Crowded Orbits, Fading Skies: A Policy Framework for Satellite Mega-Constellations

A Technical Policy Brief for FCC and International Regulators

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Abstract

Low Earth orbit is approaching a scale that current regulatory and international-governance frameworks were never designed to manage. Over 1.7 million satellites are now proposed across live filings with the US Federal Communications Commission (FCC), dominated by SpaceX's application for a roughly one-million-satellite orbital data-centre constellation and Reflect Orbital's proposal for up to 50,000 large mirror satellites designed to reflect sunlight to the ground at night. A growing, methodologically independent body of peer-reviewed research, spanning ground-based astronomy, space-based astronomy, empirical archival analysis, and atmospheric chemistry, has converged on the conclusion that unmanaged growth of this kind degrades astronomical capability and carries environmental costs that current licensing processes do not price. The most recent and policy-relevant contribution to that literature is a European Southern Observatory (ESO) study, led by astronomer Olivier Hainaut and accepted for publication in Astronomy & Astrophysics, which proposes a cumulative population ceiling of approximately 100,000 satellites conditional on each remaining fainter than visual magnitude 7. This paper surveys that wider evidence base, sets out the underlying photometric and observational physics, details the technical specifications of both pending applications, and examines the regulatory pathway and its documented gaps, notably around the National Environmental Policy Act, and the international governance vacuum surrounding optical brightness and orbital debris. It closes with a set of policy options and recommendations addressed to regulators, operators, and institutions engaged in space-economy research and policy.

Keywords: *satellite mega-constellations, light pollution, dark and quiet skies, FCC licensing, NEPA, orbital debris, space governance, space economy*

Executive Summary

The problem. Over 1.7 million satellites are now proposed across current FCC filings, dominated by SpaceX's roughly one-million-satellite orbital data-centre constellation and Reflect Orbital's 50,000-satellite mirror system. A growing body of independent peer-reviewed research across ground-based astronomy, space-based astronomy, and atmospheric chemistry has converged on the conclusion that unmanaged growth at this scale is incompatible with current astronomical capability and environmental practice. The most concrete policy figure to emerge from that literature, from a recent ESO study, is that a cumulative population of roughly 100,000 satellites is the approximate limit compatible with existing ground-based astronomy, and only if every satellite stays fainter than naked-eye visibility (magnitude 7); brightness and population are not independent variables, so a numeric cap alone, or a brightness rule alone, is insufficient.

The stakes. Both applications are under active FCC review with no fixed decision date. The US Government Accountability Office has already found that the FCC has never documented why large constellations are categorically excluded from environmental review, yet the FCC's current rulemaking is moving to narrow, not expand, that review. No international body has binding authority over optical brightness or orbital debris, so a protective US decision would not by itself constrain equivalent systems licensed elsewhere.

What this brief recommends. (1) The FCC should adopt a cumulative, cross-operator ceiling that links total satellite population to brightness, rather than treating the two as separable licensing criteria. (2) The FCC should close the undocumented NEPA categorical exclusion for constellations above a defined scale, consistent with the GAO's 2022 recommendation. (3) Regulators and the astronomical community should pursue an international brightness and debris standard through COPUOS in parallel, since no single national decision can resolve a global commons problem. These map to Options A, B and D in Table 2, and are elaborated with full technical and legal support in the sections that follow.

1 Introduction

Low Earth orbit (LEO) has moved, within under a decade, from a comparatively sparse operational environment to one approaching saturation at certain altitudes. The number of active satellites has grown from a few hundred before 2019 to over 14,000 today, rising to approximately 32,000 once defunct satellites and tracked debris are included [1]. This growth has been driven overwhelmingly by SpaceX's Starlink constellation, but the pipeline of proposed future systems dwarfs what is currently in orbit: SpaceX's own filing for an additional approximately one million satellites, Reflect Orbital's mirror constellation, E-Space's Cinnamon constellation, and China's CTC-1 and CTC-2 systems collectively point toward an orbital population in the low millions within a decade [1].

This trajectory sits inside a space economy that the World Economic Forum, in partnership with McKinsey & Company, has forecast to grow from around \$630 billion in 2023 to \$1.8 trillion by 2035, roughly double the pace of global GDP growth [8, 25]. The commercial logic driving this growth (cheaper launch, falling satellite unit costs, and new demand sources such as orbital compute) is not in question. What is in question, and what this paper addresses, is whether the regulatory and international-governance architecture built for an earlier, much smaller orbital population is adequate to manage the externalities of its next order-of-magnitude expansion: light pollution and loss of astronomical capability, disruption to circadian biology and nocturnal ecosystems, orbital debris and collision risk, and atmospheric effects from launch and re-entry.

