ngVLA Memo #48

ngVLA Radio Frequency Interference Forecast

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Abstract

Radio Frequency Interference (RFI) increasingly corrupts radio astronomy data. Transmitters are moving to higher frequencies as technology improves and bandwidth needs increase. ngVLA will be exposed to more frequent RFI at higher frequencies than the VLA, with higher time and frequency occupancy, and with higher peak power. The most serious threats will come from 5G cell phone transmissions from 25 GHz to 86 GHz, and thousands of Low Earth Orbit (LEO) satellites transmitting at significant power and with broad footprints from 10 GHz to 51 GHz. Vehicular radar will expose receivers to potentially damaging power levels from 76 to 81 GHz. An exhaustive list of current and projected RFI sources is not the intent of this paper; we will provide an overview of the sources that are expected to most affect the ngVLA during its operational lifetime, with an emphasis on upcoming sources. We will then propose a simple metric by which the threat of RFI to an observation may be quantified and compared.

1 Introduction

This document will describe significant classes of current and expected RFI sources that may impact the ngVLA. Each class of sources will be discussed briefly. A mechanism of measuring RFI impact on observations will be introduced, and some ngVLA Science Driver scenarios will be evaluated by that metric. Timescales of RFI are presented with an eye to mitigation strategies, and impact mechanisms on telescope and data are introduced.

2 Site

Activities and equipment at the ngVLA site are potential sources of RFI. As there will be few days set aside for site-wide maintenance, the assumption must be that active receivers are always present and collecting science data.

Buildings will continue to be a potential source of RFI. On-site correlators, computers, power generation, conditioning, and monitoring systems, and IT infrastructure must all be shielded against leakage throughout the ngVLA frequency range. r^2 dropoff would dictate that the buildings be located as far as practical from the core of the array.

Many threats from maintenance, employee, and visitor vehicles can be expected at the site, as detailed in Section 3.

Utility monitoring has nearly completed its shift to remote and RF-based query mechanisms, but care must be taken to understand the methods used by new utilities installed for ngVLA. Site-local electric, gas, and water monitors should be vetted by RFI screening. It is possible that new utilities infrastructure will be built near the site – wind turbines, for example – that would also need to be vetted for RFI, or at least characterized to provide opportunities for mitigation.

Handheld radios are used at the VLA for communication, and the results are quite visible in broadly corrupted P-band data. To mitigate risk, radios with tight frequency tolerances should be selected and RFI screening performed regularly.

There will be nearly 100 ngVLA antennas in a core not much bigger than today's VLA D array. This densely packed antenna array will create opportunities for self-generated RFI to impact many antennas, thus surviving correlation. As malfunctions will inevitably occur, provision must be made to rapidly detect, diagnose, and repair the offending equipment. The short core baselines also result in low interferometric attenuation through fringe-winding.

3 Vehicles

Vehicles are dependable sources of RFI today, and their emissions will grow even before ngVLA begins construction. A new and serious RFI threat has appeared: automotive radar. As of early 2018, several dozen car models are available with radar – typically billed as Autonomous Cruise Control (ACC) – in which the car uses forward-facing active radar to detect cars and other obstacles. This is but the first wave of vehicle radars; cars soon to reach market will have eight or more beams. Frequency allocation for these radars is in W band at 76-81 GHz, covering about 8% of ngVLA band 6 (70-116 GHz). Disturbingly, the emitted power – 55 dBm EIRP – can be high enough to cause damage to radio astronomy receivers, even at hundreds of meters of separation. Worse yet, these are continuous radars – not pulsed. By 2030 it is likely that all consumer vehicles will be equipped with multiple radar and other emissive systems for parking, cruise control, and autonomous driving.

Entertainment systems are ubiquitous and use a variety of RF protocols, as seen in Table 1.

Protocol	Frequencies
WiFi	900-930 MHz, 2.4–2.5, 3.6–3.7, 4.9–5.0, 5.1–5.9, 61–61.5 GHz
Bluetooth	2.4–2.5 GHz
wireless USB	3–11 GHz
wireless video	2.4–2.5, 5.7–5.9 GHz

Table 1: Protocol frequencies

More and higher-speed entertainment-enabling protocols will become available over the next decade, especially as autonomous driving becomes more common.

Arrangements to disable these features will have to be made for vehicles purchased for on-site use, and equipment and procedures for screening should be considered. Note the possibility that legal requirements for active radar could be made under the umbrella of safety such that vehicles with disabled features would not be allowed on public roads.

