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Technical and operational characteristics of radio astronomy systems in the 67-116 GHz (3-4 mm) range

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***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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REPORT ITU-R RA.2510-0

Technical and operational characteristics of radio astronomy systems in the 67-116 GHz (3-4 mm) range

(2022)

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1 Introduction

Radio astronomy at mm-wavelengths is rapidly evolving and has become a key means for investigating the universe. It has been crucial in detecting numerous interstellar molecules, such as water and carbon monoxide in space. It has been used in the detection of more than one hundred molecules, many unknown on Earth. The millimetre radiation of molecules is not absorbed by interstellar clouds of dust, which has allowed for these numerous discoveries made to date. Other topics of interest for which mm-wave observations yield key scientific insights include the observation of star and planet formation processes, study of emission from the vicinity of compact objects such as black holes, and study of the earliest galaxies.

To detect such faint, naturally occurring, signals of cosmic emissions at mm-wavelengths, parabolic reflectors are typically used, which can be combined interferometrically to achieve the highest possible spatial resolutions. The most productive facility currently in operation at the frequency bands covering 67-116 GHz is the Atacama Large Millimeter/submillimeter Array (ALMA), situated in Chile and which is expected to continue to receive technical upgrades well beyond 2030. Single dish telescopes and smaller interferometric facilities are also in operation around the world, all of which provide unique observational capabilities in these frequency bands. Most recently, a new facility that will include radio telescopes located across North America, the next generation Very Large Array (ngVLA) was rated among the top two projects in the U.S. National Academy of Sciences' Astro2020 decadal survey. The ngVLA will vastly improve the observational capabilities in the 67-116 GHz (3-4 mm) range in the northern hemisphere and is expected to start construction in the 2020-2030 decade.

In light of growing observational capabilities and developments in radio astronomy at 67-116 GHz, this Report provides technical and operational characteristics of both legacy and the new generation of instruments at radio astronomy observatories, providing information to address the two questions named to be studied in Question ITU-R 226-2/7 (2017).

This Report addresses *decides* 1 of Question ITU-R 226-2/7 and focuses on the 67-116 GHz (3-4 mm) range due to the key importance of this range for the radio astronomy systems in the coming decade and the number of new and planned high-priority instruments. Additional details on specific systems or national experiences are contained in the Annexes.

The following sections focus on the technical and operational characteristics of systems operating at frequencies in the 67-116 GHz (3-4 mm) range. This includes a summary of the propagation characteristics, with their relation to radio astronomy bands (see § 2) and existing Radio Regulation protections between 67-116 GHz (see § 3), a summary of the scientific motivation for observations in these bands (see § 4), and finally a summary of the radio astronomy facilities and instrumentation (see § 5). Additional details are contained in the Annexes, as appropriate.

2 Atmospheric conditions in the 67-116 GHz (3-4 mm) range

Above 67 GHz, atmospheric absorption is a key factor in the technical design of radio receivers and the bandwidths they cover, resulting in significant attenuation differences as a function of frequency. This is of critical importance, second only to the existence of terrain and clutter in the line-of-sight. Overall propagation loss can vary greatly with respect to, e.g., frequency, altitude, water vapor content, and elevation angle. In the 67-116 GHz (3-4 mm) range, propagation characteristics are largely driven by atmospheric characteristics, such as water vapor content, which plays a significant role in site selection for radio astronomy systems. The free-space transmission loss equation is provided in § 2.1, an overview of atmospheric attenuation characteristics is provided in § 2.2, and finally, the impacts of terrain shielding and clutter are described in § 2.3.

2.1 Free-space transmission loss

The classic free-space path loss equation is summarized in Recommendation ITU-R P.525-4, which lacks some additional information on its derivation, which is provided in the following and specifically relevant in the context of 67-116 GHz (3-4 mm) evaluations. Equation (4) in Recommendation ITU-R P.525-4, expressed in dB and units of km and GHz, is:

$$PL(\text{dB}) = 20\log D_{\text{km}} + 20\log f_{\text{GHz}} + 92.44 \tag{1}$$

This free space loss formula is derived from the following:

$$PL(\text{dB}) = -10\log\left[\left(\frac{1}{4\pi {D_{\text{km}}}^2}\right)\left(\frac{\lambda^2}{4\pi}\right)\left(\frac{1\text{ km}}{1\,000\text{ m}}\right)^2\left(\frac{1\text{ GHz}}{10^9\text{ Hz}}\right)^2\right]$$

$$PL(\text{dB}) = -10\log\left[\left(\frac{1}{4\pi {D_{\text{km}}}^2}\right)\left(\frac{c^2}{4\pi {f_{\text{GHz}}}^2}\right)\left(\frac{1\text{ km}}{1\,000\text{ m}}\right)^2\left(\frac{1\text{ GHz}}{10^9\text{ Hz}}\right)^2\right] \tag{2}$$

$$PL(\text{dB}) = -10\log\left[\left(\frac{1}{{D_{\text{km}}}^2}\right)\left(\frac{1}{{f_{\text{GHz}}}^2}\right)\left(\frac{1\text{ km}}{1\,000\text{ m}}\right)^2\left(\frac{1\text{ GHz}}{10^9\text{ Hz}}\right)^2\left(\frac{c}{4\pi}\right)^2\right]$$

The constant in equation (1) is derived from the logarithm of $c^2/(4\pi)^2$ part of the above equation, along with the dimensional adjustments.

The first part of equation (1) on the right-hand side should be self-evident; with a power expressed in e.i.r.p. (essentially, the equivalent luminosity if the power sent in the direction of the receiver were emitted isotropically), dividing by $(4\pi D^2)$ will yield a flux density value at the receiving antenna (power per unit area), minus other losses such as atmospheric attenuation.

The second term of the right-hand side of equation (1) results from the fact that an antenna with 0 dBi gain (real or theoretical) always has an effective antenna aperture (basically, an effective power collecting area) that is a function of wavelength (frequency). Since a smaller effective aperture has a smaller power collecting area, less power is collected; this term accounts for the change vs wavelength.

The second term in the right-hand side of equation (1) should be included when calculating received power, the protection criteria values for which are specified by Recommendation ITU-R RA.769, Tables 1 and 2, column 7 (input power) for an assumed receiving antenna gain of 0 dBi.

If a comparison with the protection criteria values in Recommendation ITU-R RA.769, Tables 1 and 2, columns 8 or 9 (power flux-density) is desired, the free space path loss is only a function of distance, the $1/(4\pi)$ term, and dimensional adjustments:

$$PL_{PFD}(\text{dB}) = 20\log D_{\text{km}} + 70.99 \tag{3}$$

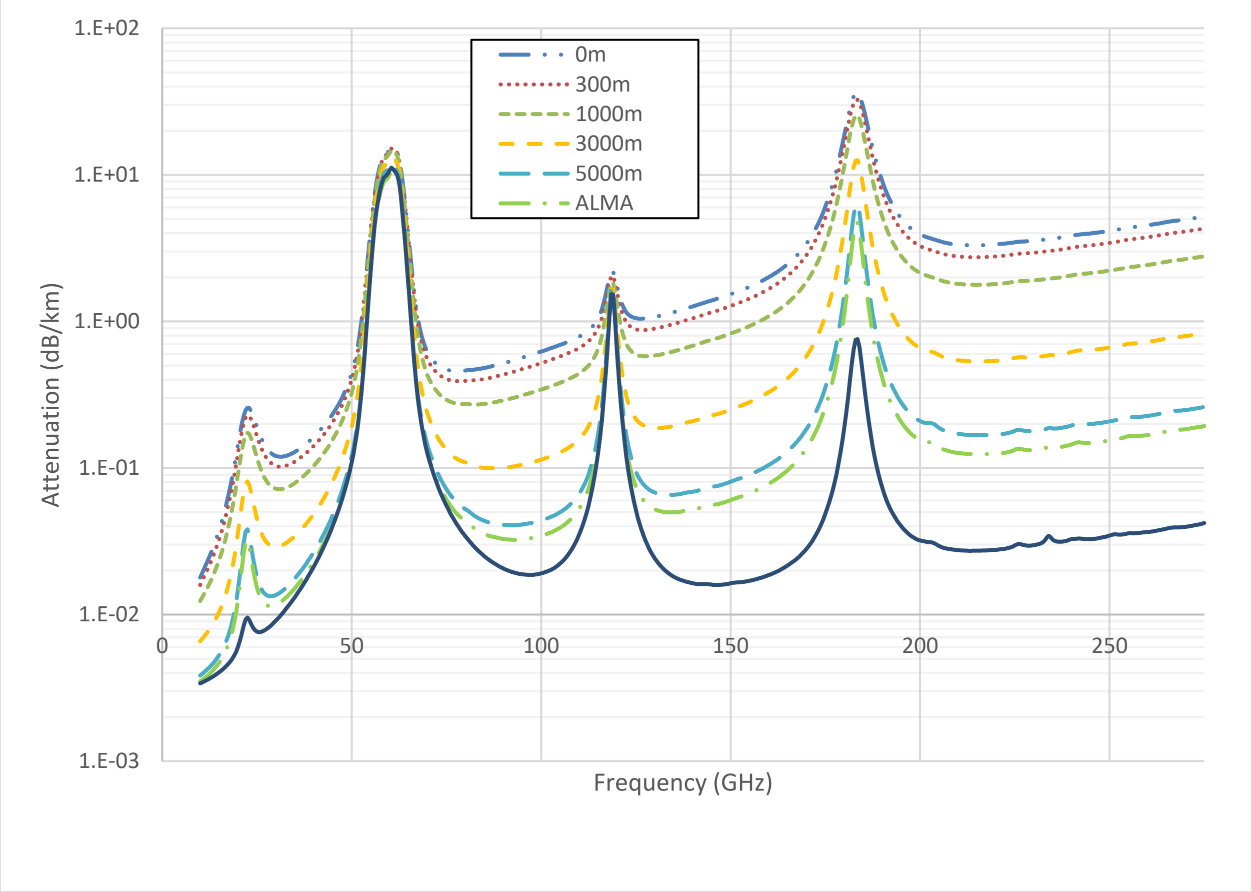
In either case, for the purpose of comparing with ITU protection criteria values for radio astronomy, the receiving gain term (G_R) should be assumed to be 0 dBi.

2.2 Atmospheric attenuation characteristics in the 67-116 GHz (3-4 mm) range

Figure 1 shows the atmospheric attenuation from 10 to 275 GHz for different elevations. The 67-116 GHz (3-4 mm) band is highlighted. At 100 GHz, for example, the attenuation at the ALMA site during the 10% best observing conditions approaches the characteristics expected at 10 GHz under more normal atmospheric conditions. In other words, while atmospheric attenuation in the standard model (blue dash-double-dot line) is significant at higher frequencies, the atmospheric attenuation at the locations of radio astronomy facilities (green dash dot and solid black) is comparable to atmospheric attenuation of the standard model at 10 GHz.

