SATELLITE CONSTELLATIONS AND ASTRONOMY:
AN ESSENTIAL READING LIST & KEY REFERENCES

As of September 7, 2023

Constellations of satellites operating at low-earth orbiting altitudes (LEO) have the potential to affect astronomical observations and limit scientific discovery. The satellite and astronomy community have collaborated to understand the impact, identify mitigating approaches and suggest future steps for both astronomy and satellite constellations to thrive in their shared space ecosystem.

To learn more about this intersection of astronomy and satellites, consider the following resources:

Less Than 5 Minutes Reads:

"'Unsustainable:' How satellite swarms pose a rising threat to astronomy," Nature Magazine, May 25, 2022 https://www.nature.com/articles/d41586-022-01420-9

"Beyond Starlink: The Satellite Saga Continues," by Monica Young, Sky & Telescope Magazine, January 22, 2021. https://skyandtelescope.org/astronomy-news/beyond-starlink-the-satellite-saga-continues/

"It looked like a bizarre alignment of meteors. It was something else," by Terry Ward, National Geographic Magazine, August 11, 2023.
https://www.nationalgeographic.com/science/article/starlink-satellites-mega-constellations

10-15 Minute Reads with Technical Discussions of Impact and Mitigations:

"Effect of upgrades to Starlink Generation 2 satellites on visual brightness," by Brad Young and Jay Respler, The Space Review, August 7, 2023. https://www.thespacereview.com/article/4634/1

"Will Satellites Cripple Ground-based Astronomy," by Jeff Hecht, Optica Newsletter, May 2021, https://www.optica-opn.org/home/articles/volume_32/may_2021/features/will_satellites_cripple_ground-based_astronomy/

"Starlink satellite trains: Is this the future of the night sky?," by Daniel Wolfe, Washington Post, January 6, 2023 https://www.washingtonpost.com/business/interactive/2023/starlink-satellite-train-spacex-visibility/

"Large LEO Constellations, Astronomy, and Space Debris Mitigation," abstract of a paper by Patrick Seitzer, University of Michigan, and J. Anthony Tyson, Vera Rubin Observatory, presented at the 8th European Conference on Space Debris, April 20-23, 2021. https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/112/SDC8-paper112.pdf

"Brightness Mitigation Best Practices for Satellite Operators," SpaceX White Paper, August 2022, https://api.starlink.com/public-files/BrightnessMitigationBestPracticesSatelliteOperators.pdf

"Mitigation of LEO Satellite Brightness and Trail Effects on the Rubin Observatory LSST," by J. Anthony Tyson, Željko Ivezić, Andrew Bradshaw, Meredith. Rawls, Bo Xin, Peter Yoachim, John Parejko, Jared Greene, Michael Sholl, Timothy M. C. Abbott, The Astronomical Journal, October 27, 2020. https://iopscience.iop.org/article/10.3847/1538-3881/abba3e/meta

"Palomar Survey Instrument Analyzes Impact of Starlink Satellites," a study of effects on the Zwicy Transient Facility at Caltech's Palomar Observatory, by Przemek Mróz and Tom Prince, The Astrophysical Journal, January 17, 2022 https://www.caltech.edu/about/news/palomar-survey-instrument-analyzes-impact-of-starlink-satellites

"As Reflective Satellites Fill the Skies, UArizona Students are Making Sure Astronomers Can Adapt," by Mikayla Mace Kelley, University of Arizona News, August 2, 2022. https://news.arizona.edu/story/reflective-satellites-fill-skies-uarizona-students-are-making-sure-astronomers-can-adapt

"Large Satellite constellations & Their Impact on Astronomy," by Olivier Hainaut, European Southern Observatory, 2022. https://www.eso.org/~ohainaut/satellites/

"Megaconstellations like SpaceX's Starlink May Interfere with Search for Life by World's Largest Radio Telescope," by Tereza Pultarova, Space.com on February 3, 2022. https://www.space.com/spacex-starlink-affects-search-for-life-radio-observatory

"Radio interference from satellites is threatening astronomy – a proposed zone for testing new technologies could head off the problem," by Christopher Gordon De Pre, Christopher R. Anderson and Mariya Zheleva, The Conversation, March 3, 2023. https://theconversation.com/radio-interference-from-satellites-is-threatening-astronomy-a-proposed-zone-for-testing-new-technologies-could-head-off-the-problem-199353

On the drivers to build commercial satellite constellations:

"The Coming Era of Satellite Direct-to-Handset Connectivity," by Ivan Suarez and Calil Queriroz, Via Satellite, November 28, 2022

https://interactive.satellitetoday.com/via/december-2022/the-coming-era-of-satellite-direct-to-handset-connectivity/

"Is the Competitive IFC Environment Prepared for the Multi-Orbit Future?," by Daniel Welch, Via Satellite, April 27, 2022
https://interactive.satellitetoday.com/via/may-2022/is-the-competitive-ifc-environment-prepared-for-the-multi-orbit-future/

"SpaceX, Amazon and FCC Leaders Discuss Satellite Spectrum Rulemaking," by Rachel Jewett, Via Satellite, October 20, 2022
https://www.satellitetoday.com/technology/2022/10/26/spacex-amazon-and-fcc-leaders-discuss-satellite-spectrum-rulemaking/

"Satellite Internet Market Size and Share – Forecast 2030," Acumen Research and Consulting, September 2022
https://www.acumenresearchandconsulting.com/satellite-internet-market

