Adaptive Radio Science and Supplemental Coverage from Space

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Abstract

Supplemental Coverage from Space (SCS) poses a significant coexistence challenge for existing and planned radio science systems (e.g. radio astronomy telescopes). Services using satellite constellations to transmit and receive directly to large numbers of mobile devices in the 614 MHz to 2.36 GHz are planned or already in testing (i.e. 38 FCC Rcd 2790(3)). The large scale constellations required for these systems, and the radio transmissions and emissions that result, represent a new and likely unavoidable set of interference sources for radio science systems and applications.

Scientific use of the radio spectrum aids in the study of Earth's atmosphere, near space environment, and the larger astronomical universe. To enable fundamental research, scientific instruments span wide bandwidths and have high sensitivity. Space based emission sources are particularly problematic for radio science observatories due to their placement between radio telescopes and the more distant astronomical environment. They also generally have very wide visibility over large spatial regions. Thus, the geographical isolation of many radio observatories will no longer provide a layer of protection from interference.

Transmissions, harmonics, and unintentional emissions are already visible from a rapidly growing constellation of low earth orbit (LEO) satellites. The signals from these systems are highly visible at high signal levels in even moderate sized astronomical radio telescopes. Avoidance of interference from them is already essentially impossible. We discuss the challenges of this new era and our efforts to model and quantify the impact of SCS on radio science observatories.

Spectrum Coexistence and Radio Observatories

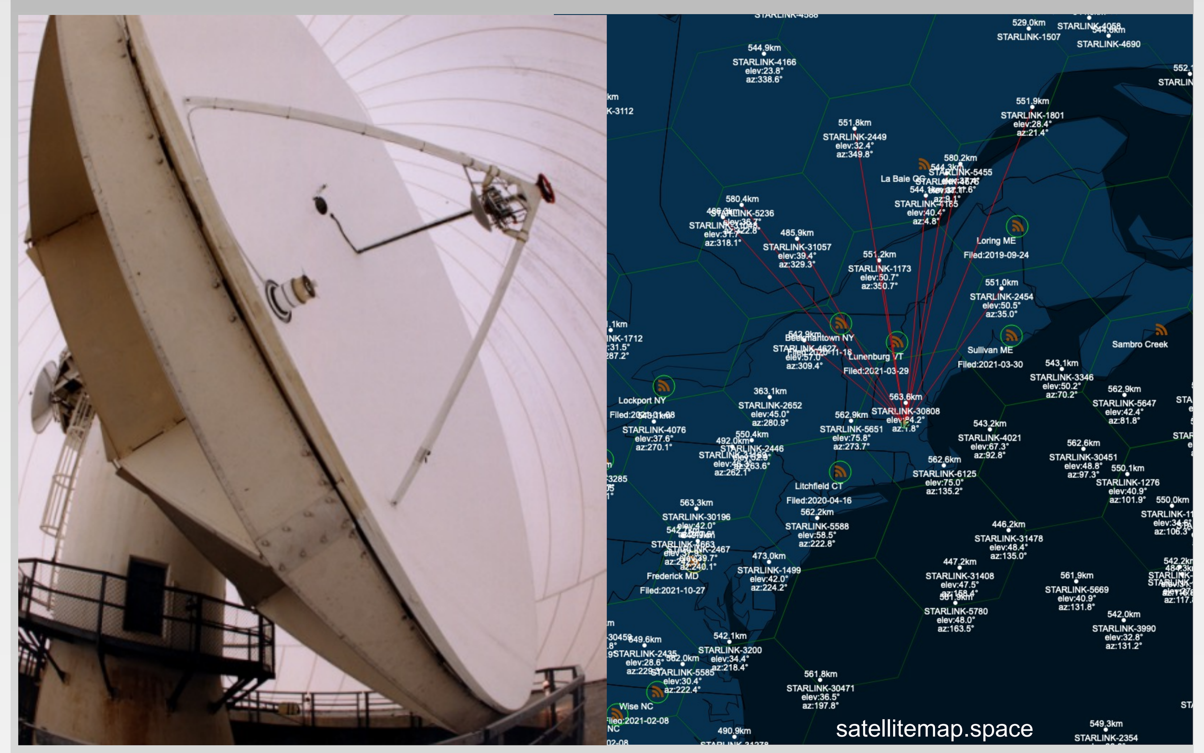
Space science research using radio signals has in many cases been organized around major radio observatories. This is due in part to the physical scale of the instrumentation involved and the need for staff to configure and operate the observing systems. Satellite platforms create transient and highly variable interference for these observatories and the aggregate effects of large constellations are not yet fully understood.

