CONSOLIDATED RECOMMENDATIONS FOR
LOW-EARTH ORBITING SATELLITE CONSTELLATION OPERATORS
TO MITIGATE VISIBILITY IMPACT ON ASTRONOMY
April 2023

Astronomers and satellite stakeholders met regularly in 2020-2021 to explore and advance the technical and policy issues surrounding the impact of satellite constellations on astronomy. In the United States, the American Astronomical Society (AAS) held the "SATCON 1" and "SATCON 2" workshops, and internationally, the UN Office for Outer Space Affairs (UNOOSA), the International Astronomical Union (IAU), and the Government of Spain jointly convened two "Dark & Quite Skies" conferences (D&QS I and II). Over 150 experts from astronomy, industry, space policy and the wider community conducted research and analysis to identify the issues and formulate recommendations toward mitigation, and then to implement and broaden the group of stakeholders.

The reports from four SATCON and D&QS reports combined: 1) provide an outline of the technical characteristics of satellite visibility and the impact on various types of ground-based optical observatories; 2) confirm an acceptable brightness level; and 3) identify various steps that satellite operators, observatories and governments could undertake to mitigate the effect of emerging satellite constellations on astronomy.

The implementation and ongoing development of these recommendations and best practices is now the core focus of the Centre for the International Astronomical Union's Centre for the Protection of Dark and Quiet Sky from Satellite Constellation Interference (CPS). The CPS is co-hosted by the International Astronomical Union (IAU), the U.S. National Science Foundation's NOIRLab, and the SKA Observatory (SKAO), an intergovernmental radio astronomy organization. For more information on the CPS and its work, see: https://cps.iau.org/

Below are the consolidated recommendations for operators of low-earth orbiting (LEO) satellite constellations, as excerpted verbatim from these four SATCON and D&QS foundational reports.

SATCON 1:
Full Report at: https://noirlab.edu/public/media/archives/techdocs/pdf/techdoc003.pdf

Recommendations for SATELLITE Operators (p. 21)

- Low-earth orbiting satellite constellation (LeoSat) operators should perform adequate laboratory Bi-directional Reflectance Distribution Function (BRDF) measurements as part of their satellite design and development phase, paired with reflectance simulation analysis
- Reflected sunlight ideally should be slowly varying with orbital phase as recorded by high etendue (effective area × field of view), large-aperture ground-based telescopes to be fainter than 7.0 V_mag +2.5 × log(r_orbit / 550 km), equivalent to 44 × (550 km / r_orbit) watts/steradian
- Operators must make their best effort to avoid specular reflection (flares) in the direction of observatories
- Pointing avoidance by observatories is achieved most readily if the immediate post-launch satellite configuration is clumped as tightly as possible consistent with safety, affording rapid passage of the train through a given pointing area
- Satellite attitudes should be adjusted to minimize reflect light on the ground

Recommendations For Observatories and Operators in Collaboration (p.22)

- Support an immediate coordinated effort for optical observations of LEOsat constellation members, to characterize both slowly and rapidly varying reflectivity and the effectiveness of experimental mitigations
- Determine the cadence and quality of updated positional information or processed telemetry, distribution, and predictive modeling required to achieve substantial improvement (by a factor of about 10) in publicly available cross-track positional determination
- Adopt a new standard format for publicly available ephemerides beyond two-line-elements (TLEs) in order to include covariances and other useful information

SATCON 2:
Full Report at: https://noirlab.edu/public/media/archives/techdocs/pdf/techdoc033.pdf

Implementation of SATCON 1 Recommendations: (p20-21)

- All operator-provided orbital solutions must include reasonable estimates of uncertainties, so observers with a variety of instrumentation can properly plan observations.
- Operators must publicly provide orbital solutions at a frequent and regular cadence for the benefit of observation planning and image masking.
- The recommended minimum update cadence is every 8 hours or whenever a maneuver happens, whichever is first.
- Operators should include future planned maneuvers whenever available.
- Operators should begin providing this information as soon as they successfully communicate with newly launched satellites.
- Operators should provide any other relevant metadata that may assist observers in assessing threats to optical and radio observations.
- This may include, e.g., reflectivity, bidirectional reflectance distribution function (BRDF), effective isotropic radiated power (EIRP), transmission band passes, nominal flux density at different frequencies, etc.

