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Topic: Will the SpaceX Starlink satellites interfere with Earthbound Astronomy? You should consider both optical and radio-astronomy, including the possible effects on the SKA project.

Per Aspera Ad Astra: An Analysis of the Harmful Consequences of SpaceX Starlink Satellites on Earthbound Astronomy.

Introduction:

The American aerospace company SpaceX (which works in close conjunction with NASA) has, since January 2020, been launching telecommunications satellites into orbit in intervals of roughly 60 per month. The company has received Federation Communications Commission approval to launch upwards of forty thousand of these satellites into orbit at 550km above the surface. The International Astronomical Union and multiple ground-based observatories have voiced their concerns surrounding the scientific impact of the Starlink “mega-constellation” of satellites. Starlinks will contaminate and occult astronomical images with bright trails of reflected sunlight in optical telescopes, and cause substantial Radio Frequency Interference for radio telescopes, as they transmit within the same operational radio bands. If a dense population of Low Earth Orbit Satellites is obtained, the impact on astronomy will be significant. Without serious mitigation measures implemented by both SpaceX and affected observatories, the effects could debilitate science.

This essay assesses the effect of vast satellite mega-constellations on ground-based optical and radio astronomy by describing the impacts on two exemplars of modern astronomy: the Vera C. Rubin Optical Observatory and the Square Kilometer Array Radio Observatory. The Starlink Satellites will negate optical astronomy by contaminating images captured by the Rubin Observatory’s ultra-wide field telescope during twilight. Thus interfering with solar-system science and jeopardizing Near-Earth Object research. Furthermore, Starlink will impede radio astronomy by reducing observational efficiency in searches for organic prebiotic molecules at the SKA Mid-frequency telescope and acting as potential ricochet sites for redirection of Earth emissions, saturating receivers of the SKA Low interferometer telescope in Australia.

The Orbit-Raising Phase:

The Starlink satellites are initially at a lower altitude than their final Low Earth Orbit at 550km above the surface. Once deployed, satellites enable their thrusters and gain altitude at low-impulse. While raising orbit, satellites must reflect most of the sunlight to which they are exposed, to decrease the thermal load on the electronics according to the law of conservation of energy (Tyson 2020). The main reflection surfaces are the solar panels and white diffuse surfaces (metal body and antennae). Since the solar panels are oriented horizontally with a larger reflective surface exposed to Earth during orbit-raise for effective drag reduction, satellites have their lowest visual magnitude during this phase. They appear as bright naked-eye objects, noticeable to both professional and amateur astronomers. For increasingly dense satellite mega-constellations (upwards of the initially granted 12,000), the frequency at which the satellite trails occlude other celestial sources increases. The occultation of stars, galaxies or nebulae can occur irrespectively of whether the satellites are illuminated by the sun or appear in Earth's shadow. Although the orbit raising stage (and consequently, the increased rate of image contamination) is temporary (Hainaut & Williams 2020), the rate of Starlink deployment will remain constant or even increase, ensuring the presence of orbit-raising satellites for the foreseeable future. An accelerated deployment rate thus delegitimises dynamic avoidance as a contamination mitigation technique.

Optical telescopes contain specialised sensors capable of probing objects with apparent magnitudes up to 27, many orders of magnitude fainter than the light reflected by satellites. Should their brightness decrease by covering their diffuse surfaces with a less reflective coating (DarkSat Starlink experiment), the light-scattering satellites will still interfere with professional systems despite not behaving as naked-eye objects (Gallozzi 2020). The astronomy community expects optical exposures to be continuously contaminated by satellites in the orbit-raising phase and by "on-station" satellites at their final altitude.

The Vera C. Rubin Observatory:

Acting as an exemplar of the impact on ultra-widefield astronomy is the Vera C. Rubin Observatory. The Observatory Camera contains 189 sensors called Charge-Coupled Devices (CCDs) within which energy conversion occurs. The reflected light from satellite trails reaches the CCDs at varying numbers of electrons per 10-micrometre pixel. The incoming photons then excite electrons, and conversions to electric charge output occur at a relatively close to ideal rate, creating high-resolution images. In rare circumstances where the satellites cause bright and short flares, the CCD photodiodes can experience saturation (their maximum charge capacity) and create unwanted "artefacts" on the exposures (Tyson 2020). These image artefacts include blooming when extra charge overflows into neighbouring pixels on the Rubin camera's sensor. More commonly, crosstalk between CCD channels occurs below saturation level. Thus the effect of lone trails in images is multiplied, additional artefacts appearing next to the main trail. Both blooming and crosstalk will impact astronomy as lost scientific data. The number of usable pixels and the ability to mask image artefacts with correction algorithms is inversely proportional to the brightness of the trail. Time would have to be invested in unexpected image correction and allocated observations would be cancelled. The decreased time budget could result in the Rubin Observatory's projects, particularly the Legacy Survey of Space and Time, lasting longer than expected. The survey will observe events like gravitational lensing (in which a galaxy cluster containing dark matter distorts light from neighbouring galaxies according to the curvature of spacetime). This project has enormous scientific importance in testing General Relativity and identifying the constitution and fundamental properties of dark matter and dark energy. The satellite interference with lensing observations causes data losses, and thus impedes cosmological discovery.

The presence of satellites is also extremely damaging to observations within our solar system, where dynamic avoidance is impractical (Tyson 2020). Therefore, the Rubin Observatory will encounter obstacles in surveying the populations of solar-system objects. A portion, ranging from 30%-90%, of all Rubin twilight images, will be contaminated with at least one satellite trail. The solar system surveys, which frequently occur during twilight, include observations of "Potentially Harmful Asteroids" on trajectories susceptible to collision with Earth. The presence of satellites in these images could make the locations of “Potentially Harmful Asteroids” untraceable with orbital tracking. If one of the “hidden asteroids” and Earth undergo an impact event, it is plausible we would face the sixth major extinction due to the associated shock waves, thermal radiation, and natural disasters.

