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LEO Satellites and Antenna Performance Investigations with the Onsala Twin Telescopes

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Abstract The advent of Low Earth Orbit (LEO) satellite constellations requires an assessment of their impact on astronomical and geodetic observations. This study investigates the signals from the Starlink constellation using the Onsala Twin Telescopes (OTTs). Additionally, holographic measurements using geostationary broadcast satellites have been used to characterize the OTTs, revealing that the feed seems not to be optimally illuminating the ring-focus antenna at 11 GHz. These initial results demonstrate the benefit of checking the entire antenna optical path with holography.

Keywords LEO satellite signals; Onsala Twin Telescopes; holography

1 Introduction

The increasing number of Low Earth Orbit satellites (LEO sats) in mega-constellations, such as Starlink and OneWeb, have the potential to greatly impact observations made with ground-based radio telescopes, across some frequency bands [1]. As shown in Figure 1, each LEO sat can have multiple steerable beams that maintain constant flux density on the ground. These downlink transmissions are strong enough to completely obscure relatively faint astronomical signals, disrupting telescope observations. Radio source intensities are commonly measured in Jansky, where 1 Jy = 10^{-26} W m^{-2} Hz^{-1}, which are often more than 100 times fainter than noise of the telescope receiver system. To process these weak signals, cryogenic broadband receivers are often used with amplification of order 10^7. Because the signal-to-noise ratio is typically $<< 0.1$ as well as Gaussian, data can be quantized with as few as two bits. Communications systems, on the other hand, do not use such sensitive receivers and compensate by transmitting at high power levels. Expressed in Jy, a LEO satellite signal at the Earth's surface is permitted to be as high as 68 MJy. Such a strong signal can be detected and contaminate an astronomical observation even if the signal is far away from the telescope main beam. Even within a few beamwidths of the main beam a LEO satellite signal can drive a receiver into non-linear operation, resulting in harmonic products that contaminate not just the band where the LEO satellite transmits but the entire band of the radio telescope, which can be many times wider. Processing such strong signals with a sensitive receiver is extremely challenging. To cope, a radio astronomy receiver needs to be both extremely sensitive as well as have a wide linear dynamic range. To minimize the production of artifacts and provide headroom for the entire signal chain, dig-

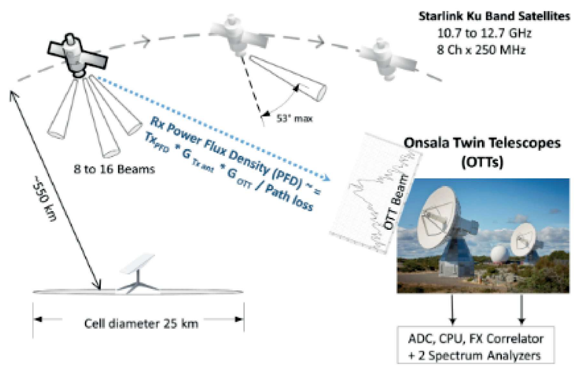

Fig. 1 Starlink LEO satellite observing configuration.

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itizers with at least four bits, but preferably eight or more bits, are needed. Additionally, it is also important to understand how LEO sat signals impact an observation so that telescope observations can be planned accordingly.

Using a model one can make predictions of the signal levels received and estimate their impact on a telescope and its observations. The modeled signal received is a function of the characteristics of the LEO sat system (the positions of each satellite in time, the number of beams and transmission characteristics) as well as the characteristics of the receiving antenna system. The model's accuracy depends on how well the telescope and LEO satellite performance are known, while validating the model requires observing satellites at many antenna positions. Our project is to develop such a model, which includes a comprehensive measurement and characterization of the level of in-band and out-of-band transmissions from mega-constellations, including the collection of channel occupancy and signal statistics. Additionally, we plan to measure the character of the emission from these satellites by tracking a few of them using the Onsala Twin Telescopes (OTTs), potentially as an interferometer.

In this paper, we present the results of our ongoing efforts to assess the impact of these satellites on radio telescope observations by using the OTTs to refine and verify our model. The results include our holographic measurements of the antenna beam and the aperture efficiency derived from the aperture amplitude and phase distributions. As well, we summarize the results of the model and provide the channel occupancy observed, as well as the PFD received as a function of elevation. The results of our study provide valuable insights into the potential impact of mega-constellations on radio astronomy and together with the model can be used to inform the development of guidelines and regulations to minimize this impact worldwide.

2 Model: Simulation and Validation

Starlink LEO sats do not broadcast directly at the OTT site, as SpaceX voluntarily masks off radio quiet zones intentionally using their system. As such, satellite beams never transmit directly on-axis at an OTT—though beams elongated by projection may do so at full power flux density (PFD). The power received by an OTT is from the sum of the PFD from all satellites and all beams (off-axis) projected in the direction that the OTTs are pointed, in aziumth (Az) and elevation (El). Currently, our simulations use a model beam for the OTTs, instead of the real ones.

