The surface brightness of the trails of megaconstellation’s satellites on large telescopes

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Abstract

On large telescopes trails of MegaConstellation’s satellites will appears significantly defocused because of their relatively short distance. Because of such effect their apparent surface brightness will be, under a range of conditions, almost constant during their apparent sweeping on the focal plane of such large facilities. A few simple relationships are worked out and discussed to show the apparent brightness of such trails, in order to evaluate their impact on operations of large optical ground based facilities. Such considerations could be used as well to propose regulatory limits in order to make such effects small enough.

1 Introduction

MegaConstellations, especially on low orbits, are gaining more and more attention by the professional astronomical community for a number of potential concerns. Among these I consider here the potential disturbance to ground-based optical astronomical observations. It is likely that such attention has been mostly spread because of the way such satellites reach their intended final orbit. This is achieved through launch of a relatively large set of these satellites into a much lower altitude than the final intended one. The latter is then achieved through continuous, low impulse, maneuvering, other than Hohmann manoeuvres. By consequences in a relatively large time shift (days to weeks) shortly after the launch, satellites are much brighter and heavily clustered with respect to their nominal final position.

Further points of concern that are not being explored at all here are the increment of space debris hazard, or the potential radio interference with both heavenly or man-made deep space sources. Moreover, I will take the opportunity to express my very own opinion on the matter, most of the relationships and findings described in the following do not cover modest apertures, like most of the ones used in amateur astrophotography or naked eye observations.

More specifically, I am going to focus on the detail of the surface brightness on the focal plane of the trails produced by the passage in the field of view of
these satellites, while I will just briefly review, offering some point of view, on their density and likelihood to be recorded during astronomical observations. A much deeper estimation of the occurrence of such phenomenon can be found using statistical method (Heinaut & Williams, 2020) and through numerical simulations (McDowell, 2020). While several are the potential MegaConstellations, I will hereby use as a reference the StarLink MegaConstellation. I adapted the orbital data as depicted in the original FCC requests (FCC Report 2017, later amended by FCC Report 2020a, and a further request in FCC report 2020b) with some degree of approximation and grouping for the sake of readability of the present manuscript. The interested reader should consult the original documents for a detailed description of the MegaConstellation that here is just roughly depicted.

2 Numerosity

Satellites in MegaConstellations are usually placed in circular, or almost circular, orbits, characterized by an inclination indicated here with $\phi_{\text{max}}$ and an altitude of flying over the Earth surface of $h$, making their distance to the barycenter of the Earth equal to $R_\oplus + h$ (see also Fig.1). The aim of such MegaConstellation is, for example in case of providing full coverage for radio or data communication, to cover the Earth surface up to the latitude defined by $\phi_{\text{max}}$ rather than to cover the sky.

In general $h < R_\oplus$ (or at least this holds for the kind of satellites close enough to the ground to exhibits a significnt apparent brightness) and, through the development of the exact computation, this point is occasionally being addressed in order to get a first-order estimation of the dependence of various parameters from the altitude of flight of these satellites (or to the ratio $h/R_\oplus$) that, to the purpose of this work, are being considered as optical sources.