- All operators should adopt a standard format for ephemerides (state vectors, i.e., position and velocity data), such as the plain text NASA Modified ITC Ephemeris format that SpaceX presently uses. (ITC is the International Telecommunications Corporation.)
- All operators should adopt the Celestrak-recommended format21 for general perturbations (Simplified General Perturbations No. 4 (SGP4) time-averaged Keplerian elements that include drag computations, i.e., the orbital solutions presently provided in TLE format).
- Promptly establish a publicly-accessible Orbital Solution Portal website under the [IAU CPS] SatHub umbrella.
- Satellite operators should pay for the hosting and upkeep of this portion of SatHub. Celestrak presently serves a function similar to this, but the public's ability to retrieve satellite orbital solutions should not be confined to one volunteer-run resource.
- The Orbital Solution Portal should retain rather than overwrite past orbital solutions, so that data can be retroactively used for older observations, and also provide an easy lookup interface for retrieving data.
- Operators and astronomers should work together to write an opensource software tool that translates between ephemerides, the Celestrak-recommended format for general perturbations, and old-style TLEs.

Dark & Quiet Skies 1
Full Report at: https://noirlab.edu/public/media/archives/techdocs/pdf/techdoc021.pdf

Recommendations for Satellite Industry (p. 150-157)

Development of software to manage impacts of satellite constellations:
- R2: Support simulations of the effects on data analysis systematics and data reduction signal-to noise impacts of masked trails on scientific programs affected by satellite constellations. Aggregation of results should identify any lower thresholds for the brightness or rate of occurrence of satellite trails that would significantly reduce their negative impact on the observations. (Industry Role - provision of data)
- R3: Support development of a software application for observation planning available to the general astronomy community that predicts the time and projection of satellite transits through an image, given celestial position, time of night, exposure length, and field of view, based on the public database of satellite ephemerides. Current simulation work provides a strong basis for the development of such an application. (Industry role – provision of predicted ephemerides)
- R4: Support the development of a predictive model for satellite brightness versus orbit relative to an observatory, to create a predictive model of how a given satellite will appear in astronomical images and data products. This requires analyzing observations of satellite trails, collecting satellite bi-directional reflectance distribution function (BRDF) measurements to characterize how incident light is reflected, diffused, or absorbed by exposed surface elements during the design process, and satellite reflectance simulation analysis. (Industry role - provision of data)

Development of hardware/facilities to manage impacts of satellite constellations
- R6: Support the provision of additional telescopes to cover observing losses for science cases requiring low elevation twilight observations (e.g. Near Earth Objects), and to compliment spectroscopic observations with simultaneous exposures to determine if satellite trails passed through the FoV, and to support identification of noise subtraction or identification of affected fibers. (Industry role – provision of positional data)

Development of software to manage satellite constellation impacts

- R8: Support the development of reliable and accurate simulations that enable calculation of equivalent power flux density at radio observatory locations. (Industry role – provision of data)
- R9: Support developments to increase the robustness of receiver electronics and prevent saturation: Increase robustness of radiofrequency system's low noise amplifiers to tolerate higher input radiation power over a wide band. Increase dynamic range of receivers within data processing trade-off limits. Design radiofrequency and digital transport system to the highest possible dynamic range. (Industry role – provision of data)

Raise awareness amongst key stakeholders

- R10: Participate in astronomy conferences and educational workshops, and likewise, encourage astronomy stakeholders to participate in satellite industry fora. (Industry, Satellite industry associations)
- R11: Include fundamental science and astronomy as considerations in initiatives to increase corporate social responsibility and in the development of best practices and standards. (Industry, Satellite industry associations)

Design missions to minimize negative impacts on astronomical observations

- R12: Conduct missions from the lowest possible altitudes, in order to minimize the time satellites are illuminated.
- R13: Minimize the number of satellites required to fulfil their missions. In general, minimizing altitude should take priority over minimizing the number of satellites.
- Minimize the time satellites spend in orbit when not in service.