The paper is structured to serve two audiences at once: a technical audience that needs the underlying photometry and instrument-level detail, and a policy audience that needs the regulatory posture and the decision points ahead. Section 2 sets out the physics of satellite brightness and sky background. Section 3 surveys the wider peer-reviewed evidence base, of which the ESO study discussed throughout this brief is one recent and policy-relevant contribution among several. Section 4 profiles the two applications driving the current FCC decision. Section 5 covers the regulatory and international-legal framework. Section 6 surveys the non-astronomical externalities. Sections 7 to 9 set out stakeholder positions, policy options, and recommendations.

2 Technical Basis for Regulation: How Satellites Degrade Astronomical Observations

2.1 The magnitude system and naked-eye visibility

Astronomical brightness is measured on the visual magnitude scale, a logarithmic system in which lower (and negative) numbers indicate brighter objects; each step of 5 magnitudes corresponds to a factor of 100 in brightness, following the convention formalised by Pogson in 1856 [26]. The threshold for naked-eye visibility under good dark-sky conditions is approximately magnitude 6 to 7 [26]. The Hainaut study adopts magnitude 7 as the operative threshold: a satellite fainter than this will not saturate the detector of a camera such as Rubin Observatory's, and, not coincidentally, will also be invisible without optical aid from a pristine dark site [1]. This dual property, sub-detector-saturation and sub-naked-eye, is why magnitude 7 functions as a single, defensible regulatory threshold rather than two separate ones. Magnitude 7 is, therefore, not only a physical property of light but a natural candidate for a licensing benchmark: a regulator does not need to invent a bespoke brightness standard, since the astronomical community already has one that tracks both instrument and human visual impact.

2.2 Trail losses versus diffuse sky brightening

Two physically distinct mechanisms degrade astronomical data. The first is direct trail contamination: a sunlit satellite crossing a telescope's field of view during an exposure leaves a bright streak, destroying the scientific signal in the pixels it crosses and, for sufficiently bright or numerous satellites, in the surrounding pixels through detector saturation and bleed. The second, and the one the Hainaut study is the first to quantify comprehensively for this generation of proposals, is diffuse and scattered light: satellites too faint to register individually nonetheless contribute a cumulative veil of light, while brighter satellites scatter light through the atmosphere in all directions, both effects raising the overall background brightness of the night sky and reducing the signal-to-noise ratio for faint, extended, or low-surface-brightness targets across the entire field, not just along satellite tracks [1]. This distinction matters for policy because the two mechanisms respond to different mitigations: trail losses can, in principle, be partially managed through observation scheduling that avoids known satellite passes, but diffuse sky brightening cannot, since it is a property of the aggregate constellation rather than of any single satellite's track. A licensing regime that treats scheduling-based avoidance as sufficient mitigation, as some operator proposals have suggested, would leave the diffuse-brightening harm entirely unaddressed.

2.3 Instrument sensitivity is not uniform

The severity of impact depends heavily on instrument design. Wide-field, high-cadence survey instruments are disproportionately affected because they sample large areas of sky repeatedly through the twilight period when LEO satellites are most numerous and brightest. This is documented independently by Rubin Observatory's own impact assessments, which find that with a roughly 42,000-satellite constellation, up to 30% of Legacy Survey of Space and Time (LSST) images would contain at least one satellite trail, with twilight images (when time-domain science such as near-Earth asteroid detection is concentrated) almost universally affected [15, 16].

A related peer-reviewed modelling study by Hu and colleagues, simulating an earlier, roughly 40,000-satellite Starlink/OneWeb baseline, found that avoiding satellites in the LSST observing schedule could roughly halve the fraction of visits containing streaks, but only at a cost of sacrificing about 10% of total observing time, illustrating that scheduling mitigation carries a real opportunity cost rather than eliminating the problem [18]. An FCC decision that relies on operator-proposed scheduling mitigation as a substitute for a brightness or population limit therefore embeds a real scientific opportunity cost, one that ought to be made explicit in any environmental review rather than treated as a costless fix.

Rubin Observatory's own technical documentation adds a further, instrument-specific effect relevant to the mirror-satellite brightness findings discussed in Section 3: cameras with large, high-density CCD mosaics suffer electronic and optical "ghosting" when a sufficiently bright satellite crosses the field, producing secondary spurious trails beyond the primary streak and, in the worst case, rendering an entire image quadrant unusable rather than just the pixels the satellite physically crossed [1].

