Concerns about ground-based astronomical observations: QUANTIFYING SATELLITES’ CONSTELLATIONS DAMAGES

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Abstract: This article is a second analysis step from the descriptive arXiv:2001.10952 ([1]) preprint. This work is aimed to raise awareness to the scientific astronomical community about the negative impact of satellites’ mega-constellations and estimate the loss of scientific contents expected for ground-based astronomical observations when all 50,000 satellites (and more) will be placed in LEO orbit. The first analysis regards the impact on professional astronomical images in optical windows. Then the study is expanded to other wavelengths and astronomical ground-based facilities (in radio and higher frequencies) to better understand which kind of effects are expected. Authors also try to perform a quantitative economic estimation related to the loss of value for public finances committed to the ground-based astronomical facilities harmed by satellites’ constellations. These evaluations are intended for general purposes and can be improved and better estimated; but in this first phase, they could be useful as evidentiary material to quantify the damage in subsequent legal actions against further satellite deployments. © 2020 S.Gallozzi, D.Paris, M.Scardia, D.Dubois

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1. INTRODUCTION

This work provides evidentiary material to quantify damages and contaminations resulting from the deployment and future service of telecommunications satellite constellations launched into Low Earth Orbit. The aim is to analyse each band suitable for ground-based astronomical observations, taking into account the open electromagnetic windows available to ground-based observations and leaving out from the discussion all bands excluded from observations due to atmospheric opacity at those frequencies, see Fig. 1.

In the second chapter, a general overview on optical ground-based astronomy is given, with technical insight on the Large Binocular Telescope observations; in the third chapter, authors try to analyse the impact of satellites’ constellations in terms of Radio Frequency Interference, RFI, for ground-based radio astronomy facilities, concentrating on mitigation techniques put in place with Iridium Constellation RFI at the Arecibo radio observatory; in the fourth chapter, the Cherenkov Astronomy is investigated as well, with particular attention to the largest Cherenkov experiments and observatories in production and those in preparation. The fifth chapter expands on the larger impact of the rapid growth of mega-constellations, their negative impact on the night sky, and what this means as we move forward in a growing era of space commercial activities; the last chapter gives some quantitative conclusion on the potential impact of satellites’ constellations on astronomy and environment as well. Legal concerns are also pointed out. Appendix A describes the basic concepts of satellite constellations and operating modes; appendix B gives a basic optical data reduction primer.

2. DAMAGES IN OPTICAL ASTRONOMY

For professional astronomical observations the number of satellites above 30 degrees over the horizon is expected to vary in terms of observing ground-based latitude and can be from 300 to 500 satellites. Considering Starlink SpaceX’s satellites size: 1.1m x 0.7m x 0.7m with 2m x 8m solar panels, the maximum angular size (for the neared orbital shell) is:

$$\theta \propto \tan^{-1}\left(\frac{9.1 \text{ m}}{\text{alt.}}\right) = \begin{pmatrix} 0.0015 \text{ deg} & 340 \text{ km} \\ 0.0009 \text{ deg} & 550 \text{ km} \\ 0.0004 \text{ deg} & 1150 \text{ km} \end{pmatrix}$$ (1)
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Fig. 1. A plot of transmission through the atmosphere versus wavelength, \( \lambda \) in metric units and frequency, \( \nu \), in hertz. The thick curve gives the fraction of the atmosphere (left vertical axis) and the altitude (right axis) needed to reach a transmission of 0.5.

Where \( \Delta h = (h_{\text{satellite}} - h_{\text{observatory}}) \).

Depending on the angular size of Starlink satellites (1) and the pixelscale of the astronomical detectors (their PSF within the optics convolutions and sky seeing of the observing night) Starlink satellites can be approximately considered point-like sources or extended.

Depending on the Reference System chosen, absolute Earth center system, ERS and observatory Local system, LRS, see Appendix C, the satellites’ orbital velocity, \( V \), and the angular velocity, \( \omega \), can be estimated by:

\[
V = \sqrt{\frac{GM_E}{R_E + \text{altitude}}} 
\]

\[
\omega_{\text{ERS}} \propto \frac{1}{R_E + \Delta h} \star \sqrt{\frac{G + M_E}{R_E + \text{altitude}}}
\]

\[
\omega_{\text{LRS}} \propto \frac{R_E / \Delta h}{R_E^2} \star \sqrt{\frac{G + M_E}{R_E + \text{altitude}}}.
\]

From (2) it is possible to compute the Starlink satellites’ orbital velocity depending on the orbital shell, see Table 1.\(^1\)

Table 1. Starlink orbital parameters in ERS and LRS

| alt. [km] | \( V \) [Km/s] | \( \omega_{\text{ERS}} \) [deg/s] | \( \omega_{\text{LRS}} \) [deg/s] |
|-----------|----------------|------------------------------|-------------------|
| 340       | 7.7            | 0.066                        | 1.2               |
| 550       | 7.6            | 0.063                        | 0.7               |
| 1150      | 7.3            | 0.055                        | 0.3               |

For high exposure astronomical images, the radial velocity is big enough to leave trails on detectors. Depending on the time that a satellite remains on a pixel the trail can be saturated or not. This is a tricky situation, but the greater the radial velocity (the lower the orbital shell), the less the time that satellites remain on pixels, saturating them.\(^2\) It is not necessary to compute the effective magnitude of trails because the scientific content can be preserved only with a masking procedure performed directly on images; in this context the effective trails magnitude is superfluous information.

Fig. 2. Illumination factor depending on the Sun altitude of the three orbital shells for Starlink satellites. For OneWeb satellites the expected illumination fraction will be the same as the highest Starlink orbital shell, see [28].

The Iridium constellation can be used as a representative constellation to quantify a mean number of flares in observations: Consider 75 satellites (66 that are operative) at 800Km altitude. Each flare illuminates \( \sim 10Km^2 \) of area on the ground. The frequency of Iridium flares at 5th magnitude is about four times per week, so \( \sim 0.008 \) flares per day per satellite. The mean number of expected flares for each constellation will be: \( \sim 483 \) (+ facebook flares: \( \sim 300 \) per 40k sats, \( \sim 750 \) per 100k sats). Instead the number becomes greater if are considered satellites’ flares within the 8th magnitude: \( \sim 0.08 \) flares per day per sat, so that the total mean number of flares are: 50,000 (+ facebook flares TBC).

\(^{1}\)There is no information about the orbital velocity of OneWeb satellites, but it is possible to extend the discussion considering the whole OneWeb fleet as the Starlink satellites at 1,150Km altitude.

\(^{2}\)Luminosity is a function of \( \omega \):
- for tracking object: \( L(\omega) \propto \omega^{-2} \)
- for streaked/trailed objects: \( L(\omega) \propto \omega^{-1.5} \)

This is a general law to compute the effective satellite magnitudes in detectors.
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Fig. 3. a) Apparent magnitude of satellites during an observing night depending on the altitude. b) Apparent magnitude as a function of zenith angle for different altitudes.

| Constellation       | N. flares within 5th mag |
|---------------------|--------------------------|
| SpaceX              | ~ 320                    |
| OneWeb              | ~ 40                     |
| Telsat              | ~ 4                      |
| Amazon              | ~ 25                     |
| Samsung             | ~ 36                     |
| Kepler              | ~ 1                      |
| Roscosmos           | ~ 5                      |
| Chinese Aerospace   | ~ 2                      |
| Boeing              | ~ 24                     |
| S&S Global          | ~ 1 – 2                  |
| CASC                | ~ 8                      |
| LuckyStar           | ~ 2                      |
| Commsat             | ~ 6                      |
| AstroTech           | ~ 4 – 5                  |

When satellites are illuminated by the Sun, depending on the observing night, the observational zenith angle, and the satellite altitude, illumination can reach an apparent magnitude which is capable of saturating astronomical detectors. Also with fainter higher altitude satellites, the mean brightness is enhanced with the cumulative sum of all flares, see Fig. 3a and 3b. These are not only simulations; since the first Starlink was launched, a direct photometric measurement of 5th Vmag was performed by T. Tyson, as shown in Fig. 10.

From the plot it is possible to see that the lower the Sun is, only the more distant satellites will be illuminated. At certain stages the lowest shells to naked eye won’t be visible at all, but the higher shells will be visible in the northern part of the sky. Also the swarm of the satellites near the horizon will be mostly invisible due to their distance and atmospheric effects. It should be remarked that the "worst case" will be experienced during summer in the northern hemisphere, in the northern half of the sky where the satellites will be visible during the entire night; though their brightness will probably be lower than the bright overhead passes after sunset and before sunrise.

The "best case" will be during the northern hemisphere winter, at midnight when the sky will be virtually free of any satellites, except for the horizon.

What is obscured and not visible with the unaided eye ($Mag_{lim} - V_{Bessol} = 6.5$) is observable with any astronomical imager. In particular, the brightness of the trail depends on the visual limiting magnitude of detectors, and the filter used for the astronomical observation. The night period also interferes with brightness of satellites because astronomical observations near twilight will be crowded with 340Km altitude very bright satellites, while after the astronomical sunset the most light pollution will be originated by the 1,150Km altitude satellites.

Only for large area Field of View (FOV), and very short exposures it can be possible to observe elongated satellites segments instead of trails. Also during the dark night it is estimated that trails leaved by satellites’ constellations will be bright enough to saturate modern detectors on large telescopes, see Fig. 3b.

As shown later, in Wide-field scientific astronomical observations will be severely affected; in the cases of modern fast wide-field surveys there will be simultaneous multiple trails inside their FOV.

Instruments with a smaller field of view would be less affected in terms of number of trailing satellites, but even few trails will damage observations enormously. Depending on the scopes of the work it is possible to use a global reference system, ERS or a local one, LRS. By choosing a good reference system, it is possible to make calculations from the point of view of the local observer, LRS or as the observatory was placed at the center of the Earth, ERS.

While LRS allows more robust computations it suffers of a completeness problem in the sample of satellites, because orbital configuration of some constellations are not well known so that this approach could lead to an underestimate of the total number of satellites. On the contrary LRS allows to easily compute the right number of intersecting satellites at each zenith angle depending on the observatory latitude and altitude. Instead ERS is a generic reference which permits to include all satellites sample in the formulas and allows to make more generic of mean number of satellites in a square degree. So ERS acts like the observatory would be placed at the center of the Earth and
so takes care only to evaluate how much satellites intersect the instrument FOV, no matter on the satellite’s orbital configuration and the observatory altitude. As seen from table n.1 radial velocity is very different but in contrary the mean density is inversely proportional, so that the mean number of satellites in FOV is similar, see APPENDIX C for details.

A. The Large Binocular Telescope “test-case”

To estimate the damage on professional optical astronomical images, authors concentrated on a small set of data coming from the Large Binocular Camera, LBC, see [6], located at the fast first focus of the Large Binocular Telescope, LBT at Mount Graham in Arizona, see [5].