This means that, although the overall number $N$ of satellites into a single layer characterized by the quantities $(h, \phi_{\text{max}})$ can be considerably large, only a fraction of these will be, at a given time, visible from an observer on the ground. An even smaller fraction will be observable at a zenital distance smaller than $z_{\text{max}}$ (or, equivalently, to an elevation larger than $90^\circ - z_{\text{max}}$) and a further fraction will be actually illuminated by the Sun at a certain specific point of the night. Astronomical observations, in fact, are usually carried out at moderate airmasses, at the point that several large facilities are built in a manner that normally cannot observe below certain elevations (Dierickx & Gilmozzi 1999, ESO 2005, 2017, Huang 1996, Mansfield 1998, Ray 1992). In some cases Active Optics, a nowadays popular -almost mandatory approach- for large ground based single dish optical facilities, relying on the component of the weight orthogonal to the optical axis in order to work properly (Wilson et al. 1987) becomes unavailable when the telescope is looking too much away from the local zenith. Typically a $z = 60^\circ$, corresponding to 2 airmasses is a normal limit unless time constraints requires differently. A $z \approx 70.2^\circ$ corresponding to 3 airmasses can be often considered an hard limit. Further to the traditional effects of differ-
Figure 1: Around the globe, satellites flying on several circular orbits at altitude $h$, limited by a common inclination over the equator of $\phi_{\text{max}}$ are assumed to spread over such a surface, with a density given by the ratio of their number with respect to the potentially occupied surface. From a certain point $P$ on Earth, distant enough from the discontinuity in the edges of the occupied surface, the amount of satellites above the horizon can be computed using the cap’s surface $S_1$. Each satellite, however, has a related point on Earth where the object is currently seen at the local zenith. Alternatively, once identified the region on Earth where satellites are observed at an elevation larger than $90^\circ - z_{\text{max}}$ their numerosity can be estimated using the cap’s surface $S_2$.

With reference to Fig. 1 one can estimate the amount of observable satellites from a certain point on the ground by computing ratios of the surfaces where the satellites, or the points where such satellites are seen instantaneously at the local zenith lies. For instance the overall surface where satellites actually can fly is given by:

$$S = 4\pi (R_\oplus + h)^2 \sin \phi_{\text{max}}$$

while replacing in the above relationship $R_\oplus + h$ with just $R_\oplus$ makes the corresponding Earth’s surface from where a satellite could appear on the local zenith. Given a certain point $P$ on Earth that is located distant enough by the edges defined by $\phi_{\text{max}}$, the area of the orbital sphere where all the observable satellites in a given time can lie is characterized by the cap’s surface given by:
If \( N \) is the overall population of satellites covering the orbital sphere, the number \( n_1 \) of these, potentially visible from the observer \( P \), is given by the ratio of these surfaces, or in other words:

\[
n_1 = N \eta_1 = N \frac{S_1}{S} = \frac{N h}{2 \sin \phi_{\text{max}} R_{\oplus} + h} \approx \frac{N h}{2 \sin \phi_{\text{max}} R_{\oplus}}
\]

that also defines \( \eta_1 \) as the ratio between the observable by the overall number of satellites. Furthermore the last approximation in the equation is achieved using, as anticipated, \( h \ll R_{\oplus} \).

A different, and more pragmatic, approach can be used where one would limit only to satellites that have, as seen from \( P \) a zenithal distance not larger than \( z_{\text{max}} \). We immediately note that for a large number of reasonable values of \( z_{\text{max}} \) as discussed before, the fraction of satellites above a certain elevation are a minority, because the others populates the more distant annulus of the cap above \( P \), where, because of both a larger distance and a more oblique perspective, their apparent angular density as seen from \( P \) is larger. Using the concept of the surface of the area on the Earth where lie points at whose local zenith a satellite is occurring, one can find similarly:

\[
n_2 = N \eta_2 = N \frac{S_2}{4 \pi R_{\oplus}^2 \sin \phi_{\text{max}}} \approx \frac{N h^2 \tan^2 z_{\text{max}}}{2 \sin \phi_{\text{max}} R_{\oplus}^2}
\]

with the same kind of approximation, and an analogue implicit definition of \( \eta_2 \). It is worth to note that in this case, as long as \( h \times \tan z_{\text{max}} \ll R_{\oplus} \) holds, the first non-vanishing term is quadratic in the \( h/R_{\oplus} \) ratio, in contrast with the linear one devised for \( n_1 \) (and \( \eta_1 \)).