Electric vehicles will be pervasive, and will likely be an excellent choice for on-site vehicles. However, the pulse width modulation used to drive motors can emit significant energy at low frequencies, and the electronics used to monitor vehicle status may involve wireless networks. Screening procedures – both for initial purchase and for regular checkup – will be needed. Similarly, cranes, lifts, hoists, and heavy equipment should be screened for emissions from electric motors and control systems.

4 Cellular communication

Roll-out of 5G cellular communications will add new threats to most ngVLA bands.

The overall threat level is high:

- Towers transmit at all times.
- All bands are threatened. While the final frequencies will not be decided upon until 2020 and will likely be a subset of those listed in Table 2, ngVLA band 5 (30.5-50.5 GHz) could be hit the hardest: with the proposed cellular bandwidth of about 11 GHz and a receiver bandwidth of 20 GHz, frequency occupancy will be about 0.5. For other bands, occupancy would still be high, but a bit lower at 0.1.

- While attempts will be made to avoid direct line of sight to towers, both radio telescope antennas and cell towers share the same need: a good view away from the ground. Many antennas will be affected by the same signal; thus the RFI will survive correlation.
- Power will be high enough to be significant, as it is today.

Frequency ranges recommended for study by WRC-15 for use in 5G are listed in Table 2.

Low	High	
470	698	MHz
698	790	
1427	1518	
3300	3800	
5150	5925	
24.25	27.50	GHz
31.8	33.4	
37	43.5	
45.5	50.2	
50.4	52.6	
66	76	
81	86	

Table 2: List of frequencies (GHz) under study for 5G based on WRC-15

5 Vehicles

Vehicular RFI threats were discussed above for site-based vehicles. Visitors and passers-by will generally not have appropriately modified or screened vehicles. It will be worth considering designated parking areas for non-sanctioned vehicles that are far away from the array core, and perhaps even shielded or underground.

Roads passing through and near the array, e.g. Route 60, will provide a flux of vehicular RFI that will not be easily controlled, and which can occur in fairly close proximity to antennas. Because radar could cause receiver damage, mechanisms to protect receiver integrity from radar flashes should be considered.

Even antennas not near public roads will have direct or first-sidelobe views of public roads, thus could easily receive enough power to damage receivers at a distance. Antenna siting should carefully consider lines of sight to current and proposed roads. Where roads are visible, if receivers are not protected then creating 'no-point' zones custom to each antenna should be considered to avoid having the main antenna beam or high-gain sidelobes point at roads.

6 Internet of Things

The devices people wear or use are prolific generators of RFI. The full range of devices is huge and increasing rapidly, and is much too large to fully examine here. Representative device classes that are likely to be seen at and near ngVLA antennas include:

wearables: Wearables generally refers to electronic devices worn on the body or in clothing. Wearables are not new – hearing aids and Fitbits are now common, and smart glasses eagerly await their return to fashion – but the market is quickly expanding, and a majority of people are likely to own wearables in the ngVLA timeframe. Not only do wearables often contain RF-loud microprocessors, but Internet of Things (IoT)-connected wearables will become very common, especially given the expected increase in availability and speed of cellular networking. They will likely be emitters of 5G, wireless video, RFID, Bluetooth, and other protocols.

implants: Implants also are not new – witness the pacemaker. In addition the plethora of medical applications existing and planned, hobbyists are designing implantable wearables. Implants are likely to take on all RFI-emitting aspects of wearables – but they may not be removable.

external medical devices: Hearing aids already use Bluetooth. Assisted mobility devices including wheelchairs and prostheses are common and their control electronics continue to become more sophisticated. Partial and whole-body exoskeletal frames are likely to become more common in the ngVLA lifetime. All will likely have noisy electronics and wireless connectivity for monitoring and control.

cell phones: Cellular phones will of course be an ever-increasing RFI problem. ITM/5G will arrive with emission in high bands and with wide bandwidths as described above.

Wearables, implants, and other IoT devices exacerbate an existing RFI situation with regards to visitors and employees. Given the dense ngVLA core, tens of antennas could easily be infected with the same RFI signal. These considerations will impact site design and access policies.

7 Ground-based radar

Primary aviation surveillance radar transmits in S band at about 25 kW peak power, and secondary radar in L band at about 1 kW. While improvements to airport radars are occurring, there seem to be no plans to significantly change bands or emitted power.

Precision Approach Radar (PAR) operates in X and Ku bands, and is sited at larger military and civilian airports to track surface movements.

There are about 150 NEXRAD radars in the United States used for long-range weather scanning. They transmit about 700 kW in S band. These are complemented by C-band Terminal Doppler Weather Radar (TDWR) sites at about 50 locations, used for local coverage of major airports.

While climate change may spur some increase in weather radar deployment, significant changes are not anticipated in the ngVLA timeframe. Table 3 shows some frequency bands for ground-based radars.