FIGURE 1

Atmospheric attenuation from 10 to 275 GHz for different geographic locations

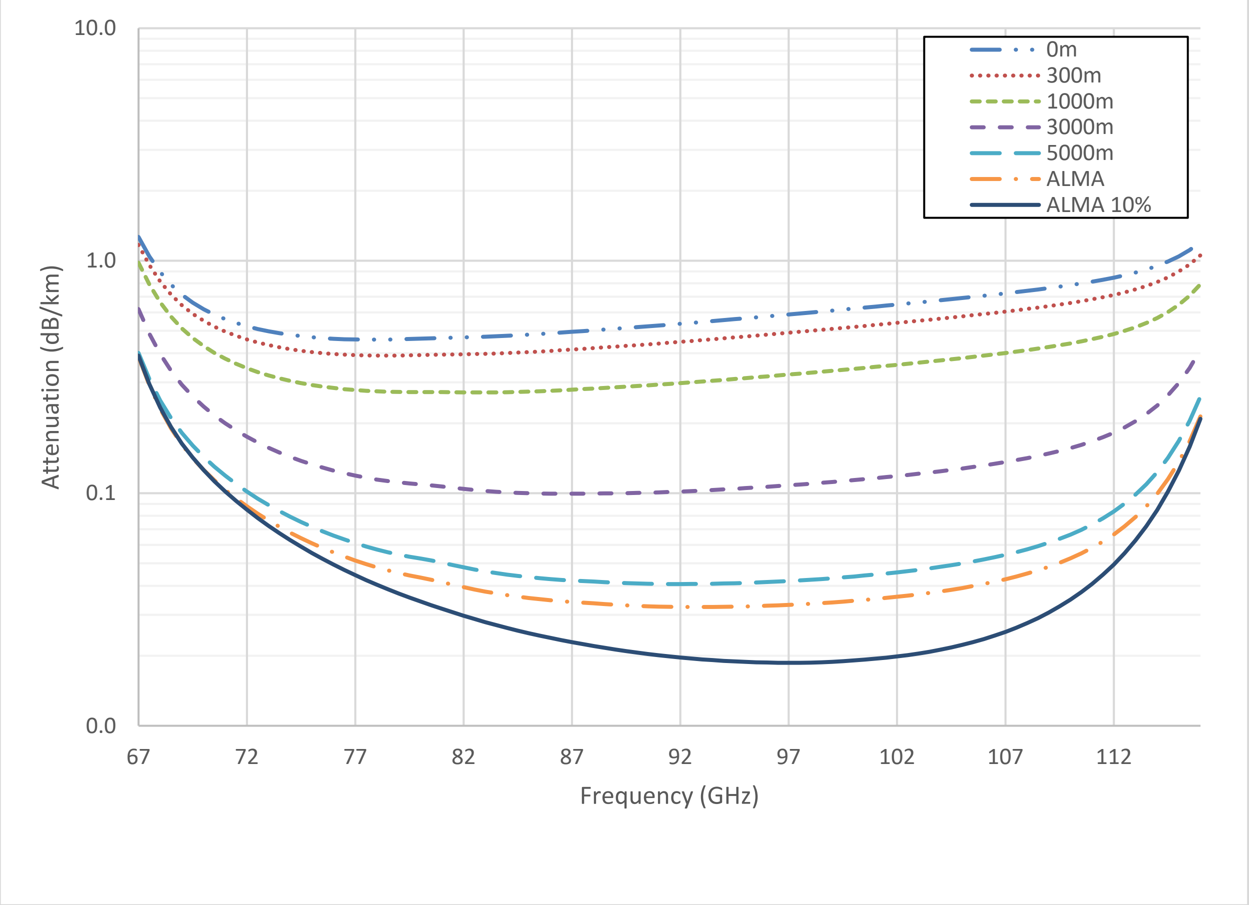


As illustrated in Fig. 1, the atmospheric attenuation at the geographic locations selected as sites of millimetre and sub-millimetre radio telescopes is significantly less than that predicted by the sea-level standard atmosphere model. This is expected, since these facilities are designed to detect faint cosmic emissions and typically placed at high and dry sites. At the best sites, the atmospheric attenuation at 100 GHz is comparable to the attenuation at 10 GHz for the standard model. These excellent atmospheric conditions require significant exclusion zones for even low power radio devices.

As shown in Fig. 2, there is a significant difference in attenuation even across the atmospheric window from 67-116 GHz. In the most extreme case from 92-102 GHz, the attenuation varies from 0.01 dB/km to over 1.1 dB/km going from the ALMA site in good observing conditions to sea level with standard atmospheric conditions. The main point of these attenuation curves is to emphasize that due to the siting of radio telescopes at high and dry sites, one must take into account local atmospheric conditions to correctly evaluate attenuation. Furthermore, the planned ngVLA will span the entire North American continent with telescope sites with a wide range of atmospheric conditions and altitudes, which has to be taken into account in the definition of protection of allocated bands.

FIGURE 2

Atmospheric attenuation from 67 to 116 GHz for different geographic locations



2.3 Terrain shielding, clutter and other sources of attenuation

Siting of radio telescopes can benefit from other sources of attenuation, e.g. terrain shielding. This can allow for placement of radio receivers, without a loss of sensitivity, closer to population centres while maintaining adequate protection.

3 Sharing and protection requirements in 67-116 GHz range

Between 67 and 116 GHz, the radio astronomy service currently already shares 79% of the band with active services, including amateur, amateur-satellite, broadcasting, broadcasting-satellite, EESS (active), fixed, fixed-satellite, inter-satellite, mobile, mobile-satellite, radionavigation, radionavigation-satellite, and space research (active). In all cases of sharing with active services where the radio astronomy service is co-primary, and in a few instances where the radio astronomy service is secondary, the footnote RR No. **5.149** applies, which encourages administrations to take all practicable steps to protect the radio astronomy service from harmful interference. This footnote includes the caution that emissions from spaceborne or airborne stations can be particularly serious sources of interference to the radio astronomy service. The remainder of the allocations to radio astronomy between 67-116 GHz are shared with other passive services, including the Earth exploration-satellite service (passive) (EESS) and space research service (SRS), and the footnote RR No. **5.340** applies, which prohibits emissions.

RAS allocations and protections in the radio regulations are motivated by atmospheric windows and propagation characteristics outlined in § 1 of this Report. Table 1 lists the type of assignment made to RAS and includes any referenced footnotes in the International Table of Frequency Allocations.

Radio Regulations No. **5.149** refers to those bands where Administrations are urged to take all practicable steps to protect the radio astronomy service and applies to both frequency bands where RAS is co-primary and to frequency bands where RAS has secondary status. Radio Regulations No. **5.340** refers to those bands where all emissions are prohibited and only applies to the four band ranges where RAS is co-primary with other passive services. These bands are used simultaneously for both continuum and spectral line observations. Throughout the 67-116 GHz band, the interference threshold levels detrimental to the RAS are given in Recommendation ITU-R RA.769 as -129 dB(W/m^2) and -228 dB(W/(m$^2 \cdot$ Hz)) for continuum observations, and -148 dB(W/m^2) and -208 dB(W/(m$^2 \cdot$ Hz)) for spectral line observations.

TABLE 1

Service allocations in the Radio Regulations for frequency bands between 67 and 116 GHz and scientific driver, referencing sections 4.1 (S1) – 4.4 (S4)

Frequency range (GHz)	**Delta frequency (GHz)**	**Current services with primary allocation**	**RAS status**	**Footnote referencing RAS**	**Science driving requirement**
67-71^	4	INTER-SATELLITE MOBILE MOBILE-SATELLITE RADIONAVIGATION RADIONAVIGATION-SATELLITE	None	None	Continuum (S1), Spectral line (S2)
71-74	3	FIXED FIXED-SATELLITE (S -> E) MOBILE MOBILE-SATELLITE (S -> E)	None	None	Continuum (S1), Spectral line (S2)
74-76	2	FIXED FIXED-SATELLITE (S -> E) MOBILE BROADCASTING BROADCASTING-SATELLITE Secondary: Space research (S-> E)	None	None	Continuum (S1), Spectral line (S2)
76-77.5	1.5	RADIO ASTRONOMY RADIOLOCATION Secondary: Amateur, Amateur-Satellite, Space research (S -> E)	RAS co-primary with active services	**5.149**	Continuum (S1, S4), Spectral line (S2, S3)
77.5-78	1.5	AMATEUR AMATEUR-SATELLITE RADIOLOCATION Secondary: Space research (S -> E)	RAS secondary	**5.149**	Continuum (S1, S4), Spectral line (S2, S3)
78-79	1	RADIOLOCATION Secondary: Amateur, Amateur-satellite, Space research (S-> E)	RAS secondary	**5.149**	Continuum (S1, S4), Spectral line (S2, S3)
79-81	2	RADIOLOCATION Secondary: Amateur, Amateur-satellite, Space research (S -> E)	RAS co-primary with active services	**5.149**	VLBI, Continuum (S1, S4), Spectral line (S2)
81-84	3	FIXED FIXED-SATELLITE (E -> S) MOBILE MOBILE-SATELLITE (E -> S) Secondary: Space research (S -> E)	RAS co-primary with active services	**5.149**	VLBI, Continuum (S1, S4), Spectral line (S2, S3)

TABLE 1 (*end*)

Frequency range (GHz)	Delta frequency (GHz)	Current services with primary allocation	RAS status	Footnote referencing RAS	Science driving requirement
84-86	2	FIXED FIXED-SATELLITE (E-s) MOBILE	RAS co-primary with active services	**5.149**	VLBI, Continuum (S1, S4), Spectral line (S2, S3)
86-92	**6**	**EESS (passive)** **SPACE RESEARCH (passive)**	**RAS co-primary with passive services**	5.340	**VLBI, Continuum (S1, S4), Spectral Line (S2, S3),**
92-94	2	FIXED MOBILE RADIOLOCATION	RAS co-primary with active services	**5.149**	Continuum (S1, S4), Spectral line (S2, S3)
94-94.1	0.1	EESS (active) RADIOLOCATION SPACE RESEARCH (active)	RAS secondary	**None**	Continuum (S1, S4), Spectral line (S2, S3)
94.1-95	0.9	FIXED MOBILE RADIOLOCATION	RAS co-primary with active services	**5.149**	Continuum (S1, S4), Spectral line (S2, S3)
95-100	5	FIXED MOBILE RADIOLOCATION RADIONAVIGATION RADIONAVIGATION-SATELLITE	RAS co-primary with active services	**5.149**	Continuum (S1, S4), Spectral line (S2, S3)
100-102	**2**	**EESS (passive)** **SPACE RESEARCH (passive)**	**Co-primary with passive services**	5.340	**Continuum (S4), Spectral line (S2, S3)**
102-105	3	FIXED MOBILE	Co-primary with active services	**5.149**	Continuum (S4), Spectral line (S2, S3)
105-109.5	4.5	FIXED MOBILE SPACE RESEARCH (passive)	Co-primary with active services	**5.149**	Continuum (S4), Spectral line (S2, S3)
109.5-111.8	**2.3**	**EESS (passive)** **SPACE RESEARCH (passive)**	**Co-primary with passive services**	5.340	**Continuum (S4), Spectral line (S2, S3)**
111.8-114.25	2.45	FIXED MOBILE SPACE RESEARCH (passive)	Co-primary with active services	**5.149**	Continuum (S4), Spectral line (S2, S3)
114.25-116	**1.75**	**EESS (passive)** **SPACE RESEARCH (passive)**	**Co-primary with passive services**	5.340	**Continuum (S4), CO (J=1-0), Spectral line (S2, S3)**

^ Note allocations in this band begin at 66 GHz.

4 Scientific motivation

RAS frequency requirements are not driven by human choice, but by physics. Hence, the science motivation is a key driver to describing the frequency bands utilized by RAS and those with special protections. In addition, in many regards, the technical and operational characteristics of radio astronomy facilities are driven by the scientific questions they are designed to address. To illustrate these points, this section describes the scientific motivations for radio astronomy observations in the 67-116 GHz frequency range. Key aspects for consideration of radio telescope designs include the spectral frequencies associated with physical phenomena, spatial resolution, and sensitivity to faint naturally occurring radio emissions. The frequency bands allocated to RAS enable observations of a multitude of physical phenomena, including thermal and non-thermal continuum emission and spectral line emission from atoms and molecules. Radio telescopes require sensitive receivers and a low noise environment in order to detect this extremely faint naturally occurring radio emission.

In this frequency range, a key motivating reason for protections of radio astronomy allocations in frequency bands where all emissions are prohibited (RR No. **5.340**) are due to the special characteristics of the molecule carbon monoxide. Similar to the very important spectral line transition for neutral hydrogen at 1420 MHz which enables scientists to detect neutral hydrogen in the Universe, the carbon monoxide molecule is the second brightest molecule. The CO J=1-0 transition falls at 115.271203 GHz at rest, making the frequency band 114.25-116 GHz critical for observations of CO J=1-0 in the solar neighbourhood and Milky Way Galaxy. As galaxies are moving away from us in the Universe, this important spectral line is redshifted[1] to lower frequencies. This fact, along with favourable propagation characteristics to permit the signal to reach the surface of the Earth, means that the entire transparent window from 67-116 GHz is very important for radio astronomy. Observations down to 67 GHz permit the study of the local universe (to an approximate redshift of 0.3). Additionally, to obtain a spectral energy distribution (the slope and/or shape of the power function across the band), it is important to have clean bands widely separated. Hence, there are a total of four bands where RR No. **5.340** applies in the 67-116 GHz range. More details on the scientific motivation for studies in these bands are provided in §§ 4.1 to 4.4.

