Atacama Large Millimeter / submillimeter Array

ALMA Spectrum and Radio Frequency Interference

White Paper

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Contents

1 Executive Summary

We present here a study of the risks posed by radio frequency interference (hereafter RFI) to ALMA today and in the near future, from both ground-based and space-based sources of radio emissions. Vulnerabilities are identified and mitigation measures are discussed and evaluated.

The ALMA operational spectrum spans from 35 GHz up to 950 GHz, divided in 10 non-contiguous frequency bands. Atmospheric water vapor attenuates emissions strongly within a large fraction of this frequency range. Also, the ALMA site is far enough from urban areas to be shielded from most ground-based emissions through distance.

The risk of RFI is highest from sources in the proximity of the ALMA site, or within the ALMA concession. For example, RFI has been identified as produced in some of the ALMA systems. Other observatories on the Altiplano are also potential sources of emission with sufficient power to produce RFI at ALMA. To minimize this risk, operations between the observatories are coordinated by the ALMA spectrum management office in collaboration with the members of the Chajnantor Working Group. Nearby, the CH27 Paso Jama international highway between Chile and Argentina passes within 10 km of the ALMA site, and can potentially pose a risk of emissions from vehicles on the highway at relatively short distance to the ALMA antennas.

The ALMA observatory has protections against potential RFI through two exempt resolutions issued by the Sub-secretariat of Telecommunications (SubTel) of the Ministry of Transport and Telecommunications of the Republic of Chile to Associated Universities Inc. (AUI) and the European Southern Observatory (ESO), on behalf of the ALMA observatory. These resolutions define a “protection zone” with a radius of 30 km and a “coordination zone” with a radius of 120 km from the array center. The authority of SubTel over these two zones only applies to the Chilean national territory, and coordination with neighbouring countries Bolivia and Argentina is desirable. When these resolutions were drafted in 2013, the potential risk of RFI from the sky was not included, with the resolutions only considering ground-based radio emissions. After ten years, the situation has changed dramatically with the present day telecommunication satellite constellations that consist of several thousand satellites, with plans for very large numbers of satellites in the near future.

The renewal process of these exempt resolutions underway currently in 2023 is an opportunity to update the exemptions and add measures that could prevent, at least partially, potential RFI due to emissions from telecommunication satellites operating over Chile. At this moment, the SpaceX Starlink and Amazon Kuiper satellite constellations have been granted permission by SubTel to operate seven and one gateway stations respectively in Chile. The nearest gateway station to ALMA is near Caldera, 540 km south-west of the ALMA site. We consider this distance sufficient to safeguard the ALMA systems from any potential RFI due to the downlink signals to the gateway station. However, with the potential for other constellation operators coming to Chile, and the number of gateway stations growing, it is important to seek suitable protections, such as gateway stations at a minimum distance from the observatory.

It is important to consider that ALMA, with relatively high operating frequencies, is not affected by RFI from telecommunication satellites at this time. Certainly, ALMA is not facing the RFI problems that affect other radio observatories (e.g. GBT, VLA, SKA) operating at lower frequencies. However, this situation may soon change as constellation operators work towards higher frequency bands, motivated by larger bandwidth for higher data-transfer rates. Other radio observatories on the Altiplano that work at lower frequencies than ALMA, e.g. <20 GHz, may be affected by present day satellites emissions.

2 About ALMA

The Atacama Large Millimeter/submillimeter Array (ALMA) is a partnership of the European Organisation for Astronomical Research in the Southern Hemisphere (ESO), the U.S. National Science Foundation (NSF) and the National Institutes of Natural Sciences of Japan (NINS) in cooperation with the Republic of Chile. ALMA is funded by ESO on behalf of its Member States, by NSF in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and by NINS in cooperation with the Academia Sinica (AS) in Taiwan and the Korea Astronomy and Space Science Institute (KASI). ALMA construction and operations are led by ESO on behalf of its Member States; by the National Radio Astronomy Observatory (NRAO), managed by Associated Universities, Inc. (AUI), on behalf of North America; and by the National Astronomical Observatory of Japan (NAOJ) on behalf of East Asia. The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning and operation of ALMA.

3 The ALMA site and the local environment

ALMA is located on the high-mountain plateau known as Llano de Chajnantor, at an altitude of 5000 m and remote from urban areas, the closest being Toconao (32 km) and San Pedro de Atacama (47 km, Figure 1). The ALMA site has natural shielding from most typical sources of electromagnetic (EM) interference. Emissions at frequencies higher than ∼100 GHz are attenuated strongly by atmospheric water vapor and do not pose a threat unless produced locally at short distance and within the ALMA site. The Chajnantor site is somewhat exposed to eventual emissions from the CH27 Paso Jama international road between Chile and Argentina, passing within ∼10 km from the central area of the ALMA array and even less distant from some of the antenna foundations (pads) in Pampa La Bola.

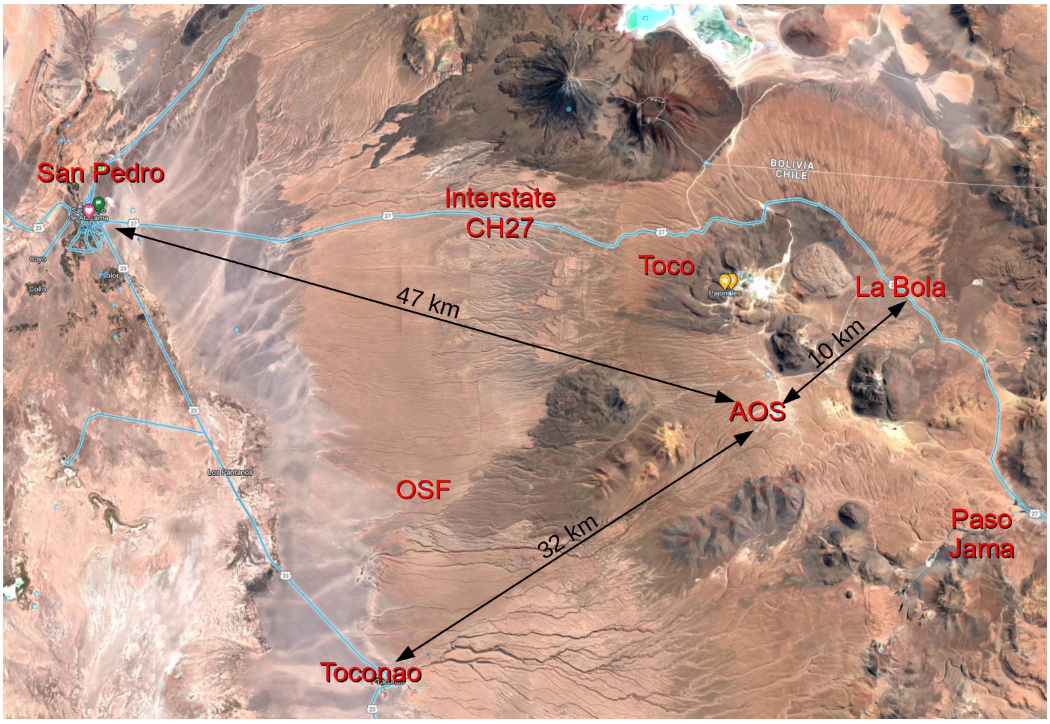

Figure 1: Google Maps image of the ALMA site seen from the sky, showing the distance of the closest urban areas and infrastructure.

3.1 The ALMA Concession and the Parque Astronómico de Atacama (PAA)

In May 2003, Associated Universities, Inc. (AUI) and the European Southern Observatory (ESO) signed the acquisition from the Ministry of National Assets [1] of land for the ALMA Operations Support Facility (OSF), 30 km from San Pedro de Atacama at an altitude of 2950 m. In November 2003, the Government of Chile, through the Ministry of National Assets, provided a 50-year land concession for the construction and operation of ALMA on the Chajnantor Altiplano at 5000 m. This area, known as *the ALMA Concession*, includes two regions: an area of 161.6 km^2 for the radio telescope at 5000 m and an additional 16 km^2 for the road between the OSF and the Altiplano. The ALMA land concession at 5000 m is shown in dark-brown color in Figure 2.

Ten years later, in 2013, the Government of Chile gave another 50-year land concession [2] to the National Commission for Research in Science and Technology (CONICYT [3]) for the exclusive use of scientific activities.