Source	Frequencies (GHz)
Surveillance	1.24–1.37
NEXRAD	2.7–3.0
TDWR	5.6–5.65
PAR, ASDE-X	9.0–9.2
PAR, ASDE-3	15.7–16.2

Table 3: Ground radar

8 Aircraft

Air traffic is expected to double in the next 30 years. Communications, tracking, and radar emissions will increase for every aircraft, so the RFI threat will be compounded. The VLA currently sits in a relatively low air-traffic area of the southwest, but the increase in traffic will cause more airways to be created and areas of low traffic density will be desirable. Areas of aircraft-related RFI sources include the following:

8.1 Communication

Aircraft datalinks and WiFi services are provided in commercial aircraft by Ku and Ka satellites from many vendors including ViaSat, Inmarsat, SES, and Hughes. Spot beams are being used to service high-traffic routes. With an increase in desired bandwidth by the public and expected increases in air travel, this will grow to be a major problem – especially in Ku – over the next two decades. While most ngVLA antennas are in low air-traffic areas, spot beams must overlap each other to provide continuous connectivity during flight; ngVLA antennas will inevitably be in their footprint.

Military fighters have a significant presence in New Mexico. F-16 Falcons use Link16 in L band, and F-22 Raptors use Intra-Flight Data Link (IFDL), also in L band. The F-35 uses the Multifunction Advanced Data Link (MADL) datalink in Ku. Funding problems during development precluded MADL interoperability with the F-22, and one method proposed to bridge the gap is to use drones, e.g the GlobalHawk, as communications bridges with MADL, Link16, and IFDL transceivers. The core ngVLA site and many outlying antennas are near Military Operations Areas (MOAs) and primary drone pilot training facilities at Holloman Air Force Base; significant communications RFI should be expected.

8.2 Navigation

Aircraft use Distance Measuring Equipment (DME) to establish their position relative to a ground station by transmitting interrogation pulse pairs in L band. The ground station responds, and travel time determines straight-line distance. Despite having been in use for 70 years, DME is being evaluated as part of the FAA NextGen air traffic system – so it is not likely to go away. Interrogation pulses are visible in VLA and will continue to be visible in ngVLA. The effective duty cycle of these pulses with typical air traffic is very low, so effective flagging mechanisms – e.g. pre-integration flagging – could reduce this threat to a minimal level.

8.3 Radar

Airborne radar altimeters operate in C band and are active on most commercial aircraft, as are weather radars that operate in C, X, and Ku bands. While altimeters are low-power (milliwatts), weather radars can transmit tens of kilowatts.

X and Ku military airborne radars expect to see large growth in the coming years; the F-16 AN/APG-68 radar transmits from 9.8 GHz to 26 GHz, and the F-22 AN/APG-77 and F-35 AN/APG-81 are in X-band. Airborne ground-mapping radars, previously in L band, are generally moving to Ku.

8.4 Drones

Holloman Air Force Base is a global training center for military drone pilots, and in fact Notices to Airmen (NOTAMs) are posted daily for drone training in central New Mexico. At least one notable incident has been reported at the VLA site of a large drone ‘visitation’. L, C, and X-band satellite links are currently used for datalink and control, and all other radar and communications systems can be present. A large increase in drone presence and use is expected.

Non-military drone use will also strongly increase, and bandwidth of civilian drones will be pushed to increase, driving datalinks to higher frequencies than the current L, S, and C bands. We are likely to see high usage in S band and above, including RFI in all 5G, WiFi, and wireless video bands. Close-flying drones will have the potential to damage receivers if protection mechanisms are not provided. Drone users include amateurs, land management agencies, realtors, hunters, ranchers, and more; drones could have a significant presence around ngVLA antennas.

White Sands Missile Range is a test center for GPS jamming, and it seems likely that they would be chosen as a test facility for drone jamming as that need increases, with resulting high-power RFI emission in military and civilian drone control frequencies.

Table 4 shows a summary of aircraft-related frequencies.

Source	Frequencies (GHz)
Nav (DME)	978–1213 MHz
Altimeter	4.2–4.4
Weather radar	5.3–5.5
Weather radar	8.7–8.9
Weather radar	9.3–9.5
F-16/APG-68	9.8–26
F-22/F-35	8–12
Mapping	12–18
Weather radar	13.2–13.4

Table 4: Aviation frequencies

9 Spacecraft

With increasing demand for bandwidth and plummeting prices for commercial space launch, communication satellite constellations will dramatically affect radio astronomy in the ngVLA timeframe. Table 5 shows several of the largest constellations planned in the mid-2020s. Note that V band is 40–75 GHz.

