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Characteristics of radio quiet zones

RA Series

Radio astronomy

International Telecommunication Union

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REPORT ITU-R RA.2259-1

Characteristics of radio quiet zones

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1 Introduction

1.1 Definition and general requirements of a radio quiet zone

Radio astronomy observations from the surface of the Earth are intrinsically sensitive to radio interference from man-made sources, whether it comes from intentional or unintentional radiators. Radio telescopes are many orders of magnitude more sensitive than radiocommunication receivers used for telecommunications. To optimize the environment in which radio astronomy observations are carried out, particularly at the most advanced and costly modern facilities, radio quiet zones (RQZs) have been implemented by some Administrations. In the context of this Report, an RQZ is meant to be any recognized geographic area within which the usual spectrum management procedures are modified for the specific purpose of reducing or avoiding interference to radio telescopes, thereby maintaining the required standards for quality and availability of observational data.

There are a number of different control methods that can be used to establish an RQZ, and these may apply to some specific frequency bands, to some specific periods of time and/or to various classes of interference sources. The controls may be technical, geographic and/or regulatory. Different RQZ definitions and management methods will therefore apply to different radio telescopes, depending on their specific requirements. In some cases, restrictions may be applied only in certain frequency bands or below a certain frequency, if no observations are carried out above that frequency at the site. As an example, transmissions below 15 GHz are restricted within a certain radius around the Arecibo Observatory, located in Puerto Rico. Since no observations are carried out, nor are any expected to be carried out above that frequency in the future, no restrictions are needed on higher frequency transmissions. The reverse is not necessarily true, however. For example, some restrictions are imposed on transmissions below 30 GHz in the vicinity of the large international ALMA observatory due to its susceptibility to interference at these lower frequencies in the signal path, even though no instrument on the ALMA site currently observes below 30 GHz. The general spectrum management philosophy for the ALMA site includes consideration of possible lower frequency instruments, whether affiliated with or independent of the ALMA observatory itself.

Historically, RQZs are implemented for the protection of radio astronomy imposed power flux or power flux-density limitations only at certain well defined coordinates, which are, as a rule, the focal point of a telescope. Most radio telescopes that are currently built are not single antenna systems, but distributed array systems, and the restrictions proposed to protect them reflect this situation. Most restrictions implemented in RQZs around the world are limited to fixed, terrestrial transmitters, not air or satellite borne transmissions. One reason for this is that interference that originates in mobile, particularly aeronautical, sources is usually of short duration; thus, while the interference is easily identified, the source of interference itself is usually gone by the time it can be identified. Another reason is that antenna footprints of air or satellite transmitters may have diameters of hundreds or thousands of kilometres, making any restriction on an RQZ impossible to implement without affecting areas much greater than the RQZ itself. However, while most sources of interference from airborne transmitters are transient, the deployment of airborne platforms which are nominally static pose additional concerns for the implementation of RQZs.

No RQZ restricts satellite transmissions. Satellite operations are covered by international regulations, while RQZ regulations have, to date, been established by the interested national administration.

It is important to emphasize that an RQZ does not imply a complete absence of radio transmissions, the existence of, and coexistence with, a range of man-made devices will always be necessary. An RQZ may include options for notification of other users and for negotiation in mitigating interference.

An RQZ is therefore a buffer zone that allows for the implementation of mechanisms to protect radio astronomy observations at a facility within the zone from harmful interference, through effective mitigation strategies and regulation of radio frequency transmitters.

A significant characteristic of radio telescopes, in relation to interference protection, is the level of sensitivity required to make astronomical observations. As a matter of comparison, a modern radio telescope is 15 orders of magnitude more sensitive than a GSM mobile phone.

One form of defining a radio telescope sensitivity is by its minimum detectable spectral flux density, as defined in equation (1).

The evolution of the sensitivity of radio telescopes (as defined in equation (1))is illustrated in Fig. 1, that shows the minimum detectable signal in terms of flux density (measured by radio astronomers in Janskys where 1 Jansky = 10^{-26} (W/(m^2.Hz))) *vs.* the year of the observation [1]. The Square Kilometre Array (SKA) is planned as the next generation radio telescope; all other points indicate actual measurements. Between 1933 and 1983 the sensitivity of radio telescopes improved some 10 orders of magnitude, a performance improvement similar to that described by Moore's law. The rapid improvement over time is due to system improvements, including decreases in system temperature and increases in collecting area, bandwidth and integration time.

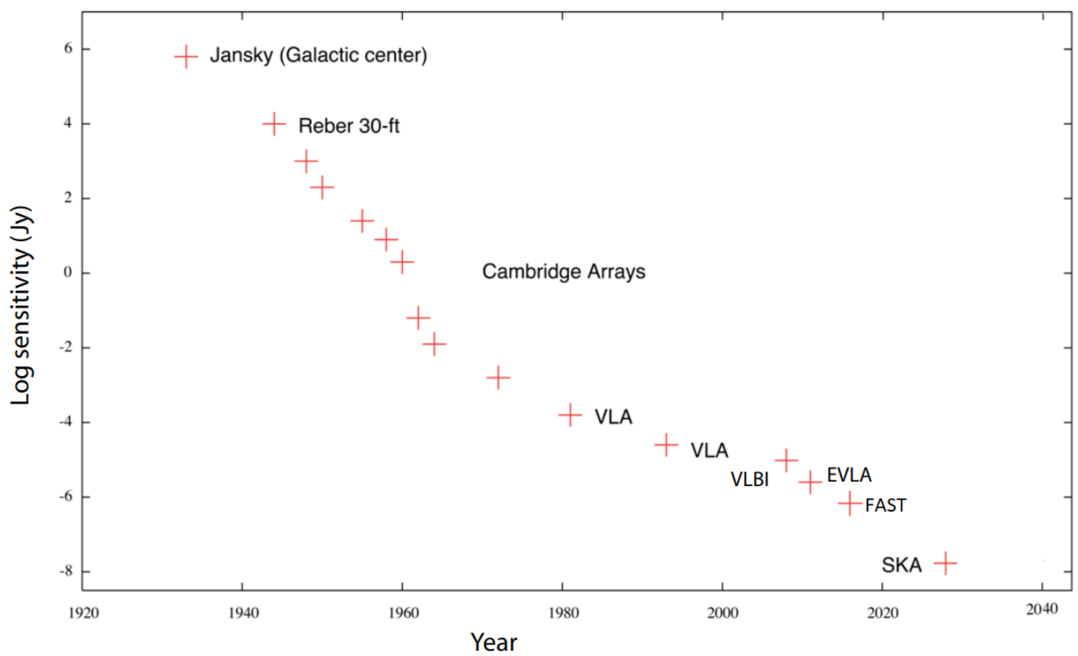
$$\Delta S = \frac{k * T_{sys}}{\sqrt{t * \Delta f_0}} \frac{1}{A_{eff}} \qquad (1)$$

where:

- ΔS : spectral flux density, in W/m^2/Hz
- k : Boltzmann constant, in W.s/K
- T_{sys} : system temperature, in K
- t : integration time, in seconds
- Δf_0 : bandwidth of the receiver, in Hz
- A_{eff} : effective area of the telescope, in m^2.

FIGURE 1

Improvement in the sensitivity of radio telescopes with time



1.2 Overview of the characteristics of the electromagnetic environment and the impact of intentional and unintentional radiators

The Electromagnetic environment surrounding radio astronomy facilities is unique and there are varieties of sources that affect this environment. Sources that affect observations are generally categorized as intentional (any type of radiocommunications transmitters) or unintentional radiators (electrical equipment which produces radio noise as a by-product of its operation). The Radio frequency (RF) environment fluctuates as these sources interact with local terrain features and varying weather conditions, all of which are factors that affect radio astronomy observations and the ability to collect usable data.

In the mid-20th century, there were relatively few types of radio transmitters in operation. They included broadcasting (both sound and television), fixed point-to-point links, radar for navigation and meteorological applications, aeronautical and maritime communications and amateur radio. In 1963, satellite transmissions began, initially from the geostationary orbit. The following decades saw a gradual increase in the use of the commercial radio spectrum. However, a significant change occurred in the 1980s and onward, with the introduction of consumer radiocommunications; initially a vehicle-based mobile telephone, and later handheld cellular phones. The final years of the 20th century also brought the introduction of wireless computer networking and a proliferation of related devices including wearable transmitters such as smartwatches and is trending into the future with a strong demand for mobility, higher data rates, and a wider range of applications. The growth in embedded radio transmitters on mobile platforms, including systems operating in the radiolocation service and those which are unlicensed or class-licensed, presents an increasing challenge to radio astronomy systems that require the radio quiet conditions afforded by an RQZ.

There are three consequences of the growth of the wireless industry in the last 50 years. First, in the early days, most transmitters, with the exception of amateur radio, were operated and controlled by government bodies or by large corporations. In recent times, it is the general public who carry and operate a majority of transmitters, albeit low powered. This complicates the analysis and control of radio transmitters near an RQZ. Secondly, the early devices were few and, in many cases, fixed. The recent trend is towards a high density of mobile devices and towards rapidly deployed fixed systems. Third, the congestion of the radio spectrum and the increase in demand has led towards technology development at ever increasing frequencies. Nowadays, there is interest in frequencies of 500 GHz and above for short-range communications. Therefore, radio quietness cannot be achieved simply by choosing frequencies that are not used by active radiocommunication systems.

The increase in radiocommunication devices has been paralleled, in the second half of the 20th century, by a growth in other electrical equipment which can unintentionally produce RFI. The number of automobiles, household appliances, microwave ovens, manufacturing and other industrial applications, computing equipment and entertainment systems (television and associated technology) has sharply increased in recent decades. As an example of unintended radiators, modern flatscreen computing displays can produce far more interference than older CRT monitors due to the use of high speed electronics. In some cases, replacement of incandescent lighting by modern LED has created significantly more interference.

1.2.1 Regulatory controls of RFI: role of regulation

Regulatory controls of local radio interference are managed on a national basis by government regulators. A core component of national regulation is a radio-frequency spectrum plan which identifies the allocation of frequency bands to services, including some bands allocated to radio astronomy. These national spectrum plans are based on the ITU Radio Regulations to the extent necessary to avoid harmful interference between different countries.

National regulation also includes a process to authorize specific transmitters (and in some cases, receivers) under a licensing programme, and technical limitations (power, bandwidth, modulation, etc.) on transmitters. However, many consumer-grade transmitters, generally low-powered devices, operate on a class-licence or licence-free basis, making it difficult to predict or manage the operation of these transmitters.

Finally, while licensing regimes are intended to minimize the probability of harmful interference between spectrum users, it is recognized that such interference may arise. Therefore, national regulation typically includes a process to identify and resolve interference complaints from licensed users. In the case of interference between different national administrations, the Radiocommunication Bureau could assist administrations, if requested, with a view to assist in resolving problems.

For RQZs, national regulators may choose to implement a variety of controls as described later in this Report, and to assist in resolving problems of harmful interference that arise if the regulations are not followed.

1.3 Goals of creating an RQZ

The basic goal of creating an RQZ is to minimize the potential for interference to radio astronomy or other passive sensing services.

The first RQZ for the protection of radio astronomy observations was established in the United States of America. In a 1954 conference in Washington D.C., sponsored by the U.S. National Science Foundation (NSF), the California Institute of Technology, and the Carnegie Institute of Washington considered the possibility of establishing a centre for radio astronomy and contracted a consortium of universities to locate a suitable site. A total of 25 sites were surveyed; the final selection being based on considerations that included the availability of public land, particularly a large flat area suitable for the siting of radio interferometers, the radio quietness of the site, and the possibility to observe some prime astronomical targets, such as the galactic centre. To avoid noise, the following conditions were deemed necessary:

1 The telescopes should be within the view of the smallest possible number of close-by inhabitants who might generate noise in the course of their daily work.

2 The telescopes should not view high tension power lines that radiate radio noise through corona discharges or otherwise.

3 The site should be in a valley surrounded by as many ranges of high mountains in as many directions as possible, to attenuate direct radio propagation from neighbouring radio stations and to reduce diffraction of tropospheric propagation into the valley.

4 The site should be at least 50 miles distant from any city or other concentration of people or industries, and should be separated from more distant concentrations by surrounding mountain ranges.

The US National Radio Quiet Zone (NRQZ) was established in 1958 [2], upon approval by the agencies managing the radio spectrum, and has been continuously in existence since then. Descriptions of this and other RQZs are given in the Annexes of this Report.

2 Characteristics of radio astronomy instruments relevant to RQZ

2.1 Geographic considerations

A radio astronomy station is always located at a site that is consistent with its intended scientific purpose. Beyond that, however, there are certain geographic considerations that can possibly ease the creation and maintenance of a quiet zone.