In October 2013, CONICYT created a foundation, called the Parque Astronómico

[1] Supreme Decree 74, May 22, 2003
[2] Diario Oficial 40.688, 2013
[3] Now transferred to the Agencia Nacional de Investigación y Desarrollo, ANID

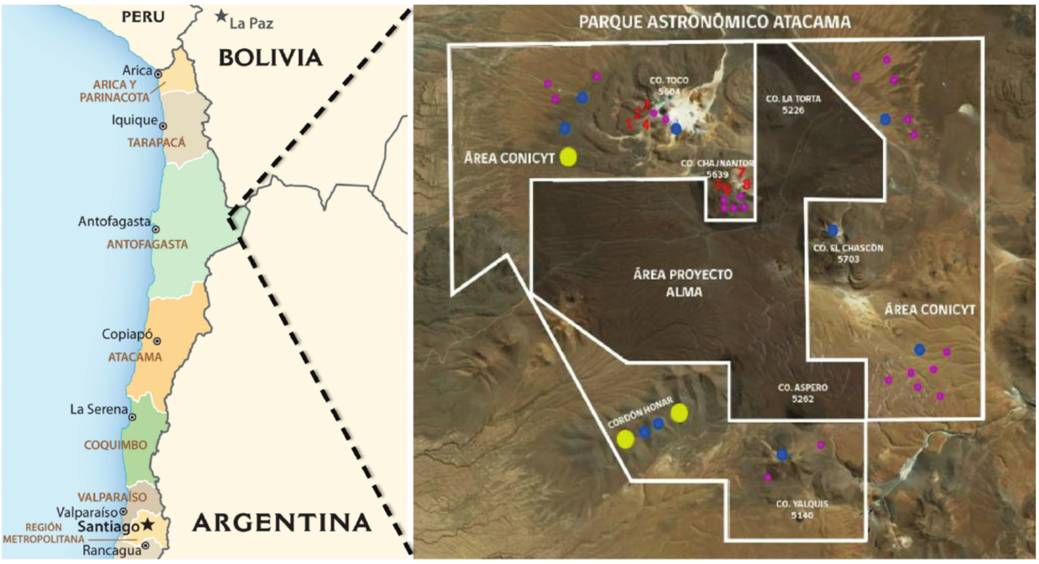

Figure 2: *The ALMA concession (dark brown) on Llano de Chajnantor, within the Parque Astronómico de Atacama (from Bustos, R., et al. PASP vol. 126, n.946, 2014). The colored dots show potential sites for other telescopes in the park.*

de Atacama (PAA [4,5]), that is responsible for managing the land concession. The main purposes of the PAA are to promote the development of the area and coordinate operations of the current and future facilities, providing regulations, security procedures and common services, while preserving and protecting the area. It also maintains a relationship with local indigenous communities and the local administration.

In addition to ALMA, there are several other astronomy projects in operation or in construction on the Altiplano, including the Atacama Pathfinder Experiment (APEX), the Atacama Submillimeter Telescope Experiment (ASTE), NANTEN-2, the Atacama Cosmology Telescope (ACT), the Cosmology Large Angular Scale Surveyor ((CLASS), the POLARization of the Background Radiation experiment (POLARBEAR), the Simons Observatory (SO), the Cerro Chajnantor Atacama Telescope (CCAT-Prime), and the University of Tokyo Atacama Observatory (TAO).

The PAA can host other types of scientific projects (e.g. meteorological or seismic stations, solar research, etc.) as long as they do not interfere with the astronomical projects. Coordination of activities between the various observatories and projects on the Altiplano takes place through the Chajnantor Working Group (CWG) of the PAA.

[4] www.conicyt.cl/astronomia/sobre-el-parque

[5] Parque Astronómico de Atacama: An ideal site for millimeter, submillimeter, and mid-infrared astronomy

3.2 The ALMA Operational Spectrum

The ALMA receiver systems cover ten frequency bands that closely match the atmospheric transmission windows, those portions of the spectrum where the atmospheric transmission at millimeter/sub-millimeter wavelengths enable ground-based science observations at the corresponding frequencies (see Figure 3).

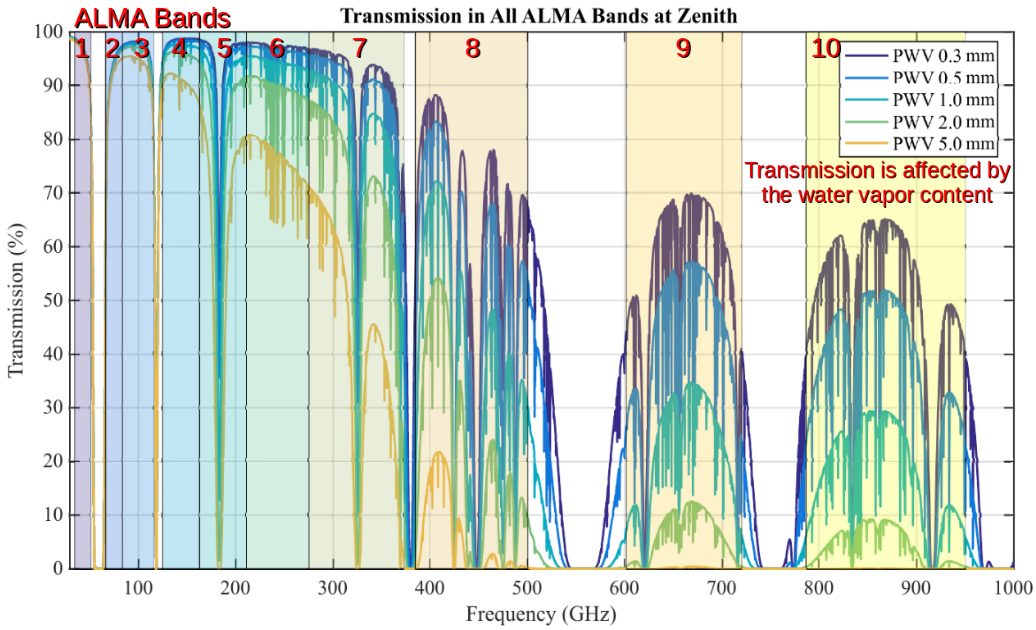

Figure 3: *The atmospheric transmission windows at mm/submm wavelengths, here shown for different values of the precipitable water vapor (PWV), define the ten ALMA frequency bands.*

In the first incarnation, the ten ALMA bands are defined as given in Table 1. Several receiver development groups are now working on upgrades (Bands 2, 6, 7, 8, 9 at this writing) with the goal of increasing the sensitivity of the receivers and doubling the intermediate frequency bandwidth (post-detection, hereafter IF), while keeping the same observing RF range. Consequently, when considering the ALMA spectrum it is important to consider the IF bandwidth will be soon extended from 8 GHz to 16 GHz per polarization channel, spanning possible frequency ranges as 2–18 GHz or 4–20 GHz depending on the receiver band.

3.3 SubTel Exempt Resolutions number 1055 & 1056

The ALMA concession was subject to two identical Exempt Resolutions, number 1055 to AUI and number 1056 to ESO, issued in August 2004 by the Subsecretariat of Telecommunications (SubTel) of the Ministry of Transport and Telecommunications of the Republic of Chile. These two resolutions expired on the same date as the first ALMA permit regulated by SubTel Exempt Resolution number 1096, released in September 2003 and valid for 10 years.

Table 1: *Definition of the ten ALMA frequency bands in the original design. The values in parenthesis are offered on a best effort basis only and are not in the baseline specifications*

Band	Wavelength of Reference [mm]	RF Range [GHz]	Sideband Scheme	IF Range [GHz]	LO Range [GHz]
1	7	35 – 50(52)	USB	4 – 12	31.0 – 40.0
2	4	67 – 116	2SB	4 – 18	79.0 – 104.0
3	3	84 – 116	2SB	4 – 8	92.0 – 108.0
4	2	125 – 163	2SB	4 – 8	133.0 – 155.0
5	1.6	(158)161 – 211	2SB	4 – 8	166.0 – 203.0
6	1.2	211 – 275	2SB	5 – 10	221.0 – 265.0
7	0.87	275 – 370	2SB	4 – 8	283.0 – 365.1
8	0.67	385 – 500	2SB	4 – 8	393.0 – 492.0
9	0.45	602 – 720	DSB	4 – 12	610.2 – 712.0
10	0.35	787 – 950	DSB	4 – 12	794.7 – 942.3

Band 1 50 – 52 GHz RF range offered on best effort
Band 2 in production phase, planning IF extension to 4 – 16 GHz
Band 5 158 – 161 GHz RF range offered on best effort
Band 6 upgrade planning IF extension to 4 – 18 GHz (maybe 20, TBD)
Band 9 upgrade planning IF extension to 4 – 18 GHz (maybe 20, TBD)

3.4 SubTel Exempt Resolutions number 3075 & 3076

In August 2013, SubTel issued the renewed Exempt Resolutions number 3075 (AUI) and 3076 (ESO), almost identical to 1055 & 1056. These resolutions are valid for 10 years and it is necessary to request their renewal in 2023. This timing provides an opportunity to upgrade the Resolutions in order to cover topics that have developed in recent years and that were not considered in the original resolutions, for example the fast-growing development of satellite constellations and including protections from spaceborne transmitters or the associated downlink stations.