Operator	$\approx N_{satellites}$	Band
SpaceX	12,000	Q, V
SpaceX	4,400	Ka, Ku
Boeing	2,900	Q, V
OneWeb	1,280	Q, V
OneWeb	700	Q, V
OneWeb	650	Ku

Table 5: Planned large constellations in LEO and Medium Earth Orbit (MEO)

The list of constellations changes frequently, as does the specification for each constellation. Table 6 shows frequencies for the SpaceX Starlink from FCC 18-38. FCC 18-38 addresses the fact that these bands will be shared by other operators, leaving it to the operators to determine how to accomplish the sharing.

Low	High	Function
10.7	12.7	downlink
13.85	14.5	uplink
17.8	18.6	downlink
18.8	19.3	downlink
27.5	29.1	uplink
29.5	30.0	uplink

Table 6: SpaceX Starlink frequencies (GHz)

OneWeb's FCC 17-77 proposal has frequencies identical to those of SpaceX.

Table 7 shows transmit frequencies from Boeing's application for a constellation that includes V-band Inter-Satellite Links (ISLs) to LEO and GEO satellites.

Low	High	Function
17.8	19.3	downlink
27.5	29.1	intersatellite
29.5	30.0	intersatellite
37.5	42.0	downlink
47.2	50.2	intersatellite
50.4	51.4	intersatellite

Table 7: Boeing frequencies (GHz)

Several hundred other satellites from operators including Telesat, O3b, Theia, and ViaSat are planned with similar frequency plans in the same timeframe. This will at least triple the occupancy of current LEO and MEO orbits.

Both FCC 18-38 and FCC 17-77 make mention of radio astronomy. From FCC 17-77:

> *. . . operations must be coordinated with the radio astronomy observatories listed in 47 CFR 2.106, n.US131, to achieve a mutually acceptable agreement regarding the protection of the radio telescope facilities operating in the 10.6-10.7 GHz band.*

And from FCC 18-38:

> *. . . Although not a condition to this authorization, SpaceX should be aware of these facts and contact the National Science Foundation Spectrum Management Unit [. . .] to assist with coordination and information on radio astronomy sites.*

Hundreds of these satellites will be visible simultaneously to any antenna in the array through primary beam and sidelobes. With many of these constellations employing spot beams for regionally high Signal-to-Noise Ratio (SNR), power levels will be quite significant even outside the primary lobe. It should be expected that astrophysical data will be corrupted at all times in any frequencies on which the constellations are transmitting. Beam hits can be expected to increase in number proportional to orbit occupancy. In addition to downlinks, satellites will have ISLs that ngVLA will see. ISL experiments have included UHF, S, C, X, Ka, and V bands (as well as optical), but should be expected to generally move up or remain in high-frequency bands such as V.

Satellite downlinks will be visible, transmitting, and powerful at all times, and the same signal will be received by most or all of the antennas in the array. No signal mitigation strategies are currently known that are likely to recover signal from underneath these transmissions. Therefore, any frequencies used by these satellites for downlink or ISL are likely to be lost to radio astronomy.

Of course, existing satellites and constellations will continue to affect observations, including those outlined in Table 8.

Low	High	Function
1.1	1.8	GNSS, SAR, Iridium, meteorology
2.0	2.3	Sirius XM, military, remote sensing
2.5	2.7	communication
3.4	4.2	communication, broadcast
7.25	7.75	downlinks
8.0	9.0	environmental, military, communications
10.7	12.8	fixed service, communications
18	20	downlinks
23	27	fixed, broadcast, communications
94.01	94.09	Cloudsat

Table 8: Current satellite downlink bands (GHz)

10 Non-science data

Science data will not be the only data affected by RFI. Pointing, flux, and polarization calibration observations are susceptible, as is holography to measure optical path performance. The following are of special note for ngVLA:

10.1 Phase calibration

ngVLA will use the water vapor line centered at 22GHz and extending across K band to assist in phase calibration. Unfortunately, many police and automatic traffic radars use K band (as well as X and Ka); RFI will have to be excised from the water vapor data.

10.2 Diagnostics

The large number of antennas and the desire for high reliability dictate the development of advanced diagnostic algorithms to recognize RFI and its possible effects throughout the system. One example would be a very strong RFI within the receiver bandpass (for example, a car radar) that causes the gain equalizers or quantizers to behave poorly. However, these symptoms can be similar to that of a failed component. Diagnostic systems will have to be designed to to differentiate RFI from other system faults.