A set of public images in V-Bessel Filter (peak around 525 nm) of the Blue Channel of Large Binocular Camera, LBC has been selected. Over some images of the selected dataset of real LBC observations, several saturated trails were simulated. Brighter trails were simulated over some calibration twilight sky-flats in order to perform a parallel data reduction chain, to investigate the impact of scientific content with altered calibration frames in comparison to reductions performed with unaffected sky-flat images.

According to radial velocity in Tab.1, each pixel of LBC camera will be crossed in ~ 1 ms; so taking into account the LBC Exposure Time Calculator, see [61], it is possible to compute the saturation magnitude in V-Bessel Filter for the Blue LBC-channel that for ~ 1 ms is

\[ M_{\text{saturation}} = -2.5 \times \log_{10} \left( \frac{f_{\text{lux}}}{\text{ExpoTime}} \right) + Z_{\text{airm}} = 0 \approx 4,74 \]

Where \( f_{\text{lux}} \) is the total flux divided by the total exposure time and \( Z_{\text{airm}} = 0 \) is the magnitude zero point for \( \text{airmass} = 0 \) at 1 second of exposure time. Because of the brightness of starlink satellites, as seen in Fig. 3b, each Sun-illuminated satellite will leave a saturated trail in LBC chips; so each saturated trail will be masked and expanded as seen in Fig.6.
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The number of 50,000 satellites has been taken by a projection of the latest approved project, but the number could be extremely underestimated because each internet provider could, in the future, claim to deploy its own private fleet and send into LEO orbit, see Tab. 2. The aim of this work is to make an estimation on the worst expectation even if some projects could be rejected or withdrawn (e.g. Boeing) or not yet confirmed, it is necessary to make a projection with a round number in order to multiply to the related factor as new projects will be included or excluded from the list, that is the reason why in this work authors concentrate on the ERS Reference System.

For the medium size of LBC FOV, the number of satellites producing trails in a mosaic of about one hour of total exposure is $\approx 30 \text{sats}$: approximately one trail every 120 seconds; so depending on which kind of observation is planned and which filter is going to be used, for LBC the normality could result in having one to two trails in each scientific exposure RAW-frame.

To test the impact of those trails on LBC professional data, a set of images has been extracted (with a 150 second single exposure in V-BESSEL filter) for a total mosaic exposure of about one hour, see Fig. 6. On those images the same standard reduction was performed in three different situations: 1) without trails, 2) with trails masked by special algorithms and 3) with trails unmasked, see Fig. 4 for data reduction results.

It is possible to remark that the final mosaic with masked satellite trails is very similar to the original mosaic without trails in it, but the exposure map is quite different, see Fig. 7.

The loss of image depth has repercussions on the magnitude estimations error, their computed value, and finally on their magnitude limit: in the chip areas intersected by trails, the probability to alter flat field images is very high. As described in Fig. 9 the mag computation is seriously affected by the presence of trails, even with the huge effort to mask them, since the precision in magnitude computation decreases, and several sources present a very high deviation from the zero value. This must be considered and more deeply investigated before starting high precision photometry studies.

All the manpower effort and scientific overheads to mitigate the impact of trails on scientific images in the dark-night observations are potentially annihilated by the impact of satellites during the twilight hours. In particular, each astronomical image, to be usable as science-ready data, needs to be reduced using standard calibration images known as sky-flats.

These images are taken with small exposures (about 10 seconds) and are usually combined to obtain a final median stacked pixel by pixel image: this process generates the calibration image known as a master flat.

Each time a bright LEO satellite (340Km or 550Km altitude) crosses the FOV during a flat exposure, the master flat is contaminated and the flat frame should be excluded by further computations/reductions.

If a significant fraction of flat image results are affected by satellite trails, a good sky-master flat cannot be produced. This situation could happen very frequently, because it is known that SpaceX satellites will be equipped with a dedicated navigation laser system that will check and correct the position of each satellite with respect to the other close satellites. This feature is used to maintain the orbital asset in an optimal configuration, and, consequently means that will not be possible to accurately predict the exact position of each satellite, only the approximate location without the intervention of its autonomous guide system.

So, considering that the number of visible satellites is greater during the twilight and that the master flat creation is an automatic standard process, if the prediction of exact satellite position is difficult, the eventuality of interrupted observations during the satellites’ passage could be quite impossible, thus the probability to alter flat field images is very high.

If a data reduction is performed with a contaminated flat-field, the whole reduction chain is compromised, so the scientific content of the night observation (even with trail masked) becomes damaged or unusable, see Fig. 8 and 9.

The flat field operation is crucial in optical astronomical data reduction, since the sensitivities of each pixel in a CCD camera usually varies with time, and it is fundamental to get a good set of flat images before (and after) each observing night in order to...
Table 2. Satellite Constellation projects comparison in terms of satellites number, orbital shell altitude, involved bands and foreseen date for service startup (*) if "?" the project has to be confirmed or authorized or even withdrawn.

| Constellation Name               | num. Satellites | Altitude [km] | Bands      | Service Start |
|----------------------------------|-----------------|---------------|------------|---------------|
| SpaceX - Starlink (USA)          | 42,000          | 1,150, 550, 340 | K, K, V    | 2020          |
| OneWeb (UK)                     | 5,260           | 1,200         | K          | 2020          |
| Iridium (USA)                   | 75              | 780           | L          | 2018          |
| Telesat (CAN)                   | 512             | ~1,000        | K          | 2021-2025     |
| Amazon - Kuiper (USA)           | 3,236           | 590, 630, 610  | ?          | 2021          |
| Samsung (KOR)                   | 4,700           | 1,400         | ?          | 2021-2030     |
| Lynx (USA)                      | 36              | 500           | ?          | 2021-2023     |
| Kepler Comm. (USA)              | 140             | 575           | X, K       | 2021          |
| Facebook Athena (USA)           | ?40, 100, 400?  | 500-550       | ?          | 2020-2030     |
| Roscosmos (RU)                  | 640             | 870           | L - X      | 2022-2026     |
| LeoSat Ent. (USA)               | 108             | ?             | K          | ?             |
| C.Aerosp.ScienceTech.Corp. (CHI)| 300+            | ~1,000        | L, K        | 2022          |
| Boeing (USA)                    | 3,116           | 1,200         | V, C, K    | ?             |
| Sky and Space Global (UK)       | 200             | ?             | L, S       | ?             |
| SES (USA)                       | 42              | ?             | K          | ?             |
| Globalstar (USA)                | 48              | 1,400         | S          | ?             |
| ViaSat (USA)                    | 24              | ?             | K, V       | ?             |
| Karousel LLC (USA)              | 12              | ?             | K          | ?             |
| Sat Revolution (USA)            | 1,024           | 350           | R, G, B, NIR | 2021-2026 |
| CASC (CHI)                      | 320             | 1,100         | L, K       | ?             |
| LuckyStar (CHI)                 | 156             | 1,000         | S          | ?             |
| Commsat (CHI)                   | 800             | 600           | optical    | ?             |
| Xinwei (CHI)                    | 32              | 600           | C, K, K    | ?             |
| Astro Tech (IND)                | 600             | 1,400         | C          | ?             |
| **TOTAL**                       | **63,381 (+Facebook?)** | **340 <-> 1,400** | **ALL** | **in 10 years** |

Better calibrate images, see Appendix B for details. Some astronomical observatories adopt a different strategy, making use of domes-flat images instead of sky-flats: these images can correct pixel-to-pixel sensitivities, but unfortunately they introduce light illumination additive gradient patterns, which are very difficult to correct/erase in a second processing step since the flat-fielding operation represents a multiplicative factor in data reductions pipelines.

It is clear that the final magnitude computation will result in higher magnitude differences between a clean reduction mosaic with respect to those with badly trailed master flats, see last plot in Fig. 9. More importantly, using a bad master flat calibration, about 90% of the sample sources are lost since they are not matched with the original catalog and/or are above the detection threshold. This is a fundamental argument to highlight the need to obtain good calibration frames to ensure proper data-reduction computation in order to reach the maximum limiting magnitude of the instrument and detect very faint objects.

This is the most serious concern about damages produced by satellite constellations in optical ground-based professional astronomical observations.

B. What about other instruments and observing methodologies?

The identification of LBT as a case study of this work depends on the characteristics of the facility, which gives the observer the opportunity to use different instruments with complementary

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5 The standard reduction pipeline for LBC camera images consists of different steps: 1) chip cross-talk; 2) pre-reduction: debias and flatfielding; 3) background subtraction; 4) astrometric solutions; 5) resampling and coaddition into mosaic final image, see [43] and Appendix B.

6 Another important limitation of of such a loss of sources is that another data reduction step becomes very difficult: find the astrometric solution for the mosaic.
observing techniques. Not only imaging can be used, but also spectroscopy and Adaptive Optics facilities, as well as interferometric NIR instruments are available.

It is clear that satellite passages in the telescope FOV will necessarily produce damages, but as in the imaging, the possibility to mitigate or correct problems can vary, depending on the data and its expected use.

In the IR range the number of relevant satellites for astronomy is just the total number of satellites in the sky, because the illumination fraction is not important, and satellites also thermally emit under Sun shadow: operating temperatures can reach $\sim 300$ K and this will produce an IR flux in M and Q-bands.

For instance, observations with IR/NIR instruments such as LUCI or MODS are taken with a small exposure in order to minimize the thermal sky background which dominates the signal in ground-based IR observations. This produces faint objects over a bright thermal background, and observational techniques are fundamental to produce scientific content. Flat strategy is important, too. Other IR facilities can implement other acquiring techniques (e.g. “chopping” or “nodding” implemented at a few Hz rate on the secondary mirror) and, in case of trails, very short exposure can be easily rejected from the reduction without affecting the whole scientific content.

Moreover, the satellites’ trails will be seen as faint sources over the very bright background, and won’t be able to saturate detectors in IR/NIR astronomy, not very relevant, even if trails need to be masked.

In spectroscopy investigations, depending on the band, the key features are also exposure time, filter, the grating and dispersing elements, dimension of the instrument FOV and length of slits involved in spectroscopy analysis. In particular, Slitless spectra without masks will be highly affected, but depending on the observing strategy, the effect could be mitigated: if small exposure spectra are taken, then those with trails could be excluded from further processing in spectral pipelines, so the real damages will be limited to overhead and adding to each observation a corresponding number of frames to substitute for all exposures lost with trails. In practice, long exposure slitless spectra could be very hard, if not impossible, see Fig. 11.

Instead, using a particular mask, if satellites pass behind the mask in a covered region of the field, spectra could be taken without great damage. It is not clear how this can be planned in dedicated scheduling operations before the data-taking, but it is clear that this corresponds to additional costs and losses of efficiency for the whole observatory infrastructure as well.

Similar discussions can be extended to Interferometry and Adaptive-Optics instruments and techniques, since in AO systems the FOV is very small, the same for Multi Conjugate Adaptive Optics (MCAO).

So in general, in very small Field of View Astronomical Observations, there are no severe damages foreseen by the impact of satellites’ constellations.

