

Dynamic Protection Zone for Radio Astronomy

Sirajum Munira*, Dola Saha*, Gregory Hellbourg[†] and Aveek Dutta*

*Department of Electrical and Computer Engineering, University at Albany, SUNY

[†]Department of Astronomy, California Institute of Technology

Email: *smunira@albany.edu, *dsaha@albany.edu, †ghellbourg@astro.caltech.edu, *adutta@albany.edu

Abstract—Large networks of low-Earth orbiting (LEO) satellites are expected to provide direct connection to mobile devices to support the exponentially growing demand for ubiquitous connectivity. The ground based radio astronomy telescopes will get highly impacted due to radio frequency interference (RFI) generated from these spaceborne sources. In this paper, we created a framework to analyze the Instantaneous Equivalent Power Flux Density (EPFD) from multiple satellites in different orbital planes. We also derived a threshold for EPFD, beyond which it is detrimental to a radio telescope, Deep Synoptic Array (DSA-2000) that will operate in a wider bandwidth covering the frequencies planned for non-terrestrial communications (NTN). Our analysis shows that the current transmission masks are insufficient even in adjacent frequency bands for radio telescopes to operate at the required sensitivity to recover weak astronomical information. The zone where the incident RFI exceeds harmful threshold depends on the orientation of the radio telescope. This study shows that the percentage of data loss for radio astronomy services (RAS) due to a given satellite network is not only high in the allocated frequency bands, but also in adjacent bands. This paper shows that an orientation-based dynamic protection zone is essential for efficient usage of spectrum as well as to continue radio astronomy services without degradation.

Keywords—Radio astronomy, spectrum sharing, NR-NTN

I. INTRODUCTION

The enhancement of the fifth generation mobile network, 5G New Radio (5G NR), to incorporate non-terrestrial communications (NTN) within the 5G system has revealed an ample opportunity for the satellite industry to launch thousands of satellites in geosynchronous orbit (GSO) and non-geosynchronous orbits (NGSO) to provide ubiquitous connections all over the globe [1], [2]. As a result, the development of a complete set of policy, rules, and regulations are required for future deployments. A non-terrestrial network refers to a network or segment of networks using radio frequency (RF) resources on board of a satellite (or Unmanned Aircraft System) to embark a relay node or base station. Typically, a non-terrestrial network provides access to user equipment by feeder link (radio link between a satellite gateway and the satellite) and service link (or radio link between the user equipment (UE) and the satellite). The support of 5G NR for NTN (NR-NTN) mainly focuses on mobile broadband services. The current frequency bands discussed for NTN are: 1980-2010 MHz and 1626.5-1660.5 MHz in the uplink direction (UE to satellite) and 2170 - 2200 MHz and 1525 - 1559 MHz in the downlink (satellite to UE) direction [3].

Radio astronomy aims at sensing astronomical information at radio frequencies, and needs high sensitivity to detect the natural emissions from celestial objects that are typically many orders of magnitude weaker than communication systems. Radio telescopes often operate beyond the protected spectrum resources allocated to passive services in order to a) maximize their sensitivity by operating in wider bandwidths and b) to observe red-shifting of spectral lines due to the expanding Universe. To do so, they are usually located in remote areas with low population sensitivity so as to minimize the spectrum occupancy and the probability of harmful interference. Such spectrum quietness will soon no longer be achievable due to the expansion of cellular base stations to satellites. Most importantly, the frequency bands that are discussed for NTN cellular services, are opportunistically used by radio telescopes when available. Furthermore, the International Telecommunication Union (ITU) has outlined several recommendations for the protection criteria for the Radio Astronomy Service (RAS) in adjacent frequency bands to prevent interference from NGSO satellite systems in terms of maximum admissible data loss [4], [5]. Hence, it is essential to create a framework to study the interference from NGSO satellite constellations to next generation radio telescope.

In this paper, we address the coexistence issues between NGSO mobile networks and next-generation planner radio telescope Deep Synoptic Array (DSA-2000). In particular, we derive an interference detrimental threshold describing the level at which the combined signal from an NGSO mobile network achieves a non-negligible contribution to radio telescope data products. We then provide an algorithm to calculate the interference from multiple satellites to a radio telescope based on its orientation. We also propose a methodology to infer the percentage of data loss given an NGSO network design. Our analysis shows that there is a requirement of deploying dynamic protection zones by collaborating with the NGSO network to adapt its transmission to the radio telescope observation parameters.

