders in your paper. Please ensure you upload any necessary grants of rights alongside the final version of your manuscript. More information is available on our [Rights and permissions page](#).

Our manuscript does not feature any figures or materials from third parties. We still provide a Third Party Rights table (empty) to acknowledge that.

COVER ARTWORK: We welcome submissions of artwork for consideration for our cover. More information can be found in our [guide for cover artwork](#). The file name(s) should include the manuscript reference number and be labelled as a cover suggestion; a short description is also preferred. Illustrations should be selected more for their aesthetic appeal than for their scientific content. We cannot promise that your suggestions will be selected for the cover, as competition is intense.

We would like to suggest one of our figures as Cover Artwork (see below). This image represents the projected contamination by satellite trails in one of the future space

telescopes considered in our article. This exposure summarizes the whole article in one single snapshot: the stripes of light reflected from artificial telecommunication satellites pollute the otherwise pristine image of two galaxies interacting in the background, hindering the potential discoveries that might lie below. The parallel, repeated structure of the satellite trails transmits clearly the artificial, human-made origin of the emission, in contrast with the natural complexity of the astronomical sources. This image represents an average example of the contamination levels that future space telescopes might suffer if the proposed telecommunication constellations become operational.

From a technical perspective, the proposed cover image provides sufficient space for *Nature's* coverlines, logos, and margins. As part of our work, we generated several hundreds of these images, allowing us for adaptations if requested by the cover editors. These images were generated in the uncompressed astronomical format (FITS), and are provided with this manuscript in the requested Adobe Photoshop PSD format, allowing to adjust brightness, contrast or saturation levels as required.