C. What about Wide Field of View Observatories?
Regardless of the minor exposure time, single exposure, wide-field survey telescopes will be particularly damaged, because of the large FOV, by the presence of multiple saturated trails within each single camera image:

- VST [6], with its 268 MegaPixels camera and a FOV of 1 square degree → 1 – 2 simultaneous trails
- LSST [5] (i.e. Rubin Observatory), with a 3.5 degree FOV → 4 simultaneous trails
- Pan-STARRS [7], with its FOV of 7 square degrees and 1.4 Gigapixel camera → 8 simultaneous trails

The same LBT problems arising from the flat-fielding procedure are common to large area survey instruments, while for the night sky observations the crucial factor is the exposure time, according to the radial velocity of each satellite in each constellation, see Fig. 10 as a single wide FOV exposure.

D. What about Variability Studies?
If few satellites cross the sky, variability studies are not really affected, but if the number of such trails increases, occultation probability will also rise. We should talk of occultation both in the case of not-illuminated satellites and in the case of bright trails, because if a particular object is observed, what is...
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Fig. 9. The left image plots the absolute $|\Delta \text{Mag}|$ between computed magnitude in V-BESSEL filter from a clean mosaic, and one with trails masked. The central image shows the same plot performed only in trail areas. The right image plots the absolute magnitude differences between a catalog extracted from a good mosaic generated with a good master flat, and a second catalog extracted from a bad mosaic generated with a bad master flat with trails inside: at least 90% of sources in the field are not detected.

Fig. 10. Starlink satellites visible in a mosaic of an astronomical image (courtesy of NSF’s National Optical-Infrared Astronomy Research Laboratory/NSF/AURA/CTIO/DELVE). The photometric single exposure measurement of this set of trails revealed a 5th Vmag apparent magnitude, from T. Tyson.

detection and investigation.

If variability studies are performed on wide field of view cameras, the probability that an artificial variation of luminosity induced by a satellite occultation increase accordingly with the number of satellites in the FOV; the luminous variation timing will help to discriminate between natural and artificial variability.

3. RADIO ASTRONOMY, HOW MUCH IS AFFECTED?

Even with the best coating and mitigation procedures to decrease the impact on visual astronomical observations, what is often omitted, or forgotten, is that telecommunication constellations will shine in the radio wavelength bands, observable from the ground, not only from reflection of solar radio flux, but above all because of the need to broadcast internet (and other TLC services) from the satellite networks to the ground stations.

Radio astronomers have been engaged for decades in the work of the United Nations Agency ITU to regulate the international use of the radio frequency spectrum. Their efforts ensured a limited number of narrow bands of the spectrum received protection to allow radio astronomy to develop and conduct essential and unique research.

Despite the special international protection for radioastronomy, some sources of radio frequency interference (RFI) are inescapable. While radio astronomers can minimize the effect of many terrestrial sources by placing their telescopes in remote sites, none can escape from RFI generated by satellites’ constellations, because the reason for existence of these networks is to provide ubiquitous TLC signals even in the most remote part of the globe.

Very often in place where radio observatories are placed (e.g. at the two SKA sites in Australia and South Africa) there is legislation to protect the telescopes from ground-based radio interference at those frequencies, the use of air and space-borne radio communications is regulated on a collaborative international basis.

So this development of TLC satellites’ constellations are not intended as a collaborative effort, but as a...
The scientific needs of radio astronomers and other users of the passive services for the allocation of frequencies were first stated at the World Administrative Radio Conference held in 1959 (WARC-59). At that time, the general pattern of a frequency-allocation scheme was:

1. that the science of radio astronomy should be recognized as a service in the Radio Regulations of the International Telecommunication Union (ITU);
2. that a series of bands of frequencies should be set aside internationally for radio astronomy;
3. that special international protection should be afforded to the hydrogen line (1400-1427 MHz), the hydroxyl (OH) lines (1645-1675 MHz), and to the predicted deuterium line (322-329 MHz)...

Since 1959, a large number of spectral lines from a wide variety of atoms and molecules in space have been discovered; the frequency range of radio astronomy now extends to at least 500 GHz. In particular, frequencies of the CO molecule (at 115, 230, and 345 GHz), isotopes (at 110, 220, and 330 GHz) and the maser of H$_2$O at 22.235 GHz [29], are critical to many aspects of astronomy, see also [25].

A. Which impacts on bands used for radio-astronomy?

There are a lot of professional on-ground radio astronomy facilities and very few radio bands free from telecommunications uses, see Fig. 12. Satellite constellations described in Table 2 use frequencies in the following bands: L, S, C, X, K$_u$, K$_a$ and V. Only K, W, D, G and Y bands are free from satellites uses.

It is possible to fill a list of radio telescopes and projects affected by radio interference coming from the satellites’ broadcast of internet/phone signals, see Table 3.

The development of the latest generation telecommunications networks (both from space and from Earth) already has a profound impact on radio-astronomical observations (at all sub-bands): with LEO satellite fleets it is quite certain that the situation could become unbearable.

In particular, low Earth orbit satellite’s spectral windows identified to communicate with Earth stations in the L (1-2 GHz), S (2-4 GHz), C (4-8.2 GHz), X (8.2-12.5 GHz), K$_u$ (12.5-18 GHz), K$_a$ (27-40 GHz) and V (40-75 GHz) bands will overlap with the nominal radio-astronomy bands, so will interfere with ground-based radio telescopes and radio interferometers, making the radio detectors enter in a non-linear regime in the K band (18-26.5 GHz) and Q band (33-50 GHz). This fact will irreparably compromise the whole chain of analysis in those bands, with repercussions on our understanding of the Universe, or even possibly making the astrophysics community blind to these spectral windows from the ground, even if they are formally free from telecommunications broadcast, see Fig. 12.

From Fig. 12 it is possible to identify free bands from TLC uses, which are: K, W, D, G and Y. Although they are theoretically free from uses, it has been noted that TLC providers usually do not respect the authorized frequency windows and often produce unauthorized RFI interference in bands formally free (e.g. K-band, as experimented in SRT, where at “some” satellite transit the SRT K-band detector saturates, entering into a non-linear regime).

There are different projects in development for ground-based radio-astronomy that will significantly overlap with telecommunications signals coming from the satellites’ constellations in orbit, see Table 3 for details:

- Australian Square Kilometre Array Pathfinder, ASKAP
Table 3. Satellite-Constellations interference with ground-based radio astronomy observatories

| Radio Project | Constellations Name | Interference Bands | No of Sats |
|---------------|---------------------|--------------------|------------|
| ASKAP         | Iridium, Roscosmos, Chinese, SkyAndSpace, CASC | L                  | 1520       |
| SRT+I-VLBI    | Iridium, Roscosmos, Chinese, SkyAndSpace, Xinwei, Astrotech | L, C, K            | 5082       |
| MeerKAT       | Iridium, Roscosmos, Chinese, SkyAndSpace, Globalstar, OneWeb, SpaceX, Kepler, LuckyStar, Xinwei, Astrotech | S, C, X, K_u       | 17288      |
| SKA1          | Iridium, Roscosmos, Chinese, SkyAndSpace, Globalstar, TeleSat, SpaceX, LeoSat, Boeing, SES, ViaSat, Karousel, LuckyStar, Xinwei, Astrotech | S, C, X, K_u, K_u, V | 2038       |
| VLA           | Iridium, Roscosmos, Chinese, SkyAndSpace, Globalstar, TeleSat, SpaceX, LeoSat, Boeing, SES, ViaSat, Karousel, LuckyStar, Xinwei, Astrotech | S, C, X, K_u, K_u, V | 21788      |
| ngVLA         | Iridium, Roscosmos, Chinese, SkyAndSpace, Globalstar, TeleSat, SpaceX, LeoSat, Boeing, SES, ViaSat, Karousel, CASC, LuckyStar, Xinwei, Astrotech | S, C, X, K_u, K_u, V | 48108      |
| ngVLA-LBA     | Iridium, Roscosmos, Chinese, SkyAndSpace, Globalstar, TeleSat, SpaceX, LeoSat, Boeing, SES, ViaSat, Karousel, CASC, LuckyStar, Xinwei, Astrotech | S, C, X, K_u, K_u, V | 48108      |

see [46]: located in Australia. The ASKAP will use 4 radio-bands: 0.7-1.012 GHz, 0.9-1.2 GHz, 1.2-1.52 GHz, 1.48-1.78 GHz.

- Sardinia Radio Telescope, SRT and SRT + Italian Very Long Baseline Array, SRT I-VLBA see [40]: located in Sardinia, Italy. The SRT will use 4 radio-bands: 0.3-0.4 GHz, 1.3-1.86 GHz, 5.7-7.7 GHz, 18-26.5 GHz.

- South African MeerKAT radio telescope, MeerKAT see [45]: located in Northern Cape, South Africa, is the precursor of SKA. MeerKAT operates in the L-Band at frequencies 0.9-1.67 GHz and UHF-Band between 0.5-1.015 GHz.

- Next Generation Very Large Array, ngVLA and ngVLA Long Baseline Array, LBA see [22]: located in New Mexico, west Texas, Arizona, and northern Mexico. The ngVLA will use 6 radio-bands: 2.4 GHz, 8 GHz, 16 GHz, 27 GHz, 41 GHz and 93 GHz.

- Square Kilometer Array, SKA see [23], [27] will interfere with K_u communication bands.

- Atacama Large Millimeter Array, ALMA see [26], the world-leading mm and sub-mm observatory built in Atacama, Chile with enormous sums spent by a broad international community, is a facility that has brought us many significant discoveries and played a crucial role in the global system of EHT (first image of ever of a black hole, published in April 2019), has its Bands 1, and 2+3 exactly in the potentially polluted part of the spectrum, WDGY bands, not part of 5G satellite communications, but foreseen for 6G technology in few years.

To aggravate the matter, with the current technological development, the planned density of radio frequency transmitters is impossible to envisage. In addition to millions of new commercial wireless hot spot base stations on Earth directly connected to the approx. 50,000 new satellites in space, we will produce at least 200 billion new transmitting objects, according to estimates, as part of the Internet of Things (IoT) by 2020-2022, and one trillion objects a few years later.

Such a large number of radio-emitting objects could make radio astronomy from ground stations impossible without a concentrated protection effort made by countries’ safe zones where radio astronomy facilities are placed. This should be followed by an international moratorium to limit satellites’ communications emissions.

B. Mitigate TLC interference: the Iridium case study
This analysis is based on Avinash A. et al 2019, see [24]. The International Telegraphic Union (ITU) granted the Radio Astronomy Service (RAS) primary status in the 1610.6-1613.8 MHz band in 1992 to observe the 1612.235 MHz spectral line emission from the hydroxyl molecule (OH). This is typically emitted by OH/IR stars (see Lewis, Eder & Terzian 1985) as a pair of narrow features, with the allocated band sized to allow for Doppler shifts of the emission, as well as guard-band separation from ITU Services using an adjacent spectrum. One such is the Iridium L-Band system, which presently uses a 1618.85-1626.5 MHz allocation.
Fig. 13. In the first image, a typical 180 ms long dynamic spectra for the dual linear polarization channels (X and Y, in the upper and lower halves of the main panel), are shown, each observed across a 25 MHz wide band centered at 1622 MHz. The two line plots in the bottom panel show the corresponding time profiles of the band-averaged intensities in X and Y, respectively. In the second image near a bandwidth of 3.125 MHz in the RAS band (centered at 1612.5 MHz), which is narrow and so has a correspondingly better spectral resolution, providing a more resolved view of the line features from the star. The third image is a 180 ms sequence of Stokes I spectra taken at 1 ms intervals, together with their arithmetic (black) and robust (coloured) means on each axis, so that only the ∼ 1612 MHz feature comes from the star. The last image shows a dynamic spectrum with the unpolarized component $I_u$ (i.e. after removing the polarized contribution from the Stokes I), and thus mostly free of RFI.

