ngVLA Memo # 119
RFI Memo # 153

Detrimental Emission Levels for Orbital RFI

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Abstract

Spectrum users are increasingly coordinating with the National Science Foundation (NSF) about the impact of new orbital satellite constellations on NSF facilities. We attempt to summarize the emission levels that correspond to different degrees of impact on radio astronomy observations as a guide to these conversations, using the International Telecommunications Union recommendation ITU-R RA.769-2 as the canonical reference.

1 Introduction

Spectrum allocations to satellite constellations are proliferating and expanding in frequency. As a result, constellation operators are coordinating with the NSF to determine their impact on NSF facilities and protected astronomy bands. While there are existing well considered standards for emission levels that broadly protect radio astronomy, such as the ITU-R RA.769-2 recommendation [1], some additional scenarios are of interest to the NSF, especially for spectrum where FCC limits are well in excess of the RA.769-2 recommendations and either radio astronomy or passive sensing has no protected allocation.

Prior studies into the impact of orbital RFI on array performance [2,3,4] have focused on the impact of existing or approved constellations and emission levels. This memo instead attempts to establish clear boundaries in emission levels that would have escalating impact. With an emphasis on orbiting RFI in the 1-116 GHz frequency range, we consider the following four escalating impact scenarios:

- Scenario A: Emission levels that protect spectrum access for all ground-based radio astronomy Observations.
- Scenario B: Practical emission levels to protect spectrum access for next-generation aperture synthesis arrays.
- Scenario C: Emission thresholds that protect spectrum access and performance outside of the transmit bands.
- Scenario D: Emission thresholds that protect system health and functionality after exposure.

We attempt to quantify the associated emission thresholds while considering both existing facilities like the VLA, VLBA and GBT as well as planned facilities like the ngVLA. Such thresholds could inform permissible emission levels at or towards observatory sites especially when constellations include features such as beamforming and variable transmission power.

All scenarios presume a receiving reflector antenna architecture with a cryogenically-cooled low noise amplifier (LNA) directly fed by a feedhorn with no intervening attenuation, as is necessary for optimal noise performance. LNA designs are also assumed to be optimized for noise temperature, at the possible expense of other figures of merit, as is routine for existing radio telescopes.

2 Scenario Assessments

2.1 Scenario A: Emission levels that protect spectrum access for all ground-based radio astronomy Observations.

Recommendation: RA.769-2 Spectral Line Levels (Table 2) - 15dB.

RA.769-2 addresses the detrimental emission levels for ground-based emission received through far sidelobes for spectral line and continuum cases. Given the spectral resolution of modern and next generation arrays (including the ALMA WSU and ngVLA), the spectral line emission levels given in ITU-R RA.769-2 Table 2 (hereafter, 'Table 2') are the most relevant.

However, the emission thresholds in Table 2 must be reduced to account for the fact that the emitters of interest are in orbit and near the receiving antenna boresight. Table 2 is calculated assuming 0dBi sidelobes, which does not account for near-in on sky sidelobes. Using a reference reflector antenna model the ITU standard assumes 15dBi sidelobe levels approximately 5-degrees off boresight. Protecting observations outside this 5-degree cone of influence can be achieved with a simple reduction of 15dB across all frequencies of interest, and is explained in Section 2.1 of the same standard.

As this scenario relates to noise power received through far sidelobes, we must consider the transmitted power spectral density received at the radio astronomy site from all transmitters in the band. With multiple constellation operators sharing spectrum, this threshold allocation would need to be shared amongst all of them to achieve the desired level of protection.

We note that this standard is stringent from the perspective of other spectrum users but is not excessive. Single dish total power measurements would still be impacted at the 10% level for 2000 second integrations, and longer integrations are not practical within the transmit spectrum. This is the only scenario that protects single-dish total power measurements in the transmit bands.

2.2 Scenario B: Practical emission levels to protect spectrum access for next-generation arrays.

Recommendation: RA.769-2 Single Dish Spectral Line Levels (Table 2) + 10dB

Interferometric aperture synthesis arrays offer a degree of spatial filtering compared to single dish total power systems. Signals received through sidelobes still contribute to system temperature (and the resulting loss in sensitivity) but can be attenuated in the generated image by factors of 20-30dB or greater depending on the position on sky and source motion. This attenuation also increases at a rate faster than the noise floor drops as successive measurements are averaged, enabling longer observations. [5]

Accounting for this natural attenuation in aperture synthesis techniques can afford us a relaxation in the 25dB range from the levels recommended in Scenario A. This is a relaxation factor we often afford ourselves in detrimental emission threshold calculations for self-generated narrow-band interference. [5,6]. However, such emission levels do not necessarily protect phased array operations and certainly do not support total power measurements in the impacted band.