Design satellites to minimize negative impacts on astronomical observations

- R15: Design satellites to minimize overall brightness at all orbital phases, dynamic variations, and specular flares when observed from the ground. Investigate and implement all commercially reasonable design and operational measures to reduce average brightness from diffuse reflection as much below 7 visual magnitude as possible. Reflected sunlight ideally should be slowly varying with orbital phase to be fainter than 7.0 Vmag +2.5 × log
- (SatAltitude / 550 km), or equivalently, 44 × (550 km / SatAltitude) watts/steradian, as recorded by high etendue (effective area × field of view), large-aperture ground-based telescopes.
- R16: Conduct reflectance simulation analyses on satellite designs and perform Bi-directional Reflectance Distribution Function (BRDF) measurements on satellites as part of development activities.
- R17: Provide greater detail on antenna power density fluxes, beam patterns and out of band sidelobes across the range of operating frequencies, than provided for ITU and regulatory filings. Design satellites to have sidelobe levels that are low enough that their indirect illuminations of radio telescopes and radio quiet zones do not interfere, individually or in the aggregate.

Conduct satellite operations in a manner that minimizes negative impacts on astronomical observations

- R18: Provide astronomers with pre-launch predictions and timely post-launch confirmations of the initial deployment orbits for satellites.
- R19: Maintain and make available to astronomers, satellite ephemeris predictions with a sky location precision of arcseconds and a time precision of a tenth of a second, up to 12 hours in

advance. Ephemeris predictions should be accompanied by covariance information and other (to be determined) metadata necessary to support mitigation efforts by observatories. (Note: these positional and timing requirements need further analysis)

- R20: Support the development of software applications for astronomical observation planning.
- R21: Minimize the possibility of specular reflections and flares interfering with observatory activities through operational means (i.e., articulating components, controlling orientation, etc.). If flares cannot be avoided, operators could work with affected observatories to predict such occurrences.
- R22: Provide predictive models for satellite brightness versus orbit, relative to geographic locations.

Support collection of observational data (partnership with Industry and observatories)

- R29: Support an immediate coordinated effort for multiple spectral bands in optical and infrared observations of LEOsat constellation members, to characterize both slowly and rapidly varying reflectivity and the effectiveness of experimental mitigations. Such observations require facilities spread over latitude and longitude to capture Sun-angle-dependent effects.
- In the longer term, support a comprehensive satellite constellation multispectral observing network with uniform observing and data reduction protocols for feedback to operators and astronomical programs. Mature constellations will have the added complexity of deorbiting of the units and on-orbit aging, requiring ongoing monitoring.

Licensing Requirements

- R34: Formulate satellite licensing requirements and guidelines that take into account the impact on stakeholders, including astronomical activities, and that coordinate with existing efforts in relation to radio astronomy and space debris mitigation.

Dark & Quiet Skies II. (p. 85 onward)
Working Group Reports at:
https://noirlab.edu/public/media/archives/techdocs/pdf/techdoc051.pdf

National policy and regulatory recommendations to implement D&QS 1 Recommendations

Provision of Industry Data during design process and after deployment: Operational Data, Spacecraft Data, and Radio Emission Data:

- Industry should provide real-time data (8-hourly updates or after maneuvers) to the astronomy community, either via government or third-party portal or central clearing house, such as the IAU Centre.
- Industry should provide measured spectral masks of the radio transmitters on board satellites to allow radio observatories to anticipate potentially contaminated channels.
- (Joint) Governments and industry should develop mechanisms to improve the ability of space operators to share proprietary and commercial or security sensitive data with third parties, including the development of common or interoperable standards for space situational awareness data.
- Industry should establish joint testing schemes in collaboration with astronomers to model reflectance on radio emission profiles.
- (Joint) Governments and industry should support the development of space domain decision intelligence collecting data of proposed satellite constellations and existing orbiting space objects, modeling satellites, their operations in the space environment, and estimate

uncertainties to assess the impact of satellite constellations on ground-based astronomical observations.

Required Engineering and Operational Constraints on Individual Satellite Units and overall mission design, which should ideally be regulated by a licensing process

Minimization and control of reflectance:

- Industry should provide real-time data on satellite attitude and spatial orientation (8-hourly updates or after maneuvers) to the astronomy community, either via government or third party portal or central clearing house, such as the IAU Centre.
- (Joint) Governments and industry should collaborate to determine a pathway to meeting the reflectance requirements.