3 The Scientific Evidence Base: Convergent Findings Across Independent Studies

Concern about satellite mega-constellations is not new, and it does not rest on a single paper. Over the past five years, a growing, methodologically diverse body of peer-reviewed work, spanning ground-based astronomy, space-based astronomy, empirical archival analysis, and atmospheric chemistry, has arrived independently at the same qualitative conclusion: unmanaged constellation growth degrades astronomical capability and carries environmental costs that current licensing processes do not price. This section surveys that literature before turning, in Section 4, to the two specific applications now before the FCC.

3.1 Ground-based astronomical impacts

The most recent contribution to this literature is a study by ESO astronomer Olivier Hainaut, released by the European Southern Observatory on 1 July 2026 and accepted for publication in *Astronomy & Astrophysics* [1]. It simulates the cumulative effect of over 1.7 million currently proposed satellites on two reference instruments, ESO's VLT/FORS2 and a Rubin Observatory-class camera, and is notable chiefly for being among the earliest studies to model diffuse background-sky brightening in detail, in addition to direct trail losses. Its headline results include field-of-view losses of up to 28% for VLT-class instruments under SpaceX's proposed constellation, and a finding that Reflect Orbital's planned 50,000-mirror fleet could raise background sky brightness by a factor of three to four and render individual Rubin-class exposures unusable whenever the mirrors are sunlit [1]. The study's most policy-relevant contribution is not any single number but a structural point: brightness and population are substitutable within its model, so a regulator cannot treat a numeric satellite cap and a brightness standard as independent licensing criteria (Section 3.5 returns to this).

This work builds on, and is consistent with, an earlier 2021 report to ESO Council co-authored by Hainaut, which found that Rubin-class instruments could see an average of 5.7 satellite streaks per image, with peaks above 20 at twilight, under a considerably smaller constellation baseline than exists today [17]. It is also complemented by Lawler, Boley and Rein's *Visibility Predictions for Near-Future Satellite Megaconstellations*, published in *The Astronomical Journal* in 2022, which adds a geographic dimension the ESO study does not foreground: observers near 50 degrees latitude, a band that includes much of the United Kingdom, continental Europe and Canada, will experience disproportionately severe light pollution relative to lower-latitude sites such as Paranal, because of how constellation orbital inclinations distribute satellite density across latitude [33]. This is a material caveat for European and Canadian regulators, since the most widely cited impact figures are anchored to a Chile-based instrument.

3.2 Space-based astronomical impacts

A parallel and independently conducted line of research addresses telescopes in orbit rather than on the ground. Borlaff, Marcum and Howell's *Satellite megaconstellations will threaten space-based astronomy*, published in *Nature* on 3 December 2025, simulates the same underlying problem for the Hubble Space Telescope, NASA's SPHEREx, China's planned Xuntian telescope, and ESA's proposed ARRAKIHS mission, using the Planet4589 orbital-constellation database maintained by astronomer Jonathan McDowell [29, 30]. Under a projected constellation population of around 56,000 satellites by the end of the decade, broadly comparable in order of magnitude to the population figures discussed for ground-based instruments, the study finds that approximately 39.6% of Hubble images and up to 96% of images from the three newer, more sensitive instruments could be contaminated by satellite trails [31]. Like the ground-based literature, the authors propose mitigation through lower operational altitudes for constellations relative to space telescopes, which would render satellites several magnitudes fainter as seen from orbit [31].

This projection is not built on simulation alone. Kruk and colleagues' *The impact of satellite trails on Hubble Space Telescope observations*, published in *Nature Astronomy* in 2023, used a citizen-science project combined with a deep-learning classifier to scan two decades of Hubble archival images and found that 2.7% of exposures were crossed by satellite trails, with the affected fraction increasing over the period studied, establishing the empirical baseline against which Borlaff's projected growth is measured [32]. Read together, the two studies show observed, present-day contamination escalating toward simulated, near-future saturation, with the empirical starting point and the simulated trajectory independently sourced.