4.1 Unveiling the formation of Solar System analogues on terrestrial scale

Planets are thought to be assembled in disks around pre-main sequence stars, but the physical processes responsible for their formation are poorly understood. Only recently, optical, infrared, and (sub-) millimetre telescopes have achieved the angular resolution required to spatially resolve the innermost regions of nearby protoplanetary disks, unveiling morphological features with characteristic sizes of >20 astronomical unit (au)[2] suggestive of gravitational perturbations of yet unseen giant planets. This in turn provides a powerful tool to measure planet masses, orbital radii, study the circumplanetary environment, and investigate how forming planets interact with the circumstellar material. Using ALMA, this has already led to multiple discoveries, including a link between dust and chemical substructures and the presence of large reservoirs of organic molecules in the inner disk regions of the stars and which are implicated in the origins of life on Earth. The angular resolution, frequency coverage, and sensitivity of current disk imagery is limited to probing for the presence of planets more massive than Neptune at orbital radii larger than 20-30 au.

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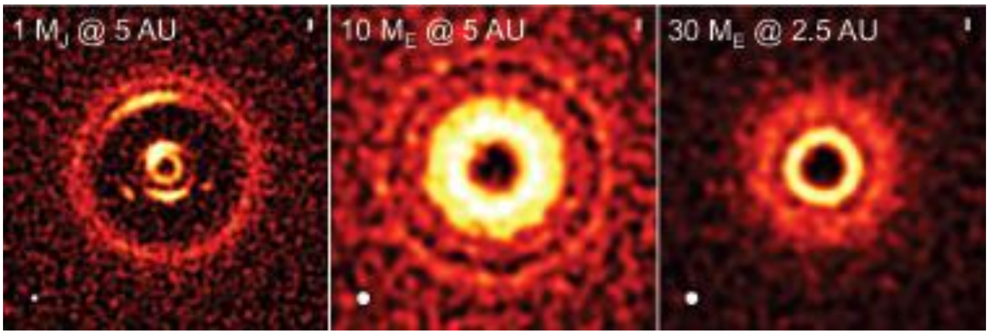
[1] Redshift is an increase in the wavelength, and corresponding decrease in frequency of electromagnetic radiation. Due to the expanding universe, light emitted from distant objects appears redshifted relative to objects at rest; in many instances, redshift is directly correlated with distance to the astronomical object.

[2] An astronomical unit (au) is a unit of length, about the distance from Earth to the Sun and equal to about 150 million kilometres ($1.495\,978\,707 \cdot 10^{11}$ m).

FIGURE 3

Simulated ngVLA observations of protoplanetary disk continuum emission perturbed by a Jupiter mass planet at 5 au (left), a 10 Earth mass planet at 5 au (centre), and a 30 Earth mass planet at 2.5 au (right)



Note to Fig. 3: The ngVLA observations at 100 GHz were simulated with 5 mas angular resolution and 0.5 µJy/bm rms [1].

The next step forward in the study of planet formation is the ability to image the formation of super-Earths and giant planets across the entire disk, particularly within 10 au from the central star. This requires an improved frequency coverage, sensitivity, and angular resolution to be able to measure the planet initial mass function down to a mass of 5-10 Earth-masses. This capability will unveil the formation of planetary systems similar to our own Solar System by probing the presence of planets on orbital radii as small as 0.5 au at the distance of ≈140 pc[3]. In addition, such observations will also reveal circumplanetary disks and sub-structures in the distribution of mm-size dust particles created by close-in planets and measure the orbital motion of these features on monthly timescales.

This in turn requires continuum observations for centre frequencies between 20-110 GHz with angular resolution better than 5 milliarcsecond (mas). This requirement will enable studies on the formation of planets in the innermost 10 au of nearby (≈140 pc) proto-planetary disks. Extensive simulations of the disks perturbed by planets (see Fig. 3; [1]), suggest that a sensitivity of 0.2 µJy/beam in the continuum at 100 GHz (Jy = Jansky)[4] is required to routinely map structures in the dust distribution created by planets of mass down to 10 Earth-masses and orbital radius of 2.5 au.

4.2 Probing the initial conditions for planetary systems and life with astrochemistry

One of the most challenging aspects in understanding the origin and evolution of planets and planetary systems is tracing the influence of chemistry on the physical evolution of a system from a molecular cloud to a solar system, while also trying to determine the potential for habitability. To make significant progress in this area requires that the frequency coverage and sensitivity to be able to detect predicted, but as yet unobserved, complex prebiotic species that are the basis of the understanding of chemical evolution toward amino acids and other biogenic molecules. In doing so, it will also allow us to detect and study chiral molecules, testing ideas on the origins of homochirality in biological systems. The detection of such complex organic molecules will provide the chemical initial conditions of forming solar systems and individual planets.

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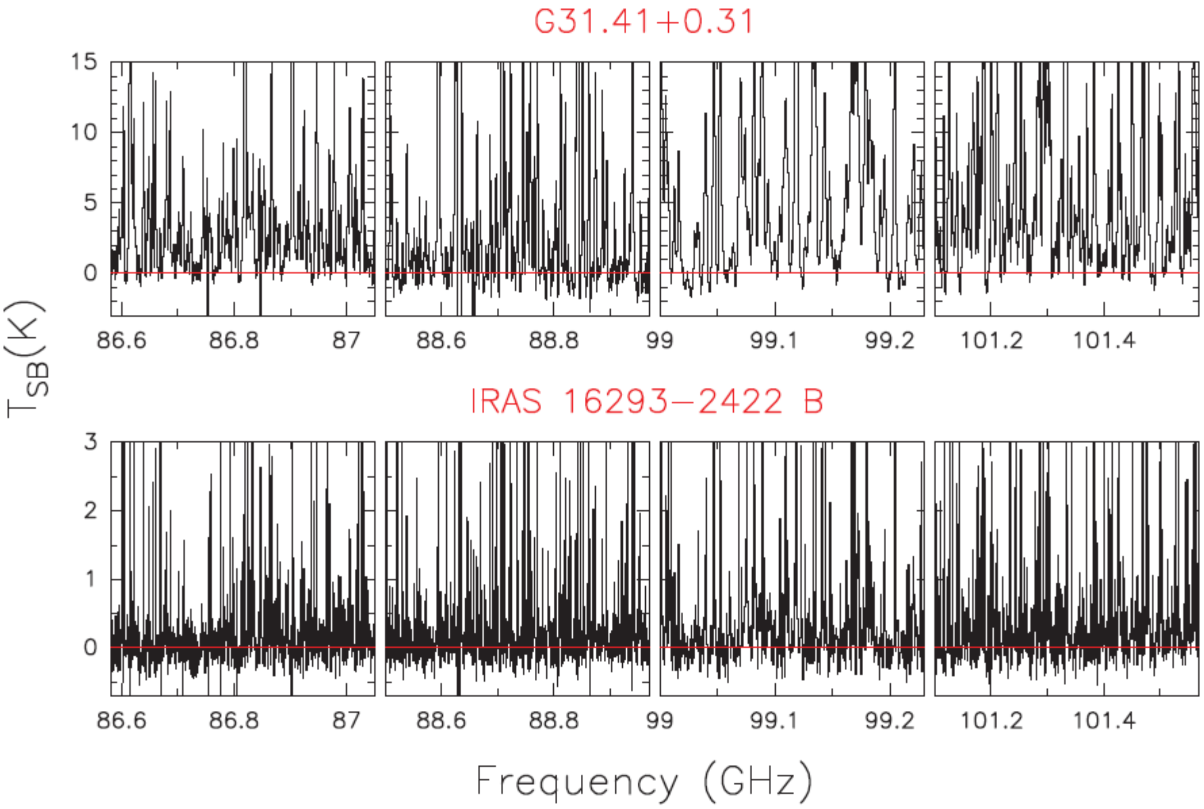
[3] 1 pc (parsec) is a non-SI unit of distance, used in astronomy. It is equivalent to 3.26 light years or 3.09×10^{16} m.

[4] 1 Jansky is a non-SI unit of spectral flux density, or spectral irradiance. It is equivalent to 10^{-26} W/($m^2 \cdot$ Hz) or −260 dB(W/($m^2 \cdot$ Hz)).

FIGURE 4

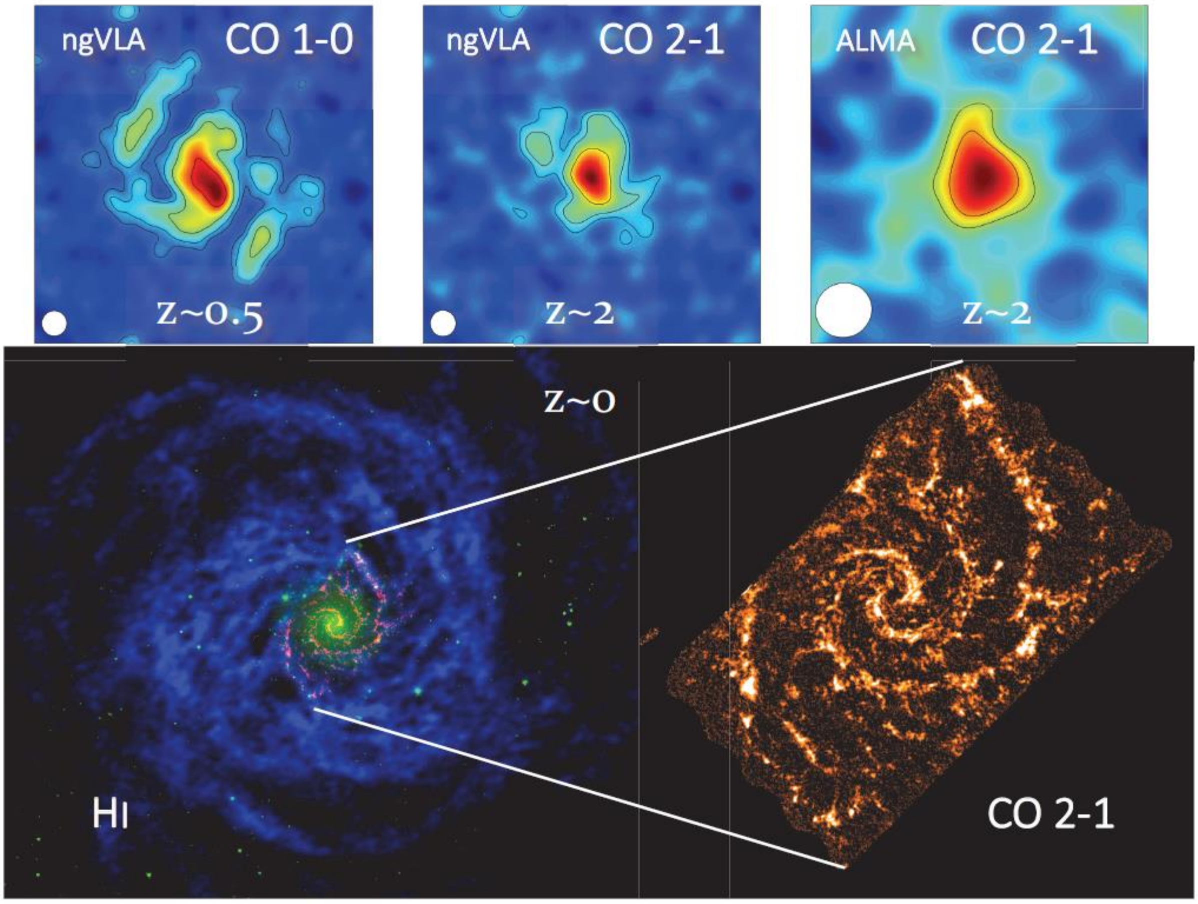
ALMA 86.6-101.6 GHz (3 mm) spectra at ~1 arcsecond angular resolution of the hot molecular core G31.41+0.31 (upper panels) and the hot corino IRAS 16293-2422 B (lower panels)



Note to Fig. 4: Red lines indicate T_{SB} = 0 K (brightness temperature measured in the synthesized beam). The 3σ noise level at each panel falls inside the red line. The (sub)millimetre spectra of chemically rich hot cores/corinos like these two examples are full of molecular lines.