Furthermore, one should recall that, in order to interfere astronomical observations with additional light on the focal plane, the satellites must be illuminated by the Sun. While a detailed discussion and computation is carried out elsewhere we note here just the angle at which the Sun should be located below the horizon in order to illuminate a satellite flying at altitude \( h \) and crossing the local zenith, as given by:

\[
z_\odot = \arccos \frac{R_{\oplus}}{R_{\oplus} + h}
\]

If such a figure is equal to 18° (defining the astronomical twilight) it means that at the beginning or at the end of the astronomical night a satellite crossing the local zenith is just barely illuminated by the Sun. The actual amount of satellites illuminated by the Sun in this condition is not precisely half of the one potentially visible under such a condition, however a figure of \( z_\odot \) significantly less than 18° degrees indicates that only the satellites into a certain region toward the Sun direction are actually illuminated. In winter times the situation will rapidly evolve into a condition in which most if not all of the satellites are actually not illuminated at all, especially if considering only the ones close to
Table 1: A simplified list of the satellites indicated in FCC Report 2020a are indicated in this table. In Italic are included a second generation group of satellites described in FCC Report 2020b, while a former layer at $h \approx 1100$ km, originally included in the FCC Report 2017 is reported for comparative purposes. As all of the $z_\odot$ for the actually planned satellites are at or above 18° it means that a significant fraction of $n_1$ (visible in the whole sky) and $n_2$ (up to a given $z_{max}$) are still being illuminated by the Sun at the beginning and the end of the astronomical night.

| $h$ [km] | $\phi_{max}$ | $N$ | $\eta_1$ | $n_1$ | $z_{max}$ | $\eta_2$ | $n_2$ | $z_\odot$ |
|---------|--------------|-----|-----------|------|-----------|----------|------|----------|
| $\approx 340$ | $\approx 53.8^\circ$ | 25532.0 | 3.16% | 807 | 60.0° | 0.34% | 87 | 18.3° |
| 540 | 53.2° | 1584 | 4.86% | 77 | 60.0° | 1.33% | 21 | 22.8° |
| 550 | 53.0° | 1584 | 4.95% | 78 | 60.0° | 1.39% | 22 | 22.9° |
| $\approx 550$ | $\approx 45.0^\circ$ | 4468.0 | 5.59% | 250 | 60.0° | 1.57% | 70 | 22.9° |
| 560 | 97.6° | 560 | 4.06% | 23 | 60.0° | 1.12% | 6 | 23.1° |
| 570 | 70.0° | 720 | 4.35% | 31 | 60.0° | 1.27% | 9 | 23.3° |
| $\approx 1100$ | $\approx 53.8^\circ$ | 9.09% | 60.0° | 5.49% | 31.0° |

In summer times there could be a residual region of the sky where for the whole night satellites are potentially illuminated. Astronomical facilities located away from the tempered zone (where, however, most of the largest facilities are located, with some noticeable exceptions) are more potentially affected by such an effect (accompanied by a rapid decrease of the illuminated portion of the sky in the winter times, and not being interested by most satellites of the MegaConstellation, if their latitude exceeds $\phi_{max}$). A through discussion on this matter is not intended to be carried out here and the interested reader can consult the references given in the introductory section.

A summary for all these figures applied to a simplified description of a Mega-Constellation is given in Tab.1

### 3 Appearance on the focal plane

Let us assume in the following, for the purpose of carrying out relationships useful to understand the effect on the focal plane of the passage in the field of view of these satellites, that one of these sources is crossing the local zenith and
Figure 2: Assuming a satellite will cross the local Zenith, a number of quantities are here defined. The satellite will fly over the circular orbit at a constant speed $v$, neglecting the movement due to the Earth rotation, and at any instant will be characterized by a certain range $\rho$. While crossing the Zenith the integrated magnitude is $V_0$ under some kind of photometric system, its light will look, through a telescope with aperture $D$ focused at infinity, as spread into a defocused image of the pupil of diameter $\beta_0$, that will change accordingly at any point of the orbit and indicated by the diameter $\beta$.

it is constantly illuminated by the Sun. The situation is depicted in Fig.2. Let us call $V_0$ the apparent magnitude while crossing the zenith. This quantity can be expressed in any kind of photometric system, as all of the considerations are going to be worked out in the following are of purely geometrical nature.

