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Dear Dr. Gaume:

This JASON letter report discusses selected mitigations of the effects of large constellations of satellites on optical observations from astronomical facilities, in particular, the Rubin Observatory. A longer discussion of the impacts on astronomy at various wavelengths, together with a broader discussion of possible mitigations will be provided later by a full JASON report.

Introduction

Large numbers of communication satellites have recently begun to be launched into low Earth orbit (LEO). These include launches of hundreds of Starlink satellites destined for 550 km LEO orbits, as well as a smaller number (74) of OneWeb satellites destined for 1200 km LEO orbits. The number of such satellites could grow to tens of thousands or more. JASON was asked by NSF and DOE to assess the impact of current and planned large satellite constellations on astronomical observations, and in particular the impact on the Vera Rubin Observatory (RO) and its Legacy Survey of Space and Time (LSST). In this letter we discuss impacts on optical observations only. A longer JASON report will also discuss impacts on astronomy at other wavelengths.

JASON was briefed by NSF and DOE, including talks on the Rubin Observatory by project members and by Space-X on Starlink. In addition, JASON members listened to talks in workshops convened by the Astro2020 Panel on Optical Interference from Satellite Constellations (27 April 2020), and the NSF NOIRLab jointly with the Committee on Light Polution, Radio Interference and Space Debris (SATCON1:

30 June - 1 July 2020). The SATCON1 workshop circulated draft working group reports, including one from the Mitigations Working Group and one from the Metrics Working Group. Both of these discussed various mitigations, including mitigations of the impact on Rubin. JASON reviewed these draft reports and their recommended mitigations in preparing this letter report. A recent paper on mitigation of the effects of LEO satellites on Rubin [5] also provided input.

While much of the discussion in the draft reports related to the Rubin Observatory, we favor those recommended mitigations that have broad applicability to the wide range of astronomical facilities funded by NSF and DOE, and we encourage NSF and DOE to support those broader mitigation efforts. Rubin is a particular case because of its large etendue[1] and the effects of detector saturation and cross-talk on key science areas such as weak lensing. It is important to distinguish between (1) saturation and (2) the more general issue of the presence of a satellite trail in an observation. The latter can cause corruption in the measurements along the track of the satellite and will be present in most wide-field telescopes (and to a lesser extent narrow field telescopes).[2]

Saturation and cross talk are most problematic for CCD detectors on large-aperture wide-field telescopes such as the Rubin Observatory.[3]

[1] Etendue = $A\Omega$, where A is the effective area of the telescope and Ω is the solid angle of the field of view.

[2] See, e.g., Hainaut and Williams [1], who provide an estimate for the number of satellites visible in a cap above zenith angle, z, $N_{vis} = (N_{const}/2)(1 - \cos(z - \arcsin(((R_{Earth}/R_{sat})\sin(z))))$, where N_{const} is the number of satellites in the constellation and $R_{sat} = R_{Earth} + h_{sat}$, with h_{sat} the height of the orbit above the Earth's surface. Estimates are also given for the fraction of contaminated observations in a specific example with $N_{const} = 26,000$ and several different cases, including: for long-slit spectroscopy ∼1% of the observations will be contaminated during twilight, multi-fiber spectrographs (e.g., 4MOST) will be contaminated at the 5-7% level at the beginning and end of night, and Rubin will be contaminated in ∼50% of twilight exposures. See Table 2 in [1] for details.

[3] Saturation sets in when the number of electrons per pixel, N_e, exceeds a critical value, which is proportional to the effective aperture of the telescope times the number of pixels covering the point spread function of the image of the satellite, *i.e.*, N_e has the proportionality: $N_e \propto (F_{sat}\ A_{tel}\ \delta\ q_e)/(\dot{\theta}\ P\ n_{pix})$, where F_{sat} is the photon flux per unit area on the telescope aperture, A_{tel} is the telescope collecting area, δ is the throughput, q_e is the quantum efficiency, $\dot{\theta}$ is the observed angular velocity of the satellite, P is the point spread function of the satellite if it were not moving, and n_{pix} is the number of pixels needed to cover the 2-dimensional point spread function of the satellite if it were not moving. The critical threshold for saturation is very dependent on the details of the detector and electronics being used.