But this system also produces a comb of RFI, with a characteristic 333 kHz spacing, extending well beyond its licensed band. The ∼ 1 Jy intensity of this comb in the RAS band for most of observatories is comparable with the signal from many of the brighter OH/IR stars. No pre-launch simulation available to the ITU or to radio-astronomers gave any hint of the existence of this noxious artifact when the System was granted spectrum. Hence the need now for RFI mitigation.

The study was made using the highly sensitive 305 m Arecibo telescope, which has 80 dB of forward gain and thus a narrow main beam. Accordingly the 66 active, low-earth-orbit satellites from the Iridium System are only generally seen at Arecibo in distant side lobes: that lessens their impact on our observations.

Iridium uses a frequency multiplexed – time multiplexed operational mode. This gives two helpful features, as the signal is strongly polarized (more specifically, has right hand circular polarization), and more unusually, has a satellite down-link time multiplexed in exactly the same band as the phone hand setup-link signal.

Each Iridium satellite operates on a 90 ms cycle, with half assigned to the up-link, and half to the down-link. That allows the folding of data at a secondary period of 180 ms, or twice the basic cycle. The timing operations of the entire Iridium constellation are governed by the System’s most intense signal, the 1626 MHz clock synchronization signal.

Data were acquired with full Stokes ($I, Q, U, V$) parameters as high time-resolution, single dish spectra. Dynamic 1024 channel spectra were recorded every millisecond using the 9 level sampling mode of an auto-correlator simultaneously in both the Iridium band, using a 25 MHz bandwidth centered at ∼ 1622 MHz and in the RAS band using a 3.125 MHz bandwidth with proportionately finer spectral resolution. These accumulate the net temporal correlation between fluctuations in every possible combination of spectral channels from every possible pairing of spectra: they are produced as cross-correlations between spectra in the native linear, in $I$, in the unpolarized flux, $I_u = I - \sqrt{Q^2 + U^2 + V^2}$, as well as between the two observed bandwidths and as auto-correlations of spectra. After folding 2 minutes of data at the period of the Iridium clock cycle, the only Iridium artifacts in our RAS band data are momentary gain compression episodes.

The bandpass gain calibration is applied to the linear polarization data before computing $Q$ & $I_u$ from the Stokes I, $Q$, $U$ & $V$ of each channel of each spectrum as $I_u = I - I_p$ (where the polarized component is estimated as $I_p = \sqrt{Q^2 + U^2 + V^2}$, which reduces the residuals from Iu.

Fig. 13 shows a typical 180 ms (two-cycle) sequence of Stokes I spectra with the OH/IR star at ∼ 1612 MHz and Iridium’s signal between 1620-1627 MHz. The mean side-lobe response of the strongest Iridium Stokes I feature here, which is only seen for ∼ 5% of the time, has ∼ 7 times the intensity of strong OH/IR star which is seen with the main beam. So Iridium can easily saturate an astronomical receiver.

C. How to extend the case study to other bands?
Mitigation techniques can help to reduce RFI significantly up to tens of DB, but never reduced to zero. A more detailed approach to different transmitters coming from other satellites needs a special study on the nature and modulations of those signals in order to apply such techniques.

Some radio astronomy sites (e.g. NRAO) rely on Radio Quiet Zones, but it is not possible to prevent satellites from shining on the ground. So SpaceX has promised to accommodate NRAO by not emitting in the direction of the Green Bank Observatory. This will be easy because some satellites use phased array technology, aiming beams only in the direction of user devices. Since there will be no user devices in the Radio Quiet Zone, there will not be any interference from SpaceX with the NRAO telescope. This will also be true of other large constellations that use millimeter waves and phased array technology. In particular, the phased array technology, see [59], can be used with transmitting devices operating above 20 GHz, so with the $K_{\alpha}$, Q, U, E, V, W, D & G - bands; from Table 2 it is possible to find satellite constellations with beam forming
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Even if a phased array can be used to exclude some places from satellite signals, this mitigation can not be considered as conclusive, because 1) the phased array does not emit zero signal outside the principal phased direction, but only produces disruptive interference to guarantee only a principal direction of propagation, but outside the main beam the signal is not zero as manufacturers declare, so filling out the whole sky with 50 thousand satellites will increment the Night Sky Background in each radio-band; and 2) the possibility to avoid signals in Radio Quiet Zones assumes that no user will ask for the service, neither single users nor passing users (from ships, cars, planes, trains, etc.). Finally, 3) because the single radio observatory can work in conjunction with other partners all around the world (in the Very Long Baseline Interferometry capability), it is required that each observatory of the long baseline to be free of pollution in the desired receiver band. This is not possible at all.

The principal issue related to the RFI induced by the satellites’ constellations is that each ground-based astronomical receiver needs to discriminate between each satellite transmitter band, so astronomical detectors will find in their data many different RFI coming from different satellites, each one with a different polarization and timing. The mitigation process could be very difficult, if not impossible, without a good characterization of each satellite signal.

With all these orbiting satellites, if in theory this cleaning process is possible, in practice the work of extracting reliable scientific content from radio-astronomy data could be so tricky that the overhead needed in terms of computation time and computing teraflops (e.g. electrical power consumption) will explode. This shows that a clear evaluation and quantification of the damage is not simple like the optical investigations.

The only working mitigation possibility is to absolutely preclude some bands from telecommunications and use them (only them) for radio-astronomy; clearly surrendering all opportunities to perform a complete multi-wavelength analysis on astronomical objects.

4. CHERENKOV ASTRONOMY: ARE TELESCOPES AND ARRAYS AFFECTED?

Gamma-ray photons have energies (E>125 keV) that span many orders of magnitude, from MeV to TeV and beyond. Consequently a single detector technology will not be able to cover the entire gamma-ray range.

While gamma rays with energies on the order of MeV and GeV are detected by satellite instruments, very high energy (VHE, E>50 GeV) gamma rays can be efficiently detected, with large collecting areas, only from the ground, e.g. with arrays of Cherenkov Telescopes (see Fig. 14).

Depending on the energy of the initial VHE cosmic gamma ray, there are many electron/positron pairs in the resulting cascade that are capable of emitting Cherenkov radiation.

As a result, a large pool of Cerenkov light comes with the air shower particles. The Cherenkov emission is at the ultraviolet and visible wavelengths, and the shower can be imaged directly with an array of pixels, within a camera placed at the telescope’s focus.

Thus for Cherenkov telescopes the atmosphere has to be considered as part of the “detector,” and the air shower analysis permits counting high energy photons, their origin and their spectral signature (e.g. their energy).

Can these kinds of ground-based facilities suffer from light pollution coming from satellites’ constellations?

Considering that the data reduction and analysis strategies are totally different from the optical case, to inspect the possible damages due to the satellites’ constellations it is possible to start analysing the FOV of some telescope involved in Cherenkov observations.

There are different facilities for Cherenkov gamma-ray astronomy in operation and development. The current-generation of Cherenkov telescopes comprises the ASTRI & mini-Array project, see [47]; H.E.S.S., see [50]; the MAGIC array, see [48] and VERITAS array, see [51]. The most important next-generation facility will be the the Cherenkov Telescope Array (CTA), see [49].

CTA will be composed of two arrays of Cherenkov telescopes of different sizes (large-sized telescopes, LST ~ 24 m; medium-sized telescopes, MST, ~ 12 m; small-sized telescopes, SST, ~ 4 m) that will be placed in two different sites, see Table 4:

- ~ 20 telescopes for the CTA North-site (Canary Islands, Spain)
• ∼ 100 telescopes for the CTA South-site (Chile)

While the CTA array in the northern hemisphere will be more limited in the number of telescopes, and will be more focused on the low and middle VHE range (from 20 GeV to 20 TeV), the CTA array in the southern hemisphere, with its prime view of the rich central region of our Galaxy, will span the entire energy range accessible to CTA, covering gamma-ray energies from 20 GeV to 300 TeV.

The three classes of telescopes will be distributed in the two array sites, with possible layout configurations as depicted in Fig. 15.

• SST ⊗ ∼ 4 m → E > 10 TeV → FOV ∼ 10 deg
• MST ⊗ ∼ 12 m → E ∼ [0.1; 1] TeV → FOV ∼ 6 – 8 deg
• LST ⊗ ∼ 24 m → E < 0.1 TeV → FOV ∼ 4 – 5 deg
• ASTRI/MA ⊗ ∼ 4.5 m → E > 1 TeV → FOV ∼ 9.6 deg
• MAGIC ⊗ ∼ 17 m → E < 1 TeV → FOV ∼ 3.5 deg
• VERITAS ⊗ ∼ 12 m → E ∼ [0.1; 30] TeV → FOV ∼ 3.5 deg
• H.E.S.S. ⊗ ∼ 28 m → E < 20 TeV → FOV ∼ 5 deg

### Table 4

| C. T. A.                  | Large-Sized Telescope (LST) | Medium-Sized Telescope (MST) | Small-Sized Telescope (SST) |
|---------------------------|-----------------------------|-------------------------------|-------------------------------|
| Required energy range     | 20 GeV – 3 TeV              | 80 GeV – 50 TeV               | 1 TeV – 300 TeV              |
| Energy range (in which subsystem provides full system sensitivity) | 20 GeV – 150 GeV             | 150 GeV – 5 TeV               | 5 TeV – 300 TeV              |
| Number of telescopes      | 4 (South) 4 (North)         | 25 (South) 15 (North)         | 70 (South) 0 (North)         |
| Optical design            | Parabolic                   | Modified Davies-Cotton        | Schwarzschild-Couder         |
| Primary reflector diameter| ∼ 23.0 m                    | ∼ 11.5 m                      | ∼ 9.7 m                      |
| Secondary reflector diameter| ∼ 103 t                 | ∼ 16 m                        | ∼ 5.9 m                      |
| Effective mirror area     | ∼ 370 m²                    | ∼ 88 m²                       | ∼ 1.8 m²                     |
| (including shadowing)     |                             |                               |                             |
| Focal length              | ∼ 28 m                      | ∼ 106 m                       | ∼ 80 t                       |
| Total weight              | ∼ 4.3 deg                   | ∼ 7.5 deg                     | ∼ 10.5 deg                   |
| Field of view             | Any astrophysical object with elevation > 24 degrees | Any astrophysical object with elevation > 24 degrees | Any astrophysical object with elevation > 24 degrees |
| Number of pixels in Cherenkov camera | 1855                      | 1764                          | 1855                         |
| Pixel size (imaging)      | 0.1 deg                     | 0.17 deg                      | 0.067 deg                    |
| Photodetector type        | PMT                         | PMT                           | SPF/PMT                      |
| Telescope readout event rate | >7.0 kHz                    | >6 kHz                        | >3.5 kHz                     |
| Telescope data rates (readout of all pixels; before array trigger) | 24 Gb/s                      | 12 Gb/s                       | 2 Gb/s                       |
| Positioning time to any point in the sky (>30° elevation) | 30 s                        | 90 s                          | 60 s                         |
| Pointing precision        | <14 arcseconds              | <7 arcseconds                  | <7 arcseconds                |
| Observable sky            | Any astrophysical object with elevation > 24 degrees | Any astrophysical object with elevation > 24 degrees | Any astrophysical object with elevation > 24 degrees |

### A. Quantifying Cherenkov damages

Considering a mean exposure time of about 20 minutes, the total number of satellites in the FOV will depend on the FOV area of each telescope. However, in order to estimate the rate of spurious triggered events, it is necessary to compute the single camera pixel crossing time (i.e. the mean time that any satellite will remain within a single pixel), which is for a typical SST camera of the order of ∼ 2 – 3 sec.

