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<th>Additional Definitions / Tolerance / Threats / Provenerance</th>
<th>Subsequent Recommendations</th>
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<td>Limit on reflected sunlight from satellites.</td>
<td>Reflected sunlight shall be slowly varying with orbital phase as recorded by high asteroid, large-area ground-based telescopes to be less than 7.0 mags (&lt;2.5x log(ε) orbital ≤ 550 km), equivalent to &lt;64x250 km r/ε orbital watts/steradian for r &gt; 550 km, V=7.0 mag for lower orbits.</td>
<td>1) Make satellite's operational orbit invisible to the unaided eye. 2) Guarantee that satellite reflections do not make the cross-tail parallel streamers in Pushun Observatory images unrecognizable, which would increase noise by ~10x. Satisfying the condition for this telescope, with the highest altitude (field of view of a primary mirror (effective area) is assumed to satisfy most other telescopes’ constraints.</td>
<td>0.25 mag / 10% network for reflec, detected visible brightness as possible for small changes in sun/viewing angle, share modeling predictions as part of coordinated process.</td>
<td>Function defining upper limit of amplitude vs. temporal frequency. A high-amplitude flare is any instance where a satellite's brightness is observed to increase by at least 2x (approx 0.75 mag) over its quiescent baseline level for the amount of time for the satellite to traverse at least 0.5° in a telescope field of view. Defined by &quot;structure function&quot;, the limits on the distribution of variability amplitude as a function of timescale. Requires from industry for clear limits on variability.</td>
<td>Operators to provide radiometric variability model based on materials reflectivity, bidirectional reflectance distribution function as function of wavelength of reflected sunlight. The physical basis of the model should be provided to the degree possible. Validation through ground-based measurement of in-orbit flare incidence and brightness compared to modeling predictions.</td>
<td>Operators to demonstrate best efforts technical approach to meeting the brightness requirements. 1) General derivation of tolerances for quantitative limits. 2) Validated modeling approach for predicting reflectively as function of solar phase angle and viewing angle. 3) Reference libraries and measuring capabilities for materials reflectivities.</td>
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<td>Flares &amp; Glints</td>
<td>Minimize the occurrence of high-amplitude flares projected onto the ground for as little fluctuation in detected visible brightness as possible for small changes in sun/viewing angle, share modeling predictions as part of coordination process.</td>
<td>Enabling time and position prediction for avoidance of bright, rarest events.</td>
<td>1) Perform adequate BRDF testing of various materials to be collected/developed. 2) Acceptable quality of BRDF measurements for this purpose. 3) Reference libraries and measuring capabilities for materials reflectivities.</td>
<td>BRDF testing of various materials (used or considered for use on LEO satellites) provides measurements that will indicate best choices for reduced brightness toward observatories. Satellite bi-directional reflectance distribution function (BRDF) measurements.</td>
<td>2) Validated modeling approach for predicting changes in reflectively for small changes in solar phase angle and viewing angle.</td>
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<td>Short- and long-term optical/IR monitoring</td>
<td>Support an immediate coordinated effort for multiple spectral bands in optical and infrared observations of LEO satellite constellations. In the longer term, support a comprehensive satellite constellation multispectral observing network with uniform observing and data reduction protocols.</td>
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<td>BRDF in an effort to minimize the brightness of satellite surfaces during the satellite design and development phases. LECh operators possessively in collaboration with astronomers should do one of the following: 1) Perform adequate BRDF testing of various materials (used or considered for use on LEO satellites) provides measurements that will indicate best choices for reduced brightness toward observatories. Satellite bi-directional reflectance distribution function (BRDF) measurements.</td>
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<td>Standardization of measurement and data reporting protocols. [Currently undevelopment by SATCON and to be disseminated via Satellite Constellation Observation Repository (SCOR).]</td>
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**Band  Wave  Lim mag  Refl Sun wrt g**

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<tr>
<th>Band</th>
<th>Wave</th>
<th>Lim mag</th>
<th>Refl Sun wrt g</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>755</td>
<td>6.8</td>
<td>1.06</td>
</tr>
<tr>
<td>r</td>
<td>622</td>
<td>7.0</td>
<td>1.14</td>
</tr>
<tr>
<td>g</td>
<td>467</td>
<td>5.5</td>
<td>0.047</td>
</tr>
<tr>
<td>u</td>
<td>367</td>
<td>5.5</td>
<td>0.047</td>
</tr>
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**Tolerance / Threshold values:**

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<tr>
<th>System</th>
<th>Tolerance</th>
<th>Threshold</th>
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<tbody>
<tr>
<td>r_orbit</td>
<td>&lt; 550 km</td>
<td>&gt; 550 km</td>
</tr>
<tr>
<td>V</td>
<td>&lt; 7.0 mag</td>
<td>&lt; 7.0 mag</td>
</tr>
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**Magnitudes:**

- **Tyson et al. (2020):**
  - V = magnitude.
  - For optical wavelengths, the faintest measurable signal is V ≥ 7.0 mag.
  - For infrared wavelengths, the faintest measurable signal is V ≥ 5.5 mag.
  - The magnitude threshold for detection is V ≥ 5.0 mag.