Flying at a certain constant linear speed and neglecting the rotation of the Earth, an assumption well valid for the kinds of orbits discussed here by about four orders of magnitude, the distance from the satellite to the observer evolves with respect to the apparent zenith distance through a relationship that is worked out in a precise manner and then provided in a simplified manner using the approximation that $h \ll R_\oplus$ as:

$$\rho = -R_\oplus \cos z + \sqrt{(R_\oplus + h)^2 - R_\oplus^2 \sin^2 z} \approx \frac{h}{\cos z} \tag{6}$$

while its apparent angular speed as seen from the observer is given (in radian per second) by the following relationship, using the same approach as the one depicted for the previous relationship:

$$\dot{z} = \frac{v}{\rho} \cdot \frac{\rho^2 + h^2 + 2R_\oplus h}{2R_\oplus \rho} \approx \frac{vh}{\rho^2} \tag{7}$$
These two relationships describe the evolution with time of the distance of the source (and hence by its integrated brightness, scaling with the inverse square of such parameter) and its apparent movement on the focal plane. However, in order to establish the detailed surface brightness one last parameter is needed, that is the apparent angular dimension of these sources, as collected on the telescope. There are basically three different effects that contributes to the apparent angular size of these sources. They each deserve at least a brief discussion, that is given in the following:

- **Defocusing due to the finite distance**

The telescope operating for astronomical purposes is of course focussed to the infinity in order to make of unresolved celestial sources the smallest possible spots on the focal plane. A source at a finite distance $\rho$, when the focal plane is optically conjugated to a point at infinity, will appears as a blurred spot of size

$$\beta \approx \frac{D}{\rho}$$

where $D$ is the diameter of the telescope. When such an angle is smaller than the normal capability of the optical system such an effect becomes unnoticeable. If the limit is dictated by the limit of diffraction $\lambda/D$ or by the local seeing, one can define a minimum distance $h_{\text{min}}$ that sometime take the name of minimum depth of focus. In the case of a diffraction limit telescope such a distance is given by:

$$h_{\text{min}} \approx \frac{D^2}{\lambda}$$

while for a seeing-limited imaging system, assuming $\mu$ is the seeing expressed in radians, this distance becomes:

$$h_{\text{min}} \approx \frac{D}{h}$$

For a $D = 8\text{m}$ telescope and $\lambda = 500\text{nm}$ an $h_{\text{min}}$ of about 1/3 of the distance Earth-Moon is achieved when a diffraction limit capability is achieved, while with a conventional seeing limited imaging such a distance drops to about 1650km for a one arcsec seeing. This explain why no refocussing is needed looking at any class of heavenly bodies, as they are all practically at infinity (or larger than any reasonable $h_{\text{min}}$). It also explains that when using much smaller aperture diameters than the one used in the state of the art telescopes used nowadays, also low Earth satellites are practically at infinity. This however does no longer holds in the case of our interest. In fact, for the largest facilities operating or planned, this is the largest contributing source for the apparent size of these satellites.
• **Finite physical size of the satellite**

Assuming the physical size of the satellite is $s$ an apparent angular size of the order of $s/\rho$ is experienced by the observer. The actual $s$ to be used, however, is depending upon the surface brightness distribution (that can include effects from the occasional direct reflection of solar light, often quoted to as *flares*) and the actual orientation with respect to the line of sight of the observer. A thin must that is not going to contribute significantly to the reflected flux with respect to the main body, for example, will not affect the overall $s$ as intended here. The maximum angular size is moreover upper bounded by $s/h$ making, for a $s = 1m$ a non completely negligible maximum figure of about $0.6^\prime$ somehow comparable to median vs. good seeing conditions. Such figure does not scale with the telescope aperture. For satellites where one or two dimensions dominates with respect to the others, the apparent value of $s$ can wildly change because of the relative attitude of itself. Because of the difficulties into predicting such a quantity, this is going to be neglected in the following discussion. This will make a point of underestimation of the actual apparent angular size of these sources. We also note that it is of the same order of magnitude in the uncertainty in the estimates of an average seeing as experienced in good observing sites, such that, from a certain point of view, it can be included in the uncertainty in the final result.