There are different types of geographic models of quiet zones. In one model, no transmitters at all are allowed within the quiet zone, in some frequency range. In another model, transmitters are allowed in the quiet zone as long as the received signal level at the radio astronomy station does not exceed a pre-determined interference threshold. Other quiet zones may be a combination of the two models, with, for example, an "inner ring/core" where no transmitters are allowed, and an "outer ring/zone" in which transmitters that meet the specified interference criteria are allowed. In cases where interference criteria are specified, it is important to establish and clearly articulate one or more reference points (latitude, longitude, and height above mean sea level) at which the interference level will be computed or measured/assessed.

Besides locating radio astronomy stations as far from heavily populated areas as possible, placing them in areas that provide some level of natural terrain shielding, such as in valleys, can be helpful. This reduces RFI from transmitters beyond the terrain blockage and allows fewer technical constraints on transmitters in those areas, which can make quiet zone compliance more amenable to potential licensees in the nearby areas.

Because residual RFI to radio telescope systems can be created by sources at the radio astronomy installation itself, terrain or other natural shielding within the installation should be a consideration during site design. Some observatories located in quiet zones have found benefits to surrounding their radio telescopes by forests of coniferous trees such as pines, which, due to the moisture content of their needles, can provide some additional protection from RFI coming from the horizon, particularly at frequencies above a few GHz.

Observatories located on mountain peaks with very long lines of sight (LoS) are particularly challenging for quiet zone coordination. There may be some situations, such as a radio telescope on a high mountain top with a large metropolitan area within line of sight, where establishing a quiet zone would be exceedingly challenging.

One of the most significant interference to radio astronomy is due to airplanes and satellites where there is mostly no geographic protection against their transmissions. Airplanes and HAPS operating at 10 and 20 km altitude would be visible for at least 400 and 500 km respectively, a satellite at 1 200 km would be visible for up to 4 000 km. Very large satellite constellations, with tens of thousands of satellites in LEO orbits, could have hundreds of satellites above the horizon for any given moment in time. This will cause an increase in the probability of main beam coupling, and in the total aggregated interference, potentially causing receiver saturation, inter-modulations, and a constant baseline of low level RFI. For airplanes and HAPS, the possibility of creating a national no-fly zone above an observatory should be examined. However, even if successful, such no-fly zones will not eliminate airborne sources of interference, because the radio horizon of an aircraft at cruising altitude may be close to 400 km, and the diameter of a no-fly zone to rid all sources of airborne interference to an observatory would therefore need to have a diameter of 800 km. In the case of large satellite constellations, local protections could be implemented to minimize the footprint satellites over an RQZ.

2.2 Frequency range

Various bands, with frequencies ranging from 13 MHz to 270 GHz, have been allocated for passive use only, but some bands allocated to radio astronomy are shared with active transmitters on a co-ordination basis using agreed protection levels (see § 2.4). In addition, there are frequency bands which are of particular interest to, and have been identified for, use for radio astronomy for which protection is encouraged but not guaranteed by the Radio Regulations. Some of these frequency bands are identified in Footnotes to the Radio Regulations, as seen for example in RR No. **5.149**, which refers to a series of frequency bands containing spectral line emissions arising from many important molecules and molecular ions that can be detectable in space such as water, hydroxyl, methanol, and ammonia. These emissions provide fundamental insight into galactic and cosmological evolution, and the physics and dynamics of their environments.

At WRC-12, bands for observations of spectral lines by passive services (including radio astronomy) at frequencies in the range 275 GHz to 1 000 GHz were identified in RR No. **5.565**.

The introduction of interference mitigation techniques to detect and remove unwanted signals from radio astronomy observations has enabled radio astronomy to be conducted at frequencies across the whole of the radio spectrum, although in bands assigned to other services the percentage of uncorrupted data finally obtained can be very low. Nevertheless, mitigation remains a crutch, as modification of the raw science signal to remove unwanted interference can have unwanted and even undetected side effects. It follows that specific bands allocated to radio astronomy remain vitally important, as they provide bands mostly free of interference required for essential instrument calibration and observations of the weakest radio sources. Improvements in receiver technology have also resulted in radio astronomical observations with increasingly larger bandwidths and becoming much more sensitive in detecting ever weaker signals. As a result, these receivers have also become more sensitive to interference but increased dynamic range in frontend components can result in less susceptibility to interference in interferometric systems.

2.3 Modes of operation

The largest classification of cosmic radio sources is associated with continuum radiation; this is emission that extends relatively smoothly over most of the spectrum. Radio astronomy observations in continuum mode strive to achieve very high sensitivities and require the most strict protection thresholds, as described in the next section. In an RQZ, observations can occur over bands not allocated to RAS thus greatly increasing the available bandwidth and hence the sensitivity of the observations. In new radio astronomy receiver systems, bandwidths of up to 2 GHz at centimetre wavelengths and 8 GHz or more at millimetre wavelengths are typical where the continuum is sampled in channels with widths of 1–30 MHz. Continuum observations across large portions of the spectrum can provide unique information on radio sources and are only feasible under the protection of an RQZ.

The second large classification of radio sources is associated with spectral lines covering a defined frequency range. These lines are generated at characteristic frequencies associated with transitions between quantized energy states of atoms or molecules. Thus, allocations for observation of these lines must be made at specific frequencies. Important new lines continue to be detected, and many thousands of lines are routinely observed. For spectral lines in distant galaxies, an observed frequency that normally falls within a radio astronomy band is Doppler shifted and as a result may fall outside the protected band due to the large velocities of the galaxies relative to the Earth. Therefore, practically all parts of the radio spectrum are of potential scientific interest. Hence, the access over large parts of the spectrum afforded by an RQZ allows observations of many lines not accessible elsewhere.

Observations of spectral lines are often composed of data taken in very narrow channels and the protection criteria for spectral line observations are less strict than for continuum observations by typically 10-20 dB in terms of the total power input to a single observational frequency channel. However, observation times of many hours are often required to obtain the sensitivities necessary to form conclusions of astrophysical interest. Moreover, spectrum free from harmful interference is necessary over bandwidths sufficiently broad to include Doppler-shifted lines, together with calibration bands bordering the line emission.

To increase both the sensitivity and resolution of radio astronomy observations, arrays of radio antennas have increasingly been deployed in radio astronomy. With such instruments two effects reduce the response to interference. These are related to the frequency of the intensity oscillations that are observed when the outputs of two antennas are combined (known as fringe rotation rate), and to the fact that the frequency components of the interfering signal received by different and widely-spaced antennas will suffer different relative time delays before they are recombined. With these effects the protection thresholds for interferometers over 10s of kilometres are about 20 dB greater than single telescope continuum systems as far as terrestrial point source interfering transmitters are concerned. For interferometers with baselines on order of decameters and a few kilometres however, space based interferers can be a sufficient distance away to appear in the far field of the interferometric measurement, resulting in correlating interference signals.

In the case of Very Long Baseline Interferometry (VLBI) the antennas are very widely separated, making the chance of occurrence of correlated interference very small. The interference threshold is then determined by the level at which the interference begins to degrade the measured correlation of the signals from two antennas. Thus, the harmful thresholds for VLBI are approximately 40 dB greater than for continuum total power systems at the same frequency. Hence RQZs around VLBI antennas can have more relaxed protection criteria.

2.4 Sensitivity

The sensitivity of an observation in radio astronomy can be defined in terms of the smallest change in the power level at the radiometer input that can be detected and measured. The harmful interference threshold level is directly related to the sensitivity; it is defined as that interference power which causes a 10% increase in the smallest power that a radiometer can detect. Under the conditions described in Recommendation ITU-R RA.769, such interference is supposed to have an insignificant impact on astronomical observations (see Recommendation ITU-R RA.769, for a mathematical formulation of the sensitivity equation). Tables 1 and 2 of Recommendation ITU-R RA.769 list harmful threshold levels, in terms of power flux and power flux densities, for continuum and spectral line observations in primary radio astronomy bands under representative conditions. These levels are generally accepted as the levels that are protective of radio astronomy observations. This, however, need not be the case when dealing with an RQZ specifically established for the benefit of radio astronomy.

The conditions under which the values in Tables 1 and 2 in Annex 1 of Recommendation ITU-R RA.769 were derived are recalled here:

– The source(s) of interference appear in the 0 dBi sidelobe(s) of the telescope.
– The integration time of the astronomical observation is 2 000 seconds in all cases.
– The bandwidth of a continuum observation is:
  • The width of the allocated primary radio astronomy band for observations below 70 GHz.
  • 8 GHz for observations above 70 GHz.
– The bandwidth of spectral line observations is as given in Table 2 of Recommendation ITU-R RA.769.

Sidelobe levels of radio telescopes are poorly known, and the 0 dBi sidelobe level assumption is probably as good an approximation as possible. It is worth noting that under this assumption the harmful interference level is independent of the collecting area and orientation of the radio telescope.

The other two assumptions may, however, be relaxed in an RQZ. Integration times as long as several days may be used to detect faint sources in modern observations, resulting in 30 dB better sensitivity than the thresholds in Recommendation ITU-R RA.769. The bandwidth of modern radio astronomy receivers is much wider than the allocated bandwidth that in some cases is only a fraction of a percent of the centre frequency, resulting in up to 20 dB more sensitivity than defined in Recommendation ITU-R RA.769.

2.5 Effect of RFI on RAS observations

The effect of RFI on radio observations varies greatly, from simple increases in noise levels that can be mitigated to levels that can destroy the receivers in a radio telescope.

The combination of high receiving gain of the astronomy antenna and high incident signal strength from a communications service could suffice to permanently degrade the performance of a RAS receiver, or perhaps even destroy it. Technical details are given in Report ITU-R RA.2188 on "Power flux-density and e.i.r.p. levels potentially damaging to radio astronomy receivers".

When RFI signals are of sufficient strength to drive the amplifiers in a radio telescope receiver system into saturation or even just into the non-linear regime, the radio observations cannot be accurately calibrated and hence no useful data can be obtained. For any radio observations, the RFI signals must allow operation of the amplifiers in the linear regime/region.

RFI that is present at low enough levels, so that radio observations are possible, still requires some form of mitigation. The simplest form of mitigation is excision in frequency and/or time if the RFI can be unambiguously detected, but this leads to loss of data and sensitivity. More sophisticated RFI mitigation methods are possible but most of them require considerable development and operational effort and can be very costly. Detailed discussion on RFI mitigation for radio astronomy is given in Report ITU-R RA.2126.

The greatest advantage of RQZs is the inherent low levels of RFI that not only protect radio astronomy receivers but also allow for simpler and easier forms of mitigation.

2.6 Geometric considerations

Radio astronomy antennas have high gain and narrow beamwidth, and the main beam is directed at least several degrees above the horizon. Interference directly into the main beam is therefore not likely from terrestrial sources, and statistically infrequent from aircraft or satellite sources. However, given the sensitivity of the radio astronomy receiver, as discussed above, even the interference into the side lobes of the antenna can be harmful to radio astronomy observations. As the side lobe gain can vary significantly depending on the orientation of the antenna and the position of the interference source, for convenience a side lobe level of 0 dBi is assumed for interference analysis. For interference calculations using the 0 dBi sidelobe level, the calculation is independent of the size or orientation of the radio antenna.

In the case of low frequency aperture array telescopes like SKA-Low, LOFAR or MWA the 0 dBi approximation should be used carefully, these type of radio telescopes create a high gain narrow beam by addition of many low-gain wide-beam antennas. RFI signals are much more likely to be received by antennas in these arrays from directions where the gain can be higher than 0 dBi.

3 The electromagnetic environment

There are a number of possible interference sources to radio astronomy observations, and they may require different types of mitigation. These are summarized in the following sections. This Chapter also provides an overview of the main propagation mechanisms that should be considered in assessing the potential for interference.

3.1 Intentional radiators

Intentional radiators are those systems and devices which produce radio-frequency emissions for the purpose of communication or sensing; that is, the transmission of radio energy is intrinsic to their operation. In general, this means that the frequency band, bandwidth, transmitted power level, modulation scheme and other radio parameters are known or can be estimated with some accuracy.

For the purposes of regulation, ITU defines a large number of radio services including terrestrial systems (such as aeronautical mobile, aeronautical radionavigation, amateur, broadcasting, fixed, land mobile, maritime mobile, maritime radionavigation, meteorological aids, radiolocation and radionavigation (radars), standard frequency and time) and satellite systems (such as Earth-exploration satellite, fixed satellite, inter-satellite, meteorological satellite, mobile satellite, space operations and space research). The latest definition of radiocommunication services can be found in Article 1 of the Radio Regulations.

3.1.1 Licensed radio devices

Licensed radio devices are those for which the national regulator has authorized operation. They may be licensed on an individual (apparatus) basis, in which case the regulator has knowledge of the location (or area of operation), frequency, power, bandwidth, modulation, antenna height and radiation pattern, and other parameters of the station. These licenses are maintained by the regulator and in most cases must be renewed on a regular basis. This allows some control within a radio quiet zone by restricting or limiting certain types of transmitters, for example, by frequency band or by power level.