Hot molecular cores, the cradles of massive stars, are the most chemically rich sources in the Galaxy and are the most important reservoirs of complex organic molecules. This rich chemistry is thought to be the result of the evaporation of dust grain mantles by the strong radiation of the deeply embedded early-type star(s). Our own Sun may have been born in a high-mass star-forming region, so our Earth may have inherited the primordial chemical composition of its parental hot core region, as suggested by recent studies of oxygen and sulphur chemistry in comets. The immediate surroundings of high-mass protostars are not the only regions rich in complex organic molecules. In recent years, the environments of some low-mass protostars have also revealed a very complex chemistry, with the presence of large molecules with abundances similar to those found towards high-mass protostars. These low-mass cores have been called hot corinos. Complex organic molecules can be observed at millimetre wavelengths and show large numbers of spectral lines, as shown in Fig. 4. In the 67-116 GHz range, one can expect to find tens of thousands of spectral lines spread across the entire radio spectrum, which detection requires highly sensitive radio telescopes.

FIGURE 5



Note to Fig. 5: Top Panels: Simulations based on M 51 with molecular mass scaled by 1.4 × (z = 0.5) and 3.5 × (z = 2) to match the lowest molecular mass galaxies observable by ALMA and NOEMA [2]. The synthesized beam shown in the bottom left corner is (left to right) θs = 0.43 arcsecond corresponding to linear scales L = 1.2, 1.7, and 3.7 kpc, respectively. Integration times are 30 hr. Bottom Panels: The spiral galaxy M 74 illustrating the CO molecular disk imaged by ALMA (red; Schinnerer in prep.), the stellar disk at 4.5 µm imaged by Spitzer (green; [3]), and the atomic disk imaged in HI by the VLA (blue; [4]), showing the gas phases to which the ngVLA will be sensitive. Bottom Right Panel: A zoom in showing the CO *J* = 2 - 1 map at 1 arcsec resolution.

4.3 Charting the assembly, structure and evolution of galaxies from the first billion years to the present

To make substantial progress in the field of galaxy formation and evolution requires a sensitivity to survey cold gas in thousands of galaxies back to early cosmic epochs, while simultaneously enabling routine sub-kiloparsec scale resolution imaging of their gas reservoirs. In doing so, this will provide a unique view into how galaxies accrete, process, and expel their gas through detailed imaging of their extended atomic/molecular reservoirs and circumgalactic regions. To reveal the detailed physical conditions for galaxy assembly and evolution throughout the history of the universe requires enough sensitivity to map the physical and chemical properties of molecular gas over the entire local galaxy population.

Thermal imaging of brightness temperatures of 0.1-0.2 K of CO (115 GHz) at 0.1 arcsecond angular resolution and 1 km/s spectral resolution is required for detailed studies of molecular gas in the nearby universe (see bottom panels of Fig. 5). This translates to about 160 uJy per resolution element or -298 dB(W/(m^2 · Hz)). Thermal imaging of 1-5 mK sensitivity between 70 and 116 GHz at

1-5 arcsecond angular resolution and 1-5 km/s spectral resolution is required to support studies of gas density across the local universe.

Full 1.2-116 GHz frequency coverage is required to obtain accurate, simultaneous measurements of star formation rates from free-free continuum and radio recombination line (RRL) emission. Angular resolutions of 0.1-1 arcsecond for continuum imaging at all available frequencies are required. For studies of galaxies in the local universe, accurate recovery of flux-density for extended objects on arcminute scales at all frequencies is required, along with the ability to make large mosaics or conduct on-the-fly line and/or continuum mappings of galaxies that extend beyond the area of a single primary beam.

4.4 Understanding the formation and evolution of stellar and supermassive black holes in the era of multi-messenger astronomy

While it is now known that black holes exist on practically all mass scales, the astrophysics of how these objects form and grow remains a mystery. The Laser Interferometer Gravitational-wave Observatory (LIGO) is now detecting black holes that are substantially more massive than previously known stellar mass black holes, and observing black hole-black hole mergers, although it is not known how black hole binaries form. While supermassive black holes (SMBHs) are thought to be widespread in galaxy centres, it is not understood how their growth was seeded or how (and how often) these extreme objects merge. To address these questions requires the combination of sensitivity and angular resolution to be able to survey everything from the remnants of massive stars to the supermassive black holes that lurk in the centres of galaxies. High-resolution imaging abilities are required to separate low-luminosity black hole systems in our local Universe from background sources, thereby providing critical constraints on the formation and growth of black holes of all sizes and mergers of black hole-black hole binaries.

To be able to survey black holes requires high angular resolution (mas – μas) imaging with relative astrometric accuracy that is <1% of the synthesized beam FWHM or equal to the positional uncertainty in the reference frame, for a bright (SNR ≥ 100) point source. Such high-resolution imaging will enable proper motion separation of local black holes (both Galactic and in nearby galaxies, out to 15 Mpc) from background sources. Long baselines are required to enable to image the SMBH binaries that will be detected in gravitational waves by LISA and pulsar timing arrays. These astrometric science goals benefit from the implementation of very long baselines (~1 000 km for mas – μas accuracy).

The field of multi-messenger astronomy continues to mature as new astronomical windows through gravitational waves and neutrino observations are continually opened. However, to progress further in the understanding of the physics associated with these phenomena requires the ability to localize and characterize the sources. Only the detection of the electromagnetic radiation associated with these energetic, and often cataclysmic events, can provide precise localization, establish energetics and allows to understand how such events interact with their surrounding environments. This requires high-resolution (long baselines), fast-mapping capabilities to make it the preferred instrument to pinpoint transients associated with violent phenomena- such as supermassive black hole mergers and blast waves.

5 Radio telescopes operating in the 67-116 GHz (3-4 mm) range

This section contains a summary of current and planned radio astronomy facilities operating in the 67-116 GHz (3–4 mm) band in § 5.1, information on receiver technology in § 5.2, and antenna beam pattern information in § 5.3.

5.1 Summary of facilities

Current and planned radio telescopes operating in the 67-116 GHz (3-4 mm) range are listed in Table 2. The highlighted facilities are selected based on their prominence for each region. These include the most powerful mm-radio telescope in the Northern hemisphere, Plateau de Bure/NOEMA and the largest fully-steerable radio telescope in Europe, Effelsberg (Region 1), the most powerful mm- and sub-mm radio telescope in existence, ALMA and the planned most powerful cm- and mm-radio telescope, ngVLA (Region 2), the telescope array that pioneered observations with a tri-band receiver system, KVN and the Nobeyama radio telescope (Region 3). The Global mm-VLBI array (GMVA) combines observing capabilities around 86 GHz (3 mm wavelengths) around the globe, providing next to the Event Horizon Telescope the highest possible angular resolution for astronomical observations from Earth.

Plateau de Bure / NOEMA (NOrthern Extended Millimeter Array)

NOEMA, the successor to the Plateau de Bure observatory, is the most powerful millimetre radio telescope of the Northern Hemisphere. It is located in the French Alps on the wide and isolated Plateau de Bure at an elevation of 2 550 metres. The telescope consists of twelve antennas, each 15 metres in diameter. Each antenna is equipped with state-of-the-art high-sensitivity receivers. Two tracks, extending on a north-south and east-west axis, enable the antennas to be moved up to a maximum separation of 1 664 metres. NOEMA participates to global VLBI, both GMVA at 86 GHz (3 mm) and EHT at 230 GHz (1.3 mm) and 373 GHz (0.8 mm) as a phased array (adding the signal from the 12 antennas provides the same sensitivity than a 50 m antenna with the same aperture efficiency than a 12 m antenna),

It should be noted that the observing bandwidth is larger than that defined in Recommendation ITU-R RA.769 (2 times 8 GHz).

Detailed information on the technical and operational characteristics of NOEMA are provided in Annex 1.

IRAM 30-meter telescope

The IRAM 30-meter telescope is a large millimetre telescope located in Spain on the Pico Veleta, in the Sierra Nevada. It is in direct line of sight with the town of Granada and located near a ski resort. It is one of the most sensitive radio telescopes in the world, with a very good surface accuracy. It operates from 70 to 370 GHz and is equipped with a suite of state the art receivers. About one third of the species known outside of our Solar System were detected by the IRAM 30-meter telescope.

It also participates to VLBI both GMVA and EHT.

Effelsberg

The Effelsberg 100-m Radio Telescope is a parabolic reflector, located about 1.3 km northeast of Effelsberg, a village in the municipality of the town Bad Münstereifel in North Rhine-Westphalia, Germany. The telescope is situated in a valley of the Eifel mountains in a rural area with several small villages, forests and farms in its vicinity. With a diameter of 100 metres it is one of the largest fully steerable radio telescopes on earth. The telescope is equipped with state-of-the-art low noise single-beam and multi-beam receivers, both at primary and secondary focus locations, covering a frequency range of about 300 MHz – 95.5 GHz. It operates as standalone single-dish telescope, but also participates regularly in world-wide and European Very Long Baseline Interferometry (VLBI) observations.

Detailed information on the technical and operational characteristics of Effelsberg are provided in Annex 2.

64-m Sardinia Radio Telescope

The Sardinia Radio Telescope (SRT) is an alt-azimuthal radio telescope of 64 m in diameter located in San Basilio, about 35 km north of Cagliari (Italy). The SRT is a fully steerable wheel and track radio telescope, equipped with active surface, shaped mirrors, beam waveguides, and microwave receivers, distributed across six focal positions remotely selectable. The antenna operates both in single dish and in interferometric mode.

Although SRT has been designed for the observation of the radio sky up to 116 GHz, at present its maximum observational frequency is 26.5 GHz. In its current first light configuration, the instrument is equipped with a 7-beam receiver operating in K Band (18-26.5 GHz), with a single-band receiver in the high C Band (5.7-7.7 GHz), and with a dual frequency receiver in P/L Band (305-410 MHz/1.3-1.8 GHz). Furthermore, two new S Band (3.0-4.5 GHz) and Clow Band (4.2-5.6 GHz) receivers are being finalized.

However, in 2019, the Italian Ministry of University and Research has assigned significant resource to the Italian National Institute for Astrophysics with the aim to upgrade the SRT to allow observations at high radio frequencies. The approved budget is equal to 18 700 000 Euro and has been used also for the supply of a multi-beam cryogenic receiver (covering the band 70-116 GHz) and a simultaneous microwave compact Triple-Band receiving system (80-116 GHz).

Detailed information on the high frequency upgrade of SRT are provided in https://www.ursi.org/proceedings/procGA21/papers/URSIGASS2021-Fr-J06-PM4-1.pdf and http://www.ursi.org/Publications/RadioScienceLetters/Volume3/RSL21-0026-final.pdf

40-m Yebes Radio Telescope

The 40-m radio telescope is located in Yebes, about 50 km from Madrid (Spain) operated by the Observatory of Yebes, *Instituto Geográfico Nacional*. The 40-m radio telescope is Nasmyth type, with a parabolic reflector, a hyperbolic sub-reflector, and focus on the receiver cabin that materializes through flat or curved mirrors. The telescope moves in azimuth and elevation, and its mount is a high-azimuth rotating head. The collecting surface is made up of 420 Aluminium panels whose position on the structure can be adjusted manually. Its structure follows a homological design.