3.3 Systemic and atmospheric risk

A third strand of the literature treats megaconstellations as a multi-domain risk problem rather than an astronomy-specific one. Boley and Byers' widely cited *Satellite mega-constellations create risks in Low Earth Orbit, the atmosphere, and on Earth*, published in *Scientific Reports* in 2021, was among the first peer-reviewed papers to frame the issue this way, spanning collision risk, atmospheric effects, and ground-level consequences of re-entry debris [34]. Two more recent studies have since quantified one part of that framing directly: Ferreira and colleagues, in *Geophysical Research Letters* (2024), provided the first quantification of ozone-depleting pollutant release from megaconstellation satellite re-entry burn-up [35], and Barker and colleagues, in *Earth's Future* (2026), extended this into a full radiative-forcing and ozone-depletion assessment covering a decade of megaconstellation missions, finding that current megaconstellation-attributable ozone depletion remains small relative to surface sources, at roughly one-tenth of total depletion from all launch and re-entry activity, but on an upward trajectory driven by the same rapid re-entry cycling (satellites now typically deorbited after five, rather than twenty-five, years) that the applications discussed in Section 4 would accelerate [36].

3.4 Independent observational confirmation

A 2026 observational study from the Xinglong Observatory in China, using the National Astronomical Observatories' 80-cm telescope and the Mini-SiTian array, provides independent, non-Western empirical confirmation of the trend described above: the fraction of images affected by satellite trails rose from an average of 0.34% in 2019 to 0.7% in 2023 at the 80-cm telescope, and reached 19% at peak summer twilight conditions for the wider-field Mini-SiTian instrument, with the increase concentrated in twilight and summer observing windows [37]. This is a useful data point precisely because it comes from actual operational data at a facility with no institutional stake in the FCC proceedings, rather than from simulation by any of the parties involved.

3.5 Synthesis

Taken together, these seven studies, spanning ground-based and space-based astronomy, empirical archives and forward simulation, and atmospheric chemistry, move the operative policy question from "is there harm?" to "what level of harm is tolerable, and how should it be priced into licensing decisions?" No single paper carries this conclusion on its own; it is the convergence of methodologically independent groups, using different instruments, different constellations, and different modelling approaches, that makes the case difficult to dismiss as one contested study rather than an emerging consensus. Within that broader picture, the ESO study's proposed threshold, a combined ceiling of roughly 100,000 satellites conditional on each remaining fainter than magnitude 7, is, as of mid-2026, the single most concrete, policy-actionable figure to emerge from the literature, and it is used as a reference point throughout the remainder of this brief for that reason rather than because it is the only study that matters [1].

4 The Two Applications Driving the Current Decision

4.1 SpaceX Orbital Data Center System

On 30 January 2026, Space Exploration Holdings, LLC (SpaceX) filed an application with the FCC (ICFS File No. SAT-LOA-20260108-00016, Call Sign S00798) for authority to launch and operate a new non-geostationary orbit (NGSO) satellite system of up to one million satellites, described as the "SpaceX Orbital Data Center System" [10, 11]. The FCC's Space Bureau accepted the application for filing on 4 February 2026 (Public Notice DA 26-113), setting an initial comment deadline of 6 March 2026 [10].

The technical filing specifies operation at altitudes between 500 and 2,000 kilometres, across 30-degree and sun-synchronous orbital inclinations, in shells of up to 50 kilometres each, chosen specifically to maximise satellite time in continuous sunlight for solar power generation [10, 11]. The satellites are designed around high-bandwidth optical inter-satellite links for data routing, with Ka-band (18.3–19.3 GHz space-to-Earth; 28.6–29.1 GHz Earth-to-space) radio spectrum requested on a secondary, non-interference, unprotected basis for telemetry, tracking and command rather than as the primary data path [11]. SpaceX has requested several regulatory waivers alongside the core application: exemption from standard NGSO processing-round procedures, exemption from the standard deployment milestone requirement (ordinarily half the constellation within six years, the full system within nine), and exemption from the associated surety bond requirements, arguing that because the requested spectrum use is non-interference and unprotected, the milestone rules designed to prevent spectrum warehousing do not apply [11].

SpaceX frames the application in explicitly civilisational terms, describing the constellation in its filing narrative as a first step toward a Kardashev Type II-level capability to harness the Sun's energy output, and situates the commercial case around the growing mismatch between terrestrial data-centre power demand and grid capacity: contemporaneous reporting notes that the largest US grid operator serving the mid-Atlantic region projects a six-gigawatt reliability shortfall by 2027, and that a substantial share of planned AI data-centre capacity may be power-constrained by the same year [9]. The application followed, by only days, SpaceX's announced combination with xAI, and preceded a planned SpaceX IPO later in 2026 [9].