At the start of a simulation cycle, the Az and El of each satellite beam in the entire constellation is randomly assigned a unique cell. Then for each time step (typically 100 s) the aggregate PFD at an OTT from all the beams is computed, using frequency channel 7 (as it is in use frequently). Time is advanced 100 s and the PFDs computed 10 times for 1000 s. This process is repeated another 10 times with a new random start time, corresponding to a new set of satellite initial positions. The result is a statistical distribution of the PFD, which can be used to estimate the expected mean and standard deviation of the PFD as a function of elevation. Because the beam positions are unknown and not necessarily stochastic, this may not represent the real-world distribution and needs to be validated.

To validate the model, the OTTs are re-positioned every 20 s so that a satellite track intersects the OTT beam. The positions are pre-computed for up to 24 hours in Python using *cysgp4* [2] and supplemental TLE data published by Celestrack. In parallel with positioning, spectrum analyzers write the max hold and average power spectrum for a polarization to a file. As well, an FX correlation spectrometer writes the integrated auto- and cross-spectral power for the OTTs, every 0.5 s, to an hdf5 file.

A four-minute segment during a 24-hour run is shown in Figure 2. Altogether 60 hours of data consisting of 10,800 intersections were collected. Over the total intersections, the channel occupancy percentages observed were: 5% for channel 0, 27% for channel 1, 48% for channel 2, 58% for channel 3, 56% for channel 4, 72% for channel 5, 82% for channel 6, and 82% for channel 7.

Figure 3 shows the observations are in good agreement with simulations at elevations $< 35^\circ$, where there are a large number of intercepts and the LEO sat projected beam illuminates the OTTs. As LEO sats come over the horizon more beams can illuminate the OTTs, and they reach a peak at about 32° elevation. At no time do signals reach the regulated PFD of -182 dBW Hz^{-1} m^{-2}.

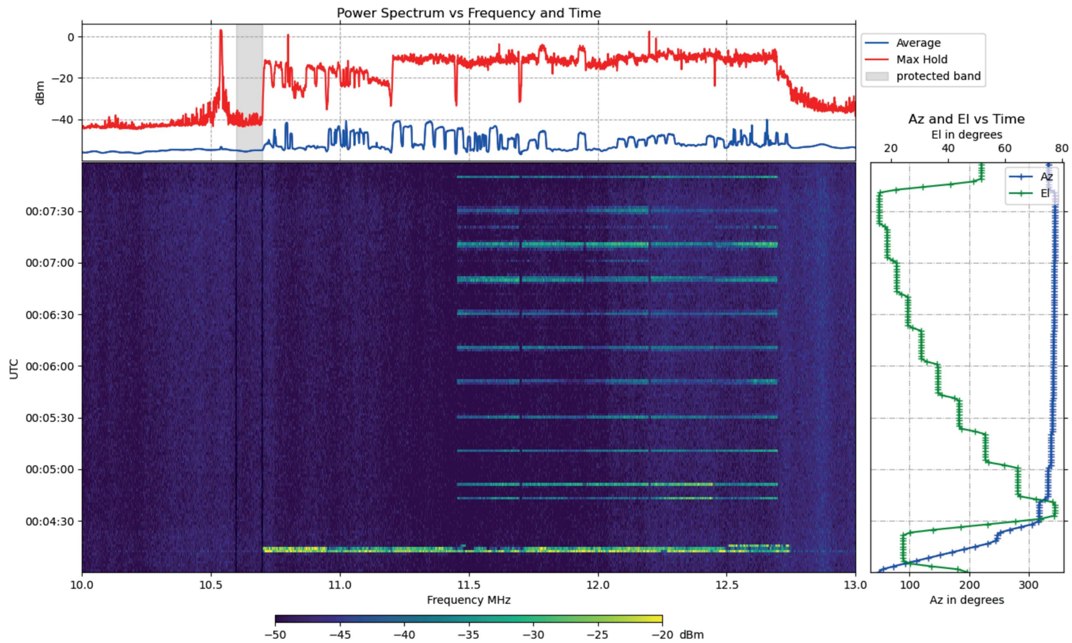

Fig. 2 A waterfall plot for four minutes of time showing Starlink transmissions at intersections every 20 seconds as well as during antenna repositioning.