Minimization of illumination of radio quiet zones:

- Industry should be encouraged to utilize satellites to avoid direct illumination of radio telescopes and radio-quiet zones, especially high-power applications.
- Industry should be encouraged to minimize antenna sidelobe levels so that their indirect illuminations of radio telescopes and radio-quiet zones do not generate interference, individually or on aggregate.
- In collaboration with the radio astronomy community and industry, governments should develop an internationally agreed mechanism to protect radio-quiet zones and observatories from unnecessary and unintentional electromagnetic radiation.

Minimization and control of intentional optical transmissions

- Industry should provide real-time data on optical transmissions from satellites (8-hourly updates) to the astronomy community.

Minimization of satellite operational altitudes

- Industry should:
    - Minimize operational altitudes – satellites in constellations with higher orbital shells are illuminated by the Sun for longer during the night and appear more ‘in focus’ to telescopes; in general, the impact on astronomy increases with constellation altitude. Scientific analysis shows that orbits on the order of 600 kilometers or below offer a compromise between brightness and the length of time satellites are illuminated during the night;
    - Minimize the number of satellite units as second priority to altitude while maintaining safe operational practices.

Orbital Control of Space Objects

- Industry should ensure that satellites are minimally reflective during the operational raising phase.
- Industry should minimize the time spent in orbit when not in service.

Cooperate:

Broader, Cross-cutting policy measures:

- Development of Industry Standards -- Government and industry should develop spacecraft systems and operational standards that take into account the impacts on astronomical science. Areas include: reflectivity of surface materials, brightness of space objects, telemetry data, spurious and out-of-band emissions and unintentional electromagnetic radiation (i.e., electronic noise).

- Incentives for corporate social responsibility -- Governments, industry and the astronomy community should create mechanisms for industry and government to take responsibility for damage to scientific space activities, in the event that regulatory, licensing and voluntary measures are insufficient.
- Industry and the astronomy community should collaborate to create rating schemes for satellite operators to demonstrate the ability to share information with the astronomy community, enact recommended mitigations and support policies to protect the dark and quiet skies.

Recommendations for industry:

- Satellite operators were more likely to adopt voluntary practices or mitigation tools if they engaged with astronomers early in their project cycle, before spacecraft designs were finalized and when modifications to architectures, spacecraft design or operations could be introduced at less cost or schedule impact.
- To that end, a series of "best practices" were identified, which could be adopted by existing and new satellite manufacturers and operators, in addition to providing guidance for regulatory authorities.
- These guidelines are at an early stage of development, and future cooperation and collaboration with industry is recommended to advance their development.

Dark & Quiet Skies II. Working Group Report Chapter 4: Industry Working Group, starting (page 236 onward)
https://www.iau.org/static/science/scientific_bodies/working_groups/286/dark-quiet-skies-2-working-groups-reports.pdf

I. Priority No. 1: Address the visible brightness of the satellites as seen from the ground.
   A. Objective: Reduce brightness to minimize impact on astronomy and night sky observers
   B. Guidelines:
      1. Endeavor to reach the fainter of these in all phases of a constellation:
         a) Unaided eye visibility[1]: V > 7.0 mag where V is the photopic vision sensitivity curve. Or
         b) $V > 7.0 + 2.5 \log_{10}(r_{orbit}/550 \text{ km})$, equivalent to $44 \times (550/r_{orbit})$ watts/steradian, where r_{orbit} is the mean altitude of the satellite orbit in km and V in this case is the Johnson V bandpass at 550 nm.
      2. Encourage that reflectance simulation analysis be performed by operators/manufacturers as part of the satellite design and development phase.
         a) Pair with laboratory Bi-directional Reflectance Distribution Function (BRDF) measurements.