Section II introduces the DSA-2000 and derives its interference detrimental level. Section III presents the system design parameters to get the interference from NGSO satellite constellation system to RAS Receivers. The simulation parameters are summarized in section IV and analyze the results from the simulation. Finally, section V concludes with the outcome of the paper and the proposed dynamic protection zones for the NGSO satellite system.

II. DSA-2000

A. Telescope description

The Deep Synoptic Array (DSA-2000) [6] is a planned innovative radio telescope made of 2048 5m-dish antennas located in the Nevada (USA) desert spread over a 15×19 km area (projected construction in 2024). The frequency coverage of the telescope includes two protected bands, at 1400-1427 MHz and 1660-1670 MHz. The telescope will span 700 MHz to 2 GHz with an instantaneous field-of-view of 10.6 deg^2 . Its design is centered around the concept of Radio Camera, involving a streamlined data processing pipeline – which includes data correlation, calibration, Radio Frequency Interference (RFI) detection and excision, and gridding (i.e. associating continuous correlated values to a discrete grid before performing large fast Fourier Transforms) [7]- to achieve a real-time production of fully sampled radio images every 15 minutes at a sensitivity of $1 \mu\text{Jy}$ per hour of integration, where $1 \text{ Jy} = 10^{-26} \text{ W/m}^2/\text{Hz}$, and at a spatial resolution of 3.5 arcsec .

B. Detrimental interference level for DSA-2000

The detrimental interference level λ_d is defined as the spectral flux density at which the RFI contribution to an image produced by a radio interferometer image can no longer be neglected compared to the natural system noise. We set this level to $\lambda_d = 10 \cdot \sigma_n \cdot R$, where σ_n is the theoretical standard deviation of the thermal noise of an image and is defined as [8]:

$$\sigma_n = \frac{\text{SEFD}}{\eta_c \sqrt{\eta_{\text{pol}} N(N-1) t_{\text{int}} \Delta\nu}} \quad (1)$$

where SEFD is the System Equivalent Flux Density - or signal detectability level - of a single telescope of the array, η_c is an efficiency factor, η_{pol} is the number of polarization, N is the number of antennas in the array, t_{int} and $\Delta\nu$ are the data integration time and frequency bandwidth used to produce the image. In the context of the DSA-2000 for a “unit image” (final images are made by assembling unit images together), we have $\text{SEFD} = 5000 \text{ Jy}$, $\eta_c = 1$, $\eta_{\text{pol}} = 1$ (we assume one single polarization in this work), $N = 2048$, $t_{\text{int}} = 1.5 \text{ s}$, and $\Delta\nu = 134 \text{ kHz}$. R is a scalar factor which describes the attenuation experienced by a source in motion relatively to the sky [9]. It is defined as:

$$R = \frac{1}{\sqrt{\pi} N} \sqrt{\frac{\lambda}{\omega_s t_{\text{int}} B_m q}} \quad (2)$$

with λ the observed wavelength, ω_s is the relative speed between the source of interference and the sky, $B_m = \left(N_b^{-1} \sum_{i=1}^{N_b} B_i^{-1} \right)^{-1}$, B_i is the i^{th} baseline length (i.e. length of the i^{th} pair of antennas of the array), $N_b = N(N-1)/2$ is the total number of baselines, and $q = \cos \delta$ where δ is the galactic declination of the source being observed. For DSA-2000, in this work, we assume $\lambda = 20 \text{ cm}$, $\omega_s = 0.25 \text{ rad/s}$ for a LEO satellite, $B_m = 3.16 \text{ km}$, and $q = 0.1$. We therefore

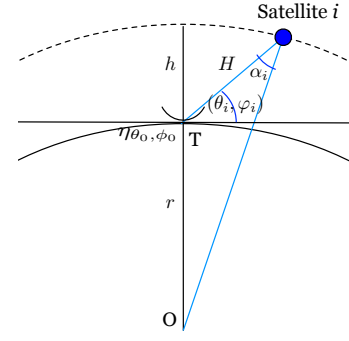


Fig. 1: Diagram describing the context of the simulation of this work. The center of the Earth is located at point O, the telescope is located at point T at the surface of the Earth. Satellites are flying in an orbit at altitude h .