<u>The SKA1-Mid:</u>

The Square Kilometre Array is the most anticipated scientific instrument in modern astronomy, and therefore the most suitable exemplar of satellites impacting radio astronomy. On completion, the SKA will be the most sensitive radio instrument ever constructed (Dewdney 2020). This ultra-sensitivity will allow the scientific community to perform more studies investigating relevant topics like the Concordance Model of Cosmology and tests that scrutinise the extent to which the general theory of relativity is valid in some of the most extreme gravitational conditions of spacetime.

The telescope functions on the principles of radio interferometry and aperture synthesis, in which the two separate arrays of multiple radio telescopes are spread out over two large areas. The telescopes are separated according to respective South African and Australian baselines to form one cumulative array with a collecting area of one square kilometre. According to Rayleigh’s Criterion, the large collecting area functions to decrease the large angular resolution created by the long radio wavelengths and effectively increase the image quality. The results of the specialised interferometry are invaluable, allowing very faint radio signals to be resolved and obtaining an angular resolution down to 0.04 arcsecond at 12.5GHz (SKAO 2018).

The South African array will consist of 197 dishes equipped with receivers operating in the 8.3GHz to 15.4GHz radio band (classified as “5b”) of the electromagnetic spectrum. The SpaceX satellites have radio transmitters communicating with Earth systems at frequencies of 10.7GHz to 12.7GHz, which operate within the same 5b band as the telescopes. This transmission will inevitably cause radio frequency interference when the satellites transmit in the direction of the telescopes (Isidro 2020). The SKA dish receivers will be saturated with the strong emissions from the overhead satellites, blinding the telescopes to very faint signals. Most of the science done within the communication range of the satellites is astrobiology. Specifically, research probing the universe for complex organic and prebiotic molecules, possibly even the precursor molecules to nucleic acids. These large molecules are typically identified in colder reaches of space, thus having less rapid rotational velocity than smaller molecules, and emitting electromagnetic radiation at a lower energy in longer wavelengths (Cavallaro 2020). SKA Observatory’s preliminary reports found that (for a population of 6,400 satellites) astrobiology observations would have to be conducted for 70% longer to obtain clear images. This is due to the increasingly difficult detection of the molecules’ faint spectral signatures when satellites interfere. SpaceX plans to deploy up to 48 000 satellites into orbit, for which the impact on SKA astrobiology will be invariably higher than the previously stated decrease in observational efficiency. A case of total non-functionality in the 5b band due to constant saturation is possible at populations closer to 100 000.

The interference with the SKA telescopes cannot be prevented by using only the internationally protected radio astronomy band (10.6GHz to 10.7GHz) within the 5b band, as the telescopes need to receive signals across a broad range of frequencies to identify precursor organic molecules. Additionally, the array’s location within a Radio Quiet Zone in the Karoo (the Karoo Astronomy Advantage Area) offers protection only from ground-based interference. Interference from overhead satellite transmissions is not limited, nor are there any other international regulations that can legally protect the astronomy community. Observatories are left with no option but to negotiate mitigation strategies directly with telecommunication satellite companies, perform fewer observations and allocate funding to mitigation instead of funding research. The SKAO suggest simple software alterations that will prevent satellites from directing their transmissions within 20 degrees of the SKA1-Mid site. This technique is currently implemented to protect other orbiting satellites but becomes increasingly ineffective as satellite populations increase. The decreased number of possible astrobiology observations reduces our opportunity to find areas in which life displays the potential to evolve (if met with the appropriate environmental conditions) and prevents us from better understanding our cosmic evolution, where and how Earth's building blocks for life originated.

Economically, South Africa as a historically overexploited country, has had very limited opportunity to be involved in cutting edge, innovating research compared to the nations that lead international science, but not for the lack of ability of our scientists. The SKA1-Mid project is thus key to wider exposure of South African science, and any amount of lost data or observation time for South African researchers at the array will be unaffordable, reducing the already minimal amount of internationally influential research coming out of South Africa and reducing the employment opportunities for the growing number of South Africa's astronomy graduates.

The SKA1-Low:

Reports and analyses regarding the impact on the Australian portion of the Square Kilometre Array, consisting of a quarter of a million antennas, are being conceptualized. Since the Australian telescopes function at lower frequencies than the satellite communication range, direct interference is not expected. The speculated impact of dense satellite mega-constellations on the SKA-Low involves radio signals from Earth emitted into space, redirected to the array site after ricocheting off satellites, then being detected and amplified by the telescopes (Isidro 2020). More studies need to be done on the possible occurrence of this interference to provide mitigation measures and determine whether it endangers scientific instruments.

Conclusion:

The recent developments of satellite mega-constellations like Starlink will harm optical and radio astronomy, extremely damaging the Vera C. Rubin Observatory and Square Kilometre Array. Near Earth Asteroid impact avoidance, the search for dark matter and the search for organic molecules represent the most vulnerable fields. Plausibly, the effects are reasonably understated as deployment and the number of satellites in orbit is bound to increase significantly. While Starlink's global connectivity goal is important, justifiable and comes with an affordable price tag, it should not collide with astronomical goals in a metaphorical Kessler Syndrome. It is equally important to examine the effects of shaky ethics and purely profit-based incentives of business operation in space on Earthbound astronomy. International collaboration is, therefore, imperative to finding effective mitigation measures and determining regulations on ethical conduct in space to preserve ground-based astronomy. (1,995 words)

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