Taking into account equation (1), (2), (3) and Table 2 within the FOV of Cherenkov telescopes of similar characteristics of those used in CTA, the crossing time is:
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![Image](https://example.com/image.png)

| FOV [deg] | Sats per FOV | t.cross @ 340Km | t.cross @ 550Km | t.cross @ 1150Km |
|-----------|--------------|-----------------|-----------------|-----------------|
| LST → 4.3 | 14           | 65[s]           | 68[s]           | 78[s]           |
| MST₁ → 6.0 | 28           | 91[s]           | 95[s]           | 109[s]          |
| MST₂ → 7.5 | 44           | 113[s]          | 119[s]          | 136[s]          |
| MST₃ → 7.7 | 46           | 116[s]          | 122[s]          | 140[s]          |
| SST → 10.5 | 86           | 159[s]          | 166[s]          | 190[s]          |
| ASTRÍ → 9.6 | 79           | 146[s]          | 153[s]          | 173[s]          |
| MAGIC → 3.5 | 11           | 52[s]           | 55[s]           | 63[s]           |
| VERITAS → 3.5 | 11       | 52[s]           | 55[s]           | 63[s]           |
| H.E.E.S. → 5 | 23           | 75[s]           | 79[s]           | 90[s]           |

The total number of satellites crossing the FOV of a typical Cherenkov 20-minutes exposure are respectively:

| ~ 30 for LST | ~ 40 for MST₁ | ~ 54 for MST₂ |
| ~ 56 for MST₃ | ~ 90 for SST | ~ 86 for ASTRÍ |
| ~ 32 for MAGIC | ~ 24 for VERITAS | ~ 25 for H.E.E.S. |

This time could be enough to trigger a spurious event, but depends on the brightness of the satellites.

If a star of 3rd magnitude is considered (e.g. ZetaUri is 2.97 mag), it can trigger a Cherenkov camera, under particular trigger configurations.

During observations near twilight conditions, the 2nd and 3rd magnitude satellites in FOV could impose a different trigger topological strategy and higher single pixel trigger threshold, which would result in a higher energy threshold of the detector. In fact, in the case of an almost-perfect alignment, a 5NN topological logic should avoid (almost completely) any possible spurious trigger due to bright stars or passing (point-like) artificial objects.

In addition to this, an individual pixel rate (IPR) control should help in order to be sure not to get any spurious trigger.

For instance, satellites with magnitude 7th will more than double the single pixel background light, while satellites with magnitude 5th will add a factor of ~ 7 more background light.

Pixels with higher levels of background light could degrade the reconstruction of Cherenkov images; in such cases it would not even be possible to remove the contribution of the affected pixels by increasing the levels of the image cleaning procedures.

In principle smaller images, which are not necessarily due to low energy events, are the most affected by this spurious effect.

Since the additional light hits (in principle) single pixels (within a given Cherenkov event trigger time window), the cleaning levels can likely be the default ones, providing information on the "hot" pixels (for each pixel and each Cherenkov trigger) is made available.

To do so, the level of the pixels’ NSB should be monitored (e.g. with dedicated quality monitoring data) with a rate higher than the inverse of the time needed for the artificial object to cross a single pixel (~ 3 sec).

B. Remarks in Cherenkov Astronomy Damages

In conclusion, the more affected cherenkov telescopes will be those at higher energy ranges, i.e. SST-like telescopes; MST & LST-like telescopes will be less affected.

The following list shows all concerns arisen for SST-like telescopes:

- Lowest orbit satellites may indeed provide additional non-negligible source of NSB in the Cherenkov cameras.
- Higher orbit satellites might have some impact on the rate of single pixels; in order to be 90% sure to avoid spurious triggers, a suitable trigger logic with a >=4NN topology may be indeed needed, while an IPR control may be also implemented.
- In order to always be able to use optimal image cleaning levels, the pixels hit by the artificial light must be somehow suppressed. Thus, the information of the NSB amount for each cameras’ pixel should be monitored by means of dedicated quality monitoring data, in time steps smaller than the typical time in which the artificial objects cross a single pixel (~ 3 sec).

5. SHORT-TERM AND LONG-TERM IMPACTS FROM MEGA-CONSTELLATION SATELLITES, AND THE FUTURE OF THE DARK SKY

Space debris designates any artificial object orbiting the Earth no longer serving its initial function (i.e. fragmented spacecraft parts, abandoned launch vehicle stages, disposed spacecraft, etc.). Currently, there are over 500,000 pieces of space debris the size of a marble or larger orbiting the Earth, traveling up to 17,500 mph. Millions of others are currently untraceable. In addition, around 4,000 active and inactive satellites are presently in Earth’s orbit. As early as 1978, Donald Kessler had published a paper, see [34], detailing and warning us of the devastating cascading effect of collision-induced debris creation (the so-called Kessler syndrome, see further below).
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would cause devastating consequences not only for the future (currently paving the way for space commercial activities). It previously in Section 2, is built and managed by SpaceX completely unavailable."

Kessler wrote that the finite probability of satellites colliding and creating more debris fragments, would thus create a snowball effect which, were the tipping point to be reached, would cause devastating consequences not only for the future of space exploration, but also to our environment, see Fig. 18.

The Kessler paper simulates the creation of a debris belt around the Earth following an increase of orbiting satellite numbers with a rate of 510 satellites per year (expecting a satellite rate launch reduced to zero in 2020): with mega-constellations this rate is instead ten times that expected by Kessler. Just considering SpaceX, it has scheduled a deorbiting rate with substitutions from 4,000 to 8,000 satellites per year.

While some measures, see [52], for the mitigation of space debris have been adopted over the years by the United Nations Office for Outer Space Affairs, the proposed seven guidelines are still rarely respected, see [53]. Furthermore, recent (successful) anti-satellite missile test attempts by China, see [54], and India, see [55], escalate the very real risk of the Kessler syndrome coming into effect much sooner than we think.

The Starlink mega-constellation satellite project, described previously in Section 2, is built and managed by SpaceX (currently paving the way for space commercial activities). It aims at deploying “the world’s most advanced broadband internet system” to “deliver high speed broadband internet to locations where access has been unreliable, expensive, or completely unavailable.”

As of October 2019, the U.S. Federal Communications Commission (FCC) had already approved 12,000 such satellites with another 30,000 pending, according to filings submitted by SpaceX to the International Telecommunication Union. A first large deployment of 60 satellites occurred in May 2019, quickly followed by three more in November 2019, January 2020 and February 2020. More recent and current launches have been occurring every month, while SpaceX announced that as many as 24 Starlink missions could be launched in 2020 alone (i.e. well over 1,000 satellites in one year alone).

This hastens an era of uncontrolled space pollution. The International Dark-sky Association, which advocates for the preservation and protection of clear dark skies, recently issued a statement, see [56], on the impact of mega-constellations, further raising concerns as to the prospect of such global-scale projects.

In its entirety, Starlink’s expected 42,000 satellites will not only be unprecedented, but also beyond any reasonable measure to adequately address the burning problem of low-Earth orbit pollution any longer (see also Sections 2 and 3). To put this into better context, nearly 9,000 satellites, probes and landers have been sent to space since 1957 – in other words, within the scope of just a few years, SpaceX (and readily every other major commercial constellation-satellite party, see Table 2) would launch considerably more satellites than humankind has ever launched in its entire history. In addition, the goals for this are embedded in timely economic and business prospects with a race to global 5G networks, prone to becoming a competitive market. By setting this precedent, SpaceX will certainly not be the sole purveyor of global internet access as part of this new mega-constellations market, see Table 2.

After the launch of a second batch of 60 satellites near the end of 2019, numerous disastrous events were reported by astronomers worldwide of Starlink satellites completely impairing telescope observations, see Fig. 2.

These observatories have a record of producing state-of-the-art observations in some of the world’s most pristine night-sky locations, and the expansion of mega-constellation satellites will only further deteriorate, perhaps even completely undermine future observations. That only about 0.4% of the planned 42,000 launched satellites (omitting the grand total of over 60,000+ satellite-constellations planned or waiting for approval) is already causing distress and observable nescuous consequences should itself be cause for extreme warning in an already unfettered business market with little to no binding international regulations on the protection of the night sky.

Recent emergency maneuvers, see [57], had to be undertaken by the European Space Agency after SpaceX failed to respond on time, to avoid a near-collision with Starlink satellites (it was SpaceX’s responsibility to perform said maneuver). The recent key legal evidence that the FCC approval of the Starlink mega-constellation may have been unlawful, see [58], with regard to the National Environmental Policy Act (NEPA) which requires federal agencies to thoroughly assess the environmental impact of projects before accepting them, is furthermore attached to the scientific motives at the basis of the concerns in this manuscript. This case alone should thus be treated even more carefully as we advance into the
uncharted territory of using space for such commercial activities.

Remarkable and inspiring night skies, which we have inherited to the pleasure of our eyes, hearts and imagination, are on the brink of being forever altered and desecrated more than they already are. On the basis of this analysis, we raise urgent concern with regard to the growing number of satellite constellations, and their impact not only on scientific observations, but also on space debris pollution and the preservation of the dark sky. International cooperation can take action by imposing thorough support and impact evaluations, in concert with international dialogue between regulatory agencies and satellite-constellation manufacturers.

Binding regulations and multi-party discussions among all and any current and future business enterprises by private entities are crucial for the preservation and protection of the night sky, and in preventing any potential disastrous Kessler syndrome effects. At present, these operations do not guarantee any safeguard for proper, responsible or reasonable commercial activity in Earth’s low-orbit. Legal and regulatory provisions along with moratoria on future launches should be imposed. The pursuit of satellite-constellation projects will most likely signal the end of humanity’s familiarity with space, scientific operations as detailed in this manuscript, and the dark sky as we know it.