obtain $R = -49.5 \text{ dB}$. The detrimental level for a DSA-2000 unit image is therefore:

$$\lambda_d = 4.8 \text{ kJy} \quad (3)$$

III. INTERFERENCE FROM NGSO NETWORKS TO RAS

In this work, we consider an NGSO network in a “Walker Star” configuration made of $N_p = 7$ orbital planes, all including the North-South rotation axis of the Earth and uniformly separated by $\beta_p = 360^\circ / 2 \times N_p = 25.7^\circ$ around the Earth with $N_s = 40$ satellites orbiting in each plane composing the considered NGSO mobile network. The satellites are assumed to be flying at a speed of 7562.2 ms^{-1} over a constant altitude in the Low-Earth Orbit at 600 km above the surface of the Earth pointing the main beam down to the Nadir point of the Earth. The DSA-2000 radio telescope is assumed to be coplanar and located at the surface of the Earth. The center of the telescope is assumed to be included in one of the 7 orbital planes, i.e. satellites will be crossing the local zenith of the telescope. Each simulation considers a $T_{\text{obs}} = 2000$ second time window at a time resolution of 1 second. During that time frame, we neglect the rotation of the Earth. This assumption imposes that the telescope remains in the same orbital plane and that the pointing direction of the telescope remains constant. The impact of the satellite interference from the NGSO network to the telescope is computed using the Equivalent Power Flux Density method described in [10].

Figure 1 shows the considered configuration for one satellite and a single radio telescope on Earth, which is used in our analysis. The single radio telescope may also represent a synthesized radio telescope in the context of array telescopes, without loss of generality. In this case, the telescope equivalent location on the surface of the Earth represents the telescope phase reference location, which may be arbitrary. We assume the telescope to be steering in a given direction identified by its azimuth φ and elevation θ . We set $(\varphi, \theta) = (0, 0)$ pointing towards the East on the horizon. The distance H of any satellite to the telescope and the satellite bearing angle α_i

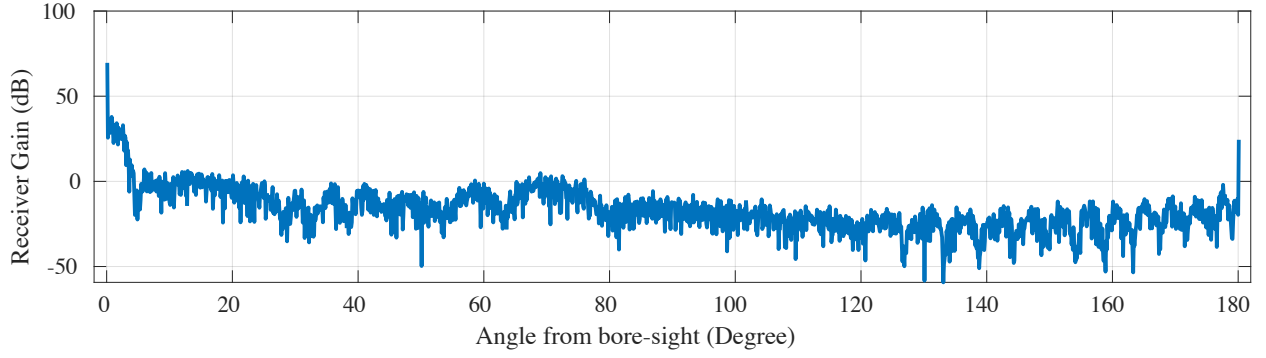


Fig. 2: Synthesized radio telescope gain combining the 2048 5m-dish antennas of the DSA-2000 array at 1550 MHz vs. angle from boresight.

are derived from the elevation angle θ by applying the law of cosines. The satellite antenna gain pattern is defined as [11]:

$$G(\alpha) = \begin{cases} G_m - 3(\alpha/\alpha_0)^2, & \text{for } \alpha_0 \leq \alpha \leq a\alpha_0 \\ G_m + L_s & \text{for } a\alpha_0 < \alpha \leq b\alpha_0 \\ G_m + L_s + 20 - 25 \log(\alpha/\alpha_0) & \text{for } b\alpha_0 < \alpha \leq \alpha_1 \\ 0 & \text{for } \alpha_1 < \alpha \end{cases} \quad (4)$$

where, $G(\alpha)$ is the gain at the angle α from the axis (dBi), G_m is the maximum gain in the main lobe (dBi), α_0 is the -3 dB beamwidth, α_1 is the value of α when $G(\alpha)$ in its corresponding equation is equal to 0 dBi, L_s is the required near-in-side-lobe level relative to peak gain in dB. Following [11] we set $L_s = -20$, $a = 2.58$, and $b = 6.32$.