"Is there a 'best' owner of satellite internet?," by Chris Daehnick, rob Hamill, Alexandre Ménard and Bill Wiseman, McKinsey, April 11, 2022.
https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/is-there-a-best-owner-of-satellite-internet

"Unintended electromagnetic radiation from Starlink satellites detected with LOFAR between 110 and 188 MHz," F di Vruno, B. Winkel, C.G. Bassa, G.I.G. Jósza, M.S. Brentjens, A. Jessner and S. Garrington, Astronomy & Astrophysics Journal,March 10, 2023
https://www.aanda.org/articles/aa/full_html/2023/08/aa46374-23/aa46374-23.html

On the Potential to Affect Indigenous Communities:

"The Impact of Satellite Constellations on Space as an Ancestral Global Commons," Nature Magazine, November 6, 2020, Aparna Venkatesan, University of San Francisco; James Lowenthal, Smith College; Parvathy Prem, Johns Hopkins Applied Physics Laboratory; and Monica Vidaurri, Howard University.
https://www.nature.com/articles/s41550-020-01238-3#:~:text=Satellite%20constellations%20could%20greatly%20improve,cost%20high%2Dspeed%20broadband%20internet.

"Digital Divide: SpaceX, Starlink and the Indigenous Spaces Between," Animikii, May 30, 2020. https://animikii.com/news/digital-divide-spacex-starlink-and-the-indigenous-spaces-between

Key Technical and Analytical Reports:

Experts from the astronomy and satellite communities met regularly in 2020 and 2021 to characterize the impact of satellite constellations in low-earth orbit on various astronomical observations. The reports from these conferences provide a thorough discussion and recommendations for satellite operators, as well as astronomers and governments.

SATCON 1 (June/July, 2020) "Impact of Satellite constellations on Optical Astronomy and Recommendations toward Mitigation," Report from SATCON1, hosted virtually by the American Astronautical Society (AAS) , on June 29 – July 2, 2020, https://noirlab.edu/public/media/archives/techdocs/pdf/techdoc003.pdf

- The goal of SATCON1 was to quantify the impacts of satellite constellations at optical wavelengths and explore possible mitigations. The full report contains findings about the nature of the visibility of satellites and their effect on various astronomical science, as well as recommendations.

SATCON 2 (July 2021): Report from SATCON2, hosted virtually by AAS on July 12-16, 2021, https://baas.aas.org/pub/2021i0205/release/1

- The primary goal of the workshop was to develop specific, implementable paths to carrying out the recommendations in SATCON1. The report included recommendations for satellite operators, for observatories and for the two communities in collaboration.

D&QS I (September 2020): Working Group Reports from the Dark and Quiet Skies for Science and Society Conference I, co-organized by the United Nations Office for Outer Space Affairs (UNOOSA), the International Astronomical Union (IAU) and the Government of Spain, held virtually on September 5-9, 2020.
https://noirlab.edu/public/media/archives/techdocs/pdf/techdoc021.pdf

- The purpose and scope of the Conference was to propose to the UN Committee on Peaceful Uses of Outer Space (UN COPUOS) a set of recommendations for local governments or international organizations to protect the science of astronomy.

D&QS II (October 2021): Working Group Reports from the Dark and Quiet Skies for Science and Society Conference II, co-organized by the United Nations Office for Outer Space Affairs (UNOOSA), the International Astronomical Union (IAU) and the Government of Spain, held virtually on October 3-7, 2021.
https://noirlab.edu/public/media/archives/techdocs/pdf/techdoc051.pdf

- The focus of D&QSII was to explore the feasibility of implementing the recommendations presented by the D&QSI conference. The report presents more extensive recommendations for satellite operators, astronomers, governments and other stakeholders. The report included discussion of the impact of optical/infrared trails of

satellites in low Earth orbit, the radio transmission by ground and space emitters on radio astronomy, and the effects on the sky from urban illumination or artificial light at night.

- Findings and Recommendations from D&QSII were presented during a Symposium during the UNCOPUOS Scientific and Technical Subcommittee Meeting held virtually and in Vienna, Austria on February 7-18, 2022. Papers and presentation materials are available at: https://www.unoosa.org/oosa/en/ourwork/copuos/stsc/2022/unoosa-symposium.html

U.S. government Accountability Office Report: "Large Constellations of Satellites: Mitigating Environmental and Other Effects," September 29, 2022. GAO was asked to assess technologies and approaches to evaluate and mitigate the potential effects of satellite constellations on orbital debris, astronomy and upper atmosphere emissions.
https://www.gao.gov/products/gao-22-105166

JASON Report (November 2020): The U.S. National Science Foundation commissioned a study by the independent science advisory group JASON Program Office of the MITRE Corporation, to assess the impact of current and planned large satellite constellations on astronomical observations, delivered November 16, 2020.
https://www.nsf.gov/news/special_reports/jasonreportconstellations/JSR-20-2H_The_Impacts_of_Large_Constellations_of_Satellites_508.pdf

"Mitigation of LEO Satellite Brightness and Trail Effects on the Rubin Observatory LSST," *U.S. Department of Energy, Astronomical Journal Online, Article* by Anthony J. Tyson, Zeljko Ivezic, Andrew Bradshaw, Meredith L. Rawls, Bo Xin, Peter Yoachim, John Parejko, Jared Greene, Michael Sholl, Timothy C. Abbott, and Daniel Polin.
https://www.osti.gov/pages/biblio/1769027