- These resolutions give ALMA the authorization as "receiving only antennas" to use the frequency bands defined in Table 1 under the assumption that *protection cannot be guaranteed in the frequency bands, or part of them, that are not allocated to radio astronomy on a primary basis.*

- They also define a "protection zone" centered at 23° 01' S, 67° 45' W (antenna pad A124 in the central part of the array, see Figure 4) *with a radius of 30 km within national territory, inside which the installation of any other radio communications system will not be authorized to any third parties operating on the receiving frequency bands*

- They also define a "coordination zone" centered at the same place *with a radius of 120 km within national territory, where coordination being understood as the process whereby the opinion of the petitioners, ESO and AUI, will be sought regarding certain requests by third parties that this Sub-secretariat deems could interfere or affect the operation of the radio telescope. Likewise, in* *case such petitioners detect any emissions that affect the operation of the radio telescope, they will notify this Sub-secretariat for its coordination.*

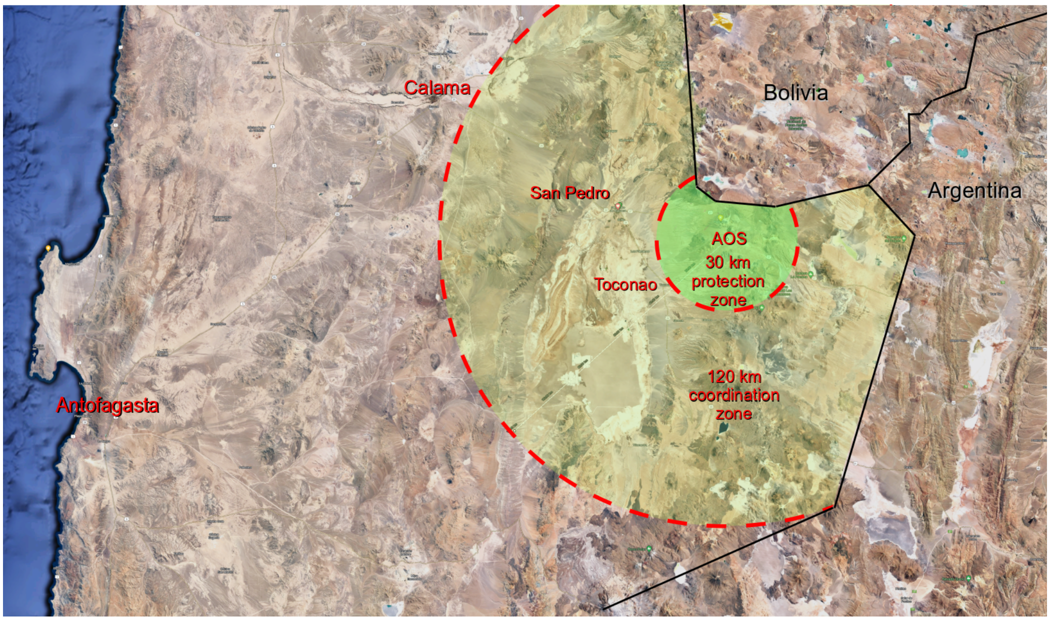

Figure 4: *ALMA protection and coordination zones, as defined by the SubTel Exempt Resolutions, with a radius of 30 and 120 km respectively within the Chilean territory. The black line shows the border between Chile, Bolivia and Argentina.*

4 Potential RFI from terrestrial emissions

4.1 Emissions from nearby urban areas (Toconao, San Pedro de Atacama, Calama, Antofagasta)

It is known that broadcast FM radio stations (87 to 108 MHz) from Calama and Antofagasta can be received on Llano de Chajnantor. These frequencies are far from the ALMA receiver spectrum and do not present any RFI to ALMA. Given the distance to these urban areas, any possible future millimeter/submillimeter emissions that overlap the ALMA spectrum with potential associated RFI will be attenuated by atmospheric water vapor and do not pose a risk of RFI to ALMA.

4.2 Cell phones and wifi

Some consumer market RF devices, such as the 5-GHz WLAN (IEEE 802.11 protocols) and the 5G cellular phones, could produce RFI at ALMA because they can operate at frequencies that fall within the IF range of the ALMA receivers (4 – 12 GHz, see Table 1). Emissions from such devices have relatively low power and are attenuated by atmospheric water vapor. As a result they do not pose a risk to ALMA unless in use at the ALMA site in the proximity of the antennas, a practice forbidden in the Chajnantor Working Group regulations [6]

4.3 Emissions from vehicles moving along nearby roads

Citizen-Band radios (e.g. 27 MHz) used by truckers on the CH27 Paso Jama interstate road can easily reach the ALMA site. These frequencies are far from the ALMA receivers spectrum and do not pose any risk of RFI to ALMA. Other devices operated by road users, such as cell phones or newer technologies such as 5G/6G, or cell phone repeaters along the highway, could produce emissions in the ALMA IF range at a relatively short distance from the ALMA antennas. At the typical frequencies and power levels, however, those emissions do not pose a significant risk of RFI to ALMA given the very good RF shielding of the IF signal chain inside the antennas. Other nearby roads (e.g. CH23, Paso Sico interstate) are much further away and do not pose any risk of RFI to ALMA.

To date, there are no reports of RFI that can be attributed to emissions from nearby roads. The situation could change, however, if telecom operators were to increase frequencies and power levels.

4.4 Automotive radar ranging systems

There is growing use for precision ranging systems for automotive applications. This is motivated by increased safety capabilities and the development of autonomous self-driving vehicles. Relatively short wavelength and large bandwidth (e.g. 4 GHz) is needed to reach satisfactory measurement accuracy and real-time response. The need for larger bandwidth has pushed the emissions of these devices to higher frequencies, overlapping with the ALMA Band-2 receiver spectrum [7]. It is likely that these devices will use even higher frequencies in the near future. The range of operation is short (up to $\sim$250 m) thus posing a risk of RFI only if used at the ALMA site in the proximity of the antennas.

4.5 Emissions from inside the ALMA concession

At both ALMA sites, the Operations Support Facility (OSF) near San Pedro de Atacama and the Array Operations Site (AOS) on the Chajnantor Altiplano, there are several devices that produce radio emissions, with the potential of producing RFI.

- **Communication radios**: ALMA has a radio system with several VHF hand-held devices and stations.
- **Private cell phones, laptop computers**: staff may forget to switch off their phones or the wifi while working in the proximity of the antennas.

[6] See Sect. 9 of *CWG Policies*,ver.A, rev.2, 2008-02-27

[7] E.g. 81 GHz, see ITU-R M.2057-1, 2018

- **Vehicles** that have devices that produce RFI.
- **The ALMA Polarization calibration source** located on Cerro Honar [8] emits CW or broadband white noise, linearly polarized, towards the ALMA central cluster in the frequency range 84–116 GHz or 211–373 GHz with maximum power of 1 μW (-60 dBW). The operation of the source is coordinated strictly with the Chajnantor Working Group spectrum managers.
- **The ALMA Water Vapor Radiometer** (WVR): this device is inside each 12-meter ALMA antenna and is known to produce RFI in two ways:

  a) emission from the Voltage Controlled Oscillator in the WVRs that produce CW signals of 15.275 GHz and corresponding harmonics;
  b) emission through the horn antenna from the mixer.

  Such RFI from the WVR has been observed affecting different ALMA receiver bands:

  B1: 3rd harmonic at 45.825 GHz affects B1 observations (nearby methanol maser at 45.843 GHz, Figure 5).
  B3: 6th harmonic at 91.7 GHz affects B3 observations (Figure 6).
  B5: 12th harmonic at 183.3 GHz (leaking from the WVR horn) can affect B5 observations.
  B6: 17th harmonic at 259.67 GHz, 18th harmonic at 274.95 GHz.
  B7: 24th harmonic at 366.6 GHz.
  B8: 30th harmonic at 458.25 GHz.
  B9: 42nd harmonic at 641.6 GHz.

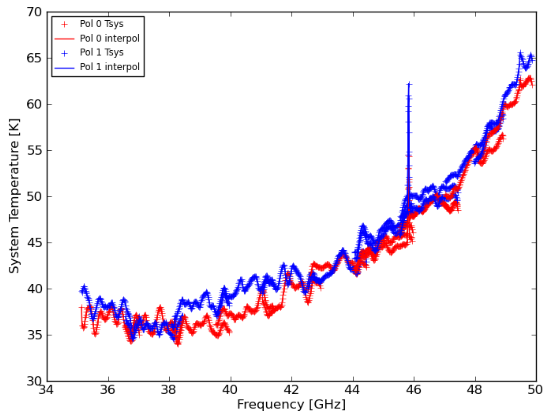

Figure 5: *ALMA Band 1 spectra showing the 3rd harmonic at 45.825 GHz of the 15.275 GHz WVR local oscillator*

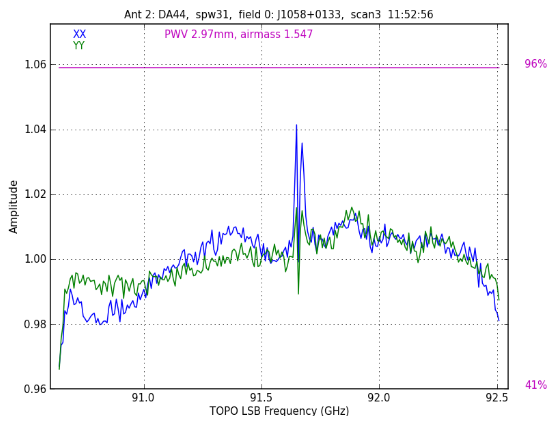

Figure 6: *ALMA Band 3 spectra showing the 6th harmonic at 91.7 GHz of the 15.275 GHz WVR local oscillator*

[8] At 23° 04' 10.4" S, 67° 45' 20.4" W

RFI from the WVR is particularly strong and affects science observations because it is produced directly inside the 12-m antennas, very close to the front-end receivers (details in ALMA Jira ticket NCR-120).