4.2 Reflect Orbital

Reflect Orbital, a US start-up, has applied to the FCC (File SAT-LOA-20250701-00129, filed 1 August 2025) for authority to test a demonstration satellite, Eärendil-1, at approximately 625 km altitude and 88-degree inclination, as the first step toward a constellation intended to reach 50,000 satellites by 2035 [7]. The stated commercial proposition, marketed as "sunlight on demand," is to use large mirrors (reported variously across filings and independent analysis as ranging from roughly 18 to 55 metres and in places up to 180 feet across) to redirect sunlight onto ground targets of at least five kilometres in diameter for a few minutes per pass, at intensities that early testing targets in the range of roughly 0.1 to 2.3 lux (comparable to or somewhat brighter than full moonlight), with a longer-term ambition of configurable illumination up to full daylight-equivalent levels (order 36,000 lux) to extend solar-power generation and provide emergency or urban lighting [3, 7].

Public comments on the Reflect Orbital application closed on 9 March 2026, drawing over 1,800 individual and organisational responses according to AAS and AIBS summaries of the docket as of that date, more than on almost any comparable FCC satellite filing then on record [1–3]. Reflect Orbital has stated publicly that environmental and astronomical concerns are being studied and will be addressed, but has not, as of this writing, published specific quantified mitigation commitments [4, 5].

5 Regulatory and International Legal Framework

5.1 The FCC licensing pathway

Both applications proceed through the FCC's Space Bureau under the agency's NGSO satellite licensing rules. The Bureau accepts an application for filing, opens a public comment period (typically around 30 days for petitions, with subsequent windows for responses and replies), and then determines whether to grant, condition, or deny the licence, taking into account whether the proposed system serves the public interest [2, 10]. As of this writing, neither application has received a final determination. Under standard welfare-economic interpretation, a public-interest determination of this kind requires weighing private commercial benefits against social costs; current licensing practice, however, treats most astronomical and ecological harms as unpriced externalities that do not formally enter the calculation. The quantitative thresholds established by the ESO study and the complementary literature reviewed in Section 3 provide, for the first time in this licensing context, a quantitative basis on which those externalities could be internalised into the public-interest test rather than left outside it.

5.2 The NEPA gap

A recurring and, in the astronomical and environmental community's view, decisive procedural weakness is how satellite licensing interacts with the National Environmental Policy Act (NEPA, 42 U.S.C. §4321 et seq.), which requires federal agencies to assess the environmental effects of major federal actions before approving them, absent an applicable categorical exclusion [12, 13]. A report by the US Government Accountability Office, published in November 2022, found that the FCC has, in practice, treated the licensing of large satellite constellations as categorically excluded from NEPA review, but had never formally reviewed or documented whether that exclusion remains appropriate given the scale of current proposals; GAO recommended that the FCC review and document the basis for the exclusion, establish a periodic review process, and publicly identify the factors it considers when assessing whether "extraordinary circumstances" should override the exclusion. The FCC agreed with these recommendations [12]. A subsequent FCC rulemaking (FCC 25-47, opened in 2025 following a January 2025 executive order on deregulation of environmental permitting) is considering how to codify environmental review of satellite licensing. NGO commenters and independent analysts have argued that, in practice, the proposals would narrow rather than broaden review, moving in the opposite direction from what they have requested [13, 14]. From a governance perspective, this represents a direct divergence between independent federal oversight, in the form of GAO's finding and recommendation, and the regulator's present rulemaking trajectory, and it is occurring at precisely the moment when constellation scales under review cross the thresholds this evidence base identifies as consequential.

In direct response to the Reflect Orbital application, Public Employees for Environmental Responsibility (PEER) and DarkSky International filed joint comments on 6 March 2026 arguing that the FCC should, at minimum, require an environmental assessment before granting a licence, on the basis that the proposal represents an unprecedented intervention in the natural night environment with plausible effects on protected wildlife, invoking consultation obligations under the Endangered Species Act with the US Fish and Wildlife Service and NOAA [5, 6]. The American Astronomical Society and 27 other scientific organisations, coordinated in part by the American Institute of Biological Sciences (AIBS), separately argued that the proposal does not meet the FCC's public interest test and should be denied outright or, at minimum, subjected to a full environmental impact assessment [2, 3].