Many administrations also have a geographic area spectrum licensing option whereby users have the right to a given frequency band in a given geographic area, possibly for a given period of time. This is often used for frequency bands with high demand; for example, the band around 2 GHz was sold as spectrum licences in many administrations for the introduction of 3rd generation mobile telephony. Under spectrum licences, users may deploy radio transmitters within the nominated frequency and geographic space as desired. This makes control for a radio quiet zone more difficult than for the individually licensed devices described above unless the spectrum licence conditions specifically include compliance with regulatory requirements for the RQZ in question.

3.1.2 Class-licensed (unlicensed) radio devices

Class-licensed devices are those which are operated without a specific licensing agreement between the user and the regulator (in some administrations this is referred to as ‘unlicensed’). These are restricted to identified frequency bands, often the same bands as ISM devices (see § 3.2.1), and devices are limited in power, bandwidth and other parameters by national regulation. Under a class licence, transmitters must not cause interference to other users, nor claim protection from interference.

Examples of class-licensed devices are cordless telephones, wireless computer networks (e.g. Wi-Fi), RFID (Radio-frequency identification) tags, automatic door sensors, vehicle keyless entry, motion sensors and many others. In general, they are consumer-grade devices or used by industry in large deployments. They are also typically low-powered and often mobile.

Ultra-wideband (UWB) devices (for communication or for sensing) are also typically class-licensed. As the name indicates, UWB systems operate over much wider bandwidths than other radio systems, although at correspondingly lower power spectral density.

Control of class-licensed transmitters for an RQZ is more difficult than for licensed devices as the location of operation and other parameters are not known to the national regulator.

3.1.3 Spacecraft-, aircraft- and platform-based radio transmitters

Transmissions from satellites, other spacecraft, aircraft and airborne platform based transmitters are authorized in or near a large number of frequency bands of interest to radio astronomy. As satellites and space systems are coordinated internationally, it is often difficult for a national regulator to control transmissions for the purpose of a radio quiet zone. Geostationary satellites maintain a constant position with regard to the telescope, and interference mitigation may be possible by avoiding the geostationary arc in observations. Non-geostationary satellites may be more problematic as they appear on the horizon and cross through the observing area. The growth of non-GSO satellite constellations (both long and short duration) providing broadband services has recently accelerated.

Aircraft-based radio transmitters (for communications and navigation) may also cause interference to radio astronomy receivers. It is sometimes practical for routine air overflight routes to be arranged to not overfly an RQZ. In Puerto Rico these have been arranged to be off-shore to the greatest practical extent.

Likewise, some transmitting systems used by aircraft, such as certain mobile-satellite earth stations, have undertaken coordination agreements, whereby they switch their uplink transmission frequencies while within an agreed distance from the telescope, when their use would interfere with an advertised telescope program. Such accommodations require an active on-going coordination activity with the operators of transmitters, and a timely communication of telescope schedules.

HAPS systems operating at 20-50 km altitude in the FSS would present the mixed case of an airborne but relatively fixed and permanent airborne interferer. A HAPS platform at 20 km is nominally visible for 500 km in any direction.

3.2 Unintentional radiators

Unintentional radiators produce radio-frequency noise as a by-product of their main function. Typically this is at lower power spectral density than intentional radiators, but over wider frequency bands. The characteristics of the emitted radio-frequency energy are usually not well defined in terms of power level, frequency or statistics. Recommendation ITU-R P.372 provides information on the general characteristics of man-made noise in a variety of environments; this represents noise from a number of discrete sources within the environment rather than a particular piece of equipment. Man-made noise is characterized by a combination of background noise with Gaussian statistics and impulse noise of higher levels but lower probability.

3.2.1 Industrial, scientific, medical

Industrial, scientific and medical (ISM) devices are those which use radio-frequency energy for a purpose other than communication. Microwave ovens (domestic and industrial), medical diathermy and RF welders are well-known examples. Specific frequency bands are allocated for ISM devices and the frequency and power characteristics are typically known. For the purposes of an RQZ, they are very similar to class-licensed devices and often share the same frequency bands.

3.2.2 Vehicles

The ignition systems of vehicles (cars, trucks, buses, trains, boats, etc.) produce radio-frequency noise. Typically this noise decreases with increasing frequency, so that bands below about 1 GHz are of most concern. In addition, other electric motors on a vehicle (fans, windscreen wipers, heaters, etc.) can also produce RF noise. Also, most vehicles include computerized engine management systems which are further potential sources of interference.

Vehicles may also include intentional radio transmitters that may not be obvious to the operator. Modern rail systems incorporate radar sensors for speed measurement as well as wireless communication between different components of the drive mechanism. Train to trackside RF communication applications are also now commonplace. Current model road vehicles are available with Bluetooth and other wireless communication systems. In addition, vehicles are increasingly being equipped with collision-avoidance radar systems, wireless charging, built-in WiFi hotspots, etc.

3.2.3 Power lines

Radio interference from power lines is typically generated from sparking, otherwise known as tracking, and corona discharge. More recently, the use of power distribution systems as a medium for the delivery of telecommunication services has been considered.

Corona discharge is an inherent property dependent on the electric field strength of a conductor and air moisture content. The onset of corona discharge is therefore highly dependent on weather conditions, becoming more aggressive with higher moisture content, and will typically occur on line voltages of approximately 70 kV and above. Corona discharge is found in all three voltage phases and is characterized as a partial discharge. That is, there is a partial breakdown of the air in the vicinity of the conductor.

Sparking is typically the only source of radio interference on low voltage lines, less than 70 kV, and is more prevalent in dry, windy conditions that may open up spark gaps. Sparking phenomena are rarer on high voltage lines due to the use of steel structures and high mechanical tension. Spark-over across gaps may take place several times in one power frequency cycle and is usually only found on one voltage phase. Unlike corona discharge, which is seen as an inherent property of a line, a spark gap is regarded as a fault on a line that can be fixed, or avoided, through proper maintenance.

Power line telecommunications (PLT) systems make use of radio frequency signals applied on mains power distribution lines. PLT signals on these lines have the potential to cause interference to radiocommunication services, including the radio astronomy service. The two main families of PLT applications that currently exist are *Access PLT*, providing last mile connectivity, and *Indoor PLT*, providing connectivity within buildings. Initial PLT systems, using frequencies up to 80 MHz and offering less than 100 Mb/s bitrate are now being replaced by new high speed PLT systems, using frequencies up to 300 MHz and offering up to 1 Gb/s bitrate. These families of applications are sometimes referred to as PLC (Power Line Communications), BPL (Broadband over Power Lines) as well as PLT (Power Line Telecommunications). Due to the ionospheric effects on HF propagation and the cumulation of PLT radiation, the implementation of PLT modems, even when far from radio astronomy observatories, may cause harmful interference to radio astronomy observations.

3.2.4 Electrical and electronic equipment

The quantity of equipment in industrial and consumer use having the potential to radiate radio interference is increasing rapidly. Typical commercial equipment my produce unintentional radiated emissions up to a limit defined by EMC standards such as CISPR-11 or CISPR-32 for ISM or IT equipment respectively. Depending on the distance to a RAS station and the topography involved, even one commercial equipment can generate interference in an observation. As an example, an equipment generating unintentional radiated emissions compliant to the CISPR-22 standard located 1 km away from a telescope can produce an interference 40 dB higher than RA.769 threshold levels. Such unintentional radiation is likely to have a broad-band, noise-like spectrum upon which narrow-band time-varying signals are superimposed.

Typically, interference problems due to equipment in industrial usage are easier to address than those arising from domestic equipment, due to more controlled operating conditions, availability of local expertise and the tendency for industrial development to be more tightly regulated. Consumer equipment is acquired and deployed with less planning, and is less well maintained. In addition, a mass deployment of consumer electronics has a cumulative harmful effect.

3.2.5 Cumulative interference, the noise floor and its increase with time

Individual interference issues arising from single or associated sources can at least in most cases be addressed through current spectrum management and administration processes. A major issue is the growing deployment of mainly unlicensed devices in industrial and domestic use, which emit signals either intentionally or unintentionally, or even both. These add up to a noise floor that rises as the number of devices increases. The difficulty in identifying and addressing contributions to the total noise increases as the noise floor rises.

For example, in the zone surrounding the Dominion Radio Astrophysical Observatory (Penticton, Canada), it has proved extremely difficult to control the deployment of electronic devices in houses in a nearby community, and politically counterproductive to try. Microwave ovens, cordless telephones and wireless computer networks, which were rare 25 years ago, are now ubiquitous in houses. There is also now a move to RF and internet linked appliances that can be controlled by 'smart' domestic systems in a drive towards saving energy as an appreciation of environmental issues gains traction. The only way found to at least partially mitigate this interference is to keep centres of community expansion well away from radio observatories, preferably out of line-of-sight.

A programme for systematically measuring the noise floor and its changes with time are essential in identifying problems before they manifest themselves as significant losses of data and observing time. A component of this programme is to work closely with the national, regional and local spectrum managers, and with local community administrations.

3.3 Propagation of RFI signals

In evaluating the potential for interference from the sources described above to a radio astronomy site, it is necessary to predict the propagation of the RFI signal.

It is essential to distinguish between propagation prediction for radio system design and that for interference analysis. System design must account for the maximum (or near maximum) loss on a path between transmitter and receiver to ensure that a sufficient power level is received. Interference analysis, on the other hand, must calculate the minimum (or near minimum) loss on a path between transmitter and victim receiver to evaluate the maximum power level likely to be received. In using the Recommendations of ITU-R Study Group 3 or other propagation prediction methods, this distinction should be observed. The most up-to-date ITU-R Recommendations on propagation from ITU-R Study Group 3 should be used.

3.3.1 Free-space

Free-space propagation loss refers to the geometric loss of radio energy due to the distance between transmitter and receiver, without any obstacles or material loss on the path. For most scenarios, it is the lower bound on the propagation loss for a path[1].

Recommendation ITU-R P.525 describes free-space propagation and provides a formula using convenient units:

$$L_{bf} = 32.4 + 20 \log f + 20 \log d \qquad \text{dB} \tag{2}$$

where:

L_{bf}: basic free space propagation loss (dB)

f: frequency (MHz)

d: distance (km).

3.3.2 Diffraction

Where the path between the transmitter and receiver is obstructed by terrain, buildings or other obstacles, additional loss due to diffraction will occur. Recommendation ITU-R P.526 provides prediction methods for diffraction over a smooth Earth, over individual obstacles, or over rough terrain (with the use of a digital terrain map).

In the case of diffraction over buildings, and to some extent in very mountainous terrain, the dominant path may not be directly over the top of the obstacle but around it. The use of two-dimensional profiles in such situations may not be appropriate.

It must also be noted that sub-path diffraction may affect paths even if the direct line between the transmitter and receiver is clear, if the clearance to the terrain (or other obstacles) is less than 60% of the first Fresnel zone. A prediction procedure is given in § 3.2 of Recommendation ITU-R P.526.

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[1] In some specialized situations, it is possible to achieve a ducting mode which provides a loss less than free space, but this is unlikely to be relevant to radio astronomy protection.

3.3.3 Gaseous absorption and rain attenuation

Atmospheric gases provide additional attenuation although the effect is very minimal except in the oxygen absorption band near 60 GHz and at frequencies above about 100 GHz. At frequencies above about 500 GHz, the attenuation due to gaseous absorption can provide significant additional protection from interference sources.

At frequencies above about 10 GHz, rain attenuation becomes significant, but only for relatively small percentages of time. Therefore, attenuation due to rain should not be included in predicting interference levels for RQZs.

3.3.4 Ducting and other enhancement mechanisms

Ducting can occur due to reflection or refraction of signals by layers in the atmosphere. It can be significant over long distances (250-300 km) and may reduce the loss due to diffraction. Ducting is modelled as a time-varying phenomenon based on the climatic statistics of the area. Recommendation ITU-R P.452 provides prediction methods for ducting and other enhancement propagation mechanisms.

In general, the inclusion of ducting in an RQZ prediction can lead to separation distances that are impractical, up to several hundred kilometres. It is possibly more appropriate to evaluate ducting statistics to determine the likelihood of interference from distant sources and use this information in the design of mitigation techniques.

Signal levels received within an RQZ may also be enhanced for short periods of time by scatter from rain. As this occurs infrequently and depends on the climate and the geometry of the interference source, receiver and rain cell, it should be considered in tracing interference problems rather than used to define the RQZ limits.

3.3.5 Reflection and scattering

At low frequencies, particularly below 200 MHz, interference may be scattered into a radio telescope from meteors or aircraft. As the sources of interference are often at a great distance from the radio astronomy site, it is difficult or impossible to control through RQZ mechanisms.

About 10^9 to 10^{12} meteors enter the Earth's atmosphere each day and produce ionization at altitudes from about 80 to 100 km. The region of mutual visibility extends out to approximately 2 000 km. At this distance the path loss due to scattering is about 195 dB at 65 MHz, with an increase of 30 dB per decade of frequency. Meteor scatter propagation is frequently the mode of reception of distant FM radio broadcasting signals in remote areas and is characterized by its 'bursty' nature [4].