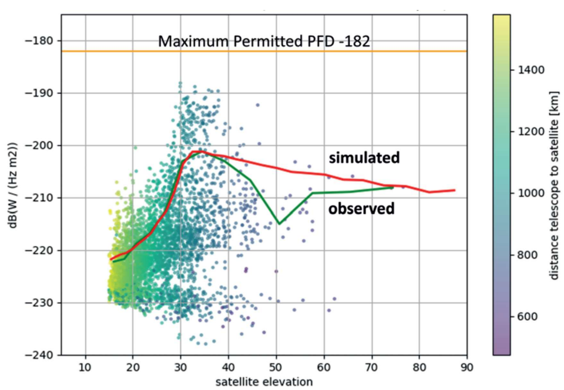

Fig. 3 Power Flux Density versus Elevation: Simulated vs. Observed. Note that at El $> 35°$ the data are sparse as there are few satellites at high elevation, and the LEO sat beams are better defined and the projected beam spillover is less.

3 Onsala Twin Telescopes and Holography

The Onsala Twin Telescopes (OTTs), at Chalmers University's Onsala Space Observatory, are part of the Observatory Geodetic VLBI program and the VLBI Global Observing System (VGOS). The telescopes consist of two 13.2-meter ring-focus paraboloids, separated by 75 meters [3]. The OTTs are able to move at up to $12° \text{ s}^{-1}$ in Az and $6° \text{ s}^{-1}$ in El. Pointing residuals are < 16 arcsec, and the surfaces have a design accuracy of < 100 µm RMS, making the antenna efficient to at least 25 GHz. Each telescope has its own dual-linear polarization receiver system. OTT South West (ONSA13SW, Ow) uses an Eleven Feed [4] covering a frequency range of 2.2 to 14 GHz, while the OTT North East dish (ONSA13NE, Oe) has a Quad-Ridge Flared Horn (QRFH) which covers the range from 3 to 18 GHz [5].

The OTTs are near ideal for studying LEO sats, as they are broadband and can slew and track at high speed. However, to characterize the off-axis PFD of the LEO sats, the antenna beam patterns need to be characterized, and one way to do that is with holography. To our knowledge this has not been done on VGOS dishes.

Initial beamcuts of Oe revealed that the first sidelobe was unexpectedly high. Early on, Oe became the antenna of choice because Ow, with its lower frequency Eleven feed, would pick up strong communications signals at low elevations, making the signal chain operate non-linearly.

Measuring an antenna's response is readily done using holography. The methodology is well known and yields the complex voltage response pattern of an antenna. The technique involves pointing one dish on a strong source, such as a satellite, while scanning the dish being measured across the source and measuring the complex power between the two antennas. In doing so one is essentially using an interferometer to measure the primary complex beam of the dish being scanned, revealing not just the amplitude of the beam pattern but the amplitude and phase response of the aperture when Fourier transformed into the spatial frequency domain. With this information the aperture and its efficiency and path length deviations can be quantified as well as visualized.

In our implementation we downconverted a TV channel from the EUTELSAT 16A geostationary TV satellite, at 11 GHz. Using an FX correlator, implemented on an RFSoC evaluation board, we sampled a 250-MHz band from the vertical polarization from the OTTs and computed the integrated auto- and cross-power spectra at one-second intervals. In parallel with this the OTTs' VLBI Field System positioned Ow at the satellite, while the Oe antenna was moved over a 108×108 point grid, sampled for a few seconds at intervals of $38\lambda/D$ first in elevation and then at the end of an El scan step in azimuth. Boresight calibrations were done to track amplitude and phase at the beginning and end of a run as well as at the end of each El scan by pointing Oe at EUTELSAT 16A.

Processing of the data was done using Python. The correlated spectra were stored in a time-ordered way in the hdf5 files. The approximate pointing times from the reference SNAP file were compared with the time stamps in the data file, and the data frames corresponding to the reference pointing intervals were extracted. During processing, the first and the last correlator integration on each grid point were omitted to minimize the impact of the dish slewing on the data. The boresight calibrations at the end of each El scan were fit to a spline function which was used for phase and amplitude calibration. After calibration, the data were gridded in azimuth and elevation dimensions.

The gridded data were then centered, and a DFT was performed. The amplitude and phase of the DFT output yielded the aperture illumination and path length deviations. The aperture efficiency was obtained by integrating the amplitude of illumination normalized over that for a uniformly illuminated aperture.

The Az and El beam cuts shown in Figure 4 show good agreement with simulations, except that there are clear signs that on boresight the satellite signal is saturating the signal chain. Also the sidelobe level of the elevation cut is very high and essentially broadening the Oe beam.

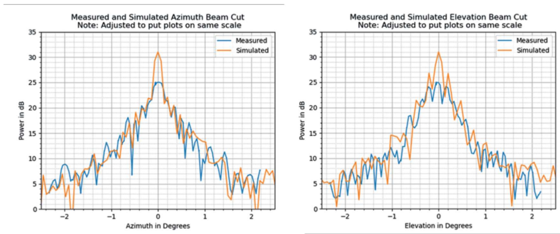

Fig. 4 Power Flux Density versus Elevation: Simulated vs. Observed. Note that at El $> 35°$ the data are sparse as there are few satellites at high elevation, and the LEO sat projected beam spillover is less.