- **Holography towers**: at the OSF there are two 50 m high towers, each equipped with a 104.02 GHz, +13 dBm (20 mW) transmitter. These transmitters are powered off most of the time and only used when needed for antenna surface assessment at the OSF by holography techniques.

4.6 Emissions from other observatories

The other observatories on the Altiplano near the ALMA site have devices that can produce RFI that may affect ALMA operations:

- **APEX holography system**: the APEX telescope has a transmitter on the shoulder of Cerro Chajnantor, emitting a narrow (1 kHz) but powerful signal at 92.4 GHz. This is known to introduce RFI in the ALMA Band 3 and strict coordination between the observatories is mandatory (Figure 7).
- **Cerro Toco holography**: The Astro-Engineering group at the Universidad Catolica of Santiago is developing a holography system for surface assessment of the telescopes at Cerro Toco using a drone to lift a radio source in the near field of the telescopes (Figure 8).
- **Microwave links to San Pedro**: Both ACT and APEX use microwave links for remote operation from their base-camps in San Pedro. APEX has a transmitter on Cerro Chico that transmits at 7.3 GHz. There are no reports of RFI from these systems: they are strongly directional and pointed towards San Pedro, away from the ALMA antenna locations.

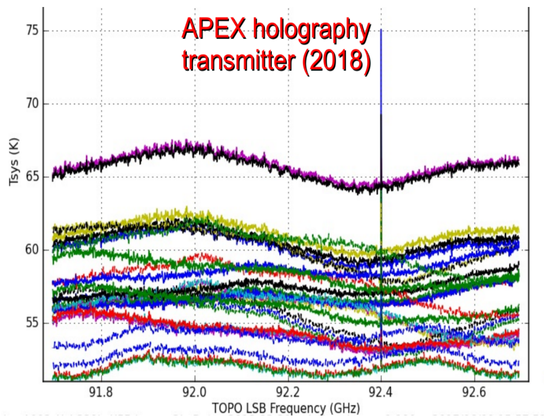

Figure 7: ALMA Band 3 spectra with strong RFI from the APEX holography transmitter at 92.4 GHz

Figure 8: The hexacopter drone with a radio source payload tested at the Universidad Catolica of Santiago

5 Potential RFI from the sky: satellite emissions

Satellite systems in orbit around the Earth are sources of RF emissions and are consequently potential sources of RFI to ALMA. The low water column in the atmosphere above the Altiplano, the main reason the site is one of the best in the world for submillimeter ground-based astronomy, does not attenuate strongly emissions in the millimeter/submillimeter (see Figure 3) and potential RFI from the sky is an important consideration for ALMA. Some of these services operate at frequencies common with the ALMA receiver systems. Besides telecommunication satellites, there are a number of other satellites for scientific application, some of which host active RF transmitters, such as the radars used for Earth exploration services.

5.1 Cloud Profiling Radar

The Radio Regulations of the International Telecommunication Union (ITU RR) regulate Space-to-Earth emissions from active Earth exploration satellite services such as Cloud Profiling Radars (CPR). The ITU has allocated frequencies at 35.5–36.0 GHz, 94.0–94.1 GHz, 133.5–134.0 GHz that are common with some ALMA receiver bands, regulated as follows [9]:

> *Chapter II – Frequencies*
> *5.549A: In the band 35.5–36.0 GHz, the mean power flux-density at the Earth's surface, generated by any spaceborne sensor in the Earth exploration-satellite service (active) or space research service (active), for any angle greater than 0.8° from the beam centre shall not exceed 73.3 dB*(W/m^2) *in this band. (WRC-03)*
> *5.562: The use of the band 94–94.1 GHz by the Earth exploration-satellite (active) and space research (active) services is limited to space-borne cloud radars. (WRC-97)*
> *5.562A: In the bands 94–94.1 GHz and 130–134 GHz, transmissions from space stations of the Earth exploration-satellite service (active) that are directed into the main beam of a radio astronomy antenna have the potential to damage some radio astronomy receivers. Space agencies operating the transmitters and the radio astronomy stations concerned should mutually plan their operations so as to avoid such occurrences to the maximum extent possible. (WRC-2000)*
> *5.562E: The allocation to the Earth exploration-satellite service (active) is limited to the band 133.5–134 GHz. (WRC-2000)*

To date, there are two active Earth exploration satellite services hosting a 94-GHz CPR: **CloudSat**, a relatively old satellite launched in 2006, and **EarthCare**, which is a new satellite being developed and expected to be launched in 2025. We are not aware of active Earth exploration satellite services operating in the 35.5–36.0 GHz or 133.5–134.0 GHz ranges.

[9] From the ITU RR 2020, Chapter II, Article 5

5.1.1 CloudSat

CloudSat is a single satellite system with only a CPR instrument onboard and poses an RFI risk to ALMA. The CPR began collecting science data in 2006 but over the years, many operational changes have occurred and the radar was switched off for several multi-month periods. Since 2011, the CPR only works with solar energy and it can be powered up only when it is illuminated by the Sun, i.e in the sunlit portions of the orbit.

CloudSat moves along a polar, Sun-synchronous orbit making one revolution in 99 minutes, roughly 14.6 complete revolutions around the Earth per day, at about 7 km/s relative to the Earth's surface. Sun-synchronous orbit means that the satellite always crosses the equator (from south to north, ascending node) at the same local solar time, which is approximately 13:30. The ground track repeats every 8 or 16 days (see Figure 9).

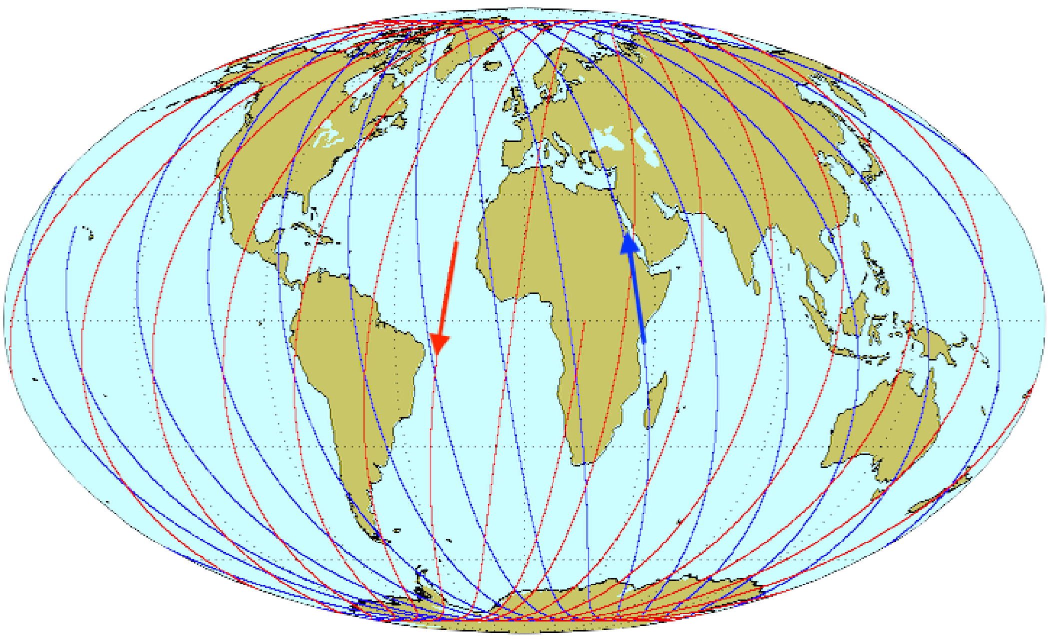

Figure 9: *CloudSat ground tracks for a 24 hour period, roughly 15 complete revolutions per day. Blue and red lines show ascending and descending tracks respectively. CloudSat always crosses the equator from south to north (ascending node) at the same local solar time, which is approximately 13:30. The ground track repeats every 16 days approximately. (Image from the CloudSat website)*

The spacecraft orbits at an altitude of 690 km, with a radar main beam of 0.25° first null to first null, pointing at 4° off-nadir to the left of the forward along-track direction of its ground track. The spacecraft suffers uncontrolled oscillations ±3° to either side of the 4° off-nadir nominal aim point.

The radar footprint on the ground is 3 km in diameter, moving at a speed of 7 km/s, so it crosses the full 16-km ALMA extended array configuration in less than 3 s. Due to the uncontrolled oscillations of the spacecraft, the beam of the radar can point to any place within +1° to +7° to the left of the forward along-track direction. The footprint on ground can be anywhere within a 73 km strip (Figure 10), from 12 to 85 km to the left of the forward along-track direction (not counting the 3 km beam footprint diameter).