The receiver antenna radiation pattern of the radio telescope is based on the synthesis of the simulated radiation pattern of the individual 5 m dish antennas composing the DSA-2000 at 1550 MHz. We assume negligible variations in radiation patterns between 1465 MHz and 1550 MHz, which is the frequency range of the current study. Figure 2 shows the DSA-2000 synthesized antenna radiation pattern.

Finally, the instantaneous EPFD for an NGSO satellite constellation system [12], [13], [14] can be expressed as follows:

$$EPFD = 10 \log_{10} \left[\sum_{i=1}^{N_s} 10^{\frac{P_i}{10}} \cdot \frac{G(\alpha, \theta_i)}{4\pi H_i^2} \cdot \frac{G_{Rx}(\varphi_i)}{G_{Rx(max)}} \right] \quad (5)$$

where $EPFD$ is the instantaneous equivalent power flux-density $\text{dB(W/m}^2\text{)}$ in the reference bandwidth at the radio telescope. N_s is the number of NGSO satellites that are visible from the radio telescope, i is the index of the NGSO satellites considered, P_i is the RF power of the unwanted emission at the input of the antenna (or RF radiated power in the case of an active antenna) of the transmitting satellites considered in the NGSO system (dBW) in the reference bandwidth, θ_i is the off-axis angle (degrees) between the bore-sight of the transmitting space station considered in the NGSO system and the direction of the radio telescope, $G(\alpha, \theta_i)$ is the transmit antenna gain (as a ratio) of the satellite considered in the NGSO system in the direction of the radio telescope, H_i is the distance (m) between the transmitting station considered in the

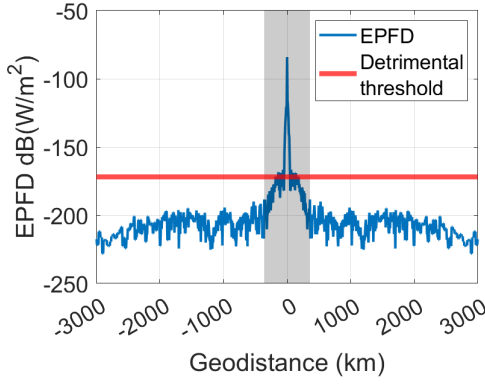
NGSO system and the radio telescope, φ_i is the off-axis angle (degrees) between the pointing direction of the radio telescope and the direction of the transmitting satellite considered in the NGSO system, $G_{Rx}(\varphi_i)$ is the receive antenna gain (as a ratio) of the radio telescope, in the direction of the transmitting satellite considered in the NGSO system, and $G_{Rx(max)}$ is the maximum gain (as a ratio) of the radio telescope. Algorithm 1 illustrates the steps to calculate the EPFD for all satellites from all the planes.