We recommend consideration of the following mitigations, separated into two categories: those that benefit a broad set of astronomical facilities and those that are more specific to the Rubin Observatory. While we do recommend mitigations that apply to satellite operators and encourage NSF and DOE to pursue these, we feel that it is best for the optical astronomical community to prepare for the worst, i.e., the possibility in the future of a mostly unregulated set of constellations from a variety of countries, with satellites numbering in the tens of thousands or more. Many additional mitigations have been recommended by various working groups. We list here those that we currently feel are high priority.

Recommended Mitigations

General recommendations listed in priority order, highest priority first – not necessarily Rubin Observatory specific

- If at all possible, discourage or prevent large constellations with orbits above 600 km. There are two critical reasons:
  1. Impact on astronomical observations. Satellites orbiting at $\gtrsim$ 1000 km are visible for a much longer fraction of the night. Satellites orbiting at 600 km or below reflect sunlight for only a few hours during and after twilight and consequently leave periods during the night that do not impact ground-based optical telescopes, see e.g., [2, 4]. While similar satellites will generally be fainter in 1000 km orbits than 600 km orbits[4], this is not enough to offset the fact that satellites will be visible for a greater part of the night for higher orbits.
  2. Failure of satellites (or the company operating them) will jeopardize de-orbit and orientation control capability. Even if this happens in only a small fraction of cases, it will contribute to an increase in the semi-permanent population of non-maneuverable space junk. We note that a massive solar coronal mass ejection event disabled satellites in the past and could do so in the future [3]. At 600 km, the orbital decay time is ∼1–40 yr (depending on ballistic coefficient and solar activity), at 800 km it is ∼40–

[4]Because streak SNR saturates as soon as the streak is longer than the point spread function, and because the angular rate at 1000 km is half that at 500 km, the satellite will be two times fainter at 1000 km altitude rather than 4 times fainter, as might be expected from range considerations.

500 yr, at 1000 km it is > 300 yr. At 1000 km, any satellite failure will be a very long-lived problem. Failed satellites become a target for collisions with other space debris; such collisions can then produce many small pieces of debris, creating a hazard for any satellites whose orbits lie in or cross that altitude range *including astronomical and Earth science satellites*. Regarding failure of companies that have developed constellations, we note that Iridium, Globalstar, and Orbcomm, have been threatened with bankruptcy at some point. Although these companies survived in modified form, their examples illustrate the potential challenges of competing in the satellite constellation business. More recently, OneWeb experienced financial problems and was then purchased by the U.K and an Indian telecom company[5]. The status of the constellations and the liability for their safe operation will be a serious long-term issue. The issues of collision and debris will be discussed in more detail in the full JASON report.

As a specific case, NSF/DOE should work with elements of the U.S. Government, as well as U.K. and India governments to limit the negative impacts of OneWeb satellites, require OneWeb to operate only at altitudes below 600 km, and discourage other large constellations planning orbits above 600 km.

- Satellite operators must bear the responsibility for all of their satellites at all times. Operators need to make accurate satellite orbital information available publicly. Organizations carrying out astronomical observations can then either: (1) Avoid times/pointings when satellites are present, or (2) Accurately determine what observations might be affected. Publicly available software should be developed for use by observatories that will incorporate the most accurate orbital information and predict whether a given observation will be impacted by the presence of a satellite (see footnote [2]) . The accuracy of predictions and post-facto information requires further study, but as a starting point we suggest: Accuracy of 1 arcminute in the along track direction and 10 arcsec in the cross-track direction[6], accurate to 10 seconds in time. A given prediction needs to be accurate for at least 10 hrs into the future to allow for timely planning of upcoming astronomical observations.