MIT Haystack Observatory

Haystack Observatory is a laboratory of the Massachusetts Institute of Technology located in Westford MA which is about 45 km from Boston. This facility is composed of researchers, support staff, and radio telescopes and radar systems which are used for radio astronomy, geospace science, and space surveillance activities. While the facility was relatively remote when first constructed in the late 1950s the surrounding area has undergone significant sparse sub-urban development. Observations using the facility cover frequencies from AM radio (~ 1 MHz) through EHF (> 100 GHz) and the site hosts several multi-megawatt radar systems which pose their own local co-existence challenges.

The Observatory is an ideal location to quantify RFI effects and develop and test RFI mitigation and spectrum co-existence techniques. As part of our Adaptive Radio Science project we have been leveraging our 18.3m Westford radio telescope to collect RF data from satellites in the Starlink constellation. These acquisition systems all leverage the Digital.RF data format and commercial software radios in combination with a 100 Gbit per second network and connection to the MIT Supercloud high performance computing system.

Data Collection with the Westford Radio Telescope



The Westford Radio Telescope is an 18.3 meter antenna system capable of operating in either a prime focus or Cassegrain configuration. The antenna system has multiple available feeds and is primarily used as a research and development testbed for Geodedic very long baseline interferometry (VLBI) signal chains and receivers [4]. Configuration of the system to act as a smallsat ground station is also possible using UHF for transmission and reception of commands and providing receive only data downlink at S-band or X-band. The primary feed on the Westford telescope is a dual polarization ultra-wideband QRFH feed [5] which covers 2 to 19 GHz using a cryogenic dewar and LNA system. System temperatures are generally well below 120K over 2 to 14 GHz with an optimum of less than 60K between 4 and 10 GHz.

Example Westford Starlink Observations

Westford observations of Starlink are made using the QRFH feed and software radios with several radios and spectrum analyzers simultaneously connected. Data captures are made using a wideband spectrum analyzer as shown in Figure 1 and as raw data collects of IQ samples. Generally, we direct the antenna pointing using individual satellite orbital predictions and allow a satellite to transit through the beam.

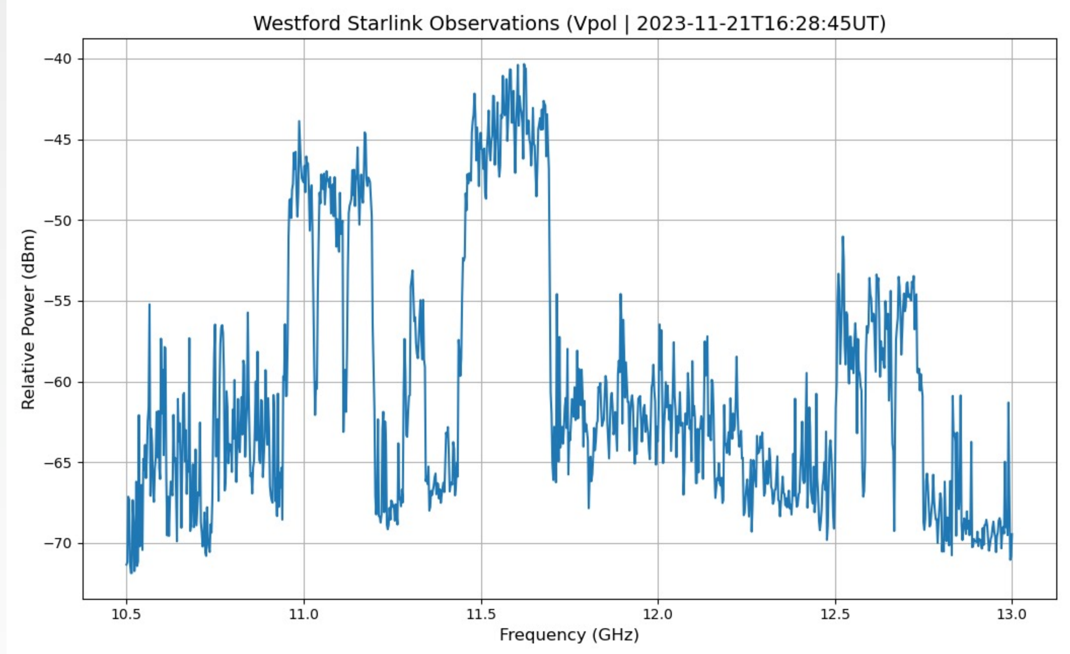


Figure 1: A wideband Starlink satellite signature captured using a Keysight N9020A spectrum analyzer in peak hold mode with a typical SNR level.