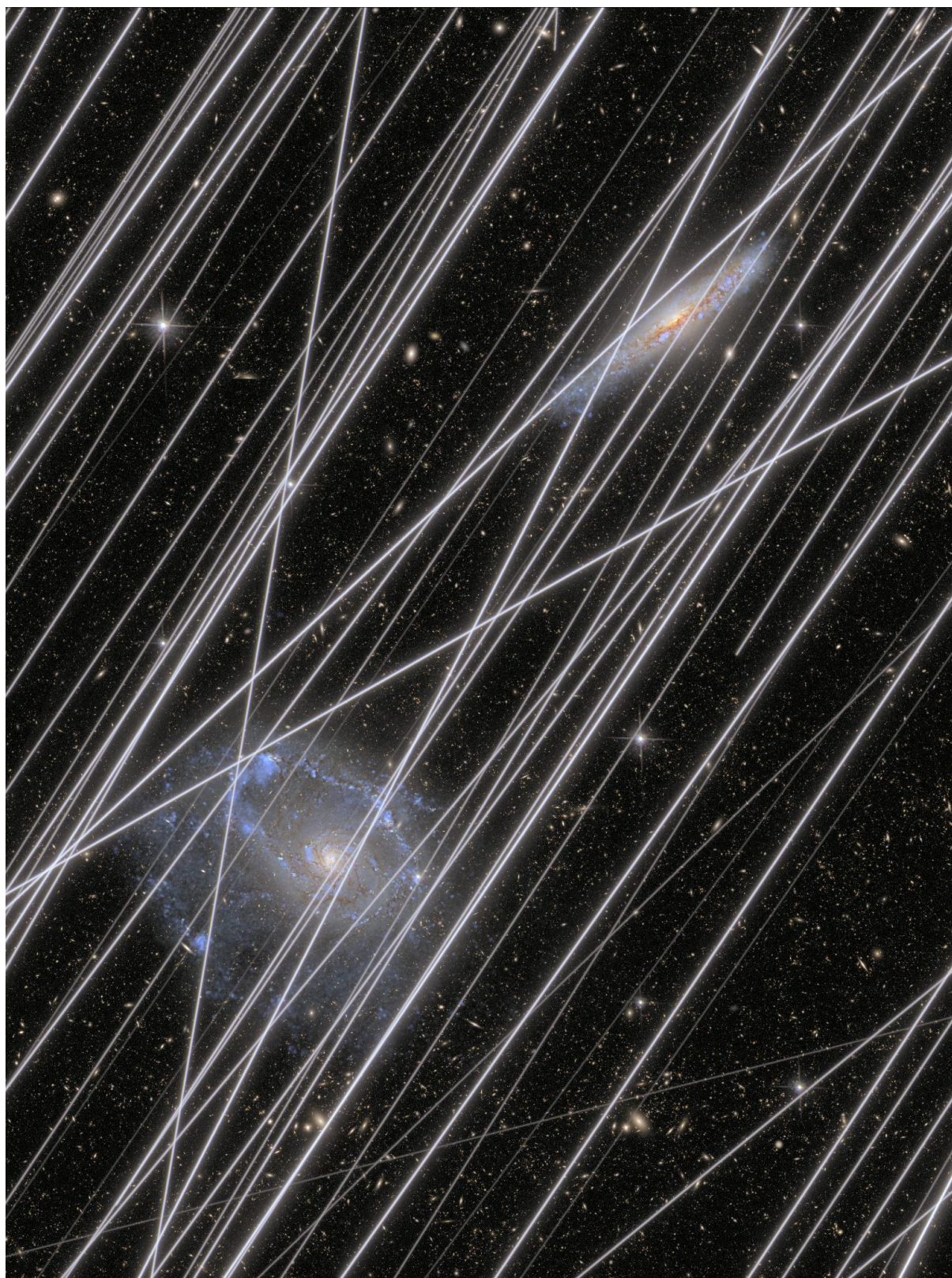


FIGURE FORMATTING: Lettering in all figures (labelling of axes and so on) should be in uniform, sans-serif font, in lower-case type, and large enough to permit substantial reduction for publication (minimum font size 5 pt). Separate parts of a figure are labelled a, b, etc. Units have a single space between the number and the unit, and follow SI nomenclature or the nomenclature common to a particular field. Thousands are separated by commas (1,000). Unusual units or abbreviations are defined in the legend. Scale bars rather than magnification factors should be used.

We have adapted our figures according to this format. In particular:

- We ensured that all figures use sans-serif lower-case type font.
- We included abcd labels in Figure 2 in the Main Text.
- Figures 7, 8, 9, 10, and 11 in Extended Data now have been combined into a single file with a multipanel figure, labeled accordingly. Their captions have been modified as needed.

IMAGE PRESENTATION: Authors should be aware that any image provided for publication, either in print or online (as Extended Data or Supplemental Information), may be subject to a quality control process to check for image integrity and manipulation. For a full discussion of our standards regarding how images should be prepared and presented, see www.nature.com/authors/editorial_policies/image.html.

We agree with all the image requirements from *Nature* journal.

EXTENDED DATA: Nature integrates the supplemental figures and tables into the final version of most papers. Extended Data do not appear in the printed version of the paper but are included online within the full-text HTML and at the end of the online PDF. Extended Data are an integral part of the paper and only data that directly contribute to the main message should be presented. All Extended Data must be referred to in the main text, figure legends and/or Methods section, and their figure legends should be listed sequentially at the end of the main text, not in the Extended Data files. Authors should assemble the Extended Data into a maximum of ten, A4 size, multi-panelled display items, submitted as individual JPEG, TIFF or EPS files. They must be provided at the same quality as figures for print, but there are important differences in their formatting. More specific instructions are provided in the Extended Data Formatting Guide (http://s3-service-broker-live-19ea8b98-4d41-4cb4-be4c-d68f4963b7dd.s3.amazonaws.com/uploads/ckeditor/attachments/7823/3h_Extended_data.pdf).

We made sure to follow all the recommendations detailed in the Extended Data Formatting Guide as requested to the best of our capabilities. All figures are provided independently for compilation with the attached TeX file.

SUPPLEMENTARY INFORMATION: Supplementary Information is online-only material published with the manuscript (<https://www.nature.com/nature/for-authors/supp-info>). For most papers, there should be no need for Supplementary Information beyond that already provided as Methods and Extended Data, the aim being to avoid unnecessary fragmentation of the paper online. Exceptions to this rule include large datasets that cannot be accommodated within Extended Data; video material; and more complex “Supplemental Methods” (and any associated references) that do not readily fit within the constraints of the Methods/Extended Data formats. Please note that after the paper has been formally accepted you can only provide amended Supplementary Information files for critical changes to the scientific content, not for style. You should clearly explain what changes have been made if you do resupply any such files.