In APPENDIX D is shown a legal approach on the possibility, under international laws, conventions and treaties to act towards the safeguard of the night sky by the whole international community.

6. CONCLUSIONS: QUANTIFYING GROUND-BASED ASTRONOMY DAMAGES

A large ground-based astronomical facility like the one taken as representative example, LBT, needs significant public funding to operate and give to the astronomical community scientific services and results. The operations of the infrastructure are managed by the LBT Observatory organization, which shares operating costs among its partners.

It is not clear the total amount of cost for the infrastructure from start of construction to the current service operations, but it is possible to highlight the annual cost for the partnership: each partner spends approximately three billion euros per year. This implies a median cost for each observing night varying from 60,000 to 80,000 euros, depending on the seasons (length of the observing night).

Fig. 19. In the four images are summarized different orbital configurations of a few satellites’ constellations: GPS, Iridium, Telesat, OneWeb, Samsung and SpaceX.

If no good strategy to mitigate the flat-field pollution by satellites’ trails is put into place, the scientific content of all images coming from the LBT astronomical observatory facilities will be strongly altered or compromised by an estimated 70-80%.

Instead, if a good strategy on flat-fielding and calibration campaign can be found, the mitigation process could minimize this percentage to 30-40% of the observing night. The value of the public investments committed to each astronomical on-ground facility due to damages from the satellites is proportional to the loss in the scientific content of related observations.

The LBT example is representative of other observatories and project partnerships (e.g. ESO VLT [7], Keck Observatory [11], etc.) because for each medium-to-large size optical observatory facility, the financial loss percentage could easily be projected and extended as a lower limit to large area survey observatories, leading to more adversely affected optical professional and amateur facilities.

A representative quantification for the Italian Institute of Astronomy cost and investments for astronomical ground-based projects & facilities is > 100 million euros for 2015-2017, see [44]:

| Premiali: CTA,SKA | FOE: CTA,SKA,ELT, SRT,LBT,TNG | TOT      |
|-------------------|-------------------------------|----------|
| 54,000,000 euros  | 46,000,00 euros               | 100,000,000 euros |

So each partner of any telescope community, because of the satellites’ constellations, can quantify the related financial loss of value in principle, losing hundreds of millions of euros/dollars (of public money) per year, and cumulatively billions in decades.

For each nation and government, this financial loss has to be extended and integrated among each partnership in optical international collaboration projects. This is a very huge loss of value for the whole scientific community and for humankind as well.

Remain totally unquantified the scientific economic loss for radio-astronomy as well as the loss of intangible asset of the whole humankind given by the loss of natural night sky.

Still unquantified is the possibility to enter in the Kessler syndrome with the creation of a very dense debrids belt around the Earth in low orbit; in particular the Kessler study underestimate the rate of satellites injection in orbit desiring the rate...
of launches coming near zero in 2020. Kessler did not find an exact number of satellites in orbit above which the probability of cascade impacts would reach 100%, but it is possible that 50-100 thousand satellites in LEO could result in a very high probability of triggering a chain reaction in a very short time. This scenario will produce a unquantifiable damage to the whole Space exploration and not only to ground based astronomical observation.

APPENDIX A, LOW EARTH ORBIT CONSTELLATIONS TECHNICAL DETAILS

This compendium comes from [41] and [42] publications.

![Fig. 20. Comparison between a LEO satellite and a MEO satellite in terms of ground coverage.](image1)

![Fig. 21. Each orbit determination puts some constraints on the ground-based stations, and this puts other constraints on the cross-link between satellites to synchronize time and orbits; for this purpose the GPS MEO satellites are used.](image2)

There are three distinct regimes where satellites tend to reside:

1. **Low Earth Orbiting**, LEO satellites are generally placed between 400 and 1,500 km in altitude; lower orbits decay too quickly due to atmospheric drag, while higher orbit lifespan is cut short from radiation exposure in the lower Van Allen belt.

2. **Medium Earth Orbiting**, MEO satellites are placed between LEO and GSO, so above 1,500 km in altitude and below 35,000 km.

3. **Geo Synchronous Orbiting**, GSO satellites are placed just above 35,000 km; they are designed with orbital periods that matches that of Earth; if placed at the equator, these satellites stay in the same place in the sky.

The total number of satellites for telecommunications are very different depending on the service to provide and the altitude, see Table 2. It is possible to focus the attention only to a few constellation projects.

There is nearly an equal divide of the 1,419 operational satellites in orbit today, between LEO with 780 (+300 Starlink) and GSO with 506. There is not much placed in the vast distance between, nearly three Earths apart.

Between LEO and GSO, radiation levels are high, so MEO satellites demand specialized hardened components, so the number of these satellites is relatively low (∼ 100) and are dedicated mainly to navigation GPS services.

The Iridium constellation today consists of 66 LEO polar satellites. Fig. 19 shows the Iridium constellation in comparison with other LEO constellations and the current 31 satellite GPS constellation in MEO. It also shows the scale of the difference in altitude with Iridium at 780 km and GPS at 20,200 km.

The lower the orbital plane, the more satellites are needed to cover the Earth in LEO than in MEO (Fig. 20). This was one of the fundamental trade-offs considered in the design of the GPS constellation; but also, the higher the altitude, the higher the cost of each launch (Fig. 21).

On the other hand, the lower the altitude, the more satellites have to be built to provide coverage. To put this in perspective, global coverage for one satellite in view at all times requires less than 10 satellites in MEO but requires closer to 100 in LEO.

The Broadband LEO constellations have their optimal geometry at the poles. This is because the satellites are in polar orbits, meaning most of the constellation orbits in high latitude regions. This is shown in Fig. 23, which illustrates the typical number of satellites in view as a function of latitude. The Broadband LEOs again perform better in terms of number of satellites visible and their HDOP and VDOP, see Fig. 22.

Complication in orbital environment reflects in the proper use of cross-link between LEO satellites and with the use of GPS satellites for clock synchronization.

Navigation from LEO gives more strength because of the number of elements: more satellites and better geometry allows looser constraints on the orbit and clock.

Depending on the altitude, radiation environment allows for ‘careful’ cost design. Using closer satellites means stronger signals and resistance to jamming.

LEOs satellites move across the sky faster than MEOs, giving some multi-path rejection and covering base-stations better than geo-stationary satellites.

Constellation is more robust and fault tolerant than single satellite displacement. This decision was deliberate, as most of the current LEO constellation proposals emphasize offering global bandwidth access for end-users.

To understand the real demand of the population requesting the service, a demand model needs to be created. A map grid of resolution $0.1 \, \text{deg} \times 0.1 \, \text{deg}$ in latitude and longitude, can be generated in order to determine the number of people covered by the beams of a satellite located in a particular orbital position.

Assuming that any of the satellites will capture at most 10% of the market at each cell of the grid, a map of the demanded data rate can be created in Fig. 24.

To maximize the throughput of the systems depending on the demand rate and the real capacity of each constellation, it is foreseen to limit the maximum number of ground stations/gateway antennas per site to 50, even though a high degree of coordination among antennas would be required to operate without
Fig. 22. Vertical (L) and Horizontal (M) Dilution of Precision as a function of latitude for LEO and MEO, and median visibility (R).

Fig. 23. The medium time before degradation of a LEO satellite depends on the altitude; for very big projects like SpaceX it is foreseen to replace 4,000-8,000 Starlink satellites every year after the first five years.

Fig. 24. User data demand rate for different orbital positions.

Fig. 25. Number of ground station locations vs. demand region coverage.

interference, see Fig. 25.9

With the full configuration, SpaceX will reach 23.7 Tbps with 123 ground stations (for only 4,425 satellites), thus requiring an extremely large number of ground segments, with hundreds of ground stations and about 3,500 gateway antennas to operate at maximum throughput.

Facebook satellites constellation is expected to increase by a factor of 10 the SpaceX performances in terms of data I/O, this can be achieved or using higher frequencies or using more satellites than SpaceX.

APPENDIX B, PRIMER OF ASTRONOMICAL DATA REDUCTION

Considering astronomical observations as a collection of CCD outputs, it is possible to summarise all different intensity contributions as \( I(x,y) \), which is measured on the coordinate pixel \((x,y)\) of a RAW image. What is necessary to know is the luminous intensity \( i(x, y) \) matrix, that actually illuminates the pixel \((x,y)\).

The data reduction processing consists in extracting the \( i(x,y) \) matrix value from the RAW image matrix, \( I(x, y) \).10

\[ corrected = victim + x_{\text{coeff}}(\text{killer}_1 + ... + \text{killer}_N) \]

9Starting from this analysis, the SpaceX company will ask US FCC to upgrade the project with another 30,000 satellites in the V band, enhancing bandwidth and throughput as well. The number of foreseen ground stations is therefore increased to hundreds/thousands for each orbiting satellite.

10When a pair of (or multiple) CCDs are read out simultaneously, one chip (called “killer”) affects the counts of other chips (called “victims”), adding or subtracting ADUs from the real value; so it is necessary to equalize and correct for this effect over all chips of an image and write-out the corrected matrix.
To perform the first step in data-processing, it is possible to identify the three main contributions to the total intensity measured on the RAW image (see Fig. 26):

1. \( b(x, y) \), the BIAS contribution that is the pre-charged value of the CCD; this contribution is constant and independent of the temperature and the exposure time. It is possible to estimate this contribution by acquiring an exposure in total darkness (with shutter closed) with the shortest exposure time possible:

\[
lb(x, y) = b(x, y) \quad (5)
\]

2. \( d(x, y, t, T) \), the DARK contribution that is noise accumulated by thermal loads during the exposure. This contribution is proportional to exposure time \( i \), and for a given exposure time it is smaller as the temperature \( T \) is lowered; it is possible to estimate this contribution by acquiring in total darkness an exposure with the same exposure time and the same temperature of the science image. This kind of exposure contains the bias pre-charged level:

\[
ld(x, y) = b(x, y) + d(x, y, t, T) \quad (6)
\]

3. \( f(x, y) \), the FLAT (RESPONSE) factor of the pixels is only dependent on the \((x,y)\) positions and is estimated by the flat-field images. To estimate this contribution it is necessary to acquire a set of images of a particular exposure time on a flat illuminated screen/surface, so that \( i(x, y) \) is constant for all flat image pixels. This image contains both the bias and the dark contributions, but the dark may be negligible due to short exposure time of such frames:

\[
lf(x, y) = b(x, y) + d(x, y, t, T) + f(x, y)N_{FAC}
\]

\[
→ lf(x, y) = b(x, y) + f(x, y)N_{FAC} \quad (8)
\]

The relation that links together the three components is:

\[
I(x, y) = b(x, y) + d(x, y, t, T) + i(x, y)f(x, y) \quad (7)
\]

The goal of a cosmetic reduction is the extraction of the real signal reaching the CCD, and to do this it is necessary to extract the \( i(x, y) \) contribution:

\[
i(x, y) = \frac{I(x, y) - [b(x, y) + d(x, y, t, T)]}{f(x, y)}
\]

\[
→ i(x, y) = \frac{I(x, y) - ld(x, y)}{ld(x, y) - lb(x, y)}N_{FAC} \quad (8)
\]

Linking the \( b(x, y), d(x, y, t, T) \) and \( f(x, y) \) to the real calibration images (bias, darks and flat-fields), it is possible to extract the exact value of \( i(x, y) \) matrix in the pre-processing phase, also known as pre-reduction and/or photometric correction.