• **Seeing**

Other than for diffraction-limited Adaptive Optics assisted telescopes, whichever source is considered, it will be fully affected by the overall atmospheric disturbance. The cone effect that the light emitted by the source will experience into the lower portion of the atmosphere where most of the turbulence actually occur is likely to make a negligible, if measurable at all, difference in the way the light experience the atmosphere turbulence, in comparison the rays coming from an unresolved source at infinity. However, speckles could makes visible effects on the trails, as they interest one specific portion of the focal plane for an extremely short time, freezing eventually such variations. In the following a nominal seeing of the order of one arcsec is going to be assumed. in all the cases described in this paper where the apparent size is dominated by the defocus, variations of this quantity has little effects of the final result.

The defocused image of an unresolved source is a small image of the pupil of the telescope, often characterized by a circular shape with a small central obstruction. The seeing (and the possible effects of the finite size) will makes the edges blurred and the central obstruction to get less noticeable, if not at all, under several conditions. In the following I describe the shape on the focal plane of such sources by a circular disk of diameter $\theta''$ of the order of

$$\theta'' \approx \sqrt{\beta''^2 + \mu''^2}$$

(11)

where $\beta'' \approx 206265 \times \beta$ to express it in arcsec. This round spots will travel on the focal plane at the apparent speed given by $\dot{\theta}'$ and one can define a maximum
travel time of this bunch of light on the focal plane as given by:

$$\Delta t \approx \frac{\theta''}{z''}$$ (12)

while the overall brightness of the sources will evolve with respect to the
distance by using an inverse square law projected on the magnitude scale:

$$V = V_0 + 5 \log_{10} \left( \frac{\rho}{h} \right)$$ (13)

while its angular size will evolve consistently. Actually, neglecting the effect
of seeing, these two compensate each others such that the surface brightness
remain constant. The integrated brightness will evolve with the inverse square
of the distance as the overall surface will proportionally evolve.

This means that, instantaneously, the light is spread onto a non negligible
(and usually significantly larger than the seeing) area, especially for the largest
facilities, leading to an instantaneous surface brightness in equivalent magnitude
per arcsec square given approximately by:

$$V_{\text{\scriptsize\large IT}} = V + 2.5 \log_{10} \left( \frac{\pi \theta''^2}{4} \right) \approx -0.26 + 5 \log_{10} \theta''$$ (14)

When the defocusing effect, because of a larger distance $\rho$ will become smaller
or negligible with respect to the seeing $\mu''$ the brightness of the satellites will
consistently diminish with an inverse square law, and augmenting $\rho$ will become
less relevant for the purposes discussed in this work. However, if one is exposing
for a given exposure time $t \gg \Delta t$ this surface brightness is being applied onto
the focal plane only for a fraction of the exposure time and it will be recorded
as proportionally diluted with respect to the other fixed sources (including the
sky background). At the end of the exposure it will be recorded a trail whose
width is of the order of $\theta''$ and an equivalent surface brightness given applying
to the last equation diluted by a proper $\Delta t/t$ factor scaled in the magnitude
scale and hence given by:

$$V_{\text{\scriptsize\large IT}}t = V_{\text{\scriptsize\large IT}} + 2.5 \log_{10} \left( \frac{\Delta t}{t} \right)$$ (15)

It is interesting that a number of approximation used here makes these effects
as somehow overestimated. For example the travel time is only applicable to
the central part of the trail, that means that only in its center part the figure
quoted by the worked out relationships will achieve such a brightness, while this
will degrades toward the edges. It has also been assumed that the defocused
spot is a circular uniform dish. For the typical size of the order of a few arcsec
experienced with $D = 4.8$m class telescopes this is a reasonable assumption
because the central obstruction will be likely washed out by the smearing effect
of the seeing and from the size of the satellite (this last parameter being ignored
here). In Tab.2 typical figures are given for a range of reasonable quantities,
while in Fig.3 a graph collecting the various quantities are depicted. The point
Table 2: Parameters for three altitude of satellites flying on a circular orbit are shown in this table. The travel time $\Delta t$ to cross the whole diameter of the spot assumes $\mu'' = 1''$ while $t_{min}$ is given in order to have the trail surface brightness equivalent to a $Vl'' = 22.0$ (see for instance Patat 2008 and references therein for a discussion on the dark sky brightness).