As an interferometer's spatial filtering is relevant to single sources of interference, this emission threshold could be given independently to each constellation operator. Their combined spectral power flux density (SPFD) will further degrade the system noise temperature in the transmit band, but transmitters are resolved and attenuated independently.

2.3 Scenario C: Emission thresholds that protect spectrum access outside of the transmit bands.

Recommendation: RA.769-2 Single Dish Spectral Line Levels (Table 2) + 46dB @ 1 GHz, decreasing to RA.769-2 Single Dish Spectral Line Levels (Table 2) + 36dB @ 50 GHz and above.

Protecting the spectrum outside the transmit band requires that the telescope not be driven into non-linear operation or saturation due to power received from the interferer. The transmit bands can then be flagged and discarded, and scientific observations can still be conducted in adjacent spectrum. We assume in this scenario that the goal is to retain this level of operation when the transmitter is not on boresight, and will adopt the same 5-degree off-boresight standard used in the preceding scenarios.

Determining the linearity limits is still difficult because the answer can be frequency, bandwidth and bit-depth dependent. E.g., EVLA 3-bit digitizers will saturate before EVLA LNAs. A more fundamental limit is LNA saturation, but we still have to make some bandwidth assumptions. We will assume up to 1 GHz of interferer bandwidth in the received band.

The next issue is defining saturation. Sometimes the 1dB compression point is used, but this is a very non-linear operating space and unsuitable for most observations, so we will adopt a 1% compression standard. We note that this level of compression could still be problematic for high dynamic range cases, so it does present some residual risk. Different LNA manufacturing processes have some variability in headroom, so we will use EVLA 1% headroom values from the project book as representative [7]. W-band LNAs are assumed to have comparable gain to EVLA Q-band LNAs but double the noise temperature.

Assuming that interferer bandwidth doesn't exceed 1 GHz, and accepting non-linearity within 5-deg of the boresight, approximate adjustments to ITU RA769-2 Table 2 for the VLA and ngVLA are summarized in Table 1.

Table 1 - Summary of Adjustments to ITU RA769-2 Table 2 for Scenario C.

Frequency (MHz)	Orbit adjustment (dB)	P_H adjustment (dB)[1]	Time base adjustment (dB)[2]	System Headroom	BW Adjustment to Headroom[3]	Total Adjustments
1420	-15	10	16.5	35	0	46.5
48000	-15	10	16.5	15	10	36.5
150000	-15	10	16.5	12	13	36.5

1 – The ITU Standard has a harmful power threshold, P_H, that is 0.1 of the system noise power. We adjust that to be equivalent to the noise power for this calculation.

2- The ITU Standard thresholds are determined over a 2000 second integration, while the noise should be determined over a 1 second integration for the linearity calculation.

3 – The interferer is assumed to have a bandwidth of 1 GHz. The BW adjustment accounts for the frequency occupancy of the LNA bandwidth. E.g., The EVLA Q-band receiver has a bandwidth of 10 GHz, so only 1/10th of the bandwidth is occupied by a 1 GHz transmitter.

The total noise power received is what matters in this scenario, and we must consider the spectral power flux density received at the radio astronomy site from all transmitters in the band. With multiple constellation operators sharing spectrum, this threshold allocation would need to be shared amongst all of them to achieve the desired level of protection. The values should also be scaled linearly if transmitting over wider bandwidths.

2.4 Scenario D: Emission thresholds that protect system health and functionality after exposure.

Recommendation: Never to exceed -79dBW/m^2 over the integrated bandwidth of the transmitter.

In this scenario we need to constrain transmitter power to avoid damage to the LNAs. Integrated input power is what matters, and the associated thresholds are a function of aperture size, frequency and transmitted/received bandwidth. Damage may also depend on the exposure duty cycle – a single exposure at a laboratory determined threshold may not cause the LNA to fail, but routine exposure to 25% of the threshold may. [8] Acceptable routine exposure levels for LNAs aren't well considered in the literature. We assume the need to account for routine exposure from overhead sources, and that retaining LNA noise performance is critical.

Input damage thresholds for radio astronomy LNAs are nominally 0dBm to 10dBm. ITU RA.2188-1 sampled a subset of available LNAs and suggests damage thresholds of roughly 7dBm to 12dBm for HMET LNAs operating in the 1-90 GHz range [9], but is not exhaustive. With routine exposure expected we will not recommend higher than -10dBm (-40dBW) before we risk significantly impacting their lifetime and/or noise performance.

If we assume a perfect 100m aperture (i.e, we constrain ourselves to never building anything bigger with current LNA technology) then the power flux density limit is -79dBW/m^2 integrated over the bandwidth of the transmitter. Over 1 GHz (as a representative bandwidth) that's -169dBW/m^2/Hz. Tying that back to the SPFDs in RA.769-2 Table 2, that is an adjustment of roughly +70dB at 1 GHz falling to +40dB at 50GHz and +35dB at 116 GHz.