The radio telescope has cryogenic radio astronomy receivers in various frequency bands between 2 GHz and 116 GHz. In mm wavelengths, three receivers are installed. The SIS (superconductor-isolator-superconductor) receiver covering the 83-116 GHz band, with an instantaneous band of 600 MHz, has been in operation since 2010 mainly to VLBI operations. In 2019, new 7 mm (31.5-50 GHz) and 3 mm (72-90.5 GHz) receivers were designed and manufactured at Yebes Observatory with funds from the Nanocosmos project, a European Union-funded synergy grant, that has enabled an increase in the instantaneous frequency coverage of the Yebes 40 m radio telescope (up to 18.5 GHz), making it possible to observe many molecular transitions with single tunings in single-dish mode. This reduces the observing time and maximises the output from the telescope.[5]

The design and manufacture of the receivers and the frequency down-conversion modules are carried out at the observatory. The radio telescope control system, as well as the programs for the first data reduction, are also designed and developed by the Observatory staff.

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[5] Tercero, F. & Lopez-Perez, Jose & Gallego Puyol, Juan Daniel & Beltrán Martínez, Francisco & García Pérez, Óscar & Patino-Esteban, Maria & López-Fernández, Isaac & Molina, Gabriel & Diez, M.C. & Garcia-Carreno, Pablo & Inmaculada, Malo-Gómez & Amils, R. & Serna Puente, Jose Manuel & Albo, C. & Hernández, Jose & Vaquero, B. & González, J. & Barbas, L. & Lopez Fernandez, Jose & Vicente, P. (2020). Yebes 40 m radio telescope and the broad band NANOCOSMOS receivers at 7 mm and 3 mm for line surveys. Astronomy and Astrophysics. 10.1051/0004-6361/202038701.

The 40-m radio telescope is dedicated to both “single dish” and Very Long Baseline Interferometry (VLBI) observations. Single dish observations are typically made in three frequency bands: 18-26 GHz, 32-50 GHz, and 72-90 GHz. VLBI observations are made in conjunction with other radio telescopes in the rest of the world. The observation frequencies used are 2 GHz, 5 GHz, 6 GHz, 8.4 GHz, 22 GHz, 43 GHz and 86 GHz. The 40-m RT is integrated in several international networks: the European VLBI Network (EVN), the VLBI millimetric GMVA network, the International VLBI Service geodetic network and others such as KaVa and Radioastron.

Detailed information is provided in https://astronomia.ign.es/en_GB/web/guest/icts-yebes/radiotelescopio-40m

14-m Metsähovi radio telescope

The 14-m Radio Telescope (MRO-14) is located in Kylmälä (GPS: N 60:13.04, E 24:23.35), about 40 km from Helsinki (Finland) operated by Aalto University Metsähovi Radio Observatory. The radio telescope is a radome-enclosed Cassegrain-type antenna with a diameter of 13.7 m. Telescope's reflector has a 0.1 mm surface accuracy (rms). The usable wavelength range of the radio telescope is 13.0 cm–2.0 mm. The antenna operates both in single dish and in interferometric modes. Due to protective radome, solar observations are also possible with MRO-14. Metsähovi is a part of EVN (European VLBI Network) and GMVA (Global mm-VLBI Array). MRO-14 is used around the clock, every day of the year (24/7 operation).

Currently, MRO-14 operates with following frequencies: 2.21-2.35 (V[6]), 8.15-8.65 (V), 21.0-22.0/22.4-23.4 (S[7]), 21.98-22.48 (V), 35.3-36.3/37.3-38.3 (S), 42.9-43.4 (V) and 81.0-90.6 GHz[8] (V). VLBI bands use cryogenic receivers, and their noise temperature varies between 60 and 120 K. Metsähovi has started a project for updating receivers’ capabilities. A new triple-band receiver system will be added to MRO-14 telescope. We expect that the new receiver will be operational in early 2026. With a new receiver, simultaneously observations with all three observing bands (K, 18-26 GHz; Q, 34-50 GHz; W, 80-116 GHz) are possible. The new receiver could be used both in the single dish and interferometric modes.

Onsala Space Observatory 20-m telescope

The Onsala Space Observatory (OSO) radome enclosed 20 m diameter telescope is located about 45 km south of Göteborg (Sweden), GPS: 57°23'45" N, 11°55'35" E. It is of Schmidt-Cassegrain type and is equipped with receivers for frequencies up to 116 GHz. The telescope itself was built in 1975-76 and upgraded in 1992. The radome was replaced in 2014. Front-ends and back-ends are updated regularly. Both the current 3 mm (covering 85-116 GHz, Belitsky et al., 2015, https://doi.org/10.1051/0004-6361/201425573) and the 4 mm (covering 67-87 GHz, Walker et al., 2016, https://doi.org/10.1117/12.2232576) receivers are dual polarisation sideband separating with USB (upper side-band) and LSB (lower side-band) having centres presently 12 GHz apart. Each sideband has IF bandwidth of 4 GHz. Both receivers are used in single-dish mode as well as in VLBI mode. OSO is hosted by Department of Space, Earth and Environment at Chalmers University of Technology, and is operated on behalf of the Swedish Research Council

Atacama Large Millimeter/submillimeter Array (ALMA)

The Atacama Large Millimeter/submillimeter Array (ALMA) is composed of 66 high precision antennas located on the Chajnantor Plateau, 5 000 metres altitude in northern Chile. It operates at wavelengths of 3.6 to 0.32 millimetres (31 to 1 000 GHz). The antennas can be moved across the

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[6] V = VLBI mode.

[7] S = Single-dish mode.

[8] 500 MHz band at once.

desert plateau over distances from 150 m to 16 km. Its high sensitivity is mainly achieved through the large numbers of antennas that make up the interferometric array. The main antennas consist of 54 × 12 m parabolic reflectors and a compact array of 12 × 7 m parabolic reflectors.

ALMA is expected to continue expanding its technical capabilities with upgrades to its receiver sensitivities and bandwidths. Specifically, the original band 2 receiver (67-90 GHz) will be upgraded to allow for observations across the entire 67-116 GHz atmospheric window using a single receiver. In addition, a second generation of the ALMA correlator is expected to double the instantaneous observing bandwidth to 16 GHz. Future upgrades are expected to improve capabilities by an order of magnitude during the 2030-2040 decade.

Detailed information on the technical and operational characteristics of ALMA are provided in Annex 3.

Next generation Very Large Array (ngVLA)

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimetre wavelengths (25 to 0.26 centimetres, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The ngVLA will be a synthesis radio telescope composed of approximately 244 reflector antennas each of 18 metres diameter, and 19 reflector antennas each of 6 metres diameter, operating in a phased or interferometric mode.

The array’s signal processing centre will be located at the Very Large Array site on the Plains of San Agustin, New Mexico, USA. The array will include stations spanning across all of North America, throughout New Mexico, west Texas, eastern Arizona, and northern Mexico. Long baseline stations are located in Hawaii, Washington, California, Iowa, West Virginia, New Hampshire, Puerto Rico, the US Virgin Islands, and Canada.

Detailed information on the technical and operational characteristics of the ngVLA are provided in Annex 4.

Korean VLBI Network (KVN)

The Korean VLBI Network (KVN) is a radio astronomy observatory located in South Korea. It comprises three 21-metre radio telescopes that function as an interferometer, using VLBI. Two are on the Korean peninsula: Yonsei University (KY) and Ulsan University (KU), and the third is located on Jeju Island on the campus of Jeju International University (formerly Tamna University; KT). A fourth telescope is under construction. This telescope is located in PyeongChang and will be able to observe up to 250 GHz, and the existing 14m dish located at the Taeduk Radio Astronomy Observatory, will be linked to the KVN in the near future via optical fiber networks.

KVN focuses on millimeter-wavelength VLBI and is designed to make simultaneous measurements at four different observing frequencies: 22, 43, 86, and 129 GHz. The telescopes can operate together with VLBI networks in Japan and China the East Asian VLBI Network.

Detailed information on the technical and operational characteristics of KVN are provided in Annex 5.

Nobeyama 45-m telescope

The Nobeyama 45-m telescope, operated by the National Astronomical Observatory of Japan, is located in the Nobeyama highlands in Japan with the altitude of 1 350 m above sea level. The antenna is a parabolic reflector with the radius of 45 m and its surface accuracy is 0.1 mm. The telescope is equipped with single-beam and multi-beam receiver systems covering 22 to 116 GHz. In the 67-116 GHz (3-4 mm) band, the telescope has two receivers; a single-beam T70 receiver for 71.5-92 GHz, and a four-beam FOREST receiver for 80-116 GHz. The telescope also works as a

VLBI element of the East Asian VLBI Network together with other radio telescopes in Japan, Korea, and China.

Detailed information on the technical and operational characteristics of the Nobeyama 45-m telescope are provided in Annex 6.

GMVA

VLBI is a unique observing technique in which radio telescopes, situated at distant locations on the Earth's surface (and even in space), observe simultaneously and combine their data to achieve very high (<0.001 arcsecond) resolution imaging. The Global mm-VLBI Array (GMVA) is a widely distributed mm-wave array, with open access for the scientific community, operating at 86 GHz. In 2022, the array consists of eight VLBA telescopes (US), the 100 m GBT (US), the IRAM 30 m telescope on Pico Veleta (Spain), the phased NOEMA interferometer on Plateau de Bure (France), the MPIfR 100 m radio telescope in Effelsberg (Germany), the OSO 20 m radio telescope at Onsala (Sweden), the 14 m telescope in Metsähovi (Finland) and the OAN 40 m telescope in Yebes (Spain). In addition, telescopes of the Korean VLBI Network (KVN), the Greenland Telescope (GLT) and the phased ALMA (Chile) can be requested to co-observe together with the GMVA. The data are correlated at MPIfR in Bonn (Germany). It should be noted that improvement of global VLBI arrays, including the GMVA is continuously ongoing, including expansion to higher bandwidth, new correlator capabilities, and new telescopes. In 2022, the standard GMVA frequency range is 86.0-86.5 GHz. The three Italian radio telescopes (64 m SRT, 32 m Medicina and 32 m Noto) will join the GMVA network around 2024 by using the compact three band receivers simultaneously covering three frequency bands: 18-26 GHz, 34-50 GHz and 80-116 GHz. The receivers are already available at Italian radio telescopes and will be commissioned as soon as some infrastructure improvements are completed.