5.3 International governance: treaty coverage and its limits

The foundational instrument of international space law, the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (the Outer Space Treaty), establishes that space is the province of all humankind, that it is free for exploration and use by all states, and that states bear international responsibility for the activities of their non-governmental entities in space, including a requirement of authorisation and continuing supervision [19, 20]. The treaty was opened for signature in 1967 and has 118 states parties as of late 2025 [21], but it was drafted before the commercial mega-constellation era and contains no provision addressing optical brightness, light pollution, or the cumulative environmental footprint of large constellations.

Two further bodies have partial, non-binding remits. The UN Committee on the Peaceful Uses of Outer Space (COPUOS), the primary multilateral forum for space governance, added the impact of large constellations on astronomy to a subcommittee's five-year agenda in 2024, and operates by consensus, producing guidelines rather than binding law [1, 28]. The International Telecommunication Union (ITU) coordinates radio-spectrum and orbital-slot allocation, and recently agreed to examine risks to radio-quiet zones over a three-year period, but its mandate does not extend to visible-light emissions [24, 28]. The IAU Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (IAU CPS), co-hosted by NSF NOIRLab and the SKA Observatory since 2022 and recently granted a further five-year mandate through March 2030, represents the astronomical community at COPUOS discussions and coordinates technical mitigation work, including US National Science Foundation-funded tools such as SatChecker for predicting satellite positions and brightness, but it is a coordination and advocacy body rather than a regulator with enforcement power [22–24].

The practical consequence, repeatedly flagged in the case-study literature on the Reflect Orbital and SpaceX filings, is that no international body currently has binding authority specifically over optical brightness or the cumulative debris footprint of large constellations, so there is no single global mechanism to prevent a mega-constellation or orbital mirror system licensed by a state outside US jurisdiction. In practice, national launch and licensing regimes can constrain operators, but they do so in a fragmented way rather than through a unified international standard. Even a maximally protective FCC decision on both pending applications would not, on its own, constrain functionally equivalent constellations licensed by other states, including China's planned CTC-1 and CTC-2 systems [1, 28].

6 Non-Astronomical Impacts Relevant to Environmental Review

6.1 Circadian and ecological effects

Independent of the astronomical case, DarkSky International's organisational statement on Reflect Orbital argues that orbital illumination systems fundamentally conflict with its Five Principles of Responsible Outdoor Lighting (necessary, targeted, low-level, controlled, and warm-coloured), and identifies specific risks to circadian biology in humans and animals and to nocturnal-navigation species [4]. The joint AIBS/AAS comments highlight that darkness is not a deficiency to be corrected but a functional ecological baseline that most terrestrial life, including migratory birds that navigate by starlight and coastal species such as sea turtle hatchlings that orient toward the brightest horizon at night, depends upon; the comments describe risks including altered metabolism and hormonal disruption from circadian interference [3].

6.2 Orbital debris and collision risk

DarkSky's statement separately flags orbital-debris hazards specific to large, thin-film mirror structures in LEO, which face elevated micro-impact and collision-generation risk given their size relative to conventional satellite buses, compounding an already congested orbital debris environment and raising the probability of cascading collision events of the kind first described theoretically by Kessler and Cour-Palais, in which debris density in a given orbital shell exceeds a critical threshold and collisions begin generating new debris faster than atmospheric drag can remove it [4, 27].

6.3 Atmospheric and re-entry effects

The ESO release itself flags, without quantifying, two further externalities squarely outside the FCC's astronomy-focused analytical frame: the atmospheric impact of a substantially higher launch cadence required to deploy and maintain constellations of hundreds of thousands to over a million satellites, and the atmospheric chemistry effects of routine satellite burn-up on re-entry at end of life, both noted as meriting assessment by researchers in the relevant fields rather than by astronomers [1]. These effects are structurally similar to the NEPA gap described in Section 5.2: they are real, plausible, and currently unassessed within the licensing process that will determine whether these constellations are built. Several of these harms also have path-dependent or effectively irreversible characteristics: an orbital debris cascade or a measurable step-change in stratospheric ozone depletion from mass re-entry cannot be readily reversed once triggered, in contrast to a licensing decision, which can in principle be revisited. This asymmetry strengthens the case for precautionary thresholds set before deployment, rather than reliance on ex post mitigation once harms are observed.

7 Stakeholder Positions

Table 1 summarises the principal stakeholder positions identified across the primary sources reviewed for this paper.