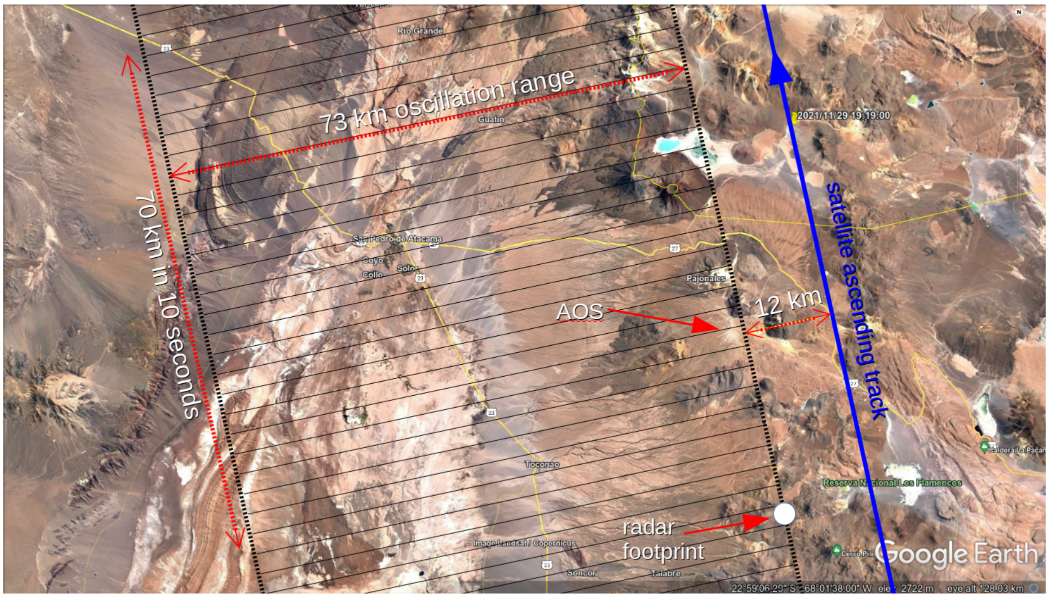

Figure 10: *CloudSat ascending track (blue) on November 29, 2021, and the 73-km-wide area potentially irradiated by the CPR emission due to uncontrolled oscillations of the spacecraft. The transit only takes a few seconds.*

5.1.2 EarthCARE

The Cloud, Aerosol and Radiation Explorer, EarthCARE, expected to be launched in 2025, is a joint venture between ESA (European Space Agency) and JAXA (Japan Aerospace Exploration Agency) that "will advance our understanding of the role that clouds and aerosols play in reflecting incident solar radiation back into space and trapping infrared radiation emitted from Earth's surface." [10] The spacecraft will have four instruments: the Atmospheric Lidar (ATLID) operating at a wavelength of 355 nm (active), a Multi-Spectral Imager (MSI) with channels in the visible, near infrared and thermal infrared (passive), a Broad-Band Radiometer (BBR) for measurements of top-of-the-atmosphere radiances and fluxes (passive) and a CPR at 94 GHz (active) similar to CloudSat's.

5.1.3 Potential threats to ALMA receivers

At the 94-GHz emission frequency of both CloudSat and Earthcare CPRs, ALMA Band-3 SIS mixers could be damaged by excessive RF power. CloudSat has a

[10] https://earth.esa.int/eogateway/missions/earthcare

Space-to-Earth 94 GHz, 1.8 kW radar transmitting 3 μs pulses at a 4300 Hz repetition rate. Assuming that the SIS mixer time constant is much shorter than the 3 μs CloudSat radar pulses, the mixer junction will reach the same temperature for a given peak pulse power as for a CW signal of the same power. The amount of RF power that can damage an ALMA Band-3 junction is 55 mW. The peak power on a 12-m diameter aperture on the ground, beam-to-beam coupled to the CPR and therefore focused on the receivers, is close to 70 mW, and hence poses a risk of damaging the SIS junctions by burnout. [11] ALMA Band-3 is the only band in operation today that can be affected directly by the CPR, if the beam of the antenna and the beam of the radar are aligned perfectly. There is no risk to other ALMA receiver bands in operation today because the harmonics are estimated to be 50 to 60 dB weaker, and so no damage is anticipated in bands higher than Band-3, namely:

- 2x 94 GHz = 188 GHz falls in ALMA Band-5, 0.7 μW, no risk
- 3x 94 GHz = 282 GHz falls in ALMA Band-7, 0.7 μW, no risk

The Band-1 engineering team (ASIAA) excludes risk of damage to Band-1 cLNAs RF detectors (private communication). There is a potential risk to the Band-2 receiver being developed currently that aims to extend its RF range beyond the original specifications, up to 116 GHz and therefore able to couple energy at 94 GHz. However, Band-2 operation is 3+ years in the future and the CloudSat CPR may not be operational when Band-2 is fully operational.

With respect to the EarthCare mission, planned to be launched in 2025 with an even more powerful 94-GHz CPR (2.2 kW), in April 2021 ESA and the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF [12]) signed a Memorandum of Understanding [13] under which they agreed that operational coordination will be needed. It is foreseen that the baseline operations plan of the EarthCare CPR will include setting the CPR to "Silent State" (i.e. no emission) for approximately 3.5 s when passing over a radio astronomy site, thus mitigating the potential for damaging radio astronomy receivers pointed near the local zenith during a satellite overpass. In parallel, ESA will also publish online the list of all events where the CPR is expected to be in direct visibility of a radio astronomy site.

5.1.4 Preventive measures

There is significant risk of damage for Band-3 mixers if the main beams of the antenna and of the radar are perfectly aligned. However, such a perfect alignment is extremely unlikely and would last only a few milliseconds, with probability of occurrence very low. Nevertheless, it is important to ensure it never happens, so several operations practices have been adopted.

[11] The details about the calculations are in ALMA Memo 576, 27 February 2008
[12] http://www.iucaf.org
[13] This MoU is available online

The footprint of CloudSat on the ground oscillates $+1°$ to $+7°$ to the left of the forward along-track direction, and ALMA has adopted a ± 10 degrees avoidance buffer (80 degrees circle) as a very conservative avoidance range. In addition:

1. Be always informed and aware of potentially dangerous transits of the CPR well in advance of the transit, and with sufficient accuracy of the transit track. At ALMA, the conditions are:

   - CloudSat transiting above 80 degrees of elevation as seen from the location of each antenna, and
   - CloudSat is illuminated by the sunlight.

   These transits can be predicted using the orbital two-line elements (TLEs) available here:

   - NORAD's TLEs updated more than once per day: https://celestrak.com/NORAD/elements/science.txt
   - CIRA's TLEs updated on a daily basis (around 16h UTC): https://cswww.cira.colostate.edu/data_dist/TLEs/CloudSat_Current_TLE.txt

   ALMA Spectrum Management Office maintains a webpage with the prediction of potentially dangerous CloudSat transits, based on the latest available TLEs: http://www.alma.cl/~gsiringo/cloudsat_aos_transits.html

2. Prevent radar-antenna beam matching at the time of the transit. This can be done by:

   a) parking all antennas in a safe position (e.g. survival stow);
   b) putting the Amplitude Calibration Device (ACD) ambient load on the Band-3 window;
   c) closing the antenna shutter and preventing signal getting to the receiver system; or
   d) some combination of the above.

   Options b) and c) are considered to have higher risk because the mechanics of the ACD or the shutter may not react in a timely manner. Parking the antennas (option a) is considered the most safe and practical measure.

5.2 Satellite constellations

Telecommunication companies around the world are rapidly expanding their business opportunities through satellite constellations. Today, there are many satellite operators building or planning to build large satellite constellations and this is now a very dynamic field with the number of satellites and their orbital and radio configurations changing very quickly, making it difficult to keep track of all the advances. Some web sites are trying to provide updated information e.g. Jonathan Space Page maintained by astronomer Jonathan McDowell.

In June 2022, the International Astronomical Union (IAU) launched the Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS) [14], co-hosted by NSF's NOIRLab and the SKA Observatory. Based on the information available currently [15], we can summarize that:

- Mega-constellations, with plans for more than 1000 satellites:
  - 17 planned constellations in total
  - 427,171 planned satellites in total
  - 6 out of 17 constellations have launched already at least one satellite
  - 5,016 total launched satellites to date in all constellations
  - 4,233 total launched satellites that are operational in their orbit
- Large-constellations, with plans for 50 to 1000 satellites:
  - 43 planned constellations in total
  - 4,831 planned satellites in total
  - 38 out of 43 constellations have launched already at least one satellite
  - 2,226 total launched satellites to date in all constellations
  - 971 total launched satellites that are operational in their orbit

These numbers are evolving rapidly and therefore conclusions that can be drawn today are likely not going to be valid for long. Consequently, it is important to review the situation frequently.

Unlike optical observations, which are impacted by satellites via reflected sunlight, for ALMA the impact is limited to those satellites that make use of certain transmission frequencies that have the potential to interfere with radio observations. For optical telescopes, sunlight reflection from satellites only happens during a limited number of hours immediately after sunset or immediately before sunrise, in contrast to radio telescopes such as ALMA that can observe 24 hours per day and therefore are, in principle, continuously exposed to RFI risks from satellites. The risk of RFI obviously increases with an increasing number of operational satellites.

5.2.1 Configuration of selected satellite constellations

We consider here six satellite constellations: Starlink Gen1, Starlink Gen2, OneWeb (phase1), Amazon's Kuiper, Kepler, AST's SpaceMobile. These satellite constellations use different frequencies for the different streams (user or gateway stations, down- or up-links) and have obtained authorization from some national

[14] https://cps.iau.org/
[15] June 2023

or international regulatory entities (e.g. the ITU or the FCC of the United States) to occupy several channels in a number of radio bands, but not always limited only to the national territory of the given regulating authority. To avoid confusion between different radio bands and frequency definitions, we will refer here to the *Waveguide Bands* standard, reported for reference in Appendix A.