All other data processing, e.g. pixel cosmic rays masking, background subtraction, final astrometric mosaic stack + RMS and exposure map, relies on a good pre-reduction procedure/frames, which depends on the quality of calibration frames used for the whole pipelines chain, see Algorithm 1.

Satellites’ Constellations pollution can alter the most important data reduction steps (both for images and spectra), compromising the whole scientific content of astronomical ground-based observations.

The use of image-masks is fundamental to scientific optical data reduction, because it is possible to avoid spurious counts content in an astronomical image. In particular it has been remarked that it is not possible to replace the altered value with the local background around bad-pixels (trails, or cosmic rays, or ghosts, etc), because the the photometry would be altered too.

To preserve photometry it is necessary to produce a parallel masks of “good” and “bad” pixels and these masks have to be updated as each reduction step is performed (e.g. if a cosmic ray falls on some pixels and saturate them, those pixels are flagged to 1, then a “dilate” operation is performed to increase the isarea of related mask by a factor to be choose (2-4-10); the more is the dilate factor the more is preserved the photometry. In particular trails in fig.4 are related to dilated masks left by the passage of 3rd Mag satellites; trails used to resample and coadd the final mosaic are best seen in the single exposure in Fig. 6.
We summarize the whole standard "data reduction chain" for LBC data, see Algorithm 1 and [43] for details.

**Algorithm 1.** Standard Scientific Data Reduction Pipeline for LBC: to obtain a photometric calibrated mosaic and RMS map starting from raw ccd images, \( i(x,y) \)

- **Init:** mk masterBias + mk masterFlat + update BPM
- while FRAMES i(x,y) do
  - \( c(t) = (v(x,y) + XTCoeff \{ h(x,y) \} + \ldots + i(x,y)) \)  \( \rightarrow \) X-Talk
  - \( i(x) = \{ [(x,y)ld(x,y)]/ld(x,y)bb(x,y) \} \)  \( \rightarrow \) Pre-Reduce
  - \( cr(i(x)) \)  \( \rightarrow \) C.R. + Trail Mask
  - \( as(cr(x)) \)  \( \rightarrow \) Astrometric solutions
  - \( bk(as(x,y)) \)  \( \rightarrow \) BackSub + SuperFlat
  - \( mos(bk(x,y)) \)  \( \rightarrow \) Resample Coadd
  - \( RMSMap \) and \( ExpoMap \)

**APPENDIX C, REFERENCE SYSTEMS ADOPTED IN THIS WORK: THE LBC CASE STUDY**

![Graphical representation of Reference systems used in this work.](image)

The number of satellites passing in an LBC-like field of \( 23 \text{arcmin} \cdot 25 \text{arcmin} = 0.16 \text{deg}^2 \) is the (Number of satellites in the FOV at time \( t = 0 \)) + (Number of satellites passing in the diagonal of the rectangular FOV during the Total Exposure Time of the Mosaic); for the LBC FOV the diagonal linear dimension is \( \sqrt{23^2 + 25^2}/60 = 33/60 = 0.566 \text{deg} \).

So in \( \sim 1 \text{h} \) of Total Exposure Time computed in ERS, where \( \rho \geq 1.2 \) is the absolute satellite density:

\[
n_{\text{FOV}}(t = 0) = 0.16 \times 1.2 = 0.192 \text{sats at } t = 0
\]

\[
+ N_{\text{cross in 1h obs}} \rightarrow
\]

In one hour a satellite travels in the sky (in ERS at about 340km altitude) = 0.06 \times 3600 = 216 degrees, so 216 degrees with a density of 1.2 sat per deg = 260sats in a deg\(^2 \), then there will transit within the LBC diagonal of \( \sim 0.566 \text{deg} \approx 122 \text{sats in 1h} \) or just 1 satellite every \( \sim 30 \text{ seconds} \).

The same quantities can be computed in LRS where \( \omega \) is greater by a factor of about 20, but at the same time \( \rho \leq 0.06 \) is the lower local satellite density.

\[
n_{\text{FOV}}(t = 0) = 0.16 \times 0.06 = 0.0096 \text{sats at } t = 0
\]

\[
+ N_{\text{cross in 1h obs}} \rightarrow
\]

In one hour a satellite travels in the sky (in LRS at about 340km altitude) = 1.32 \times 3600 = 4752 degrees, so 4752 degrees with a density of 0.06 sat per deg = 285sats in a deg\(^2 \), then there will transit within the LBC diagonal of \( \sim 0.566 \text{deg} \approx 161 \text{sats in 1h} \) or just 1 satellite every 22 seconds.

Numbers are comparable (indeed in LRS trails are slightly more frequent) that’s why in a conservative way authors decided to keep the ERS by changing the observation point of view and greatly simplifying all the stuff.

**APPENDIX D, INTERNATIONAL CONVENTIONS AND TREATIES: A LEGAL APPROACH**

The Preamble of the World Heritage Convention holds that “the deterioration or disappearance of any item of the cultural or natural heritage constitutes a harmful impoverishment of the heritage of all the nations of the world” This protection appears again in the 1994 Universal Declaration of Human Rights for Future Generations:

Persons belonging to future generations have the right to an uncontaminated and undamaged Earth, including pure skies; they are entitled to its enjoyment as the ground of human history of culture and social bonds that make each generation and individual a member of one human family.

The UNESCO has undertaken activities for the safeguarding of cultural heritage related to astronomy under the “Astronomy and World Heritage” project launched by the World Heritage Centre in 2003. This concept was taken up again by UNESCO in 2005 as:

The sky, our common and universal heritage, is an integral part of the environment perceived by humanity. Humankind has always observed the sky either to interpret it or to understand the physical laws that govern the universe. This interest in astronomy has had profound implications for science, philosophy, religion, culture and our general conception of the universe.

This in turn led to the following concepts:

Astronomical observations have profound implications for the development of science, philosophy, religion, culture and the general conception of the universe. . . discoveries of astronomers in the field of science have had an influence not only on our understanding of the universe but also on technology, mathematics, physics and social development in general. . . the cultural impact of astronomy has been marginalized and confined to a specialized public.

These protections for Starlight are necessary as the impact that Starlight has held on humanity has been expressed in works of religion, art, literature, science, philosophy, business, and travel. To note the further enforcement of the Right to Starlight:

International law enforces international legal obligations, including property interests. Here, World Heritage is the property of all humankind, and while there may be protective laws, enforcing this is another matter, as only States can sue other States under this type of international treaty.
Concerns about Ground Based Astronomical Observations: Quantifying Satellites’ Constellations Damages in Astronomy

So a State is responsible for the activities that occur within its jurisdiction – whether they are authorized or unauthorized. Within the framework of International Law and State based legal instruments, Protection of Starlight could then be implemented in the same manner:
1. Reaffirms the sovereign rights and responsibilities, towards the International Community, of each State for the protection of its own cultural and natural heritage;
2. Calls upon the International Community to provide all the possible assistance needed to protect and conserve the cultural and natural heritage of Starlight;
3. Invites the authorities of States to take appropriate measures in order to safeguard the cultural and natural heritage of Starlight;
4. Further invites the States to co-operate with UNESCO, the World Heritage Committee, the UNWTO, and the Starlight Initiative with a view to ensuring effective protection of its cultural and natural heritage in Starlight.

Having established these rights under international law, the conclusion is that there exist duties for both States and international organizations to protect the World Heritage Right to Starlight, as well as, their duties to foster the rights of travelers, hosts, and providers of travel to enjoy this Starlight “property interest” that belongs to all humanity.

The existing legal instruments demonstrate the protection for the Right to Starlight, but it is the States that act as custodians of World Heritage that are charged with ensuring these rights are enforceable, and in turn made available to all of humanity.

**Legal Considerations**

SpaceX and other private company received permission from any government agencies (e.g. Federal Communication Commission, FCC for USA) to launch these satellites into orbit. So there could be a legal claim, within the US legal system, to halt the progress of Starlink fleet.

Also, as it turns out, according to the Outer Space Treaty and its progeny, there are no private companies operating in outer space, but only governments can operate in outer space. And the legal process is that the state government, this time the USA government, is legally responsible for all objects sent into outer space that launch from USA borders. That means, that it is the USA government that is responsible for the harm caused by its corporation, Starlink, sending objects into orbit that cause harm.

So under this international law, any country that suffers harm by Starlink can sue the United States (or any other) government in the International Court of Justice in the Hague. The harm here is damage to our cultural heritage, the night sky, and monetary damages due to the loss of radio and other types of astronomy. For the scientists, the owners of the observatories have a legal argument that they have and will continue to lose money spent for their research based on Earth based observatories. Furthermore, Universities that own the observatories are state owned universities, so it is the government that owns the observatories that have lost financially because of their interruption of study of the night skies.

So it is essential that a government, like Chile, Italy or France, sues the USA in the International Court of Justice to halt deployment of satellites’ mega-constellations.

If no national or international entity will stop this displacement, the right of the private companies (e.g. SpaceX) will become acquired at the beginning of March/April 2020.

How should the international astronomical community mobilize in order to stop further Starlink launches?

1. Sue in court for luminous pollution not taken into account by US FCC: The FCC’s lack of review of these commercial satellite projects violates the National Environmental Policy Act, NEPA, which obligates all federal agencies to consider the environmental impacts of any projects they approve. So in the most basic sense, SpaceX’s satellites displacement authorization would be unlawful, see [31].

2. Sue in court for lack of jurisdiction and jurisprudence of US FCC to authorize private not geostationary satellites over other states and nations.

3. Sue in the International Court of Justice, ICJ the USA government to put on hold further Starlink launches to quantify the loss of public finances in damaging national and international astronomical projects.11

**What can be done by Astronomers**

An international appeal/petition from astronomers was launched in January 2020 and, at the time of writing, thousands of astronomers involved with astronomical observatories and facilities, have subscribed the appeal, see [29]. Another open letter has been prepared regarding same concerns on the satellites constellations deployment for the further space missions and to raise awareness to US Senate, and US commissions on the possibility that occurs the Kessler Syndrome, see [34], which is a realistic scenario with all these orbiting objects, see [36].

Requests from the astronomical community to governments, institutions, and agencies all around the world are:

1. to be committed to provide legal protection to ground astronomical facilities in all of the available observation electromagnetic windows.

2. to put on hold further Starlink launches (and other projects) and carry out an accurate moratorium on all technologies that can negatively impact astronomical space based and ground based observations, or impact on the scientific, technological and economic investments that each State engages in astrophysical projects.