Stakeholder	Position	Regulatory leverage	Source
ESO / RAS / IAU	Cap total satellites at ∼100,000, conditional on sub-magnitude-7 brightness; formal technical submission to FCC on both filings	Technical evidence submitted directly into FCC comment record; no formal decision authority	[1]
American Astronomical Society	Coordinated public comment campaign; argues FCC public-interest test is not met by either application	Public comment standing; convenes coordinated multi-organisation filings	[2, 3]
DarkSky International	Opposes orbital illumination systems in principle; calls for NEPA-standard environmental review and voluntary independent EIA from Reflect Orbital	Formal FCC comment standing; ESA/FWS consultation advocacy	[4]
PEER	Joint formal comment with DarkSky requesting mandatory FCC environmental assessment before licensing	Legal standing to petition for environmental review; can pursue litigation	[5, 6]
AIBS + 27 science organisations	Warn of harm to scientific research, human health and ecosystems; request denial or full EIA	Public comment standing only; no enforcement power	[3]
US GAO	Found FCC has never documented the basis for its categorical NEPA exclusion for large constellations; recommended periodic review (FCC agreed)	Congressional oversight body; recommendations non-binding but carry institutional weight	[12]
SpaceX	Seeks fast-track approval and multiple milestone/spectrum-rule waivers; frames system as addressing terrestrial power constraints on AI compute	Applicant; can propose voluntary mitigation commitments	[9–11]
Reflect Orbital	States environmental and astronomical effects are being studied and will be mitigated; has not published quantified commitments	Applicant; can propose voluntary mitigation commitments	[4, 7]
IAU CPS / NOIRLab / SKAO	Coordinates technical mitigation tools (e.g. SatChecker) and represents astronomy at COPUOS; five-year mandate renewed to 2030	Technical coordination and COPUOS representation; no regulatory authority	[22–24]

Table 1: Stakeholder positions on the pending FCC applications, including the regulatory leverage each stakeholder actually holds.

8 Policy Options

Table 2 sets out five policy options available to regulators, ranging from a numeric brightness-linked cap through to conditional or staged licensing.

9 Recommendations

9.1 For the FCC and equivalent regulators

- Implement Option B by closing the categorical NEPA exclusion for constellations above a defined scale or brightness threshold, using the existing FCC 25-47 docket as the near-term vehicle rather than waiting for new rulemaking authority.
- Pursue Option A as a durable, cross-operator brightness-linked population ceiling informed

Option	Description	Trade-off	Timing feasibility
A. Numeric brightness-linked cap	Adopt Hainaut's ∼100,000-satellite ceiling, strictly conditional on sub-magnitude-7 brightness, as an explicit FCC licensing benchmark applied cumulatively across operators	Evidence-based and technically precise, but requires new rulemaking authority and a cross-operator tracking mechanism such as CPS's SatChecker tooling [24]	Multi-year: requires new FCC rulemaking
B. Mandatory environmental assessment	Close the categorical exclusion identified by GAO; require an EA or EIS for constellations above a defined scale or brightness threshold	Aligns satellite licensing with standard US federal environmental practice, but current FCC rulemaking (FCC 25-47) is moving toward narrower review [13]	Near-term: achievable within the existing FCC 25-47 docket
C. Brightness and design mitigation standards	Require darkening treatments, sunshades and orbital-attitude design choices as binding licence conditions, building on SpaceX's voluntary Starlink brightness reductions	Technically precedented and lower-cost than a hard population cap, but structurally inapplicable to Reflect Orbital, where visible brightness is the product itself	Near-term: can be attached as a condition to individual licence grants
D. International brightness/debris standard	Pursue a COPUOS guideline, or an ITU-adjacent mechanism extending beyond radio spectrum to optical brightness and orbital debris	Addresses jurisdictional arbitrage directly, but COPUOS operates by consensus and any instrument would likely take years and yield non-binding guidance	Long-term: 5–10 years via COPUOS consensus process
E. Conditional or staged licensing	Approve demonstration-scale deployment (e.g. Eärendil-1) while withholding full-constellation authorisation pending independent review and published mitigation data	Preserves the innovation and testing pathway while deferring the highest-scale, highest-risk decision until better data exists	Near-term: applicable to current pending applications
Preferred bundle	A realistic path is not any single option in isolation but a combination applied in parallel: Options B, C and E implemented now at FCC level on the current applications, with Option A pursued as a durable rulemaking once precedent exists, and Option D pursued simultaneously through COPUOS so that a protective US decision is not undermined by unconstrained deployment elsewhere.		

Table 2: Policy options for regulators, ranked by scope of intervention, with an assessment of how quickly each could realistically be implemented.

directly by the ESO study and the wider evidence base in Section 3, rather than reviewing each application purely in isolation against its own narrative.