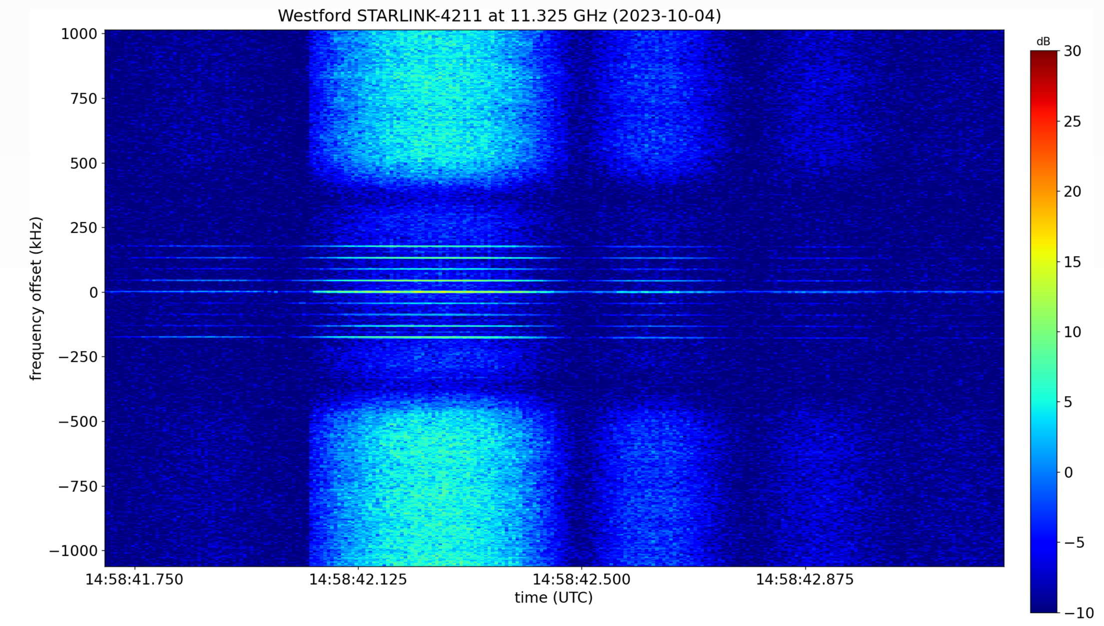


Figure 2: Time frequency spectrogram from a raw IQ capture of part of a Starlink downlink signal showing main lobe and sidelobe interactions.

Modelling of Supplemental Coverage from Space

RF energy from natural sources are generally very weak compared to the signal levels necessary to achieve useful communications. Transmission sources on satellite platforms have both their primary (licensed) emissions, harmonics and spurious signals, and unintentional radio emissions. Interaction of these signals with a radio telescope system, such as seen in Figure 3, generally falls into several categories: (1) main beam to main beam interactions; (2) sidelobe to main beam interactions; and (3) sidelobe to sidelobe interactions. Most high sensitivity radio science systems currently lack the capability to mitigate interference through adaptive beamforming or nulling. These techniques are also currently problematic due to the distortion they can create in time and frequency in the resulting measurements. While it is possible to control main beam interactions through beamforming from the transmission side to "avoid" illuminating a region. Such beamforming may make sidelobe levels worse and avoiding some level of sidelobe interactions with a radio telescope system is essentially impossible when large numbers of satellites are present.