**Equations:**

- **Etendue:**
  - Etendue is effective area × field of view.
- **Telescope:**
  - The highest effective area, which would provide the degree possible. Validation through ground-based measurement of in-orbit flare incidence and brightness compared to modeling predictions.
- **Astronomical Need:**
  - Astronomers should do one of the following: 1) Perform adequate BRDF testing of various materials to be collected/developed. 2) Acceptable quality of BRDF measurements for this purpose. 3) Reference libraries and measuring capabilities for materials reflectivities.

**Recommendations:**

- **BRDF testing of various materials (used or considered for use on LEO satellites) provides measurements that will indicate best choices for reduced brightness toward observatories. Satellite bi-directional reflectance distribution function (BRDF) measurements.**

**Definitions:**

- **BRDF (Bidirectional Reflectance Distribution Function):**
  - BRDF is a measure of the angular dependence of the reflectance of a surface. It describes how the reflectance of a surface varies with the angle of incidence and viewing angle. The BRDF is defined as the ratio between the reflectance of a surface at a particular angle and the reflectance of a perfectly diffuse surface at the same angle.

**Units:**

- **Watts steradian−1 degree−1 cm−2 cm−2 sr−1:**
  - The units of BRDF are usually expressed as watts steradian−1 degree−1 cm−2 cm−2 sr−1, where watts is the unit of power, steradian is the unit of solid angle, degree is the unit of angle, cm is the unit of length, and sr is the unit of solid angle.

**Related Technical Recommendations and Resources to be Collected / Developed:**

- **Ref: M2 and M3 from Mitigations WG report; S5 from SATCON; see also Tyson et al. (2020), Eq 5.6 for context to the formula.**

**Data:**

- **Table D-18 Report p.155:**
  - [Ref: M2 and M3 from Mitigations WG report; S5 from SATCON; see also Tyson et al. (2020), Eq 5.6 for context to the formula.]

**Additional Definitions:**

- **BRDF (Bidirectional Reflectance Distribution Function):**
  - BRDF is a measure of the angular dependence of the reflectance of a surface. It describes how the reflectance of a surface varies with the angle of incidence and viewing angle. The BRDF is defined as the ratio between the reflectance of a surface at a particular angle and the reflectance of a perfectly diffuse surface at the same angle.

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<td>Agreement to protect radio observatories</td>
<td>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.</td>
<td>Radio-quiet zones are now protected typically by national regulation from ground-based radio transmissions and EMI. No such protection exists from radiation from satellites.</td>
<td>A radio quiet zone (RQZ) is an area in which radio transmissions are restricted by law to facilitate scientific research and/or military activities. Most broadcast transmitters in the central area of an RQZ are required to operate at reduced power and use directional antennas.</td>
<td>The frequency levels for radio astronomy bands are defined in the Recommendation ITU-R RA.769. Governments can define wider frequency protections in RQZs with thresholds tailored to the specifics of the instruments and the geographic site. (See Report ITU-R RA.2259, “Characteristics of Radio Quiet Zones”)</td>
<td>National governments to require as a condition of licensing that large satellite constellations in operation mitigate the impact of their intentional and unintentional radiation at Radio Quiet Zones.</td>
<td>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.</td>
<td>1) Methods to consider aggregate effect of satellite constellations. 2) Effect of Unintended Electromagnetic Radiation in radio astronomy bands. 3) Authoritative list of worldwide radio-quiet zones for protection - ITU-R Item adopted 2023.</td>
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**Sharing technical information**

Operators should provide relevant metadata, including, e.g., effective isotropic radiated power (EIRP), transmission band passes, nominal flux density at different frequencies, measured spectral masks, etc. Such information may assist observers in assessing and avoiding threats to radio observations through observation planning including choice of frequency and through more detailed modeling.