There are mainly four types of emission from the satellites:

1. Space-to-Earth (downlink) to "User Terminals": the stream of data to the final user, who can be anywhere on the Planet.

2. Space-to-Earth (downlink) to "Gateway Stations": the stream of data to one of the ground antennas used for operation. Starlink will have many gateway stations in the United States and just a few in the rest of the world (see details below).

3. Earth-to-Space (uplink) from the "User Terminals": uplinks are not a concern for radio astronomy.

4. Earth-to-Space (uplink) from the "Gateway Stations": uplinks are not a concern for radio astronomy.

Earth-to-Space (uplink) emissions cannot affect ALMA observations as long as the emitting devices (user terminals or gateway stations) are not placed in the proximity of the antennas. We are interested in understanding Space-to-Earth emissions (downlinks) from telecommunication satellites in non-geostationary (NGSO) low-Earth orbits (LEO). Table 2 shows the main characteristics of six different satellite constellations (as of March 2023). None of these constellations make use of the full range of frequencies they have been approved to use. Also, they do not emit 100% of their power continuously over the whole band. They use discrete, narrow-band channels (e.g. 50, 100, 250 or 500 MHz) of variable intensity, digitally modulated, with all the constellations making use of adaptive coding and modulation schemes to maximize the data-transfer rates and to optimize the use of the available spectrum.

LEO satellites move along orbits ranging from a minimum of 360 km to more than 1000 km from the Earth surface, grouped in "planes" or "trains" or "shells" at different altitudes and inclinations. Table 3 shows the distribution of the first 3236 Amazon's Kuiper satellites. The satellites use a mix of mechanically or electronically steerable (phased array) antennas for communication with user terminals and gateway stations on the ground, depending on the design choice of each provider. For example, the technology used by Kuiper satellites [16]:

> *The use of high gain, steerable and shapeable phased array antennas, operation at low orbital altitudes, supports virtual spots of approximately 300 km^2 (or a radius of just under 10 km). [...] The user beams maintain continuous service to assigned virtual spots by constantly updating their coefficients to compensate for satellite motion. [...] Each Kuiper*

[16] Text extracted from the Technical Appendix to the Kuiper's ITU application

Table 2: *The main characteristics of six different satellite constellations (as of March 2023)*

Starlink Gen1: 4408 satellites planned (April 2020 filing)
Launched to date: 3866; operational: 3162

	User Terminals	Gateway Stations
Uplink	Ku: 14.0-14.5 GHz	Ka: 27.5-30.0 GHz
Downlink	X/Ku: 10.7-12.7 GHz	Ku/K/Ka: 17.8-19.3, 37.5-42.0 GHz

https://licensing.fcc.gov/myibfs/download.do?attachment_key=2274316

Starlink Gen2: 29988 satellites planned (August 2021 filing)
Launched to date: 351; operational: 109

	User Terminals	Gateway Stations
Uplink	Ku/K/Ka: 12.75-30.0 GHz	Ka/E: 27.5-30, 81.0-86.0 GHz
Downlink	X/Ku/K: 10.7-20.2 GHz	Ku/K/E: 17.8-19.3, 71.0-76.0 GHz

https://fcc.report/IBFS/SAT-LOA-20200526-00055/2378669.pdf

OneWeb: 6372 satellites planned (phase-2, 2021 revision)
Launched to date: 620; operational: 428

	User Terminals	Gateway Stations
Uplink	Ku: 12.75-13.25, 14.0-14.5 GHz	Ka: 27.5-30.0 GHz
Downlink	Ku: 10.7-12.7 GHz	Ku/K: 17.8-18.6, 18.8-20.2 GHz

https://fcc.report/IBFS/SAT-MPL-20210112-00007/3493913.pdf

Amazon's Kuiper Systems: 7774 satellites planned (November 2021 filing)
Launched to date: 0; operational: 0

	User Terminals	Gateway Stations
Uplink	Ka: 28.35-30.0 GHz	Ka: 27.5-30.0 GHz
Downlink	Ku/K: 17.7-20.2 GHz	Ku/K: 17.7-20.2 GHz

https://licensing.fcc.gov/myibfs/download.do?attachment_key=1773885

Kepler: 360 satellites planned (filed application for 114852 satellites)
Launched to date: 19

	User Terminals	Gateway Stations
Uplink	Ku: 12.75-14.5 GHz	Ka: 27.5-30.0 GHz
Downlink	Ku: 10.7-12.7 GHz	Ku/K: 17.8-20.2 GHz

https://licensing.fcc.gov/myibfs/download.do?attachment_key=2379225

AST's SpaceMobile: 243 satellites planned
Launched to date: 2

	User Terminals	Gateway Stations
Uplink	GSM: 846.5-849, 845-846.5, 788-798 MHz	Q/V: 47.2-50.2, 50.4-51.4 GHz
Downlink	GSM: 891.5-894, 890-891.5, 758-768 MHz	Ka/Q: 37.5-42.0, 42.0-42.5 GHz

https://fcc.report/IBFS/SAT-PDR-20200413-00034

Table 3: *Distribution of the Amazon's Kuiper satellites in planes at different altitudes and inclinations.*

Altitude [km]	Inclination [°]	Number of Planes	Satellites per Plane	Number of satellites
630	51.9	34	34	1156
610	42	36	36	1296
590	33	28	28	784

satellite user beam antenna produces several independent, steerable and shapeable Ka-band beams with variable channel bandwidth, enhancing the efficient use of spectrum to serve customers in proportion to their number and bandwidth demands. The user transmit beams and user receive beams on Kuiper satellites are dynamically shaped to produce almost identical spot contours on the ground. The beams from the satellites in the 590 km and 610 km shells will be adjusted to approximately match the beams from satellites in the 630 km shell. This allows all Kuiper satellites to have approximately the same spot beam footprint and support customers interchangeably.

Depending on the orbital altitude and the antennas design, the footprint on the ground of the single emitted radio beam can be a few tens of km up to a few hundreds of km, as shown in Figure 11 and 12. Depending on the maximum off-nadir steering angle of each system (typically 40 – 60 degrees), the per-satellite coverage area, not simultaneously irradiated (satellite field of view, FoV) can have a diameter of more than 1000 km. Some satellites use phased array antennas for

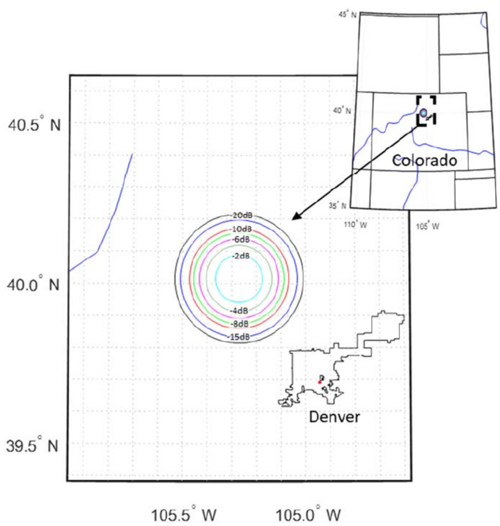

Figure 11: *Kuiper single beam footprint on the ground at nadir for user terminals communication.*

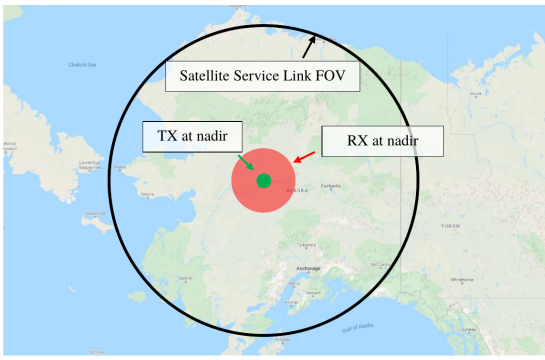

Figure 12: *Coverage area for a single Kepler satellite (FoV, black circle) and nadir transmit and receive beam sizes (red and green circles) corresponding to 3° and 13° HPBW or 68 km and 300 km footprint diameter on the ground at maximum operational altitude of 650 km. The diameter of the FoV is ∼ 1440 km. A map of the state of Alaska is used to show the relative scale.*

the communication with the user terminals. In contrast, communication with the gateway stations can be based on point-to-point connections, where satellite and gateway antennas point directly at each other. For example, this is the technology used by Kuiper satellites [16]:

> *Gateway links are always point-to-point connections, and satellites and gateways point directly at each other using coordinated system control information transferred through gateway links. Throughout the duration of a link connection, the pointing of both antennas is updated in milliseconds to maximize gateway link throughput. Both gateways and satellites use an additional antenna to support hand-off to the next gateway link. This avoids any loss of signal when moving between sites and provides a seamless handover as satellites move through multiple gateways per orbit[. . .] Mechanically steered, reflector antennas will be used for satellite communications with gateway earth stations for uplink and downlink beams. Similar to user beams, the gateway beam projection widens as the beam is steered away from nadir [. . .] The coverage area for Kuiper satellite gateway beams extends further than that for user beams. Each satellite operating in the 630 km shell can connect to any gateway earth station [. . .] within 58° from nadir corresponding to 3,200,000 km^2 gateway coverage area below each satellite.*

5.2.2 Chilean SubTel Extracto 20-Sp50711

Of most relevance to ALMA, this document gives details on the seven Starlink gateway stations that have been authorized for operation on the Chilean territory. The most northerly gateway is located near Caldera, ∼540 km from ALMA [17]. Also, it should be noted that all these gateway stations are authorized by SubTel to receive frequencies (Space-to-Earth) limited to the range 10.7 – 12.7, 17.8 – 18.55, 18.8 – 19.3 GHz, well below ALMA minimum operation frequency of 35 GHz.