[1] Some relevant information on the color dependence is contained in the analysis of satellite impacts on the Rubin Observatory by Tyson et al. (2020, Astronomical Journal, 160, 226). These limits depend on the sensitivity of the Rubin Observatory system, including the filters and detector. Brightness limits in other bands within the LSST bandpass system, which still permit cross-talk calibration, are $u \approx 5.5$ mag; $r \approx 7$ mag; $i \approx 6.5$ mag; $z \approx 6.8$ mag; and $y \approx 6.5$ mag. Remaining fainter than these limits is comparable to adhering to $V \geq 7$ mag at 550 km. Note that these are not equivalent to a wavelength-independent reflection of the solar spectrum. Visual reference for LSST filter bandpasses are found at https://www.lsst.org/scientists/keynumbers.

3. Noting that reflected sunlight is slowly varying with the orbital phase, and that flares are rare events, endeavor to reduce and/or control the effect of specular reflection (flares) in the direction of the ground, as follows:
    a) Design/manufacture satellites with reduced number of facets on the reflective surface, where practicable.
    b) Minimize non-rigid specular materials on the nadir face of the satellites, where practicable.
    c) Minimize, where practicable, the fine texture on the reflecting surface of the satellite, such as multi-layer insulation, which creates rapidly varying reflectivity known as glints.
    d) If operationally viable, adjust attitude to avoid flares projecting onto major ground-based observatory sites.

II. Priority No. 2: Address the visibility impact on astronomical sciences of large constellations of low earth orbit satellites with altitudes above 600 km.
   A. Objective: Navigate the balance between constellation size and altitude to allow achievement of satellite service objectives while minimizing impact on astronomy
   B. Guidelines
      1. Endeavor to have satellite constellations operate in orbits with altitudes below about 600 km, if practicable, when consistent with operational and safety objectives and constraints, in order to minimize the rate of sunlight streaks in the dark hours between evening and morning twilight for the largest-aperture telescopes.
      2. If the constellation cannot be planned for altitudes below ~600 km, the impact on astronomical observations would still be reduced on balance if the constellation designers were to choose a lower rather than higher operational altitude.

   Note: The altitude of the low earth orbit satellite constellation does not have uniform impact on observations around the world. Lower orbit altitudes impact programs disproportionately at latitudes outside of +35 and -35, and increasing the number of satellites on orbit impacts programs that depend on observations in twilight, such as those for planetary defense. Further, if the satellites are not dimmer than naked-eye brightness natural and cultural heritage may be affected.

III. Priority No. 3: Provide access to high accuracy public data on predicted locations of individual satellites (or ephemerides).
   A. Objective: Enable the real-time use of high-accuracy public data on satellite locations to enable some adjustments to observational strategies and reduction of disruptions.
   B. Guidelines:
      1. Endeavor to provide publicly-available live-updated positional information or processed telemetry on low earth orbit satellites that is accurate enough to enable telescope pointing avoidance and mid-exposure shuttering during satellite passage.
         a) Any information provided should be provided through a database that enables astronomers to determine that the transit of any unit across the field during the exposure interval can be predicted within 12 hours in advance of the observation, to an accuracy of 2 seconds in time. Where practicable, enable astronomers using the

database to know the position of the track to within 6 arcminutes in the cross-track direction and 6 arcminutes in position angle.

2. The satellite and observation communities should [use][develop jointly] a new standard format for publicly available ephemerides beyond two-line-elements (TLEs) in order to include covariances and other useful information.

IV. Priority No. 4: Orbit raising and deorbit considerations

A. Objective: Minimize disruptions to observations from satellites immediately post launch and during de-orbit/reentry phases of operation.

B. Guidelines:

1. Immediate post-launch satellite configuration in multiple-satellite launches be grouped as tightly as practicable, consistent with safety-of-flight and other relevant considerations, thereby affording rapid passage of the train through a given telescope's pointing area.
2. Endeavor, where practical to control post-launch and reentry attitudes to minimize reflected light on the satellites' ground track.
3. Deorbit as soon and as quickly as practicable, taking due account of relevant protocols for such operations, while also taking into account brightness mitigations, where practicable.