Algorithm 1: Calculate EPFD from multiple satellites in multiple orbital planes

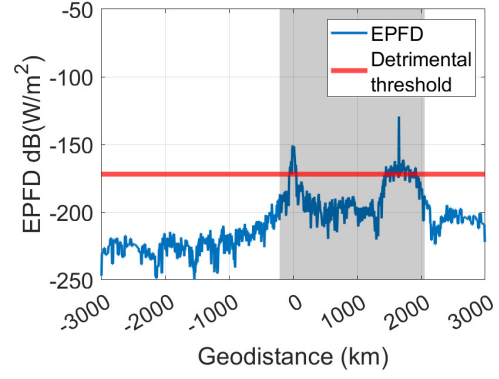
Data: $h, S, N_p, N_s, \eta_{\theta_0, \varphi_0}, \theta_{min}, \theta_{max}, L_s, \alpha_0, a, b, P, G_m, R$
Result: EPFD
 $T_{obs} = \text{getTimeToTraverseHorizon}(r, h, S);$
for $t \leftarrow 1$ **to** T_{obs} **do**
 $EPFD[t] = 0;$
 $\beta_u = \text{getArcAngleSatelliteTraversedUnitTime}(i, T_{obs});$
 for $p \leftarrow 1$ **to** N_p **do**
 $\beta_p = \text{getArcAngleBetweenOrbitalPlanes}(p, N_p);$
 for $s \leftarrow 1$ **to** N_s **do**
 $x = \text{getDistance}(\beta_u);$
 $y = \text{getDistance}(\beta_p);$
 $\{\theta, \varphi\} = \text{getAzElSatellite}(r, x, y, h);$
 $H = \text{getDistanceToSatellite}(\eta_{\theta_0, \varphi_0}, \eta_{\theta, \varphi})$
 $\alpha = \text{getAngleSatAxis}(H, h, y);$
 $G(\alpha)(\theta) = \text{getTxGain}(G_m, L_s, \alpha, \alpha_0, a, b, \theta)$
 if $\theta \in \{\theta_{min} : \theta_{max}\}$ **then**
 $G_{Rx(max)}, G_{Rx(\varphi)} = \text{getRxGain}(\theta, \varphi, R);$
 $EPFD[t] +=$
 $\text{getEPFD}(P, H, G(\alpha)(\theta), G_{Rx(\varphi)}, G_{Rx(max)});$
 end
 end
 end
end

IV. SIMULATION AND RESULTS

The simulation for getting the interference from the LEO satellite constellation for the DSA-2000 radio telescope has been performed assuming that the interference of each LEO satellite is independent of each other. The simulation parameters for deploying the model have been summarized in Table I. The number of visible satellites within 0° - 180° arc angles

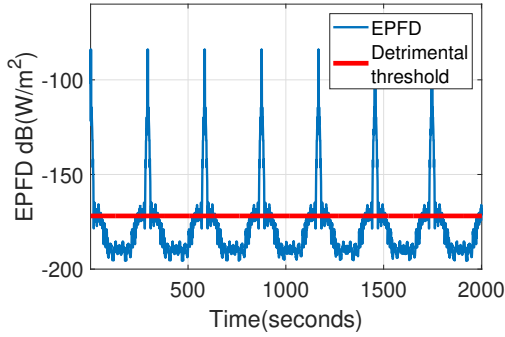


(a) Telescope elevation at 90°

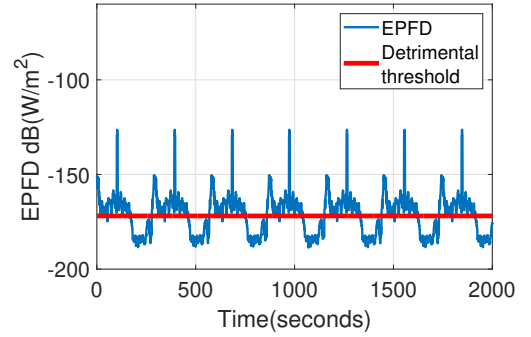


(b) Telescope elevation at 20°

Fig. 3: EPFD measured at the the radio telescope, where RFI source is a single satellite. The gray area denotes the region where RFI exceeds detrimental level.



(a) Telescope elevation at 90°



(b) Telescope elevation at 20°

Fig. 4: Aggregated EPFD measured at radio telescope, where RFI sources are multiple satellites from a constellation.

TABLE I: Simulation Parameters

Parameter	Settings
Satellite altitude, h	600 km
Earth Radius, r	6400 km
Number of Satellites, N_s	40
Speed of Satellite, S	7562.2 m/s
Maximum gain of transmitting antenna, G_m	36 dBi
Maximum gain at the receiver antenna $G_{Rx(max)}$	69.58 dBi
Transmitter Power, P	30 dBW
Center frequency, f_c	1550 MHz
Half-power beam-width of satellite, α_0	4.4127
Bandwidth of satellite beam	30 MHz
Telescope azimuth	-90° (South)
Telescope elevation	$20^\circ, 45^\circ, 60^\circ, 90^\circ$
Telescope frequency range	0.7 – 2 GHz
EPFD threshold, dB(W/m ² /1 MHz)	-171.9
Minimum elevation angle, θ_{min}	10°
Maximum elevation angle, θ_{max}	170°

have been considered for the simulation and the EPFD at the RAS receiver has been obtained for a duration of 2000s. The resulting EPFD has been compared to the threshold calculated from Equation 3 at the RAS receiver, DSA-2000.