TABLE 2

Current and planned radio telescopes operating in the 67-116 GHz (3-4 mm) band
ITU-R Region 1

Observatory name (Administration)	Longitude (E), Latitude (N), Elevation (m AMSL)	Minimum elevation (degrees)	Rx height above terrain (m)	Geographical characteristics
Plateau de Bure, 12 × 15 m Array, IRAM, France	05°54'28.5" 44°38'02" 2 553		15	Isolated high mountaintop in line-of-sight to various public facilities
Maido (la Réunion) Horns 0.25 × 0.36 m 0.70 × 0.48 m France	55°23'01" –21°04'46" 2 200			Mountain top
Effelsberg, 100 m, Germany	06°53'01" 50°31'29" 319	8	50	In a valley in Eifel mountains with good natural terrain shielding. Rural area but highly populated area Cologne/Bonn at 30-40 km distance, only

TABLE 2 (*continued*)

Observatory name (Administration)	**Longitude (E), Latitude (N), Elevation (m AMSL)**	**Minimum elevation (degrees)**	**Rx height above terrain (m)**	**Geographical characteristics**
Pico de Veleta, 30 m IRAM, Spain	–03°23’34” 37°03’58” 2 850	0	31	Mountainside overlooking nearby ski resort, line of sight to city of Granada
Yebes 40 m Yebes 14 m Spain	–03°05’22” 40°31’27” 981	0 4		Broad flat plain exposed to roads
Sardinia Radio Telescope 64 m, Sardinia, Italy	09°14’42” 39°29’34” 600	5		Partially surrounded by mountains
Onsala 25 m Onsala 20 m Sweden	11°55’04” 57°23’35” 18	6 7		Waterside, forested, relatively isolated, Gotheborg 40 km N
Metsahovi 14 m Finland	24°23’35” 60°13’04" 80	4	10	Hilly terrain. Closest settlement within 1 km. Numerous small villages within 10 km
Noto 32 m Italy	14°59’20.51” 36°52’33.78” 90	5		Partially flat exposed plain. VLBI
Medicina 32 m Italy	11°38′49″ 44°31′15″ 28	5		Flat exposed plain. VLBI
Zelenchukskaya RT-32 32 m Russia	41°33’52.6” 43°47’16.2” 970	–5	35	The Republic of Karachay-Cherkessia (Kavkaz region of the Russian Federation)
Zelenchukskaya RATAN-600 576 m Russia	41°35’12.06” 43°49’34.2” 970	3	2	The Republic of Karachay-Cherkessia (Kavkaz region of the Russian Federation)
Badary RTF-32 32 m Russia	102°14’04.95” 51°46’11.6” 832	–5	35	The Republic of Buryatia, (the southern part of Eastern Siberia)
Badary SSRT-256 256 mirror 2.5 m Russia	102°13’16” 51°45’27” 832	25	2	The Republic of Buryatia, (the southern part of Eastern Siberia)
Pushino RT-22 FIAN 22 m Russia	37°37’57” 54°49’22” 200	6	30	Moscow region of the Russian Federation

TABLE 2 (*continued*)

Observatory name (Administration)	**Longitude (E), Latitude (N), Elevation (m AMSL)**	**Minimum elevation (degrees)**	**Rx height above terrain (m)**	**Geographical characteristics**
Svetloe RTF-32 32 m Russia	29°46’54” 60°31’56” 80	–5	35	Leningrad region of the Russian Federation
Kaljazin RT-64 64 m Russia	37°54’01” 57°13’23” 195	0	60	Tver region of the Russian Federation

ITU-R Region 2

Observatory name (Administration)	**Longitude (E), Latitude (N), Elevation (m AMSL)**	**Minimum elevation (degrees)**	**Rx height above terrain (m)**	**Geographical characteristics**
Robert C Byrd 100 m Green Bank Telescope, W. VA, USA	–79º50’22” 38º25’58” 807	5	140	Flat open space ringed by forest and hills; adjacent roads
VLBA-Brewster, WA (25 m), USA	–119º40’41” 48º07’52” 250	2.25	29	Broad, flat river valley, < 1 km from state highway US97. VLBI
VLBA-Fort Davis, TX, USA	–103º56’41” 30º38’06” 1 606	2.25	29	Broad, flat open high plain. 3 km from highway TX118. VLBI
VLBA-Hancock, NH, USA	–71º59’12” 42º56’01” 296	2.25	29	Sea level in the woods, 1.5-3.0 km from multiple state and federal highways. VLBI
VLBA-Kitt Peak, AZ, USA	–111º36’45” 31º57’23” 1 902	2.25	29	High mountainside, on AZ386, 6.5 km from highway AZ86. Phoenix in line-of-sight. VLBI
VLBA-Los Alamos, NM, USA	–106º14’44” 35º46’31” 1 962	2.25	29	On a high cliff-side, 1 km from highway NM4. Exposed to Santa Fe 21 km away. VLBI
VLBA-Mauna Kea, HI, USA	–155º27’19” 19º48’05” 3 763	2.25	29	High mountainside, 3 666 m above sea level. 9.6 km from highway HI200. VLBI
VLBA-North Liberty, IA, USA	–91º34’27” 41º46’17” 222	2.25	29	In the woods just off of a busy local highway. Numerous small towns within 15 km. VLBI

TABLE 2 (*continued*)

Observatory name (Administration)	**Longitude (E), Latitude (N), Elevation (m AMSL)**	**Minimum elevation (degrees)**	**Rx height above terrain (m)**	**Geographical characteristics**
VLBA-Owens Valley, CA, USA	–118º16’37” 37º13’54” 1 196	2.25	29	Broad open plain, 5 km from highway US395. VLBI.
VLBA-Pie Town, NM, USA	–108º07’09” 34º18’04” (2 365)	2.25	29	High mountain, exposed, just off highway US60. VLBI
VLBA – St. Croix, VI, USA	−64º35’03” 17 º45’24” (-32)	2.25		
Owens Valley Radio Observatory / CRAL	–118º16’56” 37º14’02” (1 222)			Broad open plain, 5 km from highway US395.
ARO Kitt Peak 12 m, AZ, USA	–111º36’45” 31º57’23” (1 914)		12	Mountainside, exposed to south and west but hidden from Tucson
Haystack Observatory 37 m Westford, MA, USA	–71º29’19” 42º37’23” (131)	5		Broad flat open area at ambient elevation
LMT 50 m Sierra Negra, Puebla Mexico	–97º18’48” 18º59’06” (4 580)		51	Mountain top in line of sight to numerous towns and 15 km from Mexico City-Puebla-Veracruz highway
ALMA, Chajnantor, Chile	–67º45’18” –23º01’22” (5 059)	3.0		Broad flat high plain ringed by mountains, accessible by road
NANTEN2 4 m, Pampa La Bola. Chile	–67º42’08” –22º17’47” (4 800)			Broad flat high plain accessible by public road
ARO SMT 10 m, Mt. Graham, AZ, USA	–109º53’31” 32º42’05” (3186)	3.0	10	Remote forested mountaintop. Operates only above 100 GHz
JCMT 15 m, SMA 6 × 6 m, CSO 12 m, Mauna Kea, HI, USA	–155º28’30” 19º49’18” (4 092)			Isolated very high mountaintop
VLA	33°58'22" to 34°14'56" −107° 24' 40" to −107° 48' 22" (2 120)	8	51	27 antennas located in remote New Mexico high desert plateau

TABLE 2 (*continued*)

Observatory name (Administration)	**Longitude (E), Latitude (N), Elevation (m AMSL)**	**Minimum elevation (degrees)**	**Rx height above terrain (m)**	**Geographical characteristics**
Greenland Telescope (GLT)	Thule Air Base: 76°32’ 68°50’ (77) Summit Station*: 72°35’ 38°25’ (3210)	3.0		Thule Air Base: Remote flat Arctic coastal environment /Summit Station: Remote Arctic plateau
ngVLA*	33° 58' 22" to 34°14'56" −107°24'40" to −107°48'22" (0-4 092)		20	Core in remote New Mexico high desert plateau with arms reaching into Texas, Arizona, and Mexico, with stations as far as Hawaii and U.S. Virgin Islands

* Under construction or in planning stages

ITU-R Region 3

Observatory name (Administration)	**Longitude (E), Latitude (N), elevation (m AMSL)**	**Minimum elevation (degree)**	**Rx height above terrain (m)**	**Geographical characteristics**
Mopra 22 m, Australia	149º05’58” –31º16’04”	12		Hilltop ringed by mountains
ATCA 6 × 22 m, Australia	149º32’56” –30º59’52”	12		Broad flat plain
Delingha 13.7 m, China	97º33.6’ 37º22.4’ 3 200	5		Flat plain
Tianma 65 m, China	121º9.8’ 31º05.2’ 6	5		Flat plain
QTT 110 m, China	89º40.9’ 43º36.0’ 1 759	5		Plain ringed by mountains
RRI 10.4 m, India	77º38’ 12º58’			
Nobeyama 45 m, Japan	138º28’21” 35º56’40”	12	47	Broad plain at an altitude of 1,350 m ringed by mountains
VERA-Mizusawa 20 m, Japan	141º07’57” 39º08’01”	3	22	VLBI Broad plain open in north and south and shielded in east and west with a long range of mountains at both sides in 15 km

TABLE 2 (*end*)

Observatory name (Administration)	**Longitude (E), Latitude (N), elevation (m AMSL)**	**Minimum elevation (degree)**	**Rx height above terrain (m)**	**Geographical characteristics**
VERA-Iriki 20 m, Japan	130º26’24” 31º44’52”	3	22	VLBI Narrow plain surrounded by mountains
VERA-Ogasawara 20 m, Japan	142º13’00” 27º05’31”	3	22	VLBI Located in an isolated island about 900 km away from the mainland Japan
VERA-Ishigakijima 20 m, Japan	124º10’16” 24º24’44”	3	22	VLBI Located in an island in which it stands 8 km away from the populated district and is at the edge of mountains in north
Taeduk Radio Astronomy Observatory 13.7 m, Republic of Korea	127º22’18” 36º23’54”	5	10.6	Broad flat plain exposed to nearby roads
Seoul Radio Astronomical Observatory 6 m, Republic of Korea	126º57’19” 37º27’15”	5	4.5	Steep Slope side on a mountain
KVN-Yonsei 21 m, Republic of Korea	126º56’27” 37º33’55”	5	15.6	Gentle slope. Single Dish and VLBI
KVN-Ulsan 21 m, Republic of Korea	129º14’59” 35º32’44”	5	15.6	Flat open space on a hill Single Dish and VLBI
KVN-Tamna 21 m, Republic of Korea	126º27’34” 33º17’21”	5	15.6	Gentle slope. Single Dish and VLBI
KVN SNU PyeongChang 21 m, Republic of Korea	128º26’55” 37º32’00”	5	15.6	A basin surrounded by mountains Single Dish and VLBI

5.2 Receiver technology

The receiver system is the heart of a radio telescope. The most commonly used radio telescope receiver system employs the super-heterodyne technique to track source frequency using associated signal processing devices and perform frequency conversion to yield an Intermediate Frequency (IF) signal from which the source information can be extracted. The most important element in determining the performance of such receiver is the mixer. It may consist of a GaAs Schottky-barrier diode, a superconducting quantum detection device such as quasi-particle tunnel junction (SIS), or a liquid-helium-cooled InSb bolometer mixer. In case of ALMA, the original band 3 (84-116 GHz) receiver is based on SIS mixer technology, which is the case for almost all ALMA receivers. The new band 2 receiver (67-116 GHz) is expected to employ more traditional high electron mobility transistor technology for mixer design, while using novel cryogenically cooled InP amplifiers. Current and future deployments of mm and submm radio astronomical receivers are able to reach or approach quantum noise limits.

5.3 Antenna beam pattern

As is well known, an antenna gain, G, is given by $G = \eta\frac{4\pi A}{\lambda^2}$, where η is the antenna efficiency, A is the antenna area, and λ is the wavelength. For a high frequency region, such as those above 71 GHz, the wavelength is shorter than 4.2 mm. The antenna efficiency η is proportional to $\exp\left\{-(\frac{4\pi\varepsilon}{\lambda})^2\right\}$, where ε is the surface accuracy. It is easier for a small antenna to achieve very good surface accuracy. Thus, it is possible to achieve high gain for active service antennas. It should be noted that a RAS antenna needs a high gain for collecting extremely weak signals from celestial objects. Thus, the surface adjustment is very carefully made to achieve a surface accuracy of 70 μm (r.m.s.) for the Nobeyama 45 m radio telescope.

High gain antennas will allow active service operators to transmit radio signals effectively, however, it turns out it also raises the possibility to cause harmful interference to the RAS when an active service antenna directly points to an RAS antenna.