V. Priority No. 5: Continued Collaboration between the Observation and Satellite Communities.

A. Objective: Enabling astronomers and industry to collaborate to ascertain and confirm the efficacy of mitigation techniques through follow-up observations and apply/publicize positive lessons learned

B. Guidelines:

1. Support a comprehensive satellite constellation observing network with uniform observing and data reduction protocols for feedback to operators and astronomical programs. Mature constellations will have the added complexity of deorbiting of the units and on-orbit aging, requiring ongoing monitoring.
2. These standards reflect recommendations that are based on the current state of knowledge of constellation designs and the coupling between orbits and illumination. It is understood that this knowledge may evolve due to operational experience or changes in constellation designs. Periodic reassessment of these recommendations will be necessary in collaboration between operators and the astronomical community.
3. Establish a practical means for coordination between the satellite and observing communities regarding collection of data through the IAU Center on the Protection of Dark and Quiet Sky.

Possible Draft Action Plan on D&QS Non-GSO Matters

Problem-focused interaction between organizations can happen in several distinct modes (e.g., often called coordination, cooperation, collaboration) where each mode represents a higher level of joint problem solving, information sharing, shared goals, leadership commitment and trust. Interaction structures should aim to enhance these dimensions. Industry—astronomy community interaction structures should facilitate the following roughly sequential steps, moving from deconfliction to cooperation to collaboration.

The points below build upon initiatives and ideas presented in the Dark and Quiet Skies 2020 Recommendations (listed in Annex 1 below).

I. In furtherance of SatCon 3, identify core constituency from among astronomers, satellite system designers/manufacturers/operators, and regulators to discuss:
    A. Next steps to address non-GSO satellite issue impacts on astronomy
        1. Gain awareness of astronomy impacts
        2. Understand qualitative impact category
            a) High priority: NGSO constellation systems (need to work on rough criteria...e.g. totalling X units (meaning Y are overhead at any one time) in LEO or MEO. Include satellite mass (or albedo), presence of nadir facing reflective surfaces and certain spectrum usage;
            b) Second priority: all other types of satellite and space systems.
    B. How to consider/address impact of future changes in astronomy or the non-GSO satellite industry early in the respective project cycles
    C. Work under the IAU Centre umbrella to continue to host the means to mitigate the issues.
        1. Invite core constituency members and Centre personnel to participate in bilateral discussions, host a regular event (e.g. annual or semi-annual forum meeting online or in person) to review current updates, share information, and review proposals for joint research and development.
        2. Establish sub-groups that meet regularly to address specific areas that need addressing (software issues for avoidance, observations for brightness determination, better TLE determinations that are accessible by observatories, hardware testing to minimize brightness, etc) and meet with other astronomy-based working groups with overlapping topics.
        3. Engage in awareness raising activities at industry and academic conferences, and via media publications.

II. In furtherance of Sat_Con 4, 5, 6 and 7, agree on set of Best Practices Guidelines for Industry and Astronomy
    A. Identify methods for provision of/exchange of timely, transparent, and reliable data between Industry and the astronomy community to assess effectiveness of and make any necessary adjustments to Best Practices.
        1. Data should include, as appropriate, relevant information on spacecraft design, brightness, mission designs/orbital profiles, attitude control, and predicted and real-time orbital elements.
        2. Information from astronomers on observation practices and plans, as appropriate and relevant, should be provided to Industry by the astronomy community on a regular basis in a common format.
    B. Provide guidance on how to optimize (for both groups) operational altitude issues, performance objectives, numbers of satellites, and post-service considerations.
    C. Identify steps available to Industry to:
        1. Practicably minimize maximum brightness of spacecraft;
        2. Practicably reduce main-beam illumination of radio observatories and radio quiet zones;
        3. Practicably reduce individual and aggregate indirect illumination of radio observatories and radio quiet zones;
    D. To implement methods identified, the following points should be considered, as applicable:
        1. Mechanism for organizational commitment to take action;

2. Develop internal review of how company would impact along elements provided by the astronomy community;
3. Commitment/deployment of resources to work and test potential mitigation techniques;
4. Regularly monitor best practices for future research needs and potential government actions.

E. Formulate research funding requirements. Governments are supporting the development of satellite testing facilities services, and also could fund innovation / technology research on advanced non-reflective materials

III. Proposed Timeline for Actions

A. Establishment within the core constituency (IAU Centre)
B. Adopt Best Practices Guidelines - Q1 2022
C. Address potential sensitive information issues and establish meaningful data sharing mechanism - Q3 2022