5.2.3 Other satellite constellations

The Chinese state-owned China Satellite Communications Co., Ltd. (a.k.a. China Satcom) has filed ITU applications for a large satellite constellation, known as Guowang (“national network”, GW). The applications describe two orbital shells, GW-A59 at 600 km, comprising 6080 satellites in three planes [18], and GW-2 at 1145 km, comprising 6912 satellites in four planes [19], for a total of 12992 satellites.

The China Satellite Network Group Co., Ltd. also filed an ITU application for a large satellite constellation, named CSN-V1-1, made of 1560 satellites [20].

[17] Google map of all Starlink gateway stations worldwide
[18] GW-A59 ITU application
[19] GW-2 ITU application
[20] CSN-V1-1 ITU application

The China Academy of Space Technology (CAST), a major subsidiary of the China Aerospace Science and Technology Corporation (CASC), and the Innovation Academy for Microsatellites (IAMCAS) under the Chinese Academy of Sciences, are understood to be two entities contracted to manufacture satellites for Guowang. IAMCAS is expected to deliver its first 30 satellites for the project by the end of the year 2023.

These Chinese constellations have all filed applications for frequencies ranging from 1164 MHz to 51.4 GHz, therefore raising some concerns for ALMA Band-1.

The African state of Rwanda has filed ITU applications for two mega-constellations with a total of 327230 satellites [21] planning to use frequency channels 59.3 – 76.0 GHz and 81.0 – 86.0 GHz falling in ALMA Band-2 and Band-3.

5.3 Potential Impact of satellite constellations on ALMA

It is important that we evaluate the potential RFI risk to ALMA due to the satellite constellations, namely if downlink (Space-to-Earth) emissions can pose a risk to ALMA operations. However, it is noted that Earth-to-Space emissions from gateway stations may also pose a risk of RFI if the gateway station is in the vicinity of the radio telescope, due to the high transmission power. Furthermore, the presence of a gateway station implies the service beam of many satellites may systematically and simultaneously point in that direction, with an increase in the radiated power per unit of area. Considering that the beam footprint on the ground is several tens of kilometers, this is another source of RFI risk linked to the eventual presence of a gateway station near the observatory.

5.3.1 Starlink Gen1

Space-to-Earth emission of Starlink Gen1 to user terminals and gateway stations could fall within ALMA Band-1 RF frequency range (FCC application for 37.5 – 42.0 GHz). This is unlikely to impact ALMA, namely:

a) The actual specifications of Starlink user terminals do not cover frequencies higher than 20 GHz, therefore there is no emission at Band-1 frequencies towards user terminals;

b) Present-day gateway stations in Chile are not authorized for the use of those frequencies (see SubTel Extracto 20-Sp50711).

5.3.2 Starlink Gen2

Space-to-Earth emission of Starlink Gen2 to gateway stations could fall within ALMA Band-2 RF frequency range (FCC application for 71.0 – 76.0 GHz). This is unlikely to have any impact on ALMA because the present day gateway stations in Chile are not authorized for the use of those frequencies. Also, Starlink Gen2 and ALMA Band-2 are not yet fully developed and the specifications could change from

[21] Rwanda ITU application

now to the time when both Starlink Gen2 and ALMA Band-2 will be in operation. Nevertheless, SubTel should be informed of the risk in advance of any request to authorize the use of these frequencies in existing gateway stations on the Chilean territory (see SubTel Extracto 20-Sp50711) or the installation of new gateway stations in the proximity of the Parque Astronómico de Atacama. i.e. within ∼500 km distance.

5.3.3 General considerations

Based on the available information related to Starlink, OneWeb, Kuiper, Kepler satellite constellations, we can conclude that:

- Space-to-Earth to user terminals: all operational channels are within the range 10.7 – 12.7 GHz or 17.7 – 19.3 GHz in the current generation of satellite constellations and 10.7 – 20.2 GHz in Starlink Gen2 as User terminals do not work at higher frequencies. All the communication channels fall in the Ku/K/Ka bands, but they do not pose any risk to ALMA as the frequencies are far below the minimum ALMA operation frequency of 35 GHz.
- Space-to-Earth to gateway stations: all operational channels are within the ranges 17.8 – 19.3 GHz (Starlink Gen1), 20 – 30 GHz (OneWeb), or 17.7 – 19.3 GHz (Amazon's Kuiper) and are used only for communication with the gateway stations, which are mostly located within the United States. The seven gateway stations authorized in Chile to date (see below) are far enough from the ALMA site to pose no RFI risk to ALMA. The gateway station located near Caldera is the closest to ALMA, at ∼540 km distance[17].

5.3.4 Present day impact

To summarize:

- Satellite constellations will use the K,Q,U,V,E bands, but only within specific frequency ranges and in narrow-band channels.
- All downlink frequencies foreseen to date to user terminals are up to 20 GHz, well below the ALMA frequency bands.
- Other channels in higher bands are used only for earth-to-space communication and pose little concern for ALMA.
- At this time there is no risk to ALMA from the satellite constellations because all emissions from the existing systems that could eventually reach an ALMA receiver use frequencies well below the minimum ALMA frequency of 35 GHz.

5.3.5 Potential impact of future developments

At this time:

- The frequency range 37.5 – 42.0 GHz is foreseen to be used by Gen1 satellites for downlink from satellites to gateway stations, not to user terminals. This range overlaps with the ALMA receiver Band-1.
- The frequency range 37.5 – 42.5 GHz is foreseen to be used by SpaceMobile satellites for downlink from satellites to gateway stations. This range overlaps with the ALMA receiver Band-1.
- The frequency range 71.0 – 76.0 GHz is foreseen to be used by Gen2 satellites for downlink from satellites to gateway stations, not to user terminals. This range overlaps with the ALMA receiver Band-2 that will not be in operation until 2025+. By then, Gen2 specifications and modes of operation could change, e.g. they may feature laser inter-satellite links allowing them to communicate with each other even if there is no gateway station within sight.

The very purpose of the gateways is to provide high-throughput data connection with wider bandwidth (hence why they use channels in the higher frequency V and E bands). Any such station will be placed where fast-network infrastructure (fiber optics) is available. It is unlikely that future Starlink gateway stations would be located in the proximity of the ALMA site in the Atacama Desert where no such infrastructure is available. Nonetheless, the Starlink Gen2 filing needs to be considered as a possible source of RFI with direct impact on ALMA Band-2, so it is important to evaluate the potential level of impact.

Assuming that Gen2 satellites may emit downlink signals in the range 71.0 – 76.0 GHz and are powered up while crossing the sky over ALMA observing in Band-2. Signals coming from different satellites are unlocked, incoherent, and would not propagate to cross-correlation products of pairs of antennas, although they could still affect the auto-correlation of each single antenna. Excluding cross-correlation effects from different satellites, we can focus on signals from one single satellite. A LEO satellite makes an orbit every ∼90 minutes. At that speed (4°/minute) a downlink beam moving exactly through the center of an ALMA 12-m antenna beam would take only 300 ms to traverse the Band-2 beam. It would take an even shorter time when not transiting exactly through the center of the beam. We should also consider that digital signals are modulated, fast time-variable signals, with variable emitted power, and that the single-channel bandwidth is only 50 MHz, whereas a typical ALMA receiver IF is currently 4 – 8 GHz wide, and Band-2 IF is foreseen to be even larger (14 GHz). [22] Moreover, the power is distributed over a typical footprint on the ground of the order of several tens of km, only a very small fraction of that power will be collected by an ALMA dish. The satellite signal would be so fast and so diluted over the area and the integrated

[22] ALMA2030 upgrade plans foresee larger IF bandwidth, up to 16, 18 or even 20 GHz by the end of the decade.

IF band to be undetectable in total power observations. Although unlikely, the signal may still be detectable in single-dish auto-correlation spectra as a narrow 50-MHz spike of rapidly variable amplitude. In theory, this could have an impact on interferometric science observations, altering the calibration of an antenna in the array from time to time, but it is not possible to give an estimate of how much that could impact the final science products, given the many unknowns. However, these considerations are very much in the future and do not pose a real threat to ALMA today. No matter, we should endeavor to ensure that no gateway stations are built in the vicinity of ALMA and that SubTel does not authorize the use of the 71.0 – 76.0 GHz frequency range by gateway stations on the Chilean territory, most certainly in the environs of the ALMA site.

5.4 Impact of satellite constellations on the Parque Astronómico de Atacama

Satellites downlink emissions can have an impact on the other observatories operating near to ALMA in the Parque Astronómico de Atacama. Figure 13 shows the spectrum occupancy by satellites constellations and radio astronomy receivers in the RF range from 10 to 120 GHz. ALMA as well as the Simons Observatory and CLASS could be affected in the ∼25 – 52 GHZ range, whereas the other observatories, e.g. APEX or ACT, observe at higher frequency bands that are not impacted. See Appendix B for the list of frequencies used in the figure.