On the other hand, high frequencies (short wavelengths) will result in smaller beamwidths. According to section 3 of Report ITU-R RA.2189, small antenna beam sizes reduce the chances of accidental interference. The beamwidth of a dish antenna, measured in degrees, is given by the approximate equation:

$$\theta_{\mathrm{deg}} \cong \frac{1\,720}{\alpha f_{\mathrm{GHz}} d_{\mathrm{cm}}}$$

where:

θ_{deg} : the approximate beamwidth (degrees)

f_{GHz} : the frequency (GHz)

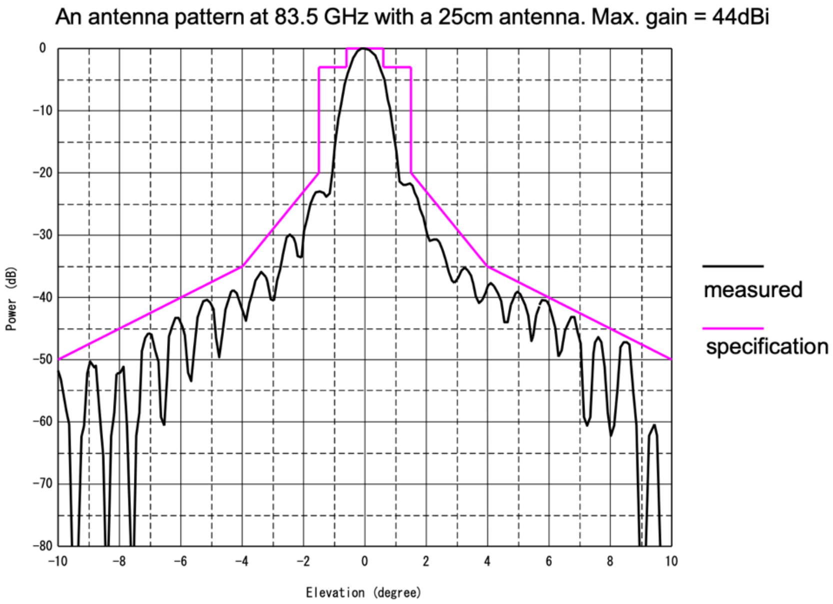
d_{cm} : the antenna’s physical diameter (cm)

α : a parameter (≤ 1) that is effectively the fraction of the diameter of the dish illuminated by the feed.

A given size antenna will produce a smaller beam width with increasing frequency; alternatively, at a given frequency, a larger dish will create a smaller beam width (assuming α remains constant). An example of such a narrow beam can be found in Fig. 6. Reference radiation patterns up to a frequency of 86 GHz are provided in Recommendation ITU-R F.699.

FIGURE 6

An example of antenna pattern at 83.5 GHz with a ϕ25 cm antenna



6 References and Related ITU-R documents

Recommendation ITU-R RA.314 – Preferred frequency bands for radio astronomical measurements

Recommendation ITU-R P.525 – Calculation of free-space attenuation

Recommendation ITU-R P.676 – Attenuation by atmospheric gases and related effects

Recommendation ITU-R F.699 – Reference radiation patterns for fixed wireless system antennas for use in coordination studies and interference assessment in the frequency range from 100 MHz to 86 GHz

Recommendation ITU-R RA.769 – Protection criteria used for radio astronomical measurements

Recommendation ITU-R P.835 – Reference Standard Atmospheres

Recommendation ITU-R P.836 – Water vapour: surface density and total columnar content

Recommendation ITU-R RA.1031 – Protection of the radio astronomy service in frequency bands shared with other services

Recommendation ITU-R RA.1272 – Protection of radio astronomy measurements above 60 GHz from ground-based interference

Recommendation ITU-R RA.1513 – Levels of data loss to radio astronomy observations and percentage-of-time criteria resulting from degradation by interference for frequency bands allocated to the radio astronomy service on a primary basis

Recommendation ITU-R RA.1750 – Mutual planning between the Earth exploration-satellite service (active) and the radio astronomy service in the 94 GHz and 130 GHz bands

Report ITU-R RA.2189 – Sharing between the radio astronomy service and active services in the frequency range 275-3 000 GHz

Report ITU-R RA.2259 – Characteristics of radio quiet zones

Report ITU-R RA.2457 – Coexistence between the radio astronomy service and radiolocation service applications in the frequency band 76-81 GHz

Science with the Next Generation Very Large Array (https://aspbooks.org/a/volumes/table_of_contents/?book_id=592)

[1] L. Ricci, A. Isella, S. Liu and H. Li, “Imaging Planetary Systems in the Act of Forming with the ngVLA,” *ASP Conference Series,* vol. 517, no. ASP Monograph 7, p. 147, 2018.

[2] C. L. Carilli and Y. Shao, “Image Capabilities: High redshift CO,” ngVLA Memo #13, 2017.

[3] R. C. Kennicut, *et al.*, “SINGS: The SIRTF Nearby Galaxies Survey, ” *The Publications of the Astronomical Society of the Pacific,* vol. 115, no. 810, pp. 928-952, 2003.

[4] F. Walter, *et al.*, “THINGS: The H I Nearby Galaxy Survey,” *The Astronomical Journal,* vol. 136, no. 6, pp. 2563-2647, 2008.

[5] P. Cortes, *et al.*, ALMA Technical Handbook, ALMA Doc. 9.3, ver. 1.0, 2022.

7 List of acronyms and abbreviations

ALMA	Atacama Large Millimeter/submillimeter Array
EHT	Event Horizon Telescope
KVN	Korean VLBI Network
ngVLA	next generation Very Large Array
NOEMA	NOrthern Extended Millimeter Array
VERA	VLBI Exploration of Radio Astrometry
VLBI	Very Long Baseline Interferometry

Annex 1

Plateau de Bure / NOEMA (NOrthern Extended Millimeter Array) / IRAM 30-meter telescope

The Plateau de Bure Interferometer, originally built in the 80s, has been transformed into a more powerful instrument, named NOEMA. It is composed of 12 antennas of 15 metres diameter. The surface precision, about 35 microns rms, allows sensitive observations from 72 to 370 GHz. The antennas have alt-azimuthal mount and Cassegrain focus.

Very sensitive state-of-the-art receivers cover two sidebands, each 8 GHz wide, and two linear polarizations. 22 GHz water vapor radiometers (WVR) are used to monitor and correct for tropospheric phase variations. At the time of writing, new receivers are being installed allowing to observe simultaneously at 3 mm (72-116 GHz) and 1 mm (200-275 GHz). In this observing mode, the high frequency part uses scaled-up version from the low frequency part phase variations to calibrate the residual phase fluctuations after WVR corrections and the fraction of time that the observatory devotes to 3 mm observing will increase. Said it otherwise, the 72-116 GHz is of paramount importance to NOEMA.

The IRAM 30-metre antenna has a surface accuracy of 60 microns rms with a Nasmyth cabin housing the receivers. This includes receivers similar to the one that equip NOEMA but also multi-pixel receivers (both heterodyne and bolometric). In particular new wideband multi-beam heterodyne receivers are being developed both at 3 mm and 1 mm. The IRAM 30 metre can be used as standalone telescope but also in conjunction with NOEMA, by providing the short-spacings filtered out on an interferometer.

Both stations participate in global VLBI (GMVA at 3 mm and EHT at 1.3 and 0.8 mm).

Annex 2

Effelsberg

The 100-m radio telescope at Effelsberg was built in 1967–1971 and thus is in operation for more than 50 years. It was the first 100-m class fully steerable single dish paraboloid. Deflections (e.g. owing to gravity) limit the physical size of a parabolic dish. This can be overcome with very stiff (and thus) heavy designs or, as in the case of Effelsberg, with a novel homology approach where deflections are permitted but in a controlled manner, i.e. retaining a paraboloidal shape at all times (the receiver can be moved along the optical axis to ensure proper focusing). The telescope has a weight of only 3 200 tons. More recently, another alternative was invented, which is to use active surfaces to correct for deflections. However, Effelsberg only has been upgraded with an active secondary mirror.

The dish has a focal length of 30 m, thus the *f*/*D* ratio is 0.3. This is somewhat smaller than in other radio telescopes of the same era and was done to reduce vulnerability to RFI. An important feature is the possibility to operate receivers in the secondary focus, where multiple receivers are installed permanently. Switching between secondary-focus receivers can be done in seconds and is great for multi-wavelength science projects, such as flux density monitoring of active galactic nuclei. The aperture area is about 7 850 m^2, however the receiver feeds apply tapering such that the effective area is smaller but with the benefit of lower antenna side lobes. The pointing accuracy is of the order of 3-4” (rms), which is sufficient for observations at 86 GHz (3 mm) where the beam size is of the order of 11” (hpbw).

While the telescope was originally not designed for such high frequencies, it turned out that the surface accuracy of the dish was much better than expected. Effelsberg participates regularly in 3-mm VLBI sessions and also spectral line observations have been performed successfully at these frequencies. However, for mechanical reasons, only the inner part of the aperture consists of filled aluminium panels, while the outer rings between a diameter of 85 and 100 m consists of perforated panels (with 7 mm holes). Thus, only the inner 85 m can be used for observations at the highest frequencies.

Key technical parameters of the 100-m radio telescope Effelsberg

– Aperture diameter: 100 m

– Collecting area: 7 850 m^2

– Receiver frequencies: 300 MHz – 96 GHz

– Angular resolution: 1 degree to 10 arcseconds

– Surface accuracy: 0.5 mm (rms)

– Focal length: 30 m

– *f*/*D*: 0.3

– Pointing accuracy (tracking): < 3-4” (rms)

- Azimuthal range: 30°–500°
- Elevation range: 8 to 90 degrees
- Height of track (amsl): 319 m
- Height of elevation axis above ground: 50 m
- Sensitivity (at 86 GHz): 500 K (Tsys), 450 Jy (SEFD), η_a=40%, η_{mb}=70%

Annex 3

Atacama Large Millimeter/submillimeter Array (ALMA)

The Atacama Large Millimeter/submillimeter Array is an aperture synthesis telescope and is one of the most complex astronomical observatory ever built on Earth. ALMA uses 66 high-precision dish antennas of two sizes: 54 of them are 12 metres across and 12 of them are 7 metres across. The total collecting area of this array is over 71 000 square feet.

The 12-metre antennas can be gently hauled around on the backs of custom-made antenna transporters in order to form arrays that are either very tightly packed configurations only 150 metres across or spread out to 16 kilometres across. Figure 7 shows an aerial view of the centre of the ALMA array. More extended arrays give ALMA a zoom lens for finer details, while more compact arrays give better sensitivity for larger, dimmer objects.

In addition to the movable array of 12 m antennas, there is the Atacama Compact Array (ACA) of twelve 7 m antennas and four 12 m antennas that images large-scale structures like giant gas clouds. The ACA has two configurations, one of which is a north-south extension to provide a better coverage of sources that are either very far north in the sky or very far south. The four 12 m antennas are used for single-dish observations to obtain total power measurements and to fill in a baseline coverage of 0 m to about 12 m, complementing both the 7 m and 12 m arrays.

In ALMA's most compact configurations, the level of detail it can see ranges from 0.7″ at 675 GHz to 4.8″ at 110 GHz. In its most extended configuration, ALMA's resolutions range from 6 mas at 675 GHz to 37 mas at 110 GHz.