No supplementary information is needed for this article beyond the figures and tables provided in Extended Data and the published Zenodo database.

SOURCE DATA: To further increase transparency, we encourage authors to provide, in spreadsheet form, the data underlying the graphical representations used in the figures. This is in addition to our well-established data-deposition policy for specific types of experiments and large datasets. Readers of the online manuscript will be able to access the Source Data directly from the figure legend. Spreadsheets can only be submitted in .xls, .xlsx or .csv formats. One file per figure is permitted; thus, if there is a multi-panelled figure the Source Data for each panel should be clearly labeled in the csv/Excel file; alternatively the data for a figure can be included in multiple, clearly labeled sheets within an Excel file. File sizes of up to 30 MB are permitted; however, it is expected that the vast majority of Source Data files will be considerably smaller than this. When submitting these files with your manuscript, please select the file type “Source Data” and use the title field in the file description tab to indicate the figure to which the Source Data pertain.

In addition to the datasets already available in the Zenodo, we have updated this public database with two additional tables ([ntrails vs nsats table.csv](#) and [mu vs wave.csv](#)) containing the processed data needed to reproduce Figures 3 and 4 of the final version of the manuscript, this is, the average number of satellite trails per telescope, number of satellites, and the surface brightness per wavelength per observatory, including the corresponding uncertainties.

We will not send your revised paper for further review. If the revised paper is in Nature format (as detailed above), in accessible style and of appropriate length, we shall start the acceptance process immediately.

In order to accept your paper, we shall need the following electronic files:

- * A cover letter describing your response to any editorial comments and detailing any format changes during revision, particularly if the overall length is affected.

Our answer to all editorial comments is provided in the present document. The overall length was not affected.

* A point-by-point response to any remaining issues raised by our referees (a word document is preferred).

The answer to the remaining comments from the referees is included at the end of the present document.

* The final version of your text as a Word document (Word Equation Editor/MathType should be used only for formulae that cannot be produced using normal text or Symbol font). If this is not possible, please provide the manuscript as a single plain vanilla TeX or LaTeX file that includes all references and abbreviations, with no special formatting, as well as a PDF version that is uploaded as a 'related manuscript file'.

We provide our reformatted version of the manuscript in LaTeX, including a copy in PDF of the rendered document. Please let us know if there is any additional information required regarding the TeX version.

* Production-quality versions of all figures (for details see http://s3-service-broker-live-19ea8b98-4d41-4cb4-be4c-d68f4963b7dd.s3.amazonaws.com/uploads/ckeditor/attachments/7822/3c_Final_art_work.pdf). As we need to be able to edit the figures so that they conform to our house style, the submission of files that are incorrectly formatted, flattened, or of insufficient resolution may delay final acceptance of your manuscript.

* The final version of any Extended Data; this should be presented as individual JPEG, TIFF or EPS files.

We have reviewed and carefully adapted all the figures following the Nature style guidelines. We placed particular care in reformatting all the figures to the file types required for each section, at the requested quality level. We applied all the rules regarding resolution, font and line sizes. We hope that the manuscript and the attached figures comply accordingly.

* The final version of any Supplementary Information; this should be presented as one file if feasible, ideally a PDF.

A rendered version of the TeX file is provided with this submission.

* The Source Data, if provided.

Source Data has been made publicly available through the associated Zenodo with this publication ([10.5281/zenodo.15707680](https://doi.org/10.5281/zenodo.15707680)). Please let us know if additional copies are required.

* For optimal quality videos please use a H.264 encoding and the standard aspect ratio of 16:9 (4:3 is second best), and do not compress the video. Videos will be rendered using the Brightcove platform; for additional source file recommendations and specification please refer to this page: <https://support.brightcove.com/video-source-file-specifications-and-recommendations>.