- **SATCON1 Rec 9 & 10; SATCON2 Report p156**
- **ITU and national governments require, as a condition of licensing, the sharing of as much relevant metadata as practicable, consistent with protection of competition-sensitive information.**
- **Satellite operators should be encouraged to share the details of their radio systems to a much greater extent than contained currently in public filings with the International Telecommunications Union or radio spectrum regulators that support their authorization or licensing.**

**Funding radio technical development**

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

- **Awareness and mitigation of the increasing activity in the electromagnetic environment due to large satellite constellations.**
- **D&QS1 Report p152:**
- **National funding agencies provide support for radio technology development through universities, national centers and industry.**
- **Existing research programs prioritize these issues: JU ICPS Industry and Technology Hub catalyzes research partnerships between industry and academic institutions.**

**Developing techniques and standards for spacecraft**

Government and industry should develop techniques and operational standards aimed to mitigate impacts on radio astronomical science. Areas include: spurious and out-of-band emissions and unintentional electromagnetic radiation (i.e., electronic noise), coordination methods.

- **Codifying industry best practices.**
- **D&QS2 Report p89**
- **Learning requirements to include technical best practices for mitigating impact on radio astronomy.**
- **Encourage the development, implementation and sharing of technical best practices, including through the JU ICPS I&T Hub.**

**Creating radio dynamic zones**

Develop inquiries and recommendations that encourage flexible technology that can better share spectral resources while ensuring protection of sensitive radio astronomy operations. Consider study of and incentives for new transmitter requirements toward a dynamic approach where coordination could be automated and based on the frequency of the scientific observation being taken and the direction in the sky where the radio telescope is pointed.

- **Coupled with dynamic spectrum hopping and other techniques, these types of dynamic models could enhance spectrum efficiency and replace the current static model of quiet zones that assume fixed transmitter requirements based on a given set of parameters.**
- **D&QS1 Report p156**
- **Expand ITU rules and national implementations of protection of radio observatories and radio-quiet zones to enable dynamic radio zones with appropriate technical coordination.**
- **Begin the technical development of the required technical coordination mechanisms and execute pilot experiments.**
**Category** | **Astronomical Need** | **Rationale** | **Additional Definitions** | **Tolerance / Threats/Provenance** | **Subsequent Recommendations** | **Policy Approach to Implementing Recommendations** | **Short-Term Implementation** | **Related Technical Recommendations and Resources to be Collected/Developed**
---|---|---|---|---|---|---|---|---
Orbit altitude | Operate in orbits with altitudes below about 600 km, if practicable, when consistent with operational and safety objectives and constraints. If the constellation cannot be planned for altitudes below ~600 km, choose the lowest practicable operational altitude. | 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 approximately 600 kilometers or below offer a compromise between brightness and the length of time satellites are illuminated during the night. This choice minimizes the rate of sunlight streaks in the dark hours between evening and morning twilight for the largest-aperture telescopes, which are located in the range of altitudes < 35 deg. | **Tolerance of at least 100 km for significant increase of frequency of streaks after twilight.** | **Subsequent Recommendations** | **Create regulatory incentive for LEO constellation operators to choose lower orbits, consistent with their mission specifications and space traffic management requirements. Fund research on carrying capacity of orbital shells at lower elevations.** | **Inform and solicit cooperation of new operators to choose lower orbits.** | **Create regulatory incentive for LEO constellation operators to choose lower orbits, consistent with their mission specifications and space traffic management requirements. Fund research on carrying capacity of orbital shells at lower elevations.** | **Inform and solicit cooperation of new operators to choose lower orbits.**

Number of constellation satellites | Minimize the number of satellites required to fulfill their missions. | The astronomy figure of merit is minimizing the number of streaks per exposure. Programs that are particularly impacted are those observing closer to the horizon in twilight. It is recognized that astronomy’s need for lower orbits and smaller numbers is in direct conflict with operator need for more satellites at lower altitudes to maintain constant latency/standard deviation. In general, minimizing altitude has the most positive impact on minimizing the incidence of streaks in dark time. Any steps that reduce the risk of debris-producing collisions thereby reduce the risk of increased diffuse scattered sunlight. | **Minimizing the number of satellites with altitudes below ~600 km, if practicable, when not in service. Conducting orbit raising and deorbiting phases is equal to the deorbit phase for the Sustainability of the pre-spacecraft.** | **Regulatory filings should contain the latency/brightness requirements for the specific areas that drive the design choice for number of satellites, to demonstrate that the minimum number (with margin) are being deployed.** | **Encourage transparency in regulatory filings to define the scope of planned constellations.** | **Astronomical definition of the threshold for harm in number of streaks per exposure.** | **Encourage transparency in regulatory filings to define the scope of planned constellations.** | **Astronomical definition of the threshold for harm in number of streaks per exposure.**