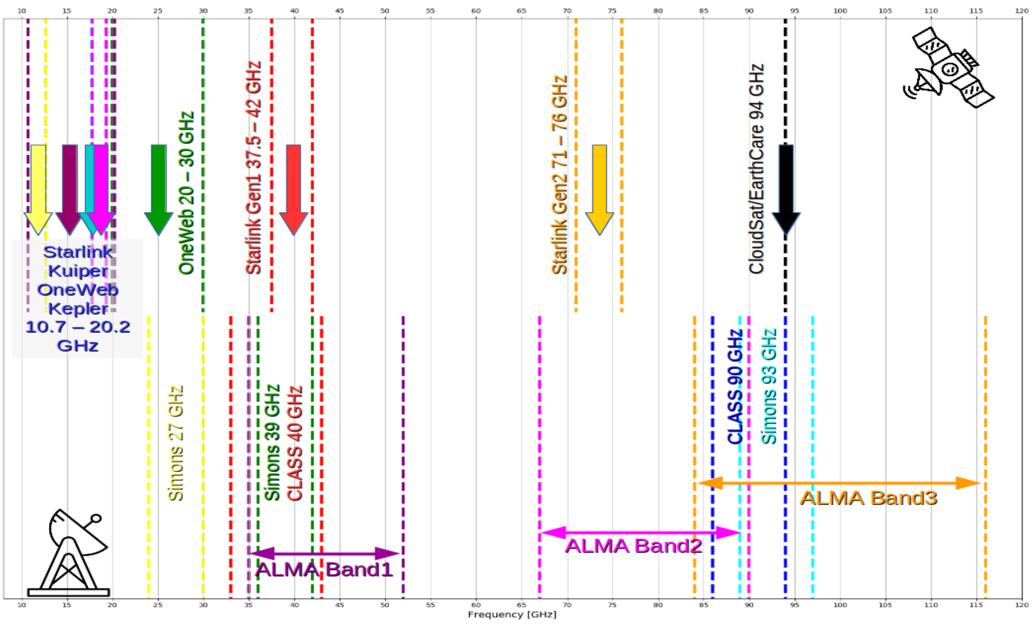

Figure 13: *Impact of the emission from satellites (top, downward arrows) on the radio observatories operating in the Parque Astronómico de Atacama (bottom). Only downlink frequencies (Space-to-Earth) are considered.*

6 ALMA Spectrum Management office

Spectrum management at ALMA was first described in the document "Frequency Management, EMC, and RFI Monitoring for ADE Maintenance Operations" [23]. Spectrum management at ALMA was originally a duty of the Observatory System Engineer, and has now passed ad interim to the Senior RF Engineer. The duties include, among others, coordination of activities concerning RF emissions and potential sources of RFI with all the facilities operating on the Chajnantor Plateau.

6.1 Remotely Piloted Aircraft Systems (RPAS) policy at ALMA

Facing growing interest from the media and frequent visits from video producers, ALMA has defined the general policy and procedures to regulate the operation of Remotely Piloted Aircraft Systems (RPAS, e.g. drones) within the ALMA concession. This should be coordinated with all the facilities operating in the PAA. The ALMA document OPER-10.08.03.00-0052-B-PRO (2017) is based on directives from the Chilean Civil Aeronautic Authority and compliance with CE or FCC EMC requirements. Apart from safety concerns related to the flying object, the most important aspect related to RFI is that any emission above 4 GHz (lower edge of the ALMA receivers IF) is forbidden (e.g. use of 5+ GHz wifi channel).

6.2 Chajnantor Working Group (CWG) spectrum coordination

ALMA spectrum management office plays a crucial role in the coordination of all matters related to radio emissions on the Chajnantor Plateau that could impact operations of any of the observatories on the plateau e.g. the use of powerful transmitters for surface-accuracy measurements by holography technique (e.g. APEX, ACT) or operation of the ALMA artificial polarization source. Coordination is carried out by means of a dedicated "CWG Spectrum Managers" group.

6.3 Interaction with Chilean institutions

The ALMA Spectrum Management Office is taking part in a number of Chilean initiatives related to RFI prevention and mitigation:

- Member of the RFI Committee of the Sociedad Chilena de Astronomía (SOCHIAS)
- Member of the Chilean Low Earth Orbit satellite group (CLEOsat)
- Participation in some activities of the PAA
- Interaction with SubTel:
  - Give advice for the assessment of new applications from satellite operators on the Chilean territory (e.g. for gateway stations)

[23] OPER-00.00.00.00-011-A-PLA, Clint Janes, 2009-10-31

- Participation in the renewal process of the SubTel Exempt Resolutions 3075 & 3076 (ALMA Concession), giving advice to ESO and AUI legal representatives.
- Invite SubTel representatives to participate in the annual CWG meeting.
- Evaluate the possibility to extend the protection and coordination zones beyond the Chilean national territory by opening a dialog with Bolivian and Argentinean equivalent institutions.

6.4 Interaction with international institutions

The ALMA Spectrum Management office also has a number of RFI-related collaborations and interactions with international institutes:

- Collaboration with the Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS)
- Participation in the RFI Working Group of the National Radio Dynamic Zone (USA), with special attention on the development of RFI measurement hardware (up to 120 GHz) that could be tested at the ALMA site for a limited period of time
- Engagement with the International Telecommunication Union (ITU), the international body whose Radio Regulations (RR), that incorporate decisions of the World Radio-communication Conferences (WRC), which do not include currently any radio astronomy bands above 275 GHz. This is considered a priority for the future of ALMA, as the lack of regulations or recommendations could have a direct impact on future ALMA operations if new commercial applications will start to occupy frequencies above 275 GHz, in the pursuit of larger bandwidth for digital data transfer.

6.5 Suggestions and RFI mitigation measures

The two identical SubTel Exempt Resolutions 3075 & 3076, released in 2013 and based on the SubTel Resolutions 1055 & 1056 written in 2004, are beginning to be outdated, as they do not reflect the actual requirements to prevent RFI at ALMA today. For example, only the ALMA RF range is considered, with the ALMA IF range not considered; the RF range given for ALMA Band-2 and Band-5 is outdated.

It is now critical to work on an updated Resolution in order to:

- Renew the protection of the concession and coordination zones for at least 10 more years, possibly longer.
- Update the frequency range with the actual ranges in use and those foreseen in the ALMA2030 upgrade.

- Take the opportunity to introduce new RFI prevention and mitigation measures that would consider the ALMA IF range, location and operation of 5G/6G transmitters, emission from satellite constellations and gateway stations in Chile.

Other measures considered by the ALMA Spectrum Management office:

- In collaboration with SubTel, evaluate the possible ways to prevent the siting of gateway stations in the surroundings of ALMA, defining a minimum distance based on the satellites beam footprint on the ground and emission power levels.
- Open a dialog with the ITU to:
  - Reinforce the recommendations to coordinate operations between satellite operators and observatories (e.g. CloudSat and EarthCare).
  - Raise awareness on the need to protect frequencies above 275 GHz, up to 1 THz, that represent the majority of the ALMA operation spectrum.

In this respect, coordinated operations should be seen as favorable over the assignment of forbidden bands or exclusive allocation of frequencies to radio astronomy because it is consistent with the implementation of efficient spectrum sharing policies.

The use of the same portion of the spectrum at different times, by different operators e.g. satellite operators using the 40-GHz downlink while ALMA is observing at 345 GHz requires efficient, dynamic, coordination and planning at national and international level that does not yet exist and that will require years of development. Nevertheless, spectrum sharing is probably the most efficient way to go to enable present and future coexistence of radio astronomy and telecommunication technologies.

A Waveguide standard of frequencies

Definition of the *Waveguide Bands* standard of frequencies:

Band Name	RF Range [GHz]
L	1 – 2
S	2 – 4
C	4 – 8
X	8 – 12
Ku	12 – 18
K	18 – 26.5
Ka	26.5 – 40
Q	30 – 50
U	40 – 60
V	50 – 75
E	60 – 90
W	75 – 110
F	90 – 140
D	110 – 170
Y	325 – 500

B List of observatories and satellites frequencies

The following tables give the list of the frequencies used by observatories and satellites shown in Figure 13:

Observatory	Receivers Frequencies [GHz]
ALMA	Band-1: 35 – 52 Band-2: 67 – 90 (116) Band-3: 84 – 116
CLASS	Q-band: 33 – 43 W-band: 86 – 94
Simons Observatory	LF-band: 27 , 39 MF-band: 93

Satellite Constellation	Space-to-Earth Frequencies (downlink) [GHz]
Starlink Gen1	10.7 – 12.7 17.8 – 19.3 37.5 – 42.0
Starlink Gen2	10.7 – 20.2 17.8 – 19.3 71.0 – 76.0(to gateway stations only)
OneWeb	10.7 – 12.7 20.0 – 30.0
Kuiper	17.7 – 20.2
Kepler	10.7 – 12.7 17.8 – 20.2
CloudSat, EarthCare:	94 (radar)