11 Bands and molecules affected

The International Astronomical Union (IAU) has published a list of astrophysically important spectral lines. Table 9 shows the relationship between the ngVLA bands and digitizers, the IAU frequencies, and the frequencies of the RFI sources discussed in this paper. The list has been grouped into individual digitizers, as large RFI power levels entering a digitizer may cause loss of effective bits throughout the digitizer's band.

Band	Frequency	RFI sources	Molecules
1	1.2–3.5	5G, Bluetooth, USB, WiFi, Wireless video	Hydrogen (HI), Hydroxyl radical (OH), Methyladyne (CH)
2	3.5–10.5	5G, USB, WiFi, Wireless video	Formaldehyde (H2CO), Helium (3He+), Methanol (CH3OH)
3	10.5–14.0	Satellite, USB	Methanol (CH3OH)
3	14.0–21.0	Satellite	Cyclopropenylidene (C3H2), Formaldehyde (H2CO)
4	20.5–27.5	5G, Satellite	Ammonia (NH3), Cyclopropenylidene (C3H2), Dicarbon monosulphide (CCS), Water vapor (H2O)
5	30.0–37.5	5G, Satellite	Cyanoacetylene (HC3N), Methanol (CH3OH)
5	37.0–44.5	5G, Satellite	Silicon monoxide (SiO)
5	44.0–51.5	5G, Satellite	Carbon monosulphide (13CS), Carbon monosulphide (C34S), Carbon monosulphide (CS), Cyanoacetylene (HC3N), Dicarbon monosulphide (CCS)
6	70.0–77.0	5G, Vehicle radar	Cyanoacetylene (HC3N), Deuterated formylium (DCO+), Deuterium cyanide (DCN), Methyl cyanide (CH3CN)
6	77.0–91.0	5G, Vehicle radar	Cyanoacetylene (HC3N), Cyclopropenylidene (C3H2), Deuterated Ammonia (NH2D), Deuterated water (HDO), Ethynyl radical (C2H), Formylium (H13CO+), Formylium (HCO+), Hydrogen cyanide (H13CN), Hydrogen cyanide (HC15N), Hydrogen cyanide (HCN), Hydrogen isocyanide (H15NC), Hydrogen isocyanide (HN13C), Hydrogen isocyanide (HNC), Methyl acetylene (CH3CCH), Silicon monoxide (SiO)

Table 9: RFI sources and important spectral line molecules for some ngVLA digitizers

12 Threat quantification

Human-initiated radio transmission causes data loss for a science observation – and is therefore classed as RFI – when:

- its presence coincides with the time of an observation
- its transmission frequencies intersect the observation frequencies
- it affects one or more receivers
- its received power is significant relative to that of the science source

This list defines dimensions over which we can define metrics to provide a simple, quantifiable evaluation of a potential RFI threat. In this section, we will develop an equation that uses these dimensions to provide a rough measure of the fraction of an observation that will be affected by RFI. We'll start by describing the axes:

12.1 Time

The fraction of time that an RFI source can be detected in the observation. If we assume that the instrument observes at all times, this reduces to the fraction of the time that the RFI transmitter is transmitting, visible to the receiver, and powerful enough to affect target data.

$$f_t = f_{trans} \cdot f_{vis} \cdot f_{power} \tag{1}$$

For example: a single high-inclination LEO satellite, constantly transmitting with significant enough power to affect observation, is visible for about 5 minutes during each pass and makes on the order of ten passes over the hemisphere per day,

$$f_t = 1.0 \cdot \left(\frac{5\,min}{passes} \cdot \frac{10\,passes}{day} \cdot \frac{1\,day}{1440\,min} \right) \cdot 1.0 = 0.03$$

In another example: aircraft DME transmitters in L-band are visible constantly at the VLA. The maximum specified query/response rate is 150 pulse pairs per second for both interrogator and responder, for a total of 300 pulse pairs per second. Pulse widths are about 4μs, and are much more powerful than the observation target.

$$f_t = \left(\frac{4 \cdot 10^{-6}\,sec}{pulse} \cdot \frac{2\,pulse}{pp} \cdot \frac{300\,pp}{sec \cdot source} \cdot 1\,source \right) \cdot 1.0 \cdot 1.0 = 0.002$$

12.2 Frequency

The fraction of observation channels affected by transmitter channels. Given C is a set of channels, we form the numerator as the intersection of the set of channels affected by the transmitter with the set of all channels in the observation.

