



Report ITU-R RA.2510-0
(10/2022)

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

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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:

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

This free space loss formula is derived from the following:

$$\begin{aligned} PL(\text{dB}) &= -10 \log \left[\left(\frac{1}{4\pi D_{\text{km}}^2} \right) \left(\frac{\lambda^2}{4\pi} \right) \left(\frac{1 \text{ km}}{1000 \text{ m}} \right)^2 \left(\frac{1 \text{ GHz}}{10^9 \text{ Hz}} \right)^2 \right] \\ PL(\text{dB}) &= -10 \log \left[\left(\frac{1}{4\pi D_{\text{km}}^2} \right) \left(\frac{c^2}{4\pi f_{\text{GHz}}^2} \right) \left(\frac{1 \text{ km}}{1000 \text{ m}} \right)^2 \left(\frac{1 \text{ GHz}}{10^9 \text{ Hz}} \right)^2 \right] \\ PL(\text{dB}) &= -10 \log \left[\left(\frac{1}{D_{\text{km}}^2} \right) \left(\frac{1}{f_{\text{GHz}}^2} \right) \left(\frac{1 \text{ km}}{1000 \text{ m}} \right)^2 \left(\frac{1 \text{ GHz}}{10^9 \text{ Hz}} \right)^2 \left(\frac{c}{4\pi} \right)^2 \right] \end{aligned} \quad (2)$$

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:

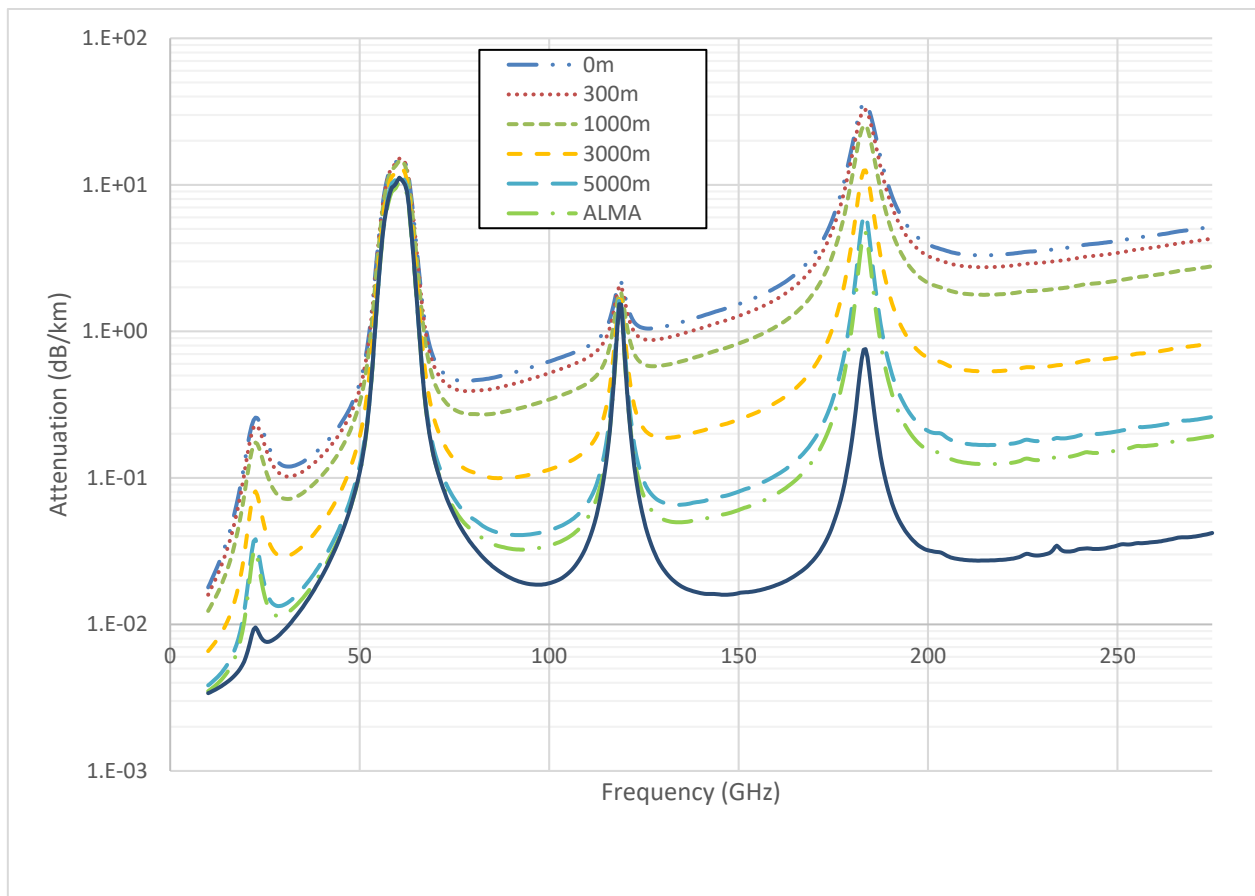
$$PL_{\text{PFD}}(\text{dB}) = 20 \log D_{\text{km}} + 70.99 \quad (3)$$

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.