A number of derived quantities can be easily worked out in order to assess the effects of these trails. For example one could define the minimum exposure time in which the trails are comparable to, or a fraction of, the natural sky brightness. Some of these quantities are listed in Tab.2 and they are intended to get a rough order of magnitude of these numbers. With reference to the graph in Fig.3, instead, one can note that at larger distance (and hence zenithal distance) the augmented blurring due to the seeing gain more relevance, especially for smaller apertures, making the surface brightness slightly fainter. However, because of geometrical effect, their apparent speed get slower, making the equivalent surface magnitude (for a long, $t \gg \Delta t$ exposure) brighter while getting closer to the horizon. Within the Field of View of even a few degrees, the surface magnitude rarely change more than a small fraction of magnitude. It is also noticeable that the dilution of such surface brightness even for just one second of exposure times place the equivalent brightness in the region of the one of the brightest planetary nebulae observable from Earth.

### Comments and conclusions

In spite of the impressive number of satellites involved in MegaConstellations, about 1% or less (see $\eta_2$ in Tab.1) are potentially in sight in a realistic range of elevations where astronomical observations are carried out. At the emergence or at the end of the astronomical night, still several are illuminated, and, at least just at the astronomical dawn, several are doing so while crossing the

| $h$ [km] | $v$ [km/s] | $V_0$ | $D$ [m] | $\beta_0''$ | $V_{\Delta t}$ | $z_0$ | $\Delta t$ [mSec.] | $t_{min}$ |
|----------|-------------|--------|----------|--------------|--------------|------|----------------------|----------|
| 340      | 7.70        | 5.02   | 4        | 2.4''        | 6.83         | 4671''/sec. | 0.56     | 10'55'' |
| 8        | 4.9''       | 8.25   | 1.30''/sec | 1.07        | 5'38''      |
| 40       | 24.3''      | 11.69  |          | 5.20         | 1'09''      |
| 550      | 7.58        | 6.06   | 4        | 1.5''        | 7.07         | 2843''/sec. | 0.63     | 9'51''  |
| 8        | 3.0''       | 8.30   | 0.79''/sec | 1.11        | 5'35''      |
| 40       | 15.0''      | 11.68  |          | 5.28         | 1'11''      |
| 1100     | 7.30        | 7.57   | 4        | 0.75''       | 7.76         | 1419''/sec. | 0.87     | 7'12''  |
| 8        | 1.50''      | 8.59   | 0.39''/sec | 1.27        | 4'54''      |
| 40       | 7.5''       | 11.70  |          | 5.33         | 1'10''      |

zero used there has been scaled from the measurements published by Tregloan-Reed et al. 2020 and converted into visual magnitude using as reference a Sun like spectra (implicitly assuming the satellite is gray) following Fukugita et al. 1996.
Figure 3: With the only exception of the two dot-dashed lines in the bottom that show the actual integrated magnitude of DarkSat all the other curves are in magnitude per arcsec square and are intended, when applicable, with a on arcsec seeing, $\mu'' = 1$. The left vertical axis is adjusted in order to have the zero-point consistent with these brightness estimates, while the one on the right side are scaled making $V_0 = 0$ and are intended to be used adding the magnitude of a generic satellite when at $\rho = 340\text{km}$. The reference lines showing the surface brightness of a state-of-the-art ground based astronomical facilities are also related to the left axis as well.
zenith. Although the ones in the lowest layer are, in such a moment, just barely illuminated at the local zenith, most of the others will continue to be illuminated till the Sun will further lower by several degrees. The surface brightness of those illuminated by the sun is, however, a sort of constant and, for the case considered in this paper, the surface brightness is fainter than the one exhibited by the planet Uranus (Zombeck, 2007) when a $D = 8m$ telescope is being considered. As these spots, a few arcsec in size, travel on the focal plane at the speed of several thousands of arcsec per second, even with a 1sec. exposure time, such a flux is diluted over the whole frame at a level that the surface brightness is of the same intensity of the peaks of the brightest planetary nebula, shading doubts on the possibility that such trails could ruin the whole frame by some sort of blooming effects. If sub-second observations are carried out (for example for very rapid transient astronomy) the immediate occupancy of the sky by such spots is of the order of $n_2 \times \theta^2$, a figure that, even piling up the numbers reported in Tab.1 in the column $n_2$, leads to figures of the order of about $10^{-7}...10^{-8}$ of the whole accessible sky.