$$f_f = \frac{|C_{affected} \cap C_{observation}|}{|C_{observation}|} \tag{2}$$

Example: an observation provides 100 channels, each 10 MHz wide, from sky frequencies 2.0–3.0 GHz. A satellite transmitter provides significant interference from 2.7–3.2 GHz. Therefore:

$$\frac{(3.0 - 2.7)\,GHz}{10\,MHz/channel} = 30\,channels$$

are affected. and

$$f_f = \frac{30\,channels}{100\,channels} = 0.3$$

Note that we use channel count to more easily account for observations that have multiple, noncontiguous observation bands. However, restatement in terms of fractional bandwidths is perfectly acceptable if one sums all bands in the observation:

$$f_f = \frac{\sum BW_{affected}}{\sum BW_{observation}} \tag{3}$$

The previous example can be calculated as:

$$f_f = \frac{(3.0 - 2.7)\,GHz}{(3.0 - 2.0)\,GHz} = 0.3$$

12.3 Antennas

The fraction of antennas used in a given observation that will receive an RFI transmission.

$$f_a = \frac{N_{affected}}{N_{observing}} \tag{4}$$

For example: a car with W-band radar drives by the isolated antenna m042, which is observing with the W-band receiver. The observation that includes m042 is a synthesis imaging observation using a subarray of 16 antennas.

$$f_a = \frac{1}{16} = 0.06$$

If the same car drives by an antenna and its entertainment system is visible to the S-band single-dish transient observation taking place,

$$f_a = \frac{1.0}{1.0} = 1.0$$

12.4 Total threat

With these metrics in hand, we can define the overall RFI threat as a fraction of the observation affected by RFI by forming the product of the terms:

$$T = f_t \cdot f_f \cdot f_a \tag{5}$$

$$T = f_{trans} \cdot f_{vis} \cdot f_{power} \cdot \frac{|C_{affected} \cap C_{observation}|}{|C_{observation}|} \cdot \frac{N_{affected}}{N_{observing}} \tag{6}$$

While these factors do not account for all possible variables, they provide a starting point with which to characterize threat.

Note that many observations will encompass several combinations of RFI sources and observation parameters. For an RFI source r and observation o, the total threat may be calculated as a sum of the individual threats for each (r, o):

$$T_{r,o} = f_t(r, o) \cdot f_f(r, o) \cdot f_a(r, o) \tag{7}$$

so:

$$T = \sum_{r,o} w_{r,o} \cdot T_{r,o} \tag{8}$$

where:

$$\sum_{r,o} w_{r,o} = 1 \tag{9}$$

For example, an observation has two bands: b_1 = 2-3 GHz and b_2 = 20-25 GHz. One RFI source is active for half the time of observation, completely overlaps band 1 in frequency but does not overlap band 2, and is visible to all antennas.

$$f_{t,1} = 0.5, \quad f_{f,1} = 1.0, \quad f_{a,1} = 1.0 \qquad \Longrightarrow T_{r_1,o_1} = 0.5$$

The second RFI is active one-half of the time, overlaps half of band 2 but does not overlap band 1, and is visible to half the antennas.

$$f_{t,2} = 0.5, \quad f_{f,2} = 0.5, \quad f_{a,2} = 0.5 \qquad \Longrightarrow T_{r_2,o_2} = 0.1$$

We can conveniently partition T by frequency, as bands 1 and 2 do not overlap. Total observation bandwidth is 6 GHz, so

$$w_1 = \frac{1\,GHz}{6\,GHz} = 0.2, \quad w_2 = \frac{5\,GHz}{6\,GHz} = 0.8$$

so the total threat is

$$T = \sum_{r,o} w_{r,o} \cdot T_{r,o} = (0.5 \cdot 0.2) + (0.1 \cdot 0.8) = 0.2$$

Note that one can partition on any convenient dimension or combination of dimensions.

13 Threat assessments

ngVLA memo #19, available at `https://library.nrao.edu/ngvla.shtml`, examines the key science goals for the ngVLA and provides a basic overview of the telescope needs. Using that data and some inferencing, the threat to some of those observations is calculated below. Simplifying assumptions are made:

- All RFI sources are received with sufficient power to corrupt data.
- 5G is deployed.
- Some planned LEO satellite constellations are active.
- Vehicle radar is active on all vehicles, is omnidirectional, and has the expected high power.
- No mitigation strategies beyond those currently employed are used.
- The entire array is participating in the observation in question.

We can begin by calculating some core properties of the RFI sources.