11 Though there are no international law that restrict mega constellations, to deploy and dispatch mega constellations an international agreement among states is needed, since satellites can not be located only over a single state (e.g. USA) but, being in LEO, they move around the globe passing over different states/nations/continents. This is a lack of jurisdiction of FCC authorization. In particular the International Court of Justice, ICJ, can be called into question whenever there is a dispute of international jurisdiction or between member states of the United Nations on the basis of international norms, treaties and / or their violations. In the beginning of chapter 5 it was explained how the World Heritage Convention regarding the “right of right sky / starlight” belongs to universal human rights and so no state can decide to contravene this convention if it interferes with the enjoyment of that right for other states. The pretext for appealing to the United Nations and the International Court of Justice (ICJ) is the loss of scientific value of the investments made for ground based projects by each state (damaged by SpaceX). Each damaged state, being damaged as consequence of a violation for an international treaty, the issue cannot be settled with a simple money compensation, but with an inhibition of the damage before the same occurs (and not after).
3. to put in place a clear evaluation of risks and predictive impacts on astronomical observatories (i.e. loss of scientific and economic value), giving stringent guidelines to private individuals, societies and industries to plan satellite investments without clearly understanding all of the negative effects on outstanding astronomical facilities.

4. that the US Federal Communications Commission (FCC) and any other national agency be wary of granting permission to ship non-geostationary low-orbit satellites into orbit or alternatively to limit the authorization of only satellites being above the airspace of the “home country”.

5. to demand a worldwide orchestration, where national and international astronomical agencies can impose the right of veto on all those projects that negatively interfere with astronomical outstanding facilities.

6. to limit and regulate the number of telecommunication satellite fleets to the “strictly necessary number” and to put them in orbit only when old-outdated technology satellites are deorbited, according to the Outer Space Treaty (1967) - the Art IX, and the United Nations Guidelines for the Long-term Sustainability of Outer Space Activities (2018) – guideline 2.2(c), requiring the use of outer space be conducted “so as to avoid [its] harmful contamination and also adverse changes in the environment of the Earth” and […] omission… risks to people, property, public health and the environment associated with the launch, in-orbit operation and re-entry of space objects”.

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NOTES
During the submission of this preprint at the same time a new article by ESO (Olivier R. Hainaut and Andrew P. Williams) was submitted to A&A, with different methodologies and different conclusions. It is not simple to compare such a different approach, but it is necessary to remark that in the ESO paper there is a huge underestimation in the total number of planned satellites, and neither VISTA nor VST were considered, while too much emphasis is given to telescopes with very short FOV, like VLT and ELT, where it is clear that statistically few satellites will fall into them.

At the following link it is possible to find the ESO article: arxiv.org/abs/2003.01992. Another article by CFA (Jonathan C. McDowell) was published specially related to Starlink Fleet; conclusions are similar to ESO’s paper, unfortunately it is necessary to note that only 12,000 starlink sats were considered, so the same concerns of ESO’s paper have to arise.

At the following link it is possible to find the CFA article: arxiv.org/abs/2003.07446.

REFERENCES
[1] S.Gallozzi, M.Scardia, M.Maris, “concerns about ground-based astronomical observations: a step to safeguard the astronomical sky”, feb.2020, arXiv:2001.10952: https://arxiv.org/pdf/2001.10952.pdf
[2] International Astronomical Union, IAU 1st statements: www.iau.org/ann19035
[3] International Astronomical Union, IAU 2nd statements: www.iau.org/iau2001
[4] ESO Very Large Telescope: www.eso.org/paranal-observatory/vlt
[5] Large Binocular Telescope, LBT: http://www.lbto.org/
[6] Large Binocular Camera, LBC: http://lbc.oa-roma.inaf.it/
[7] ESO Extremely Large Telescope, E-ELT: www.eso.org/elt and Very Large Telescope, VLT: www.eso.org/vlt
[8] Large Syhoptic Survey telescop, LSST: Vera_C._Rubin_Observatory
[9] ESO VLT Survey Telescope: surveytelescopes/vst
[10] Pan-STARRS Telescope: https://panstarrs.stsci.edu
[11] Keck Observatory: http://www.keckobservatory.org
[12] United Nations Office for Outer Space Affairs, “Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies”: introouterspacetreaty.html
[13] Committee on the Peaceful Uses of Outer Space, “Guidelines for the Long-term Sustainability of Outer Space Activities ”: https://www.unoosa.org
[14] Simulated prediction of “only” 12k Starlink satellites positions in the sky: www.youtube/LGBuk2BTyJE
[15] Simulated prediction of “only” 12k Starlink satellites naked eye view of the sky: www.youtube/9hQfKd9kfA
[16] Visualization tool to find, plot and search satellite orbits: https://celestrak.com/orbit-viz
[17] Phil Cameron, “The right to Starlight Under International Law”
[18] Starlight Initiative “Declaration in defense of the night sky and the right to starlight”: starlightdeclaration
[19] Marian Cipriano, “Starlight: a common heritage”, Published online by Cambridge University Press: 29 June 2011
[20] Marin, C., and Jafar, J. (eds) 2008, Starlight: A common Heritage(Tenerife: Instituto de As-trofísica de Canarias)
[21] Starlight Scientific Committee Report
2009, Starlight Reserve Concept:
http://www.starlight2007.net

[22] A.J. Beasley, E. Murphy, R. Selina, M. McKinno
& the ngVLA Project Team, “The Next Generation Very
Large Array (ngVLA)”, NRAO

[23] Square Kilometer Array, SKA:
https://www.skatelescope.org

[24] Avinash A. Deshpande and B. M. Lewis, “Iridium
Satellite Signals: A Case Study in Interference
Characterization and Mitigation for Radio Astronomy
Observations”, DOI: 10.1142/S22511719400009,
arXiv:1904.00502 [astro-ph.IM]

[25] Committee on Radio Frequencies Board on Physics
and Astronomy Commission on Physical Sciences,
Mathematics, and Applications National Research
Council "VIEWs of the Committee on Radio Frequencies
Concerning Frequency Allocations for the Passive
Services at the 1992 World Administrative Radio
Conference"

[26] Atacama Large Millimeter Array, ALMA:
https://www.eso.org

[27] SKA statements on satellites constellations:
ska-statement-on-satellite-constellations

[28] PATRICIA COOPER, "SATELLITE GOVERNMENT AFFAIRS
SPACE EXPLORATION TECHNOLOGIES CORP. (SPACEX)"
https://www.commerce.senate.gov

[29] APPEAL BY ASTRONOMERS:
https://astronomersappeal.wordpress.com

[30] Starlink testing encrypted internet form military US Air
Force purposes: https://www.reuters.com/article

[31] Starlink APPLICATION FOR APPROVAL FOR ORBITAL
DEPLOYMENT AND OPERATING AUTHORITY FOR THE
SPACEX NGSO SATELLITE SYSTEM: Legal-Narrative.pdf

[32] Starlink simulations from deepskywatch:
http://www.deepskywatch.com

[33] Volvach et al 2019, “An Unusually Powerful
Water-Maser Flare in the Galactic Source W49N”,
doi: 2019ARep..63..652V/doi:10.1134

[34] Donald J. Kessler, Burton G. Cour-Palais, “Collision
frequency of artificial satellites: The creation of a debris belt”,
doi: https://doi.org/10.1029/JA083iA06p02637 and direct link: pdf

[35] Ramon J. Ryan, Note, The Fault In Our Stars: Challenging
the FCC’s Treatment of Commercial Satellites as Categorically
Excluded From Review Under the National Environmental Policy
Act, 22 VAND. J. ENT. & TECH. L. (forthcoming May 2020)

[36] David Dubois, NASA “Open Letter to FCC, US Senate
and Commissions and SpeceX”, Open Letter to FCC and NASA

[37] Diego Paris, S. Gallozzi, V. Tresta “The processing system
for the reduction of the INAF LBT imaging data”, Presentation
to LBTO 2017 Users’ Meeting, Florence, 20-23 June 2017

[38] Seitzer, Pat (University of Michigan), 2020, “Presentation
to the US National Science Foundation Astronomy and
Astrophysics Advisory Committee”, Presentation to US NSF, A01A Committee

[39] Inigo del Portillo, Bruce G. Cameron, Edward F. Crawley,
"A Technical Comparison of Three Low Earth Orbit Satellite
Constellation Systems to Provide Global Broadband", 69th Inter-
national Astronautical Congress 2018, “A Technical Comparison
of Three Low Earth Orbit Satellite Constellation Systems to Pro-
vide Global Broadband”, www.mit.edu/Comparison-LEO-IAAC-
2018-slides

[40] Sardina Radio Telescope, SRT: http://www.srt.inaf.it

[41] Inigo del Portillo, Bruce G. Cameron et al, MIT, 2018
"A Technical Comparison of Three Low Earth Orbit Satel-
lite Constellation Systems to provide Internet Broadband"
doi.org/10.1016/j.actaastro.2019.03.040

[42] Tyler G. R. Reid, Andrew M. Neish, Todd F. Walter,
& Per K. Enge Stanford University, MIT, 2018 “Leveraging
Commercial Broadband LEO Constellations for Navigation"
doi.org/10.1002/navi.234 and presentations: presentation.

[43] Stefano Gallozzi, INAF-Observatorio Astronomico di
Roma, 2012 "Physical Data Reduction Methods" googledoc.

[44] INAF, "Piano della Performance dell’INAF (2017 –2019)";
https://performance.gov.it.

[45] MeerKAT, South Africa Radio Telescope:
https://www.sarao.ac.za/science-engineering/meerkat/.

[46] ASKAP, Australian Square Kilometer Array Pathfinder:
www.atnf.csiro.au/projects/askap. [47] ASTRI and ASTRI
MiniArray: www.braia.inaf.it/ astri.

[48] MAGIC TELESCOPES: magic.mpp.mpg.de.

[49] CTA Observatory: www.cta-observatory.org.

[50] H.E.S.S Telescope: www.mpi-hd.mpg.de/hfm/HESS.

[51] VERITAS Array: veritas.sao.arizona.edu.

[52] UNITED NATIONS OFFICE FOR OUTER SPACE AF-
FAIRS, "Space Debris Mitigation Guidelines of the Committee
on the Peaceful Uses of Outer Space": www.unoosa.org/pdf.

[53] The Guardian, “We’ve left junk everywhere: why space
pollution could be humanity’s next big problem”: the guardian
link.

[54] The Guardian, “Junk from China missile test raises fears
of satellite collision”: the guardian link.

[55] New Scientist, “India tests anti-satellite missile by de-
stroying one of its satellites”: New Scientist link.

[56] International Dark Sky Association, "IDA Responds to
Satellite Megaconstellations": IDA statement link.

[57] Forbes: Forbes link and CNET: CNET link

[58] Scientific American, “The FCC’s Approval of SpaceX’s
Starlink Mega Constellation May Have Been Unlawful”: Scien-
tific American link

[59] Microwave Journal, “5G Phased Array Technologies:
phased-array-technologies-ebook

[60] Anthony Mallama, “A Flat-Panel Brightness Model for
the Starlink Satellites and Measurement of their Absolute Visual
Magnitude”, https://arxiv.org/abs/2003.07805

[61] A. Grazian, et al, "The LBC Exposure Time Calculator",
lbc.oa-roma.inaf.it