We note that the value at 116GHz is actually slightly lower than the linearity limit given in the preceding case. That is because we have to consider the on-boresight response in this scenario, which is more constraining. A 100m dish at 116GHz has a little under 100dBi of gain, compared to the 15dBi near-in-sidelobe response assumed in the preceding case.

LNA damage levels when on boresight will be more limiting than off-axis linearity when considering large apertures operating at frequencies above 116 GHz.

3 Conclusions & Discussion

Retaining access to broad spectrum radio astronomy observations can be best achieved when coordinating with other spectrum users, especially orbital spectrum users whose emissions are otherwise difficult to mitigate. Establishing thresholds for emissions received at radio astronomy sites can provide a win-win solution, protecting radio astronomy while also enabling operators to fully use their allocated spectrum and maximum transmit power in other geographic areas, especially population centers. Incorporating beamforming in all future satellite constellation designs, as well as tunable transmitter power, can protect most radio astronomy sites and operational modes. Boresight avoidance of satellite downlinks may be possible with mutual operational data sharing systems being developed by NRAO.

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Table 2 - ITU-R RA.769-2 Table 2

TABLE 2*

Threshold levels of interference detrimental to radio astronomy spectral-line observations

Frequency f (MHz)	Assumed spectral line channel bandwidth Δf (kHz)	Minimum antenna noise temperature T_A (K)	Receiver noise temperature T_R (K)	System sensitivity[(2)] (noise fluctuations)		Threshold interference levels[(1) (2)]		
				Temperature ΔT (mK)	Power spectral density ΔP_S (dB(W/Hz))	Input power ΔP_H (dBW)	pfd $S_H \Delta f$ (dB(W/m²))	Spectral pfd S_H (dB(W/(m² · Hz)))
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
327	10	40	60	22.3	–245	–215	–204	–244
1 420	20	12	10	3.48	–253	–220	–196	–239
1 612	20	12	10	3.48	–253	–220	–194	–238
1 665	20	12	10	3.48	–253	–220	–194	–237
4 830	50	12	10	2.20	–255	–218	–183	–230
14 488	150	15	15	1.73	–256	–214	–169	–221
22 200	250	35	30	2.91	–254	–210	–162	–216
23 700	250	35	30	2.91	–254	–210	–161	–215
43 000	500	25	65	2.84	–254	–207	–153	–210
48 000	500	30	65	3.00	–254	–207	–152	–209
88 600	1 000	12	30	0.94	–259	–209	–148	–208
150 000	1 000	14	30	0.98	–259	–209	–144	–204
220 000	1 000	20	43	1.41	–257	–207	–139	–199
265 000	1 000	25	50	1.68	–256	–206	–137	–197

* This Table is not intended to give a complete list of spectral-line bands, but only representative examples throughout the spectrum.

(1) An integration time of 2 000 s has been assumed; if integration times of 15 min, 1 h, 2 h, 5 h or 10 h are used, the relevant values in the Table should be adjusted by +1.7, –1.3, –2.8, –4.8 or –6.3 dB respectively.

(2) The interference levels given are those which apply for measurements of the total power received by a single antenna. Less stringent levels may be appropriate for other types of measurements, as discussed in § 2.2. For transmitters in the GSO, it is desirable that the levels need to be adjusted by –15 dB, as explained in § 2.1.

4 Appendix – Comparison to Ground-Based Emission Scenarios

For context, we provide equivalent considerations for ground-based emitters in the four established scenarios. As all thresholds are specified as power spectral densities at the receiving antenna, the thresholds are rendered independent of the site topography.

The fundamental value that may change in each scenario is the gain of the receiving antenna. ITU-RA.769-2 assumes the interfering signal is received through a 0dBi sidelobe for ground-based emission and 15dBi sidelobe for space-based sources, consistent with an interferer in a far sidelobe or a near-in sidelobe 5-deg off boresight, respectively.

The gain assumption applicable to each scenario must account for the use cases associated with the receiving antenna, and the need to access lower elevations. For imaging arrays such as the VLA, observations near the horizon are a useful capability but not a driving use case at most azimuth angles. The exception is the southern horizon to enable observations of the galactic center and other sources in the southern sky.

In contrast, Antennas engaged in geodesy or inertial reference frame observations have a need for low-elevation observations at most Azimuth angles. Low-elevation observations are much more common with an array like the VLBA and this capability is important to partners such as the US Naval Observatory (USNO).

These considerations are reflected in the associated scenario recommendations.

4.1 Scenario A: Emission levels that protect spectrum access for all ground-based radio astronomy Observations.

Recommendation:

- RA.769-2 Spectral Line Levels (Table 2) - 15dB for Azimuth angles 180° ± 40° (where North = 0°).
- RA.769-2 Spectral Line Levels (Table 2) + 0dB (no change) for all other Azimuth angles.