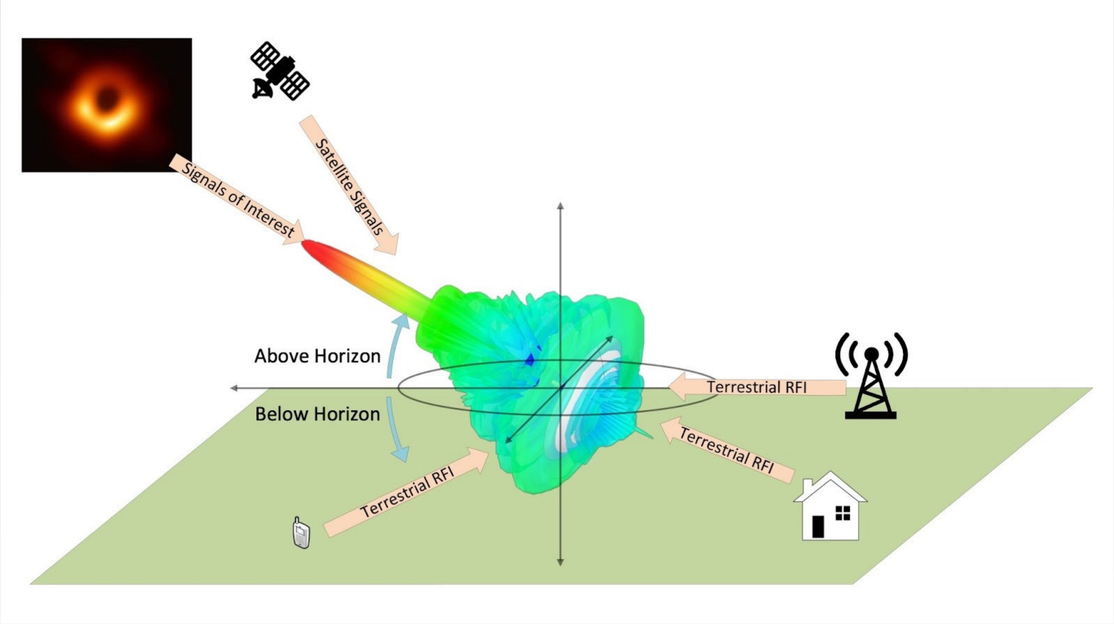


Figure 3: Interactions between a radio telescope and satellite and terrestrial RFI sources can be complex when sidelobes are considered.

Currently there are approximately 12 SCS capable satellites in orbit as part of the Starlink constellation. For interactions with the antenna mainlobe, Figure 4 shows the number of satellites at a given Signal-to-Noise Ratio (SNR) potentially visible to the Westford telescope over 4 days interval (May 13th to 17th). The telescope is assumed to be pointed at 40 deg elevation and the number of events at a given SNR are shown as a function of azimuth angle. Figure 5 presents the sidelobe interactions for the same period of time. Figure 6 presents a slice of Figure 4 and 5 counting the number of satellites at a given SNR passing through sidelobes of the antenna when it is set to 40 deg elevation and a 180 deg azimuth angle.

Each visible satellite has been assumed to transmit 40 watts of power with a main-lobe gain of 49 dB as an approximation of the actual satellite operating power. Sidelobe levels may be significantly lower (e.g. 30dB) in practice. Estimates use the range of each satellite, the gain pattern of the antenna, the aperture efficiency and the polarization mismatch, and attenuation along the path. The Westford beam pattern has been simulated while the satellite beam pattern has been approximated. For simplicity, we assume a uniform receive antenna temperature of 125K as a somewhat conservative upper bound. This is based on a model of the antenna, radome, atmosphere, and LNA performance.

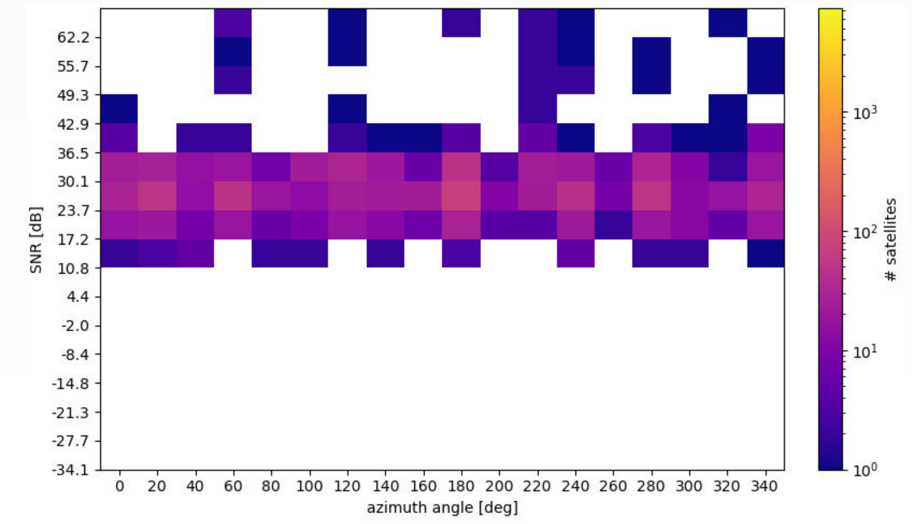


Figure 4: Predicted SCS satellite signal levels observable by the Westford telescope antenna main lobe. Events use a model SCS constellation of 12 Satellites in orbits similar to Starlink satellites.