Aircraft scatter is another way signals from distant transmitters can propagate over large distances beyond the horizon. At 12 km altitude an aircraft can be mutually visible to the transmitter and receiving site out to distances of about 800 km. For an aircraft scattering cross-section of 10 m^2 the path loss at 150 MHz for a distance of 200 km from the transmitter and receiver from the aircraft is about 229 dB. This path loss is not sufficient to bring the signal of a 100 kW e.i.r.p. FM radio broadcasting station down to a level below the Recommendation ITU-R RA.769 levels for radio astronomy.

For example, even in remote locations (e.g. Boolardy in Western Australia and the Catlow valley in Oregon), 88-108 MHz FM radio broadcasting and 175-216 MHz signals from analog and digital television create "bursty" interference throughout the day and night via meteor scatter and sporadic E ionospheric propagation. The typical signal level is equivalent to about 10 kelvin as measured with an isotropic antenna [5]. Occasionally, these have been seen to increase by 20 to 30 dB and become more constant for periods of several hours owing to propagation via tropospheric refraction. This occurs when low lying water vapor provides sufficient refraction for the wavefront to follow the curvature of the Earth for hundreds of km.

4 Methods to achieve an RQZ

A range of methods can be implemented to achieve an RQZ. These can conveniently be classified into receiver-side methods and transmit-side methods. Several of these methods may be used in combination, the choice of method being highly dependent on frequency, location, type of observation required, current land use and other factors.

4.1 Receive-side Methods

The need to achieve a very low noise figure limits the ability of radio astronomy observatories to remove RFI through filtering on the RF receiver, particularly from strong sources of interference that render radio astronomy receivers inoperable due to non-linearities. To achieve the optimal radio frequency environment in which radio astronomy observations are made, radio astronomy observatories make use of geophysical factors and their impact on radio frequency signal propagation. A judicious choice of these factors provides a methodology for meeting the requirements of an RQZ.

4.1.1 Geographic location

The nature of radio frequency propagation is such that interference power decreases with increasing distance from transmitters. The most basic approach, therefore, is to select a geographic location that is sufficiently far away from population centres and traffic. This is ideal for new, major facilities but may not be practical for all telescope facilities. For example, both the South African and Australian sites selected for the next generation Square Kilometre Array (SKA) telescope have been chosen in remote, lightly populated areas.

Mountaintop sites are often useful for their remoteness and shorter, drier vertical paths through the atmosphere. However, they may also suffer from having population centres visible on long lines of sight when not shielded by local terrain: the IRAM 30-m telescope in Spain, with a frequency range of 70 to 275 GHz, is situated near the peak of a mountain in the midst of a ski resort and in direct line of sight to the city of Granada some 30 km away.

High altitude sites are not limited to mountains. The ALMA site in northern Chile is on a broad plain near 5 000 m altitude. The South Pole is effectively a broad plane at 3 000 m altitude.

A more extreme example of a remote site is the far side of the Earth’s Moon, with the whole of the lunar mass as shielding from terrestrial interference sources. A quiet zone on the far side of the moon is effectively defined in Recommendation ITU-R RA.479. Yet more distant, the vicinity of the L-2 Lagrange point used for space radio astronomy missions is a radio quiet zone defined in Recommendation ITU-R RA.1417.

4.1.2 Site shielding

Where possible, natural shielding of the site by terrain should be used. In contrast to the mountaintop site described above, this approach gives preference to valley locations surrounded by hills or mountains. The absence of a direct LoS between interference sources and the RQZ does not guarantee absolute quiet, however, some attenuation will be provided as signals will arrive via diffraction paths over the terrain or via reflections from large structures such as wind-turbines. Diffraction losses are frequency dependent, with increased attenuation at higher frequencies. At low frequencies in particular (below about 1 GHz), site shielding may offer marginal benefit. The effect of diffraction should be estimated for the frequency range of interest using detailed knowledge of the local terrain whenever possible.

For example, the Arecibo telescope in Puerto Rico is surrounded by rugged limestone hills which are the first means of site protection.

However, in situations where terrain by itself might provide adequate protection, this could be negated by the erection of just a single large reflecting structure, such as a wind-turbine, on top of nearby hills. Fixed link transmissions, which would otherwise be shielded from the telescope site by the terrain, could be reflected into a telescope at a harmful level, even if the reflecting structure is not directly in the path of the fixed link.

4.2 Transmit-side Methods – Managing an RQZ

The major component in managing an RQZ is the control of radiators of potentially interfering signals within the zone, while ensuring the delivery of telecommunication and other services to small pockets of population within an RQZ. Since the investment in setting up and maintaining the RQZ, together with the investment in instruments within it are significant and extend over decades, both the planning of the zone and methods for dealing with potential and real sources of interfering signals have to take this into account. When defining the zone, it should not be only on the basis of the instrumentation intended for it at the time; there should also be a realistic assessment of what additional capabilities and instrumentation might be added during the life of the zone. This could affect the frequency bands used and the nature of the observations made, and consequently the definition and management of the RQZ.

An additional need is for processes by which the RQZ can be managed over decadal timescales, dealing with applications for community and industrial development and other natural processes of land management. These involve most of the procedures listed below, but on an ongoing basis.

4.2.1 Legislative and regulatory control

Legislation in a number of countries provides a regulatory framework to control sources of RFI within an RQZ. This includes the regulation of licensed and unlicensed (or class-licensed) radio transmitters, and other activities which may cause interference.

4.2.1.1 Regulation of radio devices – Restriction and Notification

Many RQZs define restriction and notification areas around the site. The restricted area (also referred to as protection area) is a zone where the installation and use of radio devices is restricted. This may be limited to transmitters within a specific frequency band or bands. Management of the restricted area may be done through the regulators licensing activity.

For example, the Administration of Mexico has created an RQZ which is indicated by footnote MX 283 to the Mexican Table of Frequency Allocations. An English-language translation of footnote MX 283 is as follows:

"The frequency band 70-350 GHz is used for the Large Millimeter Telescope (LMT) radio telescope operation installed in the Sierra Negra-Pico de Orizaba Volcano, in charge of the INAOE. The LMT requires for its correct operation a quiet zone around 100 km radius, thus the operation of any other radio communication system in that area is not allowed."

A notification area (also referred to as coordination area) is a zone within which any proposed radio installations (in the specified frequency bands) must be notified to the regulator and the telescope operator. This notification process then starts a negotiation period where the telescope operator assesses the effect of the proposed radio transmitter on radio astronomy observations and attempts to find a suitable solution for both parties. Typically, these solutions may include beam shaping, spectral shaping and separation, and reduction in e.i.r.p. of the transmitted signal. The national regulator may be involved in the negotiation. Typically, the notification area is much larger than the restricted area.

For example, the Government of Chile has designated two partly-overlapping zones for the purpose of protecting radio astronomy observations. The first is a protection zone with a radius of 30 km; third-party transmitters operating within certain frequency bands may not be stationed within this zone. This is augmented by a coordination zone with a radius of 120 km; operators wishing to station certain kinds of transmitters within this zone are subject to coordination with the operators of the ALMA telescope, within certain frequency bands.

In general these regulations can only be applied to licensed (apparatus or spectrum) radio devices, and are of limited value in controlling unlicensed radio devices or unintentional radiators.

It is essential to note that the use of notification and restriction zones involves an ongoing, collaborative, dynamic management of the RQZ over the lifetime of the radio astronomy observatory. It also implies that implementation of RQZs should provide for as many options as possible (for example, in terms of frequency bands) to allow for later expansion of radiotelescope capabilities.

4.2.1.2 Physical control of access to site

Regulatory control may also be extended, in limited geographical areas, to cover unlicensed radio devices or unintentional radiators. As these types of devices are generally low power, the geographic limit is often not much of a constraint. Within the immediate vicinity of the telescope site, physical access may be controlled to ensure that no transmitting devices are brought onto the premises.

For example, in Brazil a municipal law defines an “electrical silence zone” specifying a circle of 4 km diameter, centred at the Itapetinga observatory. No urban expansion is allowed in this area to avoid interference from power line transmission, microwave ovens, radio control devices, neon signs, and other devices capable of producing radio interference. The few people already living in this area receive instruction in order to avoid generating harmful interference to the observatory. This area is also protected from urbanization and deforestation, since it is classified as a permanent protection area (PPA) according to federal law.

4.2.1.3 Legislative control of activities near site

The national regulator or other appropriate government body may also implement legislation to control certain classes of activities in areas within the RQZ. For example, heavy industry or manufacturing may be prohibited in areas where the noise from machinery would create unacceptable levels of interference.

For example, the West Virginia Radio Astronomy Zoning Act [6] regulates the emissions of unshielded electrical equipment within 10 miles of radio astronomy receiving equipment anywhere within the State. For equipment located three (ten) miles from the radio astronomy receiver, the electric field must not exceed 2 μV/m (9 μV/m) when measured at a distance of 10 (50) feet from the equipment. Intermediate limits for equipment located between three and ten miles are specified in the Act, along with monetary fines and mechanisms for relief from interfering equipment.

As a further example, the Murchison Radio Observatory (MRO) in Western Australia is protected under an agreement with the Government of Western Australia which requires that new mining activities within 70 km of the site core are coordinated with the telescope requirements to ensure that harmful interference is not generated.

Table 1 shows examples of a number of different national RQZs and the methods of control or regulation they use.

TABLE 1

Control at various national RQZs

RQZ/country	Control of licensed radio transmitters	Control of class-licensed radio devices	Aircraft controls	Control of unintentional radiators
LMT/Mexico	100 km radius – no other radiocommunications			
NRQZ/USA – 4-2021	34 000 km^2 area – fixed transmitters required to coordinate		No fly zone in a radius of 2.5 miles around GBT, with a ceiling of 2500 ft AGL	Controls on electronic equipment within 10 miles
ALMA/Chile	No transmitters within 30 km; coordination within 120 km			
Arecibo/Puerto Rico	Restrictions within 4 miles (6.4 km) generally; amateur radio stations excluded within 10 miles (16.1 km); coordination required for Puerto Rico and neighbouring islands	Restrictions within 4 miles (6.4 km) generally	No fly zone over telescope	Restrictions within 4 miles (6.4 km)
Various/Australia	Notification zones for coordination to as much as 250 km		No fly zone over telescopes	
MRO/Australia	Frequency band plan – RAS is primary within 70 km; coordination zone to 260 km	Class licences – no interference allowed within 70 km	No fly zone over site	Protocol for electronic equipment used by RAS within 10 km
Yebes/Spain	Power limits defined within 5 km or 20 km depending on the frequency range	No construction should appear above an elevation of 3 degrees as viewed by the telescope within a radius of 1 km		1 km separation to industrial facility high voltage power line or railway
IRAM/Spain	Restrictions on transmitters up to 5 km radius; coordination to 10 km radius			1 km minimum separation to industry, rail, HV power lines
Itapetinga/Brazil	4 km diameter zone with no new urban activity	4 km diameter zone with no new urban activity		4 km diameter zone with no new urban activity

TABLE 1 (*end*)

RQZ/country	Control of licensed radio transmitters	Control of class-licensed radio devices	Aircraft controls	Control of unintentional radiators
AGAA/South Africa	No transmissions in area of 140 km^2, essential services only in area of up to 123 408 km^2		Core area of 140 km^2 controlled to 18 500 m altitude	Protocols for electronic equipment and activities used in the RQZ
Pushchino/Russian Federation	2 km diameter zone with no new urban activity	Control within 5 km zone (Pushchino town)		Control the level of attended interferences
DRAO/Canada	Licensing tightly controlled out to 200 km	Nothing within 60 m vertically of line-of-sight and restrictions within 2 km, whichever is the larger	Designated airspace 1 nautical mi le radius to 1 000 ft above ground level.	No new urban activity within line of sight, and restricted out to 2 km, whichever is the larger
FAST/China	No transmitters within 5 km; coordination within 75 km radius			

4.2.2 Alternative technologies and network design

The national regulator or the telescope operator may choose to provide alternative technologies to those which cause harmful levels of interference. For example, if television broadcasting is of concern, the provision of cable television over fibre-optic cable may be appropriate. One mobile radio network could be replaced by another at a more convenient frequency band.

Additionally, future RQZs may employ advanced techniques designed to facilitate sharing in multiple dimensions (e.g. time, frequency, location, etc), allowing customized coordination methodologies. For example: dynamic sharing in time may allow protection beyond what traditional radio quiet zones can achieve. This type of dynamic coordination may also be paired with the alternative technologies detailed above to maximize the benefits for all users.

5 Implications in establishing an RQZ

5.1 Maintenance of RQZs

RQZs require considerable effort to maintain after their creation. Almost all of the burden falls upon the operator of the radio astronomy facility, and therefore must be properly accounted for when estimating the facility's operating budget and staffing level.