This shows up in both the simulated and measured aperture illumination at the top of Figure 5. While the hole in the center of the aperture illumination is a feature of the ring-focus design, the bunny ear features are not. This under-illumination shows up along with the effect of the feed legs in the measured result as well. Together they result in an aperture efficiency of only 40%, which is significantly less than the 70% expected design efficiency and simulated efficiency of 57% reported in [5] and confirmed by us.

The aperture phase, in path length deviations, is shown in the bottom half of Figure 5. Where the aperture is well-illuminated, the phase accuracy is high. More sensitive and carefully phase-calibrated measurements are needed to better reveal the phase path deviations.

The aperture efficiency is poor, likely due to under-illumination of the sub-reflector, as well as poorly aligned ridges in the QRFH. The phase path deviations are higher than expected, possibly due to higher phase noise where the illumination is poor.

4 Conclusions

There is good agreement between the LEO satellite model and measured results. To improve the statistics at high elevations more measurements are needed at lower latitude sites. The beam pattern of Oe needs to

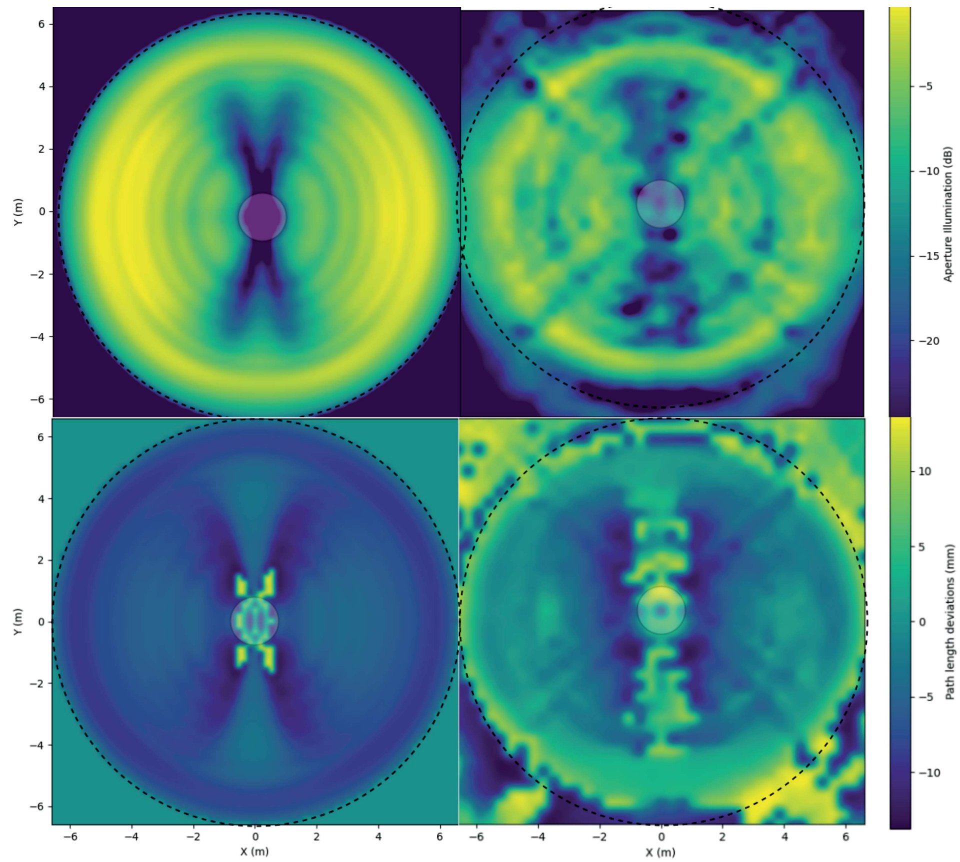

Fig. 5 Aperture illumination (top) and path deviations (bottom). GRASP simulations (left) vs measured values obtained from holography (right).

be incorporated into the model, especially because it deviates from the nominal response used.

The preliminary holography measurements agree well with simulations, especially in amplitude. The poor aperture illumination in elevation not only causes a loss in aperture efficiency but causes the beam to be broadened, making it more susceptible to LEO satellite interference. The poor aperture illumination could be due to a manufacturing issue with the feed. It could be that the ring-focus design is also more sensitive to such issues. As well, feed leg blockage likely was not accounted for in the GRASP simulations.

To address these issues, simulations with an improved feed could be done. As well, the holography system could be improved—first by sampling the l,m plane over a larger range to improve resolution as well as by scanning continuously instead of stepping through a set of discrete points, and last by utilizing more signal bandwidth to improve sensitivity.

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