[5] `https://spacenews.com/bankruptcy-court-frees-payment-to-oneweb-satellites-to-restart-satellite-manufacturing/`

[6] 1 arcsec = 1/3600 deg; 1 arcmin = 1/60 deg

- Steps should be taken by satellite operators to reduce the reflectivity of their satellites, following the example of Space-X, which has taken significant steps to darken their satellites with the goal of an apparent visual magnitude m=7. Reduction in reflectivity is important in all orbital phases: parking orbits, orbit raise, operational orbit, and de-orbit.
- Operators should be required to have a well-defined, quantitative de-orbit plan that minimizes time for de-orbiting, both to decrease likelihood of a collision and to decrease time during which satellites may be brighter than in the operational orbit. Similarly, require operators to have a quantitative plan for residence time in parking orbits and the time needed for raising satellites to operational orbit. Minimize both of these.
- The long-term, 10-year evolution of the numbers of large satellite constellations is unknown, particularly since companies in countries other than the U.S. have announced intentions to launch large constellations. Therefore the baseline assumption should be that large number of satellites will be present in the future, possibly in orbits above 600 km. Many wide-field telescopes such as Rubin, ATLAS, and ZTF have developed software to mitigate the effects of satellite tracks in images. NSF should ensure that the wider community has access to software tools for both prediction of times and locations of satellites, and identification and removal of satellite artifacts in observations, and that funds for such mitigation be made available without taking away from the budget for science research.

Recommendations Specific to the Rubin Observatory

Some key science projects of Rubin will ultimately be limited by systematics. However, it is not clear to us whether large satellite constellations will be the dominant systematic limitation on Rubin investigations such as dark energy/weak-lensing. Many questions will only be answered when on-sky data become available during the engineering verification of the Rubin Observatory and its LSST. Near-term investment of resources on the impacts of large constellations should be moderate until data are in hand. The process for fully understanding Rubin and LSST systematics will likely have a long time scale, probably several years.

- The Rubin Observatory should undertake a comparative study of saturation and cross-talk effects from different sources (e.g., bright stars, satellite streaks) as well as the effects of "ghost" images on sensitive weak-lensing measurements. This will help determine the principal sources of systematic uncertainty. These estimates should be checked against on-sky data.
- The Rubin Observatory should consider 2 x 15 s observations, even though they result in a reduction of ~8% in effective observing time. Paired observations have advantages in mitigating effects of, for example, cosmic rays, but also have useful science benefits, e.g., for fast moving NEOs because the pair of observations provides directional information not necessarily available in a single observation. In the context of mitigation of the effects of LEO satellites, in most cases, one of the two 15 s images will be free of the track of a given satellite since a LEO satellite at 500 km will traverse the 3.5 deg field of Rubin in less than about 5 s, while the time gap between 15 s exposures is about 4 s (2 s for shutter open and close, and 2 s for readout). Consequently, each pixel in the image will have one of the exposures free of the satellite track, albeit with a factor of $\sqrt{2}$ decrease in sensitivity (0.4 mag). One prompt processing possibility would be to release an image that contains the lesser flux for a given pixel between the two images, a product that would be largely free of satellite tracks, and sufficient for many types of prompt science. More extensive processing could be implemented later to regain most of the $\sqrt{2}$ decrease in sensitivity, if desirable.

Other mitigations for the Rubin Observatory have been suggested (see e.g., [5]), such as increasing readout time to reduce cross-talk or electronics modifications to mitigate saturation. These involve detailed knowledge of the Rubin readout electronics and are best evaluated by the Rubin Observatory project.

References

[1] Hainaut, O.R. and Williams, A.P., 2020. Impact of satellite constellations on astronomical observations with ESO telescopes in the visible and infrared domains. Astronomy & Astrophysics, 636, p.A121.

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[3] Odenwald, S., Green, J. and Taylor, W., 2006. Forecasting the impact of an 1859-calibre superstorm on satellite resources. Advances in Space Research, 38(2), pp.280-297.

[4] Seitzer, Patrick. Mega-Constellations of Satellites and Optical Astronomy. AAS (2020): 410-03.

[5] Tyson, J.A., Ivezic, Z., Bradshaw, A., Rawls, M.L., Xin, B., Yoachim, P., Parejko, J., Greene, J., Sholl, M., Abbott, T. and Polin, D., 2020. Mitigation of LEO Satellite Brightness and Trail Effects on the Rubin Observatory LSST. arXiv preprint arXiv:2006.12417.

Sincerely,

JASONs

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