One activity that must be supported is routine monitoring of the radio environment. This activity is often conducted with standalone monitoring stations that are typically separate from the radio telescope itself. The monitoring station data will be much less sensitive to RFI than the actual telescope, but is useful for finding strong RFI that may suddenly appear due to, for example, an unauthorized transmitter within the quiet zone. The monitoring station antenna is sometimes located near the highest point of the telescope structure (or structures), is sometimes on a tower located elsewhere on the radio astronomy site, and is sometimes vehicle-mounted, which can help better pinpoint the location of the RFI.

Another activity is identifying sources of RFI that appear in telescope data, but that might not be sufficiently strong to detect with the monitoring station(s). Analysis of these cases can be very difficult, because radio telescopes are not particularly good spectrum analysers when examining terrestrial interference. This is for several reasons, including: the use of wide channel bandwidths that make identification of exact frequency difficult; the use of Doppler tracking, which causes the topocentric reference frequency of the radio astronomy observation to change during accumulation of a single spectrum; long integration times that mask the time variability of the RFI; unpredictable antenna response in the direction of the RFI, which is often coming from the horizon, and which prohibits calibration of signal strength; and unknown direction from which the RFI is arriving.

Once RFI has been identified, quiet zone administrators themselves, or engineers operating under their direction, must mitigate the source of the RFI. Experience has shown that the bulk new RFI cases arise from equipment on the observatory grounds itself, such as computers, monitors, industrial equipment, equipment brought in by visitors, etc. Because of this, most observatories establish RFI buffer zones within the observatory grounds, with increasingly stringent restrictions on potentially RFI-generating equipment as distance to the radio astronomy equipment decreases. Quiet zone staff must establish these zones, educate staff and visitors, and be prepared to enforce the local rules. Considerations for RFI zones should ideally be in place before the observatory is even built, as physical barriers, RFI shielding of buildings and outdoor equipment, and other construction-related activities will likely be needed.

Quiet zone staff will also need to address cases of RFI that arise from sources beyond the observatory grounds. Unauthorized transmitters that otherwise require an operating license may be the easiest situation to deal with, since national regulators can be contacted if needed to enforce the quiet zone rules. The most difficult case that arises in quiet zone administration is RFI from unlicensed devices that are external to the observatory property. This may include RFI from Wi-Fi, cordless telephones, wireless speakers, and similar equipment that is often employed in homes and businesses, and which may not be covered under quiet zone rules. Dealing with these situations within existing quiet zones is becoming increasingly problematic. No clear solution is at hand.

A substantial burden in large quiet zones can be the processing of license applications for new transmitters within the quiet zone. Some quiet zones may be easy to administer, if transmitters are simply not allowed within the quiet zone. Other quiet zones may establish harmful interference thresholds, in which case license proposals must be carefully analysed using the best-available engineering methodologies, to see if the transmitted signal will exceed established interference thresholds at the observatory. In at least one existing quiet zone, this single activity requires more than one full time employee.

Lastly, observatories should not underestimate the need for education and public outreach to explain the need for the quiet zone, and to make spectrum users aware of their obligations under quiet zone rules. Inviting the public and potential spectrum licensees to the observatory to show off the radio astronomy facilities and talk about astronomical discoveries that have been made is a proven method to obtain cooperation in keeping the quiet zone quiet.

5.2 Increase in capabilities

Experience shows that RQZs have often been designed with particular telescopes in mind. The most usual subsequent evolution of the telescope has then been to increase its utility for higher frequencies through an upgrading of the instrument. This happened for instance with the Arecibo telescope, which was constructed initially for operation from 50-700 MHz, while it is currently capable of observations up to 13 GHz. More recently a trend exists towards co-location of telescopes onto sites where their purposes can be adequately met, while they share in the economies of installed infrastructure and regulation, as well as to shared access to power, communications, and roads. This in turn may well be accompanied by an increase in the frequency range to be protected for the instruments on a site. It is accordingly advisable to design the parameters of an RQZ as broadly as circumstances will allow.

5.3 Life of a facility

Modern radio telescopes tend to be expensive in terms of the funding available for basic science, so their construction envisages a useful life of upward of 50 years. These might also be replaced or upgraded in turn to become yet larger instruments. Hence once an RQZ is agreed to, it is required to be in place for a considerable time. This suggests that its economic impact and its potential impact on future population distribution and development in the affected area be taken thoroughly into account when designing an RQZ.

5.4 Evolution in the EMC environment

The pace of technical development in society must be expected to continue to result in new innovations leading to changes in the EMC environment around an RQZ. Whereas the almost unpopulated karst terrain around the Arecibo telescope in 1960 offered considerable protection, by 1989 this was grossly inadequate. Indeed the original 1960 restriction to enable EMC was simply on the operation of any "machinery, mechanism, instrument or device, which may cause interference with electromagnetic reception by the facility". After just 29 years this had to be clarified to explicitly cover "among others, (1) AM, FM, or TV transmitters or repeaters, or both, (2) commercial communications transmitters, repeaters, or both, (3) arc welding, (4) high voltage transmission or distribution power lines without adequate insulation, (5) radio control devices, (6) defective household appliances, (7) diathermic machines, (8) neon signs, (9) high power arc lights, (10) high power electric motors/generators with brushes, (11) high power microwave industrial equipment, and (12) industrial electric controls with electromagnetic radiation". Time and experience will add more items to such lists.

6 Challenges for radio quiet zones

The new era of, before unimagined, large satellite constellations in LEO orbit and the unavoidable future deployment of airborne platforms (such as HAPS) will undermine the ability of nationally recognized RQZ to protect radio astronomy observations. The international nature of satellite systems makes it difficult to enforce RQZ protections on their emissions. With the advancement in satellite transmitter and antenna technology, RAS observing techniques, and considering that the pressure on more efficient use of the radio spectrum is always increasing, it is necessary to extend RQZ protections to afford some level of protection from airborne and satellite systems.

A clear example where this is possible is described in Recommendation ITU-R RS.2066, dealing with possible damage to RAS stations from powerful emissions from EESS (active) systems working around 9.6 GHz. This Recommendation requires operators to coordinate with RAS stations to avoid damage to its very sensitive receivers. Recommendations for the protection of radio astronomy from large satellite constellations are included in [7].

Internationally recognized RQZs could provide protection from active air- and space-borne systems with the capability of intentionally avoiding illumination of the area. Although this kind of protection may not reach the protection levels defined in Recommendation ITU-R RA.769, by combining it with new mitigation and scheduling techniques, it may allow RAS observations to still be conducted within a RQZ in the frequency ranges protected by it.

7 References

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Annexes: 13

Annex 1

Characteristics of radio quiet zones: Mexico's radio quiet zone around the Large Millimeter Telescope (LMT)

1 Radio quiet zone around the Gran Telescopio Milimétrico (GTM) or Large Millimeter Telescope (LMT)

a) Introduction

The Large Millimeter Telescope (LMT) or Gran Telescopio Milimétrico (GMT) is a radio telescope with a 50 meter diameter single-dish optimized for astronomical observations. It has been erected in Mexico's Sierra Negra-Pico de Orizaba Volcano at longitude (West) −97°18'48", latitude (North) 18°59'06" at an elevation of 4 580 m. The construction of this instrument involved a binational collaboration between Mexico and the USA – 4-2021 standing out the National Institute of Astrophysics, Optics and Electronics (INAOE) and the University of Massachusetts in Amherst (Umass) as the leaders of this project. It represents the largest and most complex scientific instrument built in Mexico, see http://www.lmtgtm.org/.

b) Description of RQZ

The frequency operation range of the LMT is 70-270 GHz, so in order to protect the operation of this instrument from harmful interference, the Administration of Mexico has created an RQZ which is indicated by the footnote MX 283 of the Mexican Table of Frequency Allocations. An English-language translation of footnote MX 283 is as follows:

"The frequency band 70-350 GHz is used for the Large Millimeter Telescope (LMT) radio telescope operation installed in the Sierra Negra-Pico de Orizaba Volcano, in charge of the INAOE. The LMT requires for its correct operation a quiet zone around 100 km radius, thus the operation of any other radio communication system in that area is not allowed."

The Radio Quiet Zone around the LMT is shown in Fig. 2.

FIGURE 2

The RQZ around the LMT

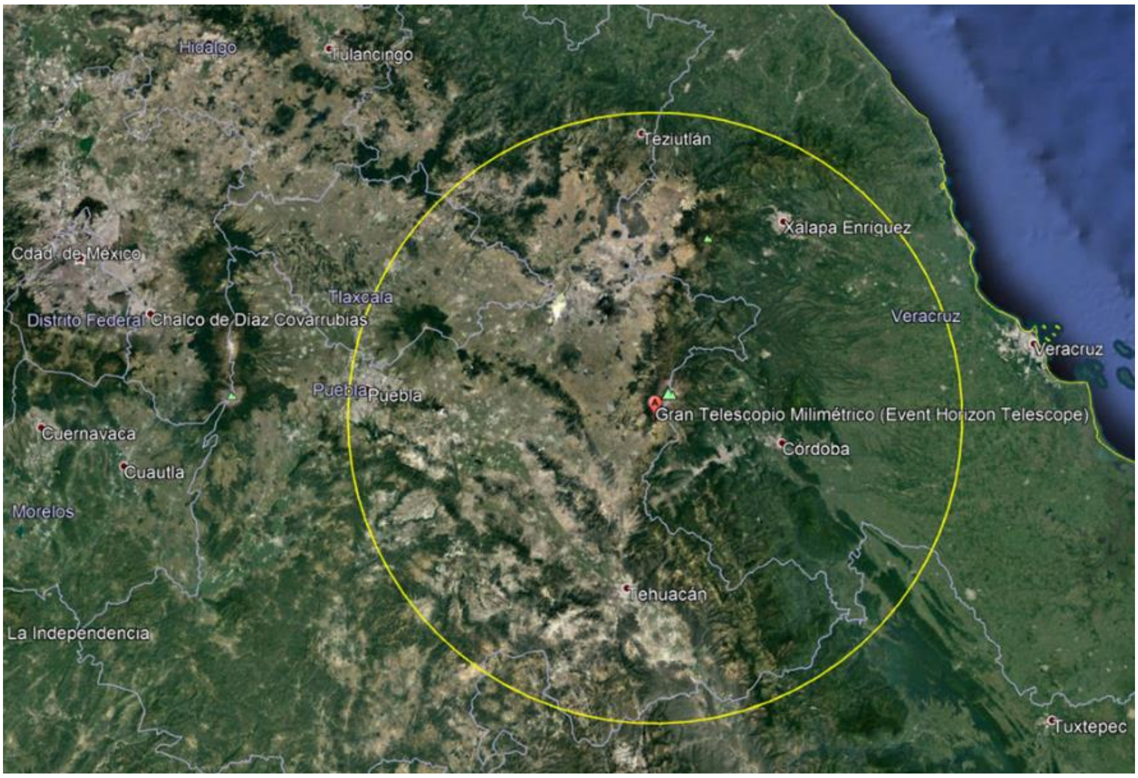


FIGURE 3

The RQZ regional view

A radius circle of 100 km around the telescope is shown, corresponding to the region established by the Administration of Mexico in footnote MX 283 to their Table of Frequency Allocations. Within this quiet zone, no other communications system is allowed to operate.

It is important to highlight that within the radius of 100 km of the RQZ there are some main cities such as Puebla, Córdoba, Veracruz and Tehuacán, however, it is possible to keep the RQZ established due to the density of systems operating at frequencies above 70 GHz.

Annex 2

Characteristics of radio quiet zones: the US national radio quiet zone

1 The US national radio quiet zone

a) Introduction and description

The US national radio quiet zone (NRQZ) was established by the Federal Communications Commission (FCC) in Docket No. 11745 (19 November 1958) and by the Interdepartment Radio Advisory Committee (IRAC) in Document 3867/2 (26 March 1958) to minimize possible harmful interference to the US National Radio Astronomy Observatory (NRAO) in Green Bank, WV (https://greenbankobservatory.org/about/national-radio-quiet-zone) and the Sugar Grove Research Station in Sugar Grove, WV. The rules regarding operation of the NRQZ are part of the US code, specifically Title 47, part 1.924 of the Consolidated Federal Register, i.e. 47 CFR 1.924. Information pertaining to the operation of the NRQZ on the part of the NRAO may be found at https://greenbankobservatory.org/about/national-radio-quiet-zone.

The purpose of the NRQZ is to minimize the potential of harmful interference on highly sensitive Radio Astronomy operations and other facilities that are susceptible and sensitive to interference.

Over the life of the Quiet Zone, several major telescopes have operated at the NRAO's Green Bank Observatory station, including; a since-collapsed 100 m meridian instrument operating up to 5 GHz from 1960-1988; an equatorially-mounted 43 m (140') steerable paraboloid usable up to 45 GHz since 1965; and many smaller telescopes, including a FOUR-element interferometer. At present, the main beneficiaries of the NRQZ are the National Science Foundation's 100 m Green Bank Telescope (GBT), an off-axis, fully-steerable, 100 m alt-az mounted paraboloid with an active (deformable) surface, with a receiving room elevation of 139.6 meters, which has operated in the range 0.3-49 GHz since August 2000 and is presently operating in the range of 0.1-116 GHz and the Sugar Grove Research Station.