Key technical parameters of ALMA

- Number of antennas: 66
- Reflector diameters: 54 × 12 m; 12 × 7 m
- Collecting area: 6 600 m^2
- Receiver frequencies: 31 GHz – 950 GHz
- Angular resolution: 0.2 arcseconds to 0.004 arcseconds
- Baseline lengths: 150 m to 16 km
- Elevation: 5 000 m

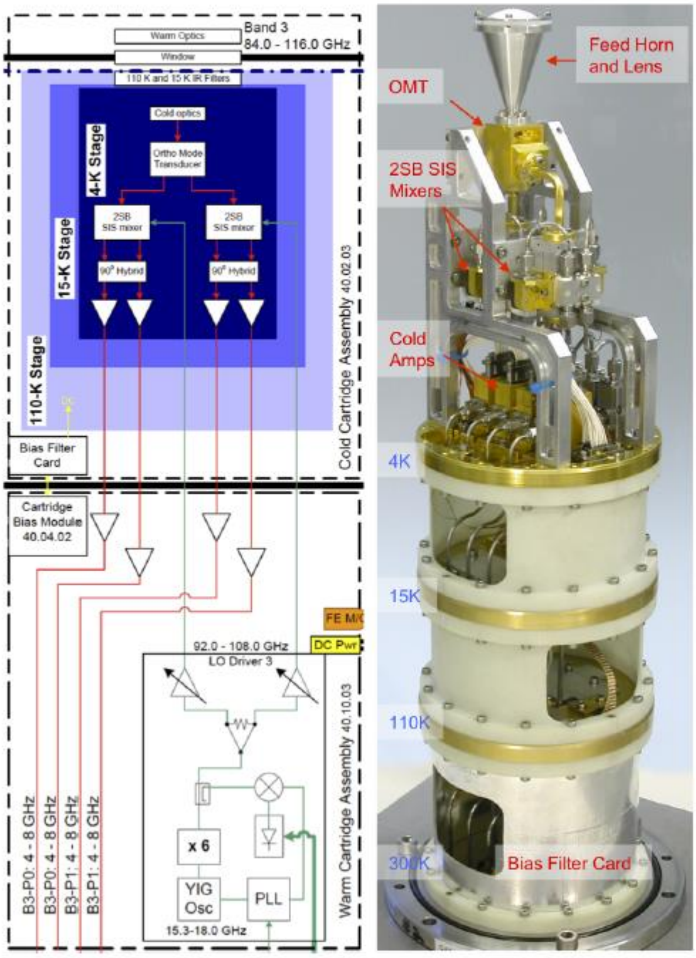
FIGURE 7

Aerial view of the ALMA Central Cluster (Credit: ALMA Observatory/Guy Wenborn)

The ALMA front end can accommodate up to 10 receiver bands, covering most of the range from 35-950 GHz (8.5 to 0.32 mm wavelength). Each band is designed to match approximately the atmospheric transmission windows, as shown in Fig. 1. Currently, the band 3 receiver covers 84.0-116 GHz, with a local oscillator range of 92-108 GHz and an IF range of 4-8 GHz, with a receiver temperature of better than 39K across 80% of the band. For this receiver a single feed-horn feeds an ortho-mode-transducer (OMT) which splits the incoming signal into two linear orthogonal polarizations and feeds the SIS mixers. Figure 8 shows the physical picture of the band 3 receiver next to its block diagram.

FIGURE 8

Block diagram of the band 3 receiver (left) and a picture of the physical receiver cartridge (right) [5]



All signals received by ALMA antennas are processed in one of two correlators: the 64-input Correlator and the ACA Correlator. Both correlators run simultaneously and independently. Both correlators are able to generate auto-correlation and cross-correlation products at the same time. The auto-correlation is used for spectroscopic total power array observations. For more technical information on ALMA, please refer to the ALMA technical handbook [5], which is updated with every proposal cycle.

Annex 4

Next generation Very Large Array (ngVLA)

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimetre wavelengths (25 to 0.26 centimetres, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The ngVLA will be a synthesis radio telescope composed of approximately 244 reflector antennas each of 18 metres diameter, and 19 reflector antennas each of 6 metres diameter, operating in a phased or interferometric mode.

The array's signal processing centre will be located at the Very Large Array site on the Plains of San Agustin, New Mexico, USA. The array will include stations spanning across all of North America, throughout New Mexico, west Texas, eastern Arizona, and northern Mexico. Long baseline stations are located in Hawaii, Washington, California, Iowa, West Virginia, New Hampshire, Puerto Rico, the US Virgin Islands, and Canada. The outer stations are expected to consist of clusters of a few 18 m antennas.

In the following, the expected key technical characteristics of ngVLA are summarized and are defined by the required scientific capabilities to address the science areas described in § 4 of this Report.

Frequency coverage: The ngVLA will be able to observe in all atmospheric windows between 1.2 and 116 GHz. These frequency limits are bracketed by spectral line emission from HI and CO respectively.

Continuum sensitivity: Better than 0.07 µJy/beam at 30 GHz and 0.5 µJy/beam 100 GHz.

Line sensitivity: 1–750 mK at 5"–0.1" angular resolution and 1–5 km/s spectral resolution between 70 and 116 GHz.

Angular resolution: A synthesized beam having a FWHM better than 5 mas with uniform weights is required at both 30 and 100 GHz, while meeting the continuum sensitivity targets.

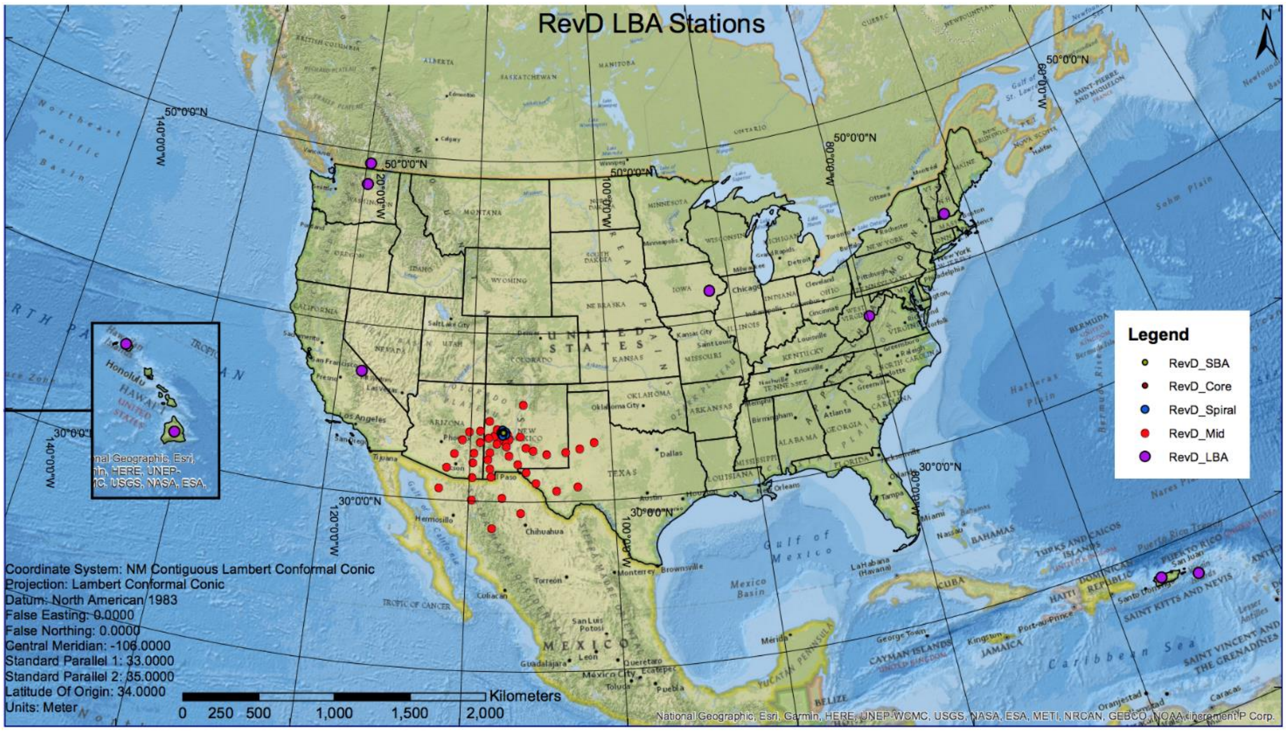
Survey speed: The array shall be able to map a ~7 square degree region to a depth of ~1 µJy/beam at 2.5 GHz and a 10 square degree region to a depth of ~10 µJy/beam at 28 GHz within a 10-hour epoch to localize transient phenomena identified with other instruments. Holding collecting area and receiver noise constant.

Beamforming for pulsar search, pulsar timing and very long baseline interferometry

The array is expected to support no less than ten beams spread over one to ten subarrays that are transmitted, over the full available bandwidth, to a pulsar search engine or pulsar timing engine. VLBI recording of a single element, or phased array output, requires at least three beams.

FIGURE 9

Distribution of anticipated ngVLA stations across North America



The ngVLA science goals require continuous frequency coverage from 1.2-116 GHz, with a gap at the atmospheric absorption band between about 50~70 GHz. This will be implemented in size, single pixel, cryogenically-cooled receiver bands. One of which covers the range of 67–116 GHz. The receiver gain is expected to be >30 dB between feed horn input and cryostat output, with a receiver temperature goal of better than 69 K (49 K average). The aperture efficiency requirement is 0.92. The receiver gain and bandpass stability requirement is <0.26 dB/K and <0.013 dB variation in over 60 minutes. The goal of the receiver dynamic range is 42 dB, with a minimum of 31 dB.

For more detailed and up-to-date information on ngVLA, please consult the ngVLA project design documents at https://ngvla.nrao.edu/page/projdoc

Annex 5

Korean VLBI Network (KVN)

The Korean VLBI Network (KVN) as a dedicated millimetre wavelength VLBI network consisting of three 21 m radio telescopes located in Seoul, Ulsan and Jeju island in the Republic of Korea has been in operation since 2009. All KVN radio telescopes are shaped-Cassegrain-type antennas with an alt-az mount. The KVN has introduced a unique multi-frequency band receiver system that performs simultaneous observations at four radio frequencies, such as 22, 43, 86 and 129 GHz. The baseline lengths are in a range of 305-476 km with a highest angular resolution of ~1 milliarcsecond. Recently, the 4th KVN radio telescope is under construction. This telescope is located in PyeongChang and will be able to observe up to 250 GHz. An annual KVN operation time is around 3 500 hours in both VLBI and a single dish mode. The KVN is also participating in global VLBI observing sessions as a key station of the EAVN (East Asian VLBI Network) and a member of the EVN (European VLBI Network) and the GMVA (Global Millimeter VLBI Array).

The KVN antennas are designed to be a shaped-Cassegrain-type antenna with an altitude-azimuth mount. The characteristics of the antenna optics are summarized in Table 3.

The KVN has the unique capability to observe four frequency bands, simultaneously. KVN quasi-optics are designed to enable this multi-frequency observation. The characteristics of the KVN receiver are summarized in Table 4.

TABLE 3

KVN antenna optics specifications

Main reflector parameters (Axisymmetric paraboloid)	**Parameters**
Diameter	*D* = 21.03 m
Focal length	*f* = 6.78 m
Focal ratio	*f/D* = 0.32
Panels manufacturing accuracy	65 μm
Alignment surface accuracy	50–54 μm
Sub-reflector (Hyperboloid)	**Parameters**
Diameter	*d* = 2.25 m
Manufacturing surface accuracy	50 μm
Expected total surface accuracy	124 μm at EL 48◦
Slewing speed	3 ◦/sec
Slewing acceleration	3 ◦/sec^2
Operating range	Az.: ±270°, El.: 0°–90°

TABLE 4

Frequency range of the KVN receiver

Band	**Frequency range (GHz)**	**IF range (GHz)**
K	18.0-26.0	8.192-16.384
Q	35.0-42.0 (Low)	8.192-16.384
	42.0-50.0 (High)	
W	85.0-100.0 (Low)	8.192-16.384
	100.0-116.0 (High)	
D	125.0-142.0	8.0-10.0
mm	210-270	8.0-16.0

Annex 6

The Nobeyama 45-m telescope

The Nobeyama 45-m telescope is a single-dish radio telescope with a parabolic antenna of 45-m diameter. The telescope is located in the Nobeyama Radio Observatory of the National Astronomical Observatory of Japan, with the altitude of 1 350 m above sea level. The telescope is located on the rolling Nobeyama highlands at the foot of Mt. Yatsugatake, where the air is dry especially in winter, providing a suitable environment for millimeter wave observations.

The antenna is a Cassegrain-modified-Coude reflector with an alt-az mount. The observable elevation range is 11-80 degrees. The radio waves reflected by the secondary mirror are guided through the beam waveguide system to the receiver cabin in the antenna support structure. The receiver room houses five receivers covering 20 to 116 GHz. In the 67-116 GHz (3-4 mm) band, the telescope has two receivers; a single-beam T70 receiver for 71.5-92 GHz, and a four-beam FOREST receiver for 80-116 GHz.

The telescope mainly works as a single-dish telescope, and also is integrated into VLBI networks, such as Japanese VLBI Network (JVN), and East Asian VLBI Network (EAVN). As an element of EAVN, 22 GHz and 43 GHz receivers are used.

Frequency coverage: 20-25, 42-46, 71.5-116 GHz

Beam size (half-power-beam-width): 20.7 arcsec at 75 GHz, 14 arcsec at 115 GHz

System noise temperature: 120-270 K (T70), 150-300 K (FOREST)