Effect of In-band Emission from a Single Satellite: First, we simulate the program for two worst-case scenarios, when the radio telescope is oriented a) towards the zenith, and b) near the horizon. For both cases, we assumed the azimuth angle of the radio telescope as -90° . Since the receiver has a symmetric

three-dimensional radiation pattern, the azimuth angle doesn't play any significant role in this case. Figure 3 shows the EPFD at the radio telescope, where RFI source is a single satellite with maximum gain towards the Nadir. Both the telescope and the satellite are operating in 1550 MHz. The gray area shows the area where RFI exceeds the detrimental level, which is 10% plus the threshold to accumulate the measurement errors. Figure 3a shows the gray area of about 360 km when the telescope is looking toward the elevation angle of 90° . On the other hand, when it is looking toward the horizon at 20° , figure 3b shows severe RFI is detected over the detrimental level for a geo-distance of more than 2000 km.

Effect of In-band Emission from Satellite Constellation: Figure 4 shows the aggregated EPFD measured at the radio telescope for multiple LEO satellites in multiple planes. Based on the satellite constellation, the effect of 40 satellites in each plane has been observed for a duration of 2000 seconds. It is observed that peak power is higher when the telescope is oriented towards the zenith due to high gain of the main lobe compared to when it is pointing towards the horizon. However, due to presence of side lobe, the EPFD is above the detrimental threshold for 61.48% of the time when pointing towards horizon compared to 25.45% when pointing towards zenith. Both the scenarios are much larger than the 2% minimum

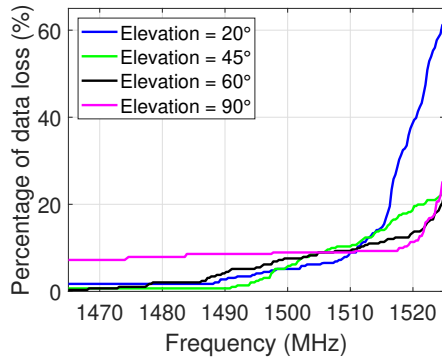


Fig. 5: Percentage of data loss due to out-of-band emissions from LEO 5G-NTN satellites operating at 1525-1559 MHz.

allowable time [14].

Effect of Out-of-band Emission from Satellite Constellation: As the range of the frequencies of the DSA-2000 radio telescope covers from 0.7 GHz up to 2GHz, the LEO satellite frequency bands operating at L-band downlink frequencies of 1525-1559 MHz for NTN communication may create severe interference at this frequency band adjacent to DSA-2000. This out-of-band emission can be caused by the adjacent frequencies affected by the filters and amplifier characteristics [15]. To observe the out-of-bands (OOB) emission from the adjacent frequency band, the spectral mask of the MSS system, based on [16] is not efficient enough to protect the RAS receiver from OOB emissions completely.

Figure 5 shows the percentage of time for OOB emissions exceeding the threshold level in the reference bandwidth of 4 kHz for MSS systems for the frequency offsets as a percentage of necessary bandwidth from the edge of the total assigned band [17]. The simulation has been performed for the frequency range from 0% to the spurious boundary at 200%. The edge of the total assigned band is 1525 MHz. From the figure, it is seen that even at the 200% frequency offset (1465 MHz), which is considered as the spurious boundary of the frequency band of 1525 MHz to 1559 MHz, the minimum percentage of time is over 2% of allowable time for exceeding the limit. This can easily show us how significantly the interference can harm the RAS protection system.

Based on our analysis, it is evident that there is a need for Dynamic Protection Zone (DPZ) based on a) aggregated EPFD from multiple satellites, b) out-of-band emissions and c) the orientation of the RAS receiver, where the satellite transmission needs to be turned off to maintain the measurements required for scientific observations.

V. DISCUSSION AND CONCLUSION

In this paper, we investigated a framework of RFI simulation from the NGSO satellite system to an RAS telescope for the frequency range of mobile satellite systems in the NTN communication. To measure the effect of the RFI in the radio telescope, we derived a threshold limit for the EPFD to

protect the telescope from harmful emissions of the satellite transmitter. Our analysis indicates that the percentage of time RFI being above the detrimental threshold depends on the orientation of the telescope. This makes a compelling case for careful deployment of the Dynamic Protection Zone for RAS. It is essential that the NGSO network dynamically adapts its transmissions based on the radio telescope observation parameters.

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