Minimizing brightness mitigation times | Minimize the time satellites spend in orbit when not in service. Conducting orbit raising and deorbiting phases as quickly as practicable, taking due account of relevant protocols for such operations and space sustainability practices, while also taking into account brightness mitigations, where practicable. | During the orbit raising period, satellites are in a lower altitude and therefore brighter and faster. In a closely packed configuration, which severely impacts related eye visibility of the night sky and astronomical observations. Assuming a steady state constellation in its final configuration, the number of satellites in orbit raising and deorbiting phases is equal to 2 x (Final constellation number / average satellite lifetime). For a constellation of 42,000 satellites, with a lifetime of 1 yr, 2 x (42000/1) = 85,800 satellites per year. | **NOAO guidelines call for a 270 degree phase.** | **“Regulatory filings should contain the latency/brightness requirements for the specific areas that drive the design choice for number of satellites, to demonstrate that the minimum number (with margin) are being deployed.** | **Encourage transparency in regulatory filings to define the scope of planned constellations.** | **Astronomical definition of the threshold for harm in number of streaks per exposure.** | **Encourage transparency in regulatory filings to define the scope of planned constellations.** | **Astronomical definition of the threshold for harm in number of streaks per exposure.**

TLE/ephemeride accuracy | Satellite ephemeris data with covariances shall be provided in a standardized format (e.g., CCSDS OEM) and made publicly available as quickly as practicable, taking due account of relevant protocols for such operations and space sustainability practices, while also taking into account brightness mitigations, where practicable. | 1) Provide the astronomy community with the information necessary to enable active avoidance of satellites. 2) Move away from TLEs to a more comprehensive ephemerides exchange format such as CCSDS OEM Ephemerides Messages that include information on uncertainties. 3) 1 second cross-track uncertainty will allow for pass predictions for fibre spectrographs. 4) 1 second timing uncertainty will ensure data loss during shuttering is not unreasonably large and on the same order as the average shutter speed. | **The Consultative Committee for Space Data Systems (CCSDS) is a multi-national forum for the development of data exchange standards for spaceflight.** | **1-second tolerance: 1 second across-track uncertainty / 1 second timing uncertainty 8 hours in advance.** | **Create regulatory incentive for LEO constellation operators to choose lower orbits, consistent with their mission specifications and space traffic management requirements. Fund research on carrying capacity of orbital shells at lower elevations.** | **Inform and solicit cooperation of new operators to choose lower orbits.** | **Create regulatory incentive for LEO constellation operators to choose lower orbits, consistent with their mission specifications and space traffic management requirements. Fund research on carrying capacity of orbital shells at lower elevations.** | **Inform and solicit cooperation of new operators to choose lower orbits.**
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<td>Cadence sufficient for ephemeris prediction</td>
<td>Operators shall provide data on satellite attitude and ephemerides with covariances every 8 hours or at intervals that are commensurate with staying below the ephemeris prediction accuracy requirements, particularly when maneuvers are executed.</td>
<td>1) After 8 hours, typically maneuver plans have changed and the uncertainties in the ephemerides have grown beyond the required limits. 2) The attitude uncertainties stem from 1 second timing accuracy requirement, as ( 360\text{deg} / 7200\text{s} = 0.05\text{deg/s} ). 360deg is the number of degrees traveled in one second if the orbital period is two hours.</td>
<td>Satellite attitude is the orientation of the satellite and/or its gimbaled parts with respect to an external reference frame (e.g. GCRF). Satellite ephemerides refer to the position of satellites with respect to the geocentric center of attraction and a frame of reference (e.g. ITRF or GCRF). GCRF is the geocentric celestial reference frame. ITRF is the international terrestrial reference frame that is corotating with the Earth.</td>
<td>Tolerances for 8-hour updates depend on the frequency of unscheduled maneuvers. Attitude uncertainties shall be less than 0.05 deg (1-sigma).</td>
<td>D&amp;AQS2 Report p88, D&amp;AQS2 Report p88, Implementation of SATCON1 Rec 9 &amp; 10.</td>
<td>D&amp;AQS2 Report p88, D&amp;AQS2 Report p88, Implementation of SATCON1 Rec 9 &amp; 10.</td>
<td>Operators shall provide attitude data and update attitude, ephemerides and maneuver plans at least every 8 hours.</td>
<td>1) T/LUE: Ephemeris accuracy</td>
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