The NRQZ is bounded by North American Datum 83 (NAD-83) meridians of longitude at 78 º 29 ' 59.0" W and 80 º 29 ' 59.2" W and latitudes of 37º 30' 0.4" N and 39º 15' 0.4" N, and encloses a land area of approximately 34,000 sq. km (13,100 sq. miles) centred near the state border between Virginia and West Virginia and including a portion of Garrett County, MD. Approximately 600,000 people live within the NRQZ. Its location within the United States of America is shown in Fig. 4, along with the locations of the radio telescopes found within the map borders.

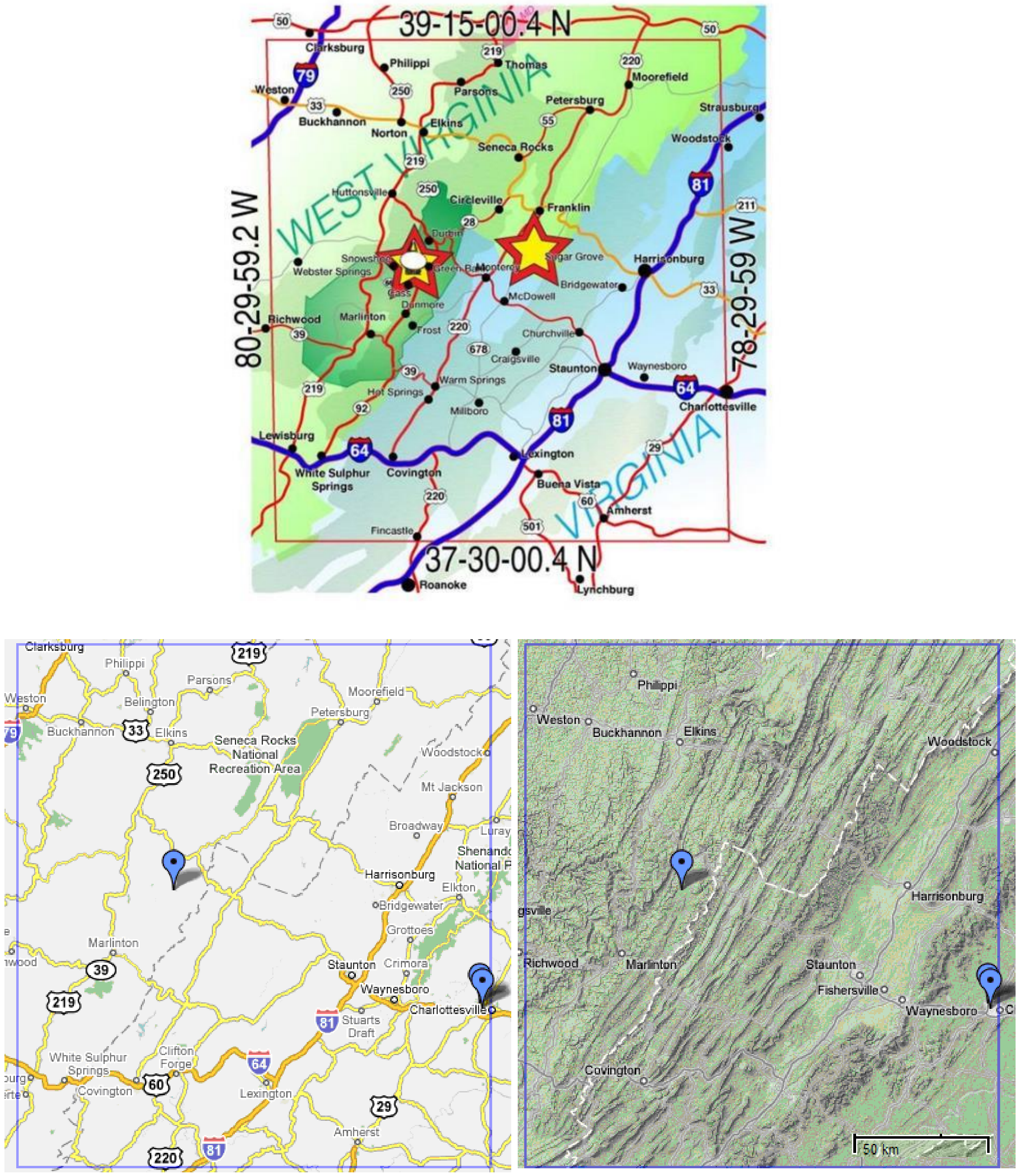
FIGURE 4

The US NRQZ

Note to Fig. 4 : The NRQZ is the blue rectangle near the map centre. Markers in the Zone represent the 100 m Robert C. Byrd Green Bank Telescope (GBT) in West Virginia (to the West) and NRAO HQ in Charlottesville, VA. Other radio astronomy stations are also shown outside the NRQZ.

FIGURE 5

The US NRQZ in greater detail. Top: Full extent of the NRQZ; the GBT is indicated by the left star and the Sugar Grove Research Station by the right star. Bottom Left: Major roads and cities within the NRQZ are shown. Bottom Right: the terrain is indicated. The hilly terrain surrounding the GBT shields the site. The GBT is indicated by the blue symbol to the West, NRAO administrative buildings in Charlottesville, VA are indicated at the Eastern boundary of the NRQZ



b) Coordination with transmitters

1) Transmitters which are required to coordinate

Applicants with new or modified, fixed, licensed terrestrial transmitters that would be located within the bounded area of the NRQZ zone submit written frequency coordination requests to the Director, National Radio Astronomy Observatory, Green Bank, WV. Notification can be prior to or simultaneously with the application to the appropriate government authority.

Engineering reviews are completed to determine if the proposed communications system are potential sources of interference to the NRAO and the Sugar Grove Research Station. Facilities that meet NRQZ coordination requirements are provided documentation verifying successful coordination. These documents can be used in conjunction with the applicant's filing request for an approved grant by federal agencies. Facilities that do not meet NRQZ protection criteria are required to provide additional documentation that indicates how the applicant would meet any requested power restrictions.

The NRAO reference point is the 100m Robert C. Byrd Green Bank Telescope also known as the GBT and is shown in the NRQZ map in Figs 4 and 5, near the western boundary of the Zone. Its precise coordinates are 79º 50' 23.4" W, 38º 25' 59.2" N (NAD83), at ground 806 metres or 2644 Feet AMSL (NAVD88). Topographic maps and a modified Longley-Rice Rounded Obstacle propagation model are used to calculate the arriving signal level.

2) Transmitters which are not required to coordinate

Airborne and space-borne emitters and unintentional radiators are also sources of potential interference inside the bounded area of the NRQZ. Though they are excluded from explicit Quiet Zone coordination they may be subject to other regulatory coordination requirements, such as the WVRAZ.

Coordination of these emitters is difficult and very limited. Many factors are considered should coordination be possible, and could include the physical location of the device and the cooperation of the spectrum user. The NRAO has established zones that outline mitigation policy. For example, Zone 1 and 2 are on Observatory property and subjected to Site Policy, being most restricted in Zone 1, whereas Zones 3 and 4 are defined by the WVRAZ, and Zone 5 by the NRQZ.

Examples of these intentional radiators are airborne transmitters, space-borne transmitters, and license-exempt or short-range devices (SRD). Some examples of unintentional radiators are power line communications (PLC), leaky cable TV distribution lines, and greeting cards that play music.

c) Threshold levels for coordination

NRQZ thresholds for coordination exist at all frequencies. Within protected radio astronomy bands, the threshold for coordination is that given in Recommendation ITU-R RA.769. Outside those bands, the NRAO threshold level is given as a function of frequency. Based on a 20 kHz measurement bandwidth, the calculated power density of the transmitter at the reference point should be less than

– 1×10^{-8} W/m^2 for frequencies below 54 MHz

– 1×10^{-12} W/m^2 for frequencies from 54 MHz to 108 MHz

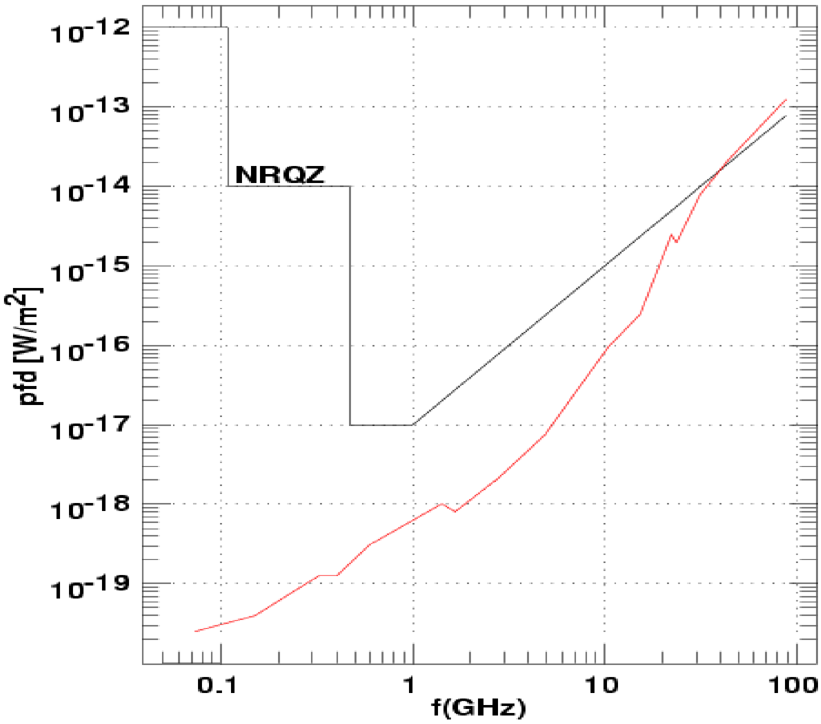
– 1×10^{-14} W/m^2 for frequencies from 108 MHz to 470 MHz

– 1×10^{-17} W/m^2 for frequencies from 470 MHz to 1 000 MHz

– freq^2 (in GHz) $\times 10^{-17}$ W/m^2 for frequencies above 1 000 MHz.

FIGURE 6

Coordination threshold levels for the NRQZ



— Applicable values outside protected radio astronomy bands

— RA.769-2 levels applicable inside protected bands

d) Coordination mechanism

Applications for licences to transmit within the NRQZ are received by the US Government (the FCC or NTIA), following the same rules as any other application. Those applications that fall within the NRQZ should be flagged upon reception and referred to the NRAO Green Bank Interference Office for comment. To speed coordination, applicants are encouraged to contact NRAO at or before the time of submission of the license application. This is also included in the FCC Rules and Regulations 1.924 (a) (2): "When an application for authority to operate a station is filed with the FCC, the notification required in paragraph (a)(1) of this section may be made prior to, or simultaneously with the application."

The following information is used by the NRAO in order to coordinate transmitters; name and address of the applicant, the radio service under which the transmitter operates, the frequency or frequency bands of the transmitter(s), the transmitter output power, system losses, the geographical location, the site ground elevation(s) above mean sea level (AMSL), the antenna height above ground level (AGL), the usable bandwidth or emission type, the antenna gain and orientation in azimuth (degrees True North).

In some instances, the power level requested by an applicant is projected to exceed the levels shown in Fig. 6 at the reference point of the GBT. When this occurs, applicants may discuss possible modifications to their transmitters (e.g. using a directional antenna, relocating the antenna to an area that provides additional terrain shielding, or selecting a different frequency where the power density limits are different) with the Interference Office at NRAO. A technical solution can almost always be found to provide most if not all the area coverage desired by the applicant while simultaneously minimizing the impact of the interference. In the extremely rare case when differences between the applicant's desires and NRAO's evaluation cannot be resolved, both the applicant and the NRAO would forward their comments on the transmitter installation to the appropriate US agency for a final resolution. In most cases the FCC (for private sector licenses) and or the NTIA (for government licenses) has sided with the NRAO in these disputes. If the applicant is unhappy with the decision, he/she may appeal to the FCC's Administrative Tribunal, and request relief.

Other users of the NRQZ may have their own coordination requirements.

e) The West Virginia Radio Astronomy Zoning Act

Only the US Federal Government has the authority to regulate the operation of transmitters. However, the State of West Virginia created the Radio Astronomy Zoning Act (WVRAZ) to regulate the emissions of unshielded, terrestrial, electrical equipment within 10 miles radius of radio astronomy receiving equipment anywhere within the State. This act limits the permitted electrical field of affected equipment, varying progressively with the distance from the radio astronomy receiver. Intermediate limits for equipment located between three and ten miles are specified in the Act. For example, equipment located three miles from the radio astronomy receiver the electric field must not exceed 2 μV/m when measured at a distance of 10 feet from the equipment. Along with the specified peak field strength restrictions, the Act includes monetary fines and mechanisms for relief from interfering equipment.