Since the assumption is that the entire array is participating,

$$f_a = 1.0 \qquad \text{for all scenarios}$$

Under the above assumptions, 5G cellular towers and satellites can be considered continuous and always present at their transmit frequencies, so

$$f_t = 1.0 \qquad \text{for 5G and satellites}$$

Vehicle radar is present only when an equipped car is within sight of an antenna. We assume that at least one vehicle is within line-of-sight of the array throughout the daylight hours. During the night, we approximate that a vehicle is within line-of-sight for 20 minutes out of every 40.

$$f_t = \frac{12 + (12 \cdot 0.5)\,hours}{24\,hours} = 0.75 \qquad \text{for vehicle radar}$$

RFI due to entertainment systems and IoT is likely present when vehicles are present, as vehicles are not only emitters but vectors for people. We will therefore assume the same f_t for IoT as for vehicle radar:

$$f_t = 0.75 \qquad \text{for IoT}$$

Aircraft navigation systems are constantly present, but there is a significant decrease in traffic in the early morning hours. We will assume that there are 10 aircraft emitting DME pulses visible during 20 hours of the day. Following the example in Section 12.1 where we determined $f_t = 0.002$ per source,

$$f_t = \frac{18\,hours}{24\,hours} \cdot \frac{0.002}{source} \cdot 10\,source = 0.015 \qquad \text{for aircraft navigation}$$

We can now apply these assumptions to some ngVLA Science Drivers.

13.1 Unveiling the Formation of Solar System Analogues

Requirements: 20–110 GHz, angular resolution ≤0.01", 0.5 μJy/beam, highest possible bandwidth

The very broad frequency range of this observation set encompasses many of the RFI sources described in this paper – 5G, satellite, aircraft communication, IoT, and vehicle radar – consuming 42 GHz of the observation spectrum.

We can take advantage of the reduction in f_t for several of the RFI classes as calculated above. We'll partition the problem by RFI frequency class:

$$w_{\text{IoT}} = \frac{2\,GHz}{90\,GHz} = 0.022 \qquad T_{\text{IoT}} = 0.75 \cdot 1.0 \cdot 1.0 = 0.75$$

$$w_{\text{vehicle radar}} = \frac{6\,GHz}{90\,GHz} = 0.067 \qquad T_{\text{vehicle radar}} = 0.75 \cdot 1.0 \cdot 1.0 = 0.75$$

All other RFI sources are always-on, so

$$w_{\text{others}} = \frac{(42 - 6 - 2)\,GHz}{90\,GHz} = 0.38 \qquad T_{\text{others}} = 1.0 \cdot 1.0 \cdot 1.0 = 1.0$$

So

$$T = \sum_{r,o} w_{r,o} \cdot T_{r,o} = (0.022 \cdot 0.75) + (0.067 \cdot 0.75) + (0.38 \cdot 1.0) = 0.45$$

45% of this observation is expected to be affected by RFI.

13.2 Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

Requirements: 16–50 GHz

Of the 34 GHz of specified observation bandwidth, 16 GHz intersects expected RFI sources in 5G, and satellite bands. As those bands are considered always-on,

$$T = f_t \cdot f_f \cdot f_a = 1.0 \cdot \frac{11\,GHz}{34\,GHz} \cdot 1.0 = 0.32$$

32% of the observation could be affected by RFI.

13.3 Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present

Requirements: Access to lines of the following molecules: HCN, HCO^+, N_2H^+, H_2CO (4.8 GHz and 14.5 GHz), NH_3, CH_3OH (36 GHz), deuterated molecules 70 GHz, tracers 90 GHz, CO (115GHz), H1 (1.4 GHz).

From the IAU list of astrophysically important molecules, we can find the frequency ranges of interest for the above molecules. Table 10 shows the recommended IAU molecular frequency ranges and what, if any, RFI affects them.

Species	Low	H igh	RFI
Hydrogen (HI)	1.3700	1.4270	
Formaldehyde (H2CO)	4.8136	4.8345	satellite
Formaldehyde (H2CO)	14.44	14.50	satellite
Ammonia (NH3)	23.61	23.72	satellite
Ammonia (NH3)	23.64	23.75	satellite
Ammonia (NH3)	23.79	23.89	satellite
Ammonia (NH3)	24.11	24.16	satellite
Methanol (CH3OH)	36.13	36.21	
Deuterated formylium (DCO+)	71.97	72.11	5G
Deuterated water (HDO)	80.50	80.66	vehicle radar
Deuterated Ammonia (NH2D)	85.84	86.01	5G
Hydrogen cyanide (HCN)	88.34	88.72	
Formylium (HCO+)	88.89	89.28	
Diazenylium (N2H+)	93.08	93.27	
Deuterated Ammonia (NH2D)	110.04	110.26	
Carbon monoxide (CO)	114.88	115.39	

Table 10: Molecular frequencies (GHz)

If we assume that band 4 (20.5–27.5 GHz) is used for many of the molecular species, we find that the possible impact from 5G and satellite RFI is

$$f_f = \frac{5\,GHz}{7\,GHz} = 71\%$$

Bands 6.3 and 6.4 (91–116 GHz) would be used for the high-frequency species. They are currently expected to be clear except for a narrow possible exclusion from Cloudsat at 94 GHz.