* Completed and signed copy of the manuscript checklist (<https://www.nature.com/documents/nature-manuscript-checklist-research.pdf>).

We have completed and attached a copy of the manuscript checklist.

* Completed and signed copy of the AOP (ahead of print) publication form (http://s3-service-broker-live-19ea8b98-4d41-4cb4-be4c-d68f4963b7dd.s3.amazonaws.com/uploads/ckeditor/attachments/7790/AOP_May_2013.pdf).

We have attached a signed copy of the AOP publication form.

* Completed and signed copy of the colour charge form (<https://www.nature.com/documents/nature-colour-figure-form.pdf>). Nature requests that authors of accepted manuscripts contribute towards the total cost of reproduction of colour figures in print.

We have attached a signed and completed copy of the colour charge form.

NOTE: These last three forms should be uploaded as scanned PDFs as a separate attachment, by choosing the file type 'Related Manuscript File'.

We provide the three scanned documents as requested.

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Nature Portfolio journals [encourage authors to share their step-by-step experimental protocols](#) on a protocol sharing platform of their choice.

We hope to hear from you within two weeks; please let us know if the process may take longer.

Yours sincerely,

Dr Urmila Chadayammuri
Associate Editor
Nature.

2. Referees' final comments:

Referee #1 (Remarks to the Author):

Many thanks for the detailed replies to all of my comments. All fine on my side: all my questions and doubts are addressed. The new version is even clearer and more compelling than the original.

Olivier Hainaut, ESO (ohainaut@eso.org)

Some additional comments that do not require reply:

- the revision of the surface brightness is an impressive piece of work. But indeed, it has little effect on the detectability and corresponding statistics. The Earthshine contribution is an important result -until now, it was (naively?) considered negligible.

We thank the referee for their kind words and revision. The addition of Earthshine was indeed an important effect that certainly made the publication substantially more complete and accurate to the real situation. On behalf of our team, thank you for pointing this effect out.

- thank you for the new Table 1

- Thank you for Section 5.1. A typo at l.477: " the brightness of the satellite trails as a function of the distance to the satellite and the trail width (Fig. 8). " --> Fig.9.

Corrected in the new version of the manuscript.

- Fig.2: excellent idea to put the data on Zenodo.

Referee #2 (Remarks to the Author):

Thank you for incorporating significant changes into the manuscript based on comments from all the referees. Thank you especially for creating a Zenodo data repository to go along with the paper.

During the review process, two new relevant papers have come out (as preprints), which you might consider referencing: <https://arxiv.org/abs/2505.06424v1> and <https://arxiv.org/abs/2506.19092v1>. I recognize you are at the 50 reference limit/guideline for Nature, but I note this doesn't apply to Supplementary Information.

Thank you for these very relevant references. We have included them as part of the supporting material in Section 5.1.

There is a typo in footnote 14 (Section 4), SatCheker -> SatChecker.

Thanks for spotting this typo, we have corrected it in the new version.

I stand by my original remarks that the paper is overall original, significant, and worthy of publication. The treatment of uncertainties appears sound, and while I do wish the authors would publish tools to enable the community to test their own preferred assumptions (e.g., effective size and albedo), I recognize this is a computationally expensive request and not strictly required for publication.

I have no further suggested revisions.

Additional Comments (no response needed):

I had not fully appreciated that the single Starlink 1619 observation is the only publicly ID'd satellite in the Hubble archive. Thank you for digging further into this and clarifying that this single data point is useful as a reality check, not as a basis for the simulated brightness distribution.

Thank you for your thorough response to the point about Starlink darkening mitigations vs actual observed brightnesses, and the extremely humbling illustration of how huge satellites can still appear bright (especially in near-IR!) even when they are not illuminated by the Sun.

Comparing forecast pixel loss fractions to Hubble's 5% cosmic ray loss fraction is a very good way to put things in perspective.

Referee #4 (Remarks to the Author):

I co-reviewed this manuscript with one of the reviewers who provided the listed reports.

We thank all the referees for their kind comments. Their careful revision improved this article significantly.