The West Virginia Radio Astronomy Zoning Act, Chapter 37A, Article 1 of the West Virginia State Code, is available online at http://www.wvlegislature.gov/WVCODE/Code.cfm?chap=37a&art=1#01.

f) Work effort required to administer and service the National Radio Quiet Zone

The NRAO presently employs one person full-time to respond to transmitter applications (which in a typical year number 2000 or more facilities) but this effort is supplemented by other NRAO staff making site visits to assist in the verification of RFI-mitigation efforts by applicants: The Quiet Zone administrator and two-three dedicated engineers form the so-called "Interference Protection Group" in Green Bank. US governmental entities, the FCC and the NTIA, perform additional work (e.g. review, comments, returns and approval or denial of the applications) necessitated by the coordination of licensed transmitters that operate in the Quiet Zone, however the full extent of the work effort required to administer is unknown.

Annex 3

Characteristics of radio quiet zones: the ALMA radio quiet zone in Chile

1 The Radio Quiet and Radio Coordination Zones around ALMA and other telescopes in northern Chile

a) Introduction and description

Associated Universities Inc. (AUI), which operates the US National Radio Astronomy Observatory (NRAO) under a cooperative agreement with the US National Science Foundation (NSF), along with the European Southern Observatory (ESO) and the National Astronomical Observatory of Japan (NAOJ) are jointly constructing the Atacama Large Mm-submm Array (ALMA) radiotelescope in an uninhabited region of northern Chile at an elevation of 5 000 m. ALMA is a reconfigurable array of some fifty movable 12 m diameter dishes and approximately eighteen 7 m dishes which will observe in the frequency range 30-950 GHz on baselines ranging up to 35 km, see http://www.alma.nrao.edu/.

To protect the operations of the ALMA telescope, the Chilean national telecommunications authority SUBTEL issued identical Resolutions 1055 to AUI and 1056 to the European Southern Observatory (ESO) in August 2004. The English-language translation of Resolution 1055 is presented in Attachment 1 to this Annex, as it is the policy of SUBTEL that the publication of such decrees is left to the parties concerned.

The Government of Chile has designated two partly-overlapping zones for the purpose of protecting radio astronomy observations, both centred on 23º 01’ S by 67º 45’ W:

i) Protection Zone: with a radius of 30 km, within Chilean national territory. Third-party transmitters operating within certain frequency bands may not be stationed within this zone.

ii) Coordination Zone: with a radius of 120 km, within Chilean national territory. Operators wishing to station certain kinds of transmitters within this zone are subject to coordination with the operators of the ALMA telescope, within certain frequency bands.

These zones are represented in the map in Fig. 7.

b) Transmitters which are required to coordinate

The regulations generally apply to fixed, terrestrial transmitters which require licences. The following sorts of transmitters are explicitly exempted: those performing space radio communications; those performing terrestrial radio communications with installations authorized outside the protection zone and using mobile stations; systems using high altitude platform stations (HAPS).

FIGURE 7

The ALMA radio quiet and coordination zones

Note to Fig. 7 : The two concentric circles centered in northeastern Chile have the radii of the ALMA Protection Zone (30 km) and Coordination Zone (120 km) created by Chile. Legal protections granted by Chile extend only within its national borders. Locations of several radio astronomy stations in Chile and Argentina are indicated.

c) Threshold levels for protection and coordination

i) Within the Protection Zone

Within the 30 km radius Protection Zone, transmitters operating in the bands listed in Table 2 will not be licensed to third party operators. The bands in Table 2 correspond to the receiver bands at which ALMA operates or is expected to operate.

TABLE 2

Frequency bands relevant to the ALMA Protection Zone

31.3-45 GHz
67-90 GHz
84-116 GHz
125-163 GHz
163-211 GHz
211-275 GHz
275-370 GHz
385-500 GHz
602-720 GHz
787-950 GHz

ii) Within the Coordination Zone

At frequencies higher than 31.3 GHz, any equipment authorized to third parties is required to limit its in-band and spurious emissions so as not to produce any harmful interference in the reception frequencies listed in Table 2, for which the protection criteria established in Recommendation ITU-R RA.769 apply.

Transmitters operating at frequencies below 31.3 GHz are required to limit their e.i.r.p. to a pfd of less than 2×10^{-6} W/m^2 within the observatory area, understood as a circle of 20 km radius whose centre coincides with the coordination zone. As an example, a transmitter located 10 km outside the observatory area would have a permissible e.i.r.p. of 2.5 kW. Furthermore, such equipment is required to limit any spurious emissions within the range of receiving frequencies authorized for the radio telescope (Table 2), for which the protection criteria established in Recommendation ITU-R RA.769 apply.

d) Implementation of the coordination zone

SUBTEL will require "Good Practices" regarding adjusting antenna beams, transmitter power and filtering of harmonic emissions. Authorization for any transmitter will be submitted to a coordination process, whereby SUBTEL will inform ESO and AUI about applications that could affect the operation of the radiotelescope, asking for their technical opinion. In the case that ESO and AUI would detect emissions affecting the radiotelescope operation, they will inform SUBTEL for their coordination. No formal mechanism for resolution of disputes is yet in place.

Attachment 1
to Annex 3

English language text of Resolution 1055

Republic of Chile

Ministry of Transport and Telecommunications

Sub-Secretariat of Telecommunications

Modifies permit for Limited Telecommunications Service

Exempt Resolution Nº 1055

Santiago, 17 August 2004

On this date the following has been resolved:

considering

a) decree Law Nº 1.762 of 1977;

b) law Nº 18.168 of 1982, the General Telecommunications Law;

c) the Technical Framework relating to Limited Telecommunications Services, Exempt Resolution Nº 391 of 1985 modified by Exempt Resolution Nº 524 of 1989 and Exempt Resolution Nº 563 of 2003, all of the Sub-secretariat of Telecommunications;

d) Resolution Nº 520 of 1996 that established the rearranged, coordinated and systemized text of Resolution Nº 55 of 1992, both of the General Comptroller of the Republic;

e) exempt Resolution Nº 1 of 1999 of the Sub-secretariat of Telecommunications that authorizes Heads of Divisions and Departments to sign “By order of the Sub-Secretary of Telecommunications” and delegates the powers mentioned therein,

whereas

what was requested by the petitioner with SUBTEL ingress Nº 42111 of 10.06.2004. (SL-383/2004),

I hereby resolve

1 to modify the Limited Telecommunications Service Permit granted to ASSOCIATED UNIVERSITIES INC (AUI), Tax Nº 69.507.700-9 domiciled at Camino El Observatorio Nº 1515 in the Municipality of Las Condes, Metropolitan Region, granted by means of Resolution Nº 1096 of 08.09.2003 of the Sub-Secretariat of Telecommunications;

2 the period of this modification expires on the same date as the one mentioned in the Resolution that granted the permit mentioned in Nº 1;

3 the deadline for commencing the works will be (2) two months and for completing them it will be (5) five months. Likewise, the deadline for beginning the service will be (6) six months. All of these deadlines will come into force as of the date this Resolution has been totally dealt with;

4 the technical characteristics and the location of the facilities of the system granted, including this modification, are as follows:

4.1 It is possible to accept what was requested, so use of the frequency bands is authorized with the technical characteristics that are mentioned hereafter:

Receiving frequency bands of the radio telescope:

31.3-45 GHz
67-90 GHz
84-116 GHz
125-163 GHz
163-211 GHz
211-275 GHz
275-370 GHz
385-500 GHz
602-720 GHz
787-950 GHz

The radio telescope may operate within all of the frequency bands mentioned; however, protection cannot be guaranteed in the frequency bands, or part of them, that are not allocated to radio astronomy on a primary basis.

Type of station: Radio astronomy station, an array of receiving only antennas

Location: Chajnantor Plain, Municipality of San Pedro de Atacama, 2nd Region.
Area centered on 23º 01’ S by 67º 45’ W

Number of antennas: 64 Cassegrain type parabolic antennas

Diameter of antennas: 12 m

4.2 For the purpose of protecting the radio telescope’s reception, the following zones have been defined:

a) Protection Zone centered on 23º 01’ S by 67º 45’ W and with a radius of 30 km within national territory, inside which the installation of any other radio communications system will not be authorized to any third parties operating on the receiving frequency bands mentioned in point 4.1.

b) Coordination Zone; coordination being understood as the process whereby the opinion of the petitioners, ESO and AUI will be sought regarding certain requests by third parties that this Sub-secretariat deems could interfere or affect the operation of the radio telescope. Likewise, in case such petitioners detect any emissions that affect the operation of the radio telescope, they will notify this Sub-secretariat for its coordination. The deadlines involved for each coordination process will depend on each case.

The coordination zone will be centered at 23º 01’ S by 67º 45’ W with a radius of 120 km inside national territory. Within this zone, any emissions by other petitioners or licensees will be limited, bearing in mind the following cases:

– Any emissions from each equipment authorized to third parties and which transmit on frequencies lower than those of the radio telescope’s reception (<31.3 GHz), will limit their e.i.r.p. in accordance with the values included in Table 3, as a function of the distance measured from the emission source to the edge of the area of the observatory, which is equivalent to a power flow density of less than 2×10^{-6} W/m^2 within the observatory area. The area of the observatory will be understood as a circle of 20 km radius whose centre coincides with the coordination zone.

Furthermore, such equipment shall limit any out-of-band and non-essential emissions within the range of receiving frequencies authorized for the radio telescope, for which the protection criteria established in Recommendation ITU-R RA.769-1, or any other that replaces or complements it, will apply.

TABLE 3

e.i.r.p. maximum acceptable as a function of distance

Distance *d* (km)	**e.i.r.p. (kW)**
10	2.5
20	10.0
30	22.5
40	40.0
50	62.5
60	90.0
70	122.5
80	160.0
90	202.5
100	250.0

– At frequencies higher than 31.3 GHz, any equipment authorized to third parties shall limit their in-band, out-of-band and non-essential emissions, so as not to produce any harmful interference in the reception frequencies authorized for the radio telescope, for which the protection criteria established in Recommendation ITU-R RA.769-1, or any other that replaces or complements it, will apply.

4.3 It is worth mentioning that it is not possible to guarantee protection against interferences generated by the following types of services or systems that operate on bands not allocated to radio astronomy:

– those performing space radio communications;

– those performing terrestrial radio communications with installations authorized outside the protection zone and using mobile stations;

– systems using high altitude platform stations (HAPS);

5 the petitioner shall provide whatever information is necessary for undertaking the procedure of international coordination of frequencies with ITU. It is worth mentioning that such procedure will only allow the coordination of those frequencies included in the bands allocated to the radio astronomy service on a primary basis;

6 the petitioner may not initiate services unless the works and installations required by the approved modification have been previously authorized by the Sub-secretariat. For this purpose he shall request by registered letter that it be checked that the works and installations have been properly executed and that they correspond to the project approved;

7 the petitioner is under the obligation to be aware of and comply with the provisions of the General Telecommunications Law, its Regulations and its amendments, in what they are applicable to him.

BE IT NOTED, NOTIFIED AND COMMUNICATED.

BY ORDER OF THE SUB-SECRETARY OF TELECOMMUNICATIONS

(Signature and seal)

VICTOR GARAY SILVA

HEAD OF CONCESSIONS DIVISION

Annex 4

Characteristics of radio quiet zones: the radio coordination zone around the Arecibo telescope in Puerto Rico

1 The coordination zone around the Arecibo Telescope

a) Introduction and description

The Arecibo Telescope is at longitude (West) −66° 45’ 11.1”, latitude (North) 18° 20’ 36.6” at an elevation of 497 m above mean sea level, in Barrio Esperanza, of the Municipality of Arecibo. It was built in 1960-3 in what was then a remote site on the island of Puerto Rico. It is screened from most centres of population by low karst hills. In 1960 the island’s population was about 2.35 million: it has since increased by 36%, so the population density of 1100 per square mile is now the 29th highest in the world (United Nations Department of Economic and Social Affairs, 2018). Consequently settled areas have moved a little closer to the telescope over the past 40 years, while there has been an accompanying and far more than commensurate increase in the use of the radio spectrum on the island, and in the vicinity of the telescope from both licensed and unlicensed devices.

Initially the telescope’s primary reflector was formed from chicken wire, as it was only intended to be used at frequencies in the range 50-700 MHz. It was subsequently upgraded in 1972-3 to have a reflecting surface of perforated aluminium panels set to about 3 mm rms (to enable it to be used to observe pulsars and the neutral hydrogen line at 21 cm/1 420 MHz). When used with the then extant set of slotted wave-guide line-feeds, it had a usable sensitivity to ~3 GHz. More recently still, in the 1990s, the telescope was upgraded for the second time by installing a Gregorian reflector system, to remove the spherical aberration introduced by the spherical primary reflector. This provides a deployable sensitivity from 300 MHz-11 GHz.

The initial defence against radio-frequency interference (RFI) is provided by the rugged limestone karst country surrounding the telescope. This is shown in Fig. 8.