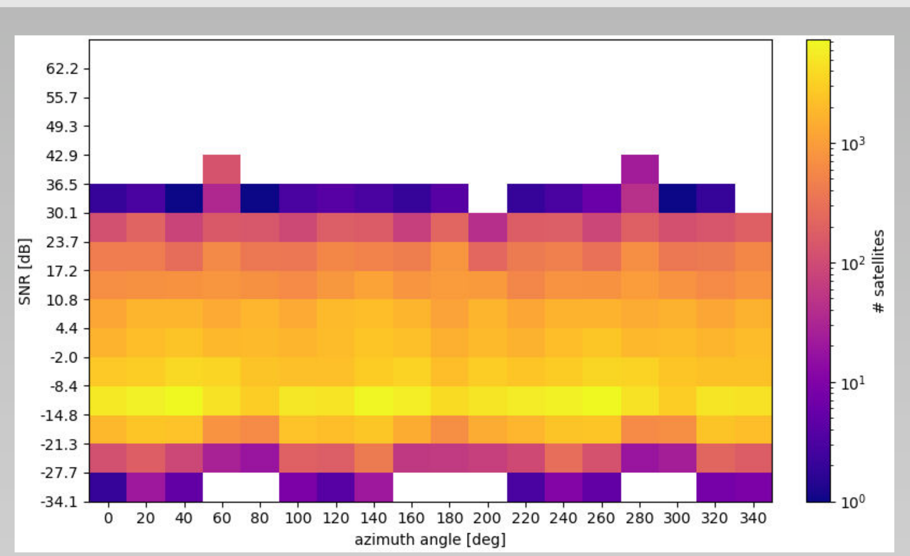


Figure 5: Predicted SCS satellite signal levels observable by the Westford telescope antenna sidelobes. Events use a model SCS constellation of 12 Satellites in orbits similar to Starlink satellites.

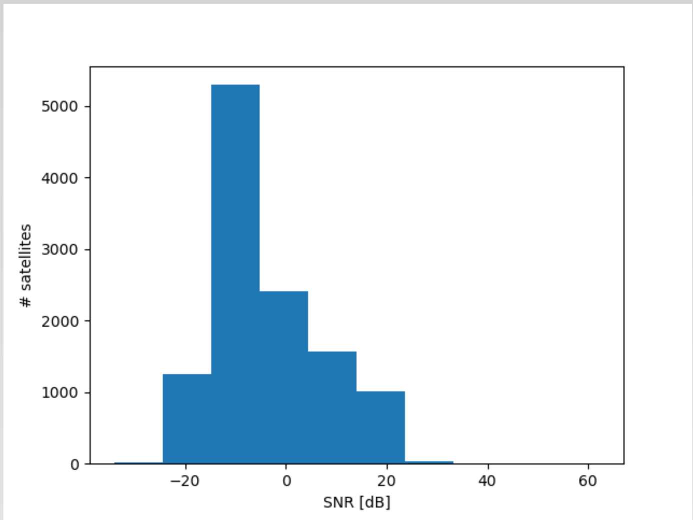


Figure 6: Predicted SCS satellite signal levels observable by the Westford telescope antenna sidelobes for a 40 deg elevation and 180 deg azimuth position of the telescope. Events use a model SCS constellation of 12 Satellites in orbits similar to Starlink satellites.

DISCUSSION

Adaptation to an environment where radio telescope systems encounter large numbers of interference events at low levels via sidelobe to sidelobe interactions will be very challenging. As satellite constellation sizes grow current radio telescope systems will likely find the bands associated with SCS unusable without additional technological and signal processing solutions that enable co-existence. Traditional flagging and removal techniques will end with significant detectable signatures regardless of the integration levels. This will likely result in transmission bands being fully discarded. Harmonics, spurious, and unintentional emissions are not yet well characterized by experiment and have the potential to also be problematic when satellites cross the main beam of a given telescope.

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