- Apply Option C by making any brightness-mitigation commitments from operators, including Reflect Orbital, a binding, quantified condition of licence grant rather than a voluntary undertaking referenced only in comment responses.
- Use Option E for the current applications specifically: authorise demonstration-scale deployment (e.g. Eärendil-1) while withholding full-constellation approval pending independent environmental and astronomical review.

9.2 For satellite operators

- Publish quantified, independently verifiable brightness and mitigation data at the application stage, following the precedent SpaceX has already set with post-2020 Starlink darkening measures.
- For systems whose commercial function depends on visible brightness by design, such as Reflect Orbital's illumination service, treat brightness and beam geometry as binding design constraints from the outset (Options C and E combined), not as post-hoc mitigations negotiated after regulatory pressure.
- Engage directly and early with the astronomical, ecological and public-health research communities on siting, scheduling, beam geometry and total-population limits before scaling deployment.

9.3 For the astronomical and scientific-policy community

- Continue to supply quantitative, peer-reviewed evidence of the kind surveyed in Section 3 directly into national licensing processes, since the FCC's own procedural framework does not generate this evidence itself.
- Pursue Option D through parallel, sustained engagement with COPUOS and the ITU, using the IAU CPS as the coordinating body, to reduce the risk that a protective US decision on the current applications is undermined by unconstrained deployment of comparable systems from other launching states [22, 28].

9.4 For research and policy institutions engaged with the space economy

For university-based initiatives on the commercial and public value of orbital infrastructure, including the Space Economy Initiative at Cambridge Judge Business School, this case is a useful structural illustration rather than a peripheral controversy. The licensing and governance frameworks built for spectrum and orbital-slot allocation were not designed to price externalities such as optical brightness, ecological disruption, or atmospheric re-entry effects, and the growth trajectory of the sector, toward the WEF's projected $1.8 trillion by 2035, is now outpacing the frameworks meant to govern it [8, 25].

There is a clear research agenda here. Two methods look tractable in the near term: revealed-preference proxies, such as astro-tourism revenue and telescope-siting investment, that can approximate the economic value attached to dark-sky access; and ecosystem-service valuation methods, already established in environmental economics, that could be adapted to nocturnal ecosystems disrupted by orbital illumination. A further extension would treat the atmospheric and ozone-layer effects of launch and re-entry (Section 3.3) as a long-run cost analogous to the social cost of carbon, so that recurring re-entry emissions are priced on a comparable basis to other regulated atmospheric externalities. The aim in each case is the same: to let the FCC's public-interest determination, and any future international instrument, weigh both sides of the ledger on comparable terms, rather than treating astronomical and ecological costs as unpriced externalities outside the analysis.

10 Conclusion

The evidence surveyed in this paper, from ground-based and space-based astronomy, empirical archives, and atmospheric chemistry, converges on a single conclusion: satellite mega-constellation growth at the scale now proposed is incompatible with current astronomical capability and current environmental practice, absent deliberate intervention. That evidence arrives at the precise moment when two live regulatory decisions, on SpaceX's orbital data-centre filing and Reflect Orbital's mirror constellation, will materially determine whether the thresholds this literature identifies are respected or exceeded. The tension is structural rather than incidental: SpaceX's proposal is driven by a genuine and well-documented terrestrial power constraint on AI compute growth, and Reflect Orbital's commercial logic depends on brightness itself, while the scientific, ecological and cultural value of the night sky depends on darkness remaining the default state. The absence, documented in this paper, of a NEPA-standard environmental review pathway and of any binding international brightness or debris standard, means the decision now rests substantially on the FCC's discretionary weighing of public interest, informed by the roughly 3,300 public comments the two applications had together attracted as of March 2026, rather than on a settled legal or scientific framework designed for systems of this scale.

Three steps could realistically be taken within the next 12 to 24 months, without waiting for a multi-year rulemaking process: first, closing the NEPA categorical exclusion for large constellations within the existing FCC 25-47 docket (Option B); second, adopting a brightness-linked cumulative population ceiling as interim FCC licensing guidance, even ahead of formal rulemaking (Option A); and third, committing, through COPUOS, to begin developing a global brightness and debris standard so that a protective US decision is not undermined by unconstrained deployment elsewhere (Option D). How the FCC resolves the pending applications, and whether these parallel steps are taken, will likely set the template for how this tension is managed as the space economy continues its projected expansion toward $1.8 trillion by 2035.

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