Longer exposures makes the dilution effect such that in one hour equivalent exposure (even stacking shorter exposures) it could be hard to actually detect them. The altitude of the same kind of satellite will make no difference till the distance in which they are outside of the depth of focus of the telescope conjugated to infinity. After such a distance the actual surface brightness of these device will lower making the overall effect less relevant, although they could be illuminated even in some significant portion of the astronomical night.

It is worth noting to point out that both the statistical and numerical analysis carried out implies that one is not going to actively avoid the fall of these trails into the field of view of their observations. These phenomenon can be predicted with precision of the order of a tiny fraction of second in time and probably of a few arcsec in position, making an avoiding scheme scheduling probably extremely efficient, and the knowledge of the position of the trail in a specific frame, well a-priori known.

Observations at dawn and dusk can be further potentially affected, as pointed out by others, but a fair comparison should recall that the natural sky brightness is then much higher, so the comparison should take into account this. As this phenomenon would be rapidly changing with time and direction in the sky it would deserve a specific detailed computation to be addressed.

All these considerations drops when smaller apertures are considered, as the satellites will be basically unresolved and appears in focus as in the range of depth of any relatively small optics, including the naked eye. This will makes these satellites visible or barely visible to the naked eye, and will affect significantly astrophotographers. Unless an avid observer of the sky, one should not expect the scenes of multiple trails of bright satellites other than shortly after the injection into their initial orbit, at an even lower altitude, making them disappearing almost completely within the boundary of the astronomical night.

It is questionable if these appearance have a positive or negative role in the common understanding of our sky, and in the role that this can have into helping, or damaging, how astronomy play a role in cultural development.
Although my intention was solely to place under a solid numerical framework the effects on professional astronomy, especially at the large ground based facilities, I would like to express my own position on this specific point.

Astronomical photography for the purpose of beauty can still be made by just avoiding or removing numerically trails. Trails can be in fact used to add some features on the images, leading to challenges, like having a trail crossing the very center of a particular astronomical objects, or a few of them ”framing” another, and so on, leaving as the only limits fantasy and creativity and adding variables to the artistic tuning of the final product.

Observing them by naked eye still requires reaching dark enough sky and are in fact already playing a role into making more people used to look to this or that constellation, in order to look for a sign of a new modernity crossing them, and I would question if these are actually pushing in or out new generations to look more at the sky.

To some extent the way these satellites are injected into orbit makes them an ideal opportunity as they attract the attention of the general public, or at least a fraction of them, for a limited amount of times, making them, later, an occasion for a challenge or for the more sophisticated hunters while offering further options to understand the background over which these phenomenon appears.

Limits must be placed by the regulators in order to avoid that the effects depicted here could be grossly overload, but the effects in terms of the fraction of the sky’s surface and the intensity of the disturbance are probably at a level that moderate mitigation effects could leads to little or no disturbance at all, at least in the optical domain.

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Note

The original manuscript has been originally submitted to PASP, in June 17th, 2020. This version incorporates a few corrections in parts non relevant for the computation and discussion of the surface brightness of the satellite’s trails.