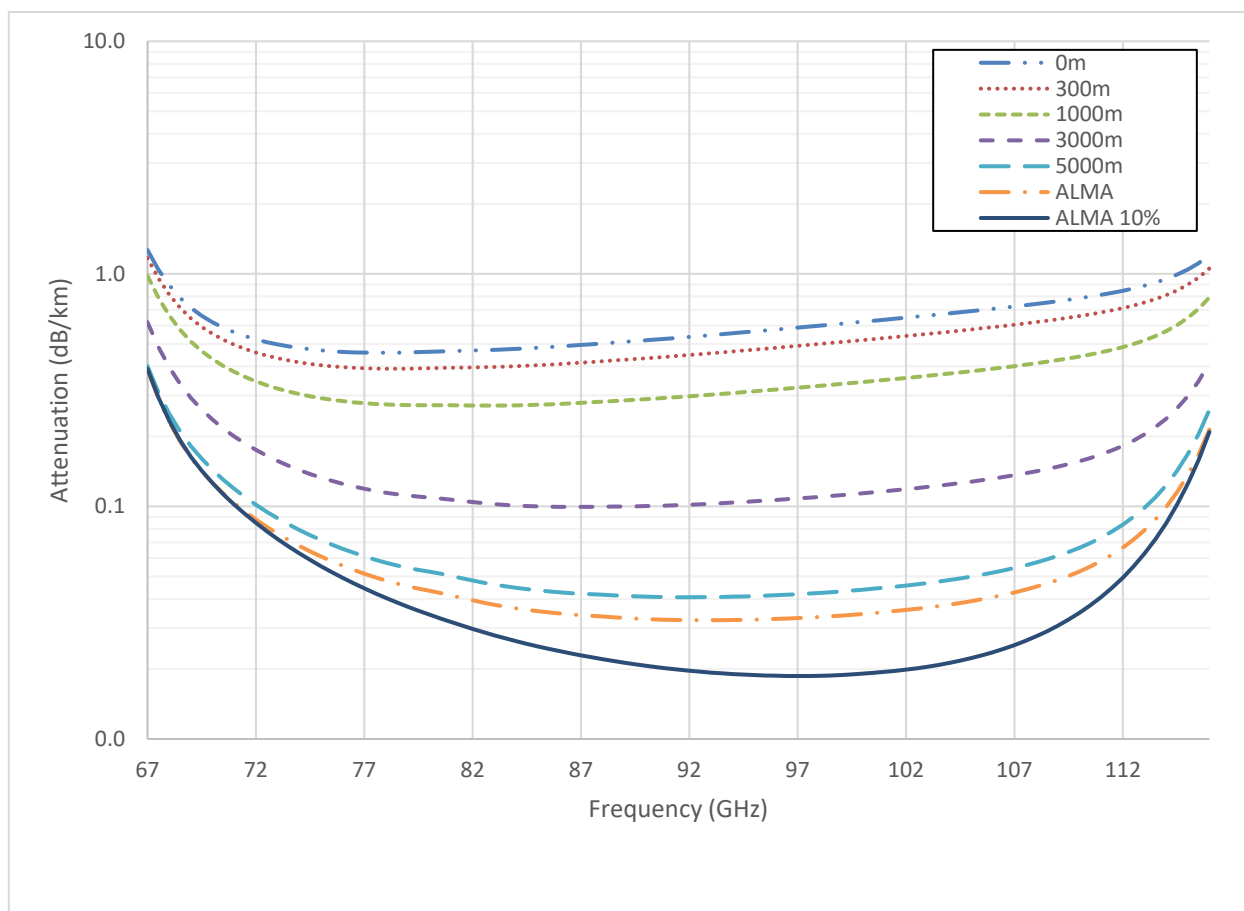
FIGURE 1
Atmospheric attenuation from 10 to 275 GHz for different geographic locations



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 $-129 \text{ dB(W/m}^2\text{)}$ and $-228 \text{ dB(W/(m}^2 \cdot \text{Hz))}$ for continuum observations, and $-148 \text{ dB(W/m}^2\text{)}$ and $-208 \text{ dB(W/(m}^2 \cdot \text{Hz))}$ 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 redshifted¹ 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.

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).