We retain the same standard applied in orbital RFI scenario for southern Azimuths (for a North American telescope) to account for southern sky observations near the horizon with single dish telescopes. A relaxation of up to 15dB, reverting to the 0dBi sidelobe assumption, may be appropriate depending on the specific use cases and capabilities of the telescope. E.g., a telescope that does not access elevations below 10-deg in elevation could accept the RA.769-2 levels at all Azimuth angles.

As with the orbiting emitter scenario, this threshold allocation would need to be shared amongst all transmitters impacting the telescope site in order to achieve the desired level of protection.

4.2 Scenario B: Practical emission levels to protect spectrum access for next-generation aperture synthesis arrays.

Recommendation:

- RA.769-2 Single Dish Spectral Line Levels (Table 2) + 10dB for Azimuth angles 180° ± 40° (where North = 0°).
- RA.769-2 Single Dish Spectral Line Levels (Table 2) + 25dB for all other Azimuth angles.

As with the preceding scenario, we protect the southern sky where observations at low elevation are most common. At other Azimuth angles, this recommendation is relaxed by 15dB compared to the orbiting emitter case to reflect the fact that interference source is received through a 0dBi far sidelobe. We assume that retaining performance near the horizon at all Azimuth angles is not strictly required for an aperture synthesis array, though this is a useful capability and near-horizon observations help calibrate for atmospheric opacity.

4.3 Scenario C: Emission thresholds that protect spectrum access and performance outside of the transmit bands.

Recommendation:

- *Telescopes observing below 10-deg elevation*: RA.769-2 Single Dish Spectral Line Levels (Table 2) + 46dB @ 1 GHz, decreasing to RA.769-2 Single Dish Spectral Line Levels (Table 2) + 36dB @ 50 GHz and above.
- *Other telescopes*: RA.769-2 Single Dish Spectral Line Levels (Table 2) + 61dB @ 1 GHz, decreasing to RA.769-2 Single Dish Spectral Line Levels (Table 2) + 51dB @ 50 GHz and above.

For telescopes operating near the horizon (VLBI, Geodesy, etc.) the interfering signal can be received through near-in sidelobes much like it can from orbital RFI. Therefore, the recommendation remains unchanged from the orbital RFI scenario.

For telescopes operating at higher elevations only, the signal can be assumed to enter through a 0dBi sidelobe and a 15dB relaxation can be afforded compared to the values computed in Table 1 of this memo.

As with the orbital scenario, this emission threshold allocation would need to be shared amongst all transmitters impacting the telescope site in order to achieve the desired level of protection and retain system functionality outside of the transmit band.

4.4 Scenario D: Emission thresholds that protect system health and functionality after exposure.

Recommendation:

- Never to exceed -40dBW when integrated over the bandwidth of the transmitter and geometric collecting area of the receiver.

For telescopes operating near the horizon (VLBI, Geodesy, etc.) the interfering signal can be received through near-in sidelobes much like it can from orbital RFI. Therefore, the total integrated power recommendation remains unchanged from the orbital RFI scenario. However, given the localized nature of the transmitter, the aperture size of the receiving antenna can be incorporated into the calculation (rather than assuming a 100m aperture as given in the orbital scenario.)

For telescopes operating at higher elevations only, the signal could be assumed to enter through a 0dBi sidelobe and a 15dB relaxation can be afforded, but such an assumption is inherently risky if the transmitter is not at the horizon, or the power is scattered/reflected on the receiver structure resulting in gain greater than 0dBi in that specific direction. Given the impact on system health and functionality, the more conservative interpretation is preferred for this scenario.

5 References

[1] International Telecommunication Union (ITU) "Protection criteria used for radio astronomical measurements" Recommendation ITU-R RA.769-2, 2003.

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[3] De Pree, C. et al. "Coordinated Starlink User Terminal Testing Near the Very Large Array" EVLA Memo #222, April 2023.

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[5] Perley, R. "RFI Emission Limits for Equipment at the EVLA Site" EVLA Memo #106, September 2006.

[6] Selina, R. "System Electromagnetic Compatibility and Radio Frequency Interference Mitigation Requirements" ngVLA Doc. # 020.10.15.10.00-0002-REQ, Rev B, 2020.

[7] Haywood, R. et al. "Receivers" EVLA Project Book, Chapter 5, March 2009.

[8] Chen, D. et al. "Research on the Effect of High Power Microwave on Low Noise Amplifier and Limiter Based on the Injection Method" Journal of Electromagnetic Analysis and Applications, Vol. 2 No. 2 (2010), Article ID: 1393 , 5 pages DOI:10.4236/jemaa.2010.22016

[9] International Telecommunication Union (ITU) "Power flux-density and e.i.r.p. levels potentially damaging to radio astronomy receivers" Report ITU-R RA.2188-1, October 2022.