13.4 Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

Requirements: 1–2 GHz, 5–20 GHz. 1–3.5 GHz, 20–34 GHz.

Several bands are mentioned in telescope requirements: 1–2 GHz, where 5G and satellite transmissions can cover nearly the entire range (excluding the H1 protected band) for almost 100% impact, and 5–20 GHz. In this band, 5G, IoT, radar, and satellites have coverage. While future technology may well recover data from under IoT and radar, they comprise a very small set of frequencies in this band. Continuous 5G and satellite RFI totals 3 GHz of the 15 GHz range, for 33% possible data contamination.

Gravitational wave experiments specify a 1–3.5 GHz range, over which the coverage is similar to above: nearly 100%, with a window for H1. The second window contains 5 GHz of 5G and satellite, for a 36% possible data loss.

14 Vulnerability cross-section

As radio telescope parameters such as bandwidth, observing time, and antenna count increase, the cross-section threatened by transmitters increases. Even if one assumes no changes in RFI source properties, ngVLA will face an increase in threat by virtue of its increased cross-section. Given that the cross-section exposed to the RFI threat is defined by an N-dimensional volume in parameter space, target cross section increases as a power of the number of relevant parameters. For example, ngVLA will more than double VLA bandwidths and provide ten times the number of antennas, so the vulnerability cross-section on the receiver-bandwidth plane is 20 times that of the VLA.

15 Levels of RFI impact

RFI can impact the telescope to varying degree:

1. receiver damage
2. receiver compression/saturation and intermodulation products
3. gain-slope equalizer/quantizer errors
4. lost bits/clipping
5. noisy/flagged data

Level of impact can help determine the priority of addressing an RFI concern; damage will warrant special treatment of the front-end devices, and others will merit attention during the design of hardware and software. Table 11 shows impacts expected of typical RFI exposure.

Source	Damage	Compress	Eq/quant	Bits	Flag
Vehicle radar	x	x	x	x	x
Satellite		x	x	x	x
Aircraft radar		x	x	x	x
Aircraft nav			x	x	x
Aircraft comm			x	x	x
Cellular					x
IoT					x
Self-generated					x

Table 11: Level of impact for RFI sources

16 Timescales

The timescale of RFI emission will also help prioritize RFI-related design. While some RFI will be continuous, others are emitted in short bursts or even single short pulses. If the hardware and data processing pipeline are designed to be aware of RFI at an appropriate timescale, steps can be taken to mitigate its impact.

One example is an aircraft DME pulse-pair: pulses are short and have a low duty cycle. If the pulses can be recognized and a real-time flag delivered to the correlator, the correlator could be designed to prevent the RFI-corrupted data from entering the integration buffer ('fast flagging').

Another example might be sources that use Frequency-Hopping Spread-Spectrum (FHSS) modulation: for a given channel, the transmitter time occupancy may be a small fraction, e.g. $\frac{1}{32}$. A fast flagging system could recover astrophysical data during the other $\frac{31}{32}$ of the time. FHSS is often implemented with tens of channels and channel-hopping times on the order of milliseconds.

While some transmitters use FHSS and may therefore be amenable to fast flagging, the presence of numerous transmitters may leave little time on a given channel. Such may be the case for FHSS satellite downlinks with hundreds of satellites in view at any time, and for cellular networks with hundreds of cell clients communicating with a given tower.

Table 12 shows some expected timescales. *Time on channel* specifies the duration of active transmission on a given channel. *Visible to antenna* defines the length of time during which the transmitter would be detectable by an antenna if transmitting.

Source	Time on channel	Visible to antenna
Vehicle radar	continuous	minutes
Self-generated	continuous	always when present
Cellular tower	numerous FHSS	always
Satellite	numerous FHSS	always, with variation over tens of seconds
IoT	milliseconds	minutes
Cellular device	milliseconds	minutes
Ground-based radar	microseconds	always if visible
Aircraft radar	microseconds	when present
Aircraft nav	microseconds	always
Aircraft comm	continuous	seconds

Table 12: Timescale of RFI sources

Both time on channel and visibility to antenna contribute to the calculation of f_t introduced in Section 12.1. The design of the system dictates their effect on f_t. For example, a system capable of fast flagging may be able to reject aircraft navigation pulses, thereby making $f_t \sim 1$ for observations in that band despite the fact that DME pulses are always visible to an antenna. Challenge awaits in designing systems with fast flagging and other algorithms to increase f_t for other RFI sources.