FIGURE 8

Aerial view of the Arecibo Telescope set in its surrounding karst countryside

The approach road is clearly seen. Very few people dwell within the area covered by the picture.

Spectrum at frequencies of less than 11 GHz is well used on the island. Figure 9 shows the average power received over 24 hours by the Arecibo RFI monitoring system, which consists of an omnidirectional antenna covering 10-1 400 MHz, and a log periodic antenna that covers 1.7-10 GHz. The antennas are mounted on the hilltop above the control room. Most RFI signals reach the telescope's receivers after being scattered from the telescope structure into the primary reflector, and thence into the observing system. Nevertheless, the RFI reaching the receivers is much sparser than that appearing in Fig. 9, as the metallized radome protecting the secondary and tertiary mirrors from the weather greatly reduces the access of stray signals to the focus.

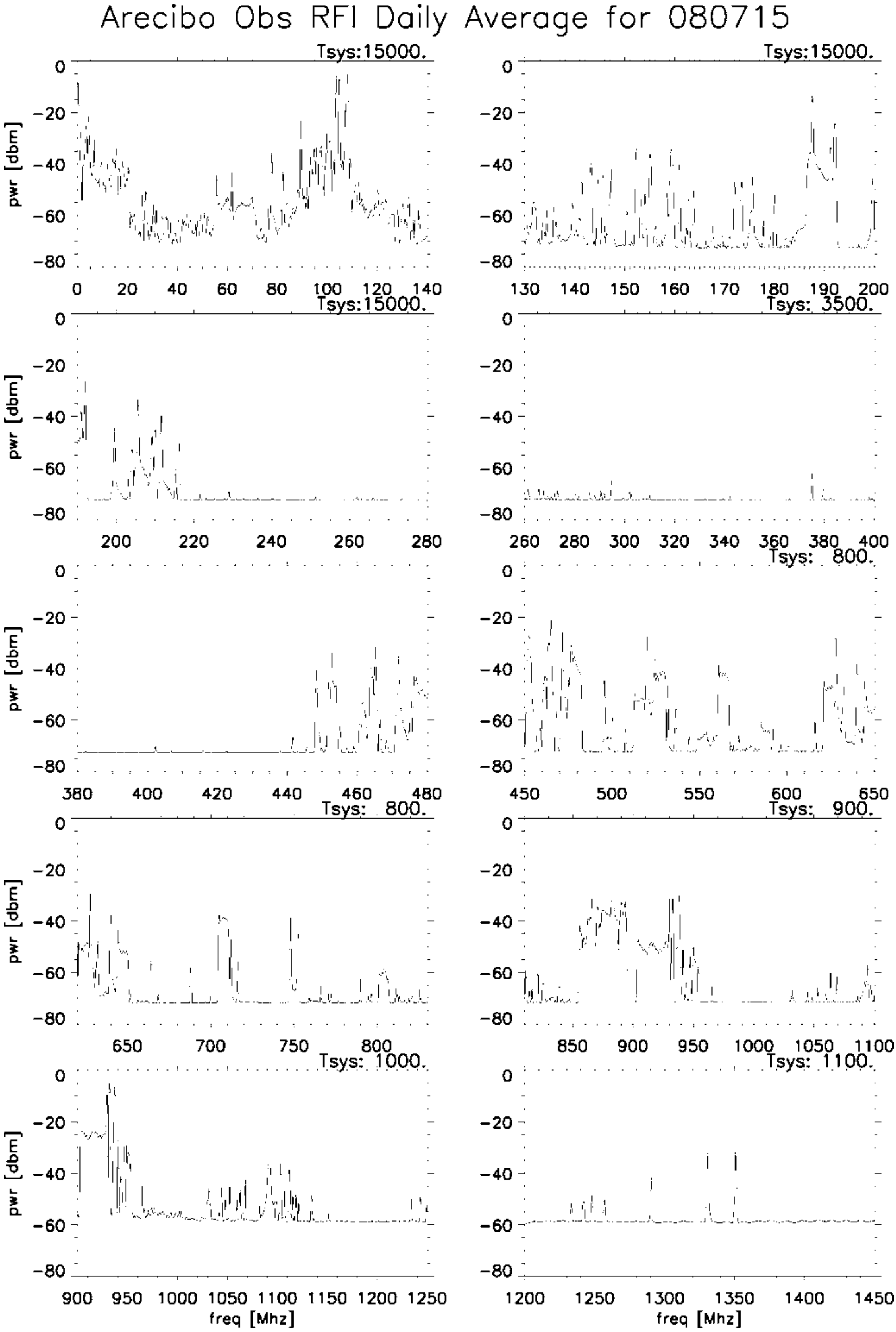
There have been recent reports indicating an increase in the RFI signals from unauthorized unlicensed devices operating in frequency bands below 5 150 MHz. In any case, all unlicensed devices found to be operating within the 4 mile exclusion zone are required to be shut off, by order of the Observatory Spectrum manager.

There was also a large increase in RFI following the Hurricane season of 2017 when the entire island was devastated by Hurricane Maria. The incidents of RFI have drastically increased since then and the Observatory is working to mitigate the impact.

The Arecibo 305-m telescope platform collapsed in December, 2020 after several cable failures. The National Science Foundation has noted that the Observatory will not close and is considering instrumentation for the future. A large portion of the 305-m reflector is still intact. There is a 12-metre telescope on the grounds of the Observatory which is functional at both S- and X-bands (2-4 and 8-12 GHz), and coordination remains a requirement as the site will remain an active Observatory.

FIGURE 9a

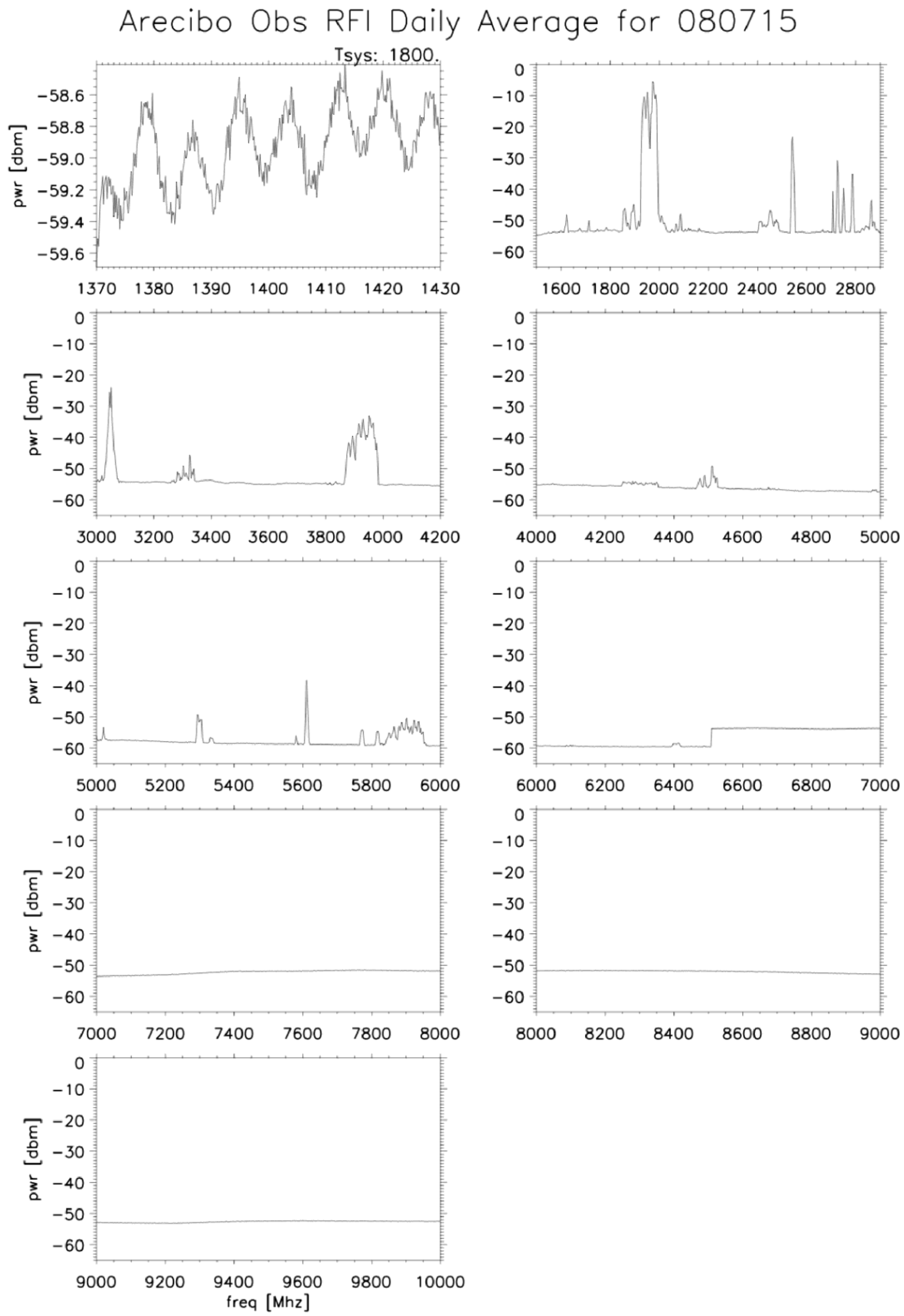
Average daily spectra from the Arecibo hilltop monitor over the 24 hours of 15 July 2008



The intensity scale is uncalibrated; panels cover frequencies from 20 to 1 450 MHz.

FIGURE 9b

Average daily spectra from the Arecibo hilltop monitor over the 24 hours of 15 July 2008



The intensity scale is uncalibrated; panels cover frequencies from 1.37 to 10 GHz.

b) Local legislation

To enable and protect the operation of the Arecibo Telescope, the Puerto Rican Government passed the Radio Astronomy Zoning Act, Act No. 88, on July 14, 1960. This provided for a four mile exclusion zone around the facility. Within this radius no machinery, mechanism, instrument or device, which may cause interference with electromagnetic or reception by the facility, can be established or operated.

With the evolution of technology and the increasingly common usage of more sophisticated equipment, it became necessary to amend the 1960 Act, to clarify its definition of ‘electrical machinery’. This is now understood to mean, as a result of Act No. 41 of August 5, 1989.

‘Electrical Equipment’ shall mean any machinery, mechanism, instrument, device or other facility capable of producing electromagnetic emissions which may damage or interfere with the operation or investigations at the Facility, such as, among others, (1) AM, FM, or TV transmitters or repeaters, or both, (2) commercial communications transmitters, repeaters, or both, (3) arc welding, (4) high voltage transmission or distribution power lines without adequate insulation, (5) radio control devices, (6) defective household appliances, (7) diathermic machines, (8) neon signs, (9) high power arc lights, (10) high power electric motors/generators with brushes, (11) high power microwave industrial equipment, and (12) industrial electric controls with electromagnetic radiation”.

Two further measures to protect the Observatory are in place. Scheduled airline flightpaths have been arranged so that they do not overfly the Observatory. And the Observatory has protection against the installation of microwave links that would pass too close to the Observatory under Article 4.02 of the June 19, 1992 Zoning Law on Telecommunication Facilities.

c) FCC Dispensation – Puerto Rico Coordination Zone

The radio spectrum is heavily utilized in Puerto Rico, despite the small size of the island. The US Federal Communications Commission (FCC), which governs all non-federal government licensing concerns in Puerto Rico (and the continental United States of America) is ever concerned to see that broadcasting licensees cover as much of the population as possible. Under this dictum, it urges existing TV stations to increase their broadcast power to the maximum allowed by their licenses, and to locate their broadcast antennae on high ground. The relocation of the local Arecibo TV station from a coastal site to a mountain top under this policy resulted in the second harmonic of the station being broadcast line-of-sight directly at the Observatory. This experience led to a federally mandated Radio Astronomy Coordination Zone being established in Puerto Rico, with the cooperation of the PR government and people.

Part 5 of Chapter I of Title 47 of the Code of Federal Regulations states:

5.70 Notification to the Arecibo Observatory.

Any applicant for a new permanent base or fixed station to be located on the islands of Puerto Rico, Desecheo, Mona, Vieques, and Culebra, or for a modification of an existing authorization which would change the frequency, power, antenna height, directivity, or location of a station on these islands and would increase the likelihood of the authorized facility causing interference, shall notify the Interference Office of the Observatory in writing or electronically to prcz@naic.edu the technical parameters of the proposal.

(1) The notification to the Interference Office, Arecibo Observatory shall be made prior to, or simultaneously with, the filing of the application with the Commission (FCC). The notification shall state the geographical coordinates of the antenna (NAD-83 datum), antenna height above ground, ground elevation at the antenna, antenna directivity and gain, proposed frequency and FCC Rule Part, type of emission, effective radiated power, and whether the proposed use is itinerant.

Generally, submission of the information in the technical portion of the FCC license application is adequate notification. In addition, the applicant shall indicate in its application to the Commission the date notification was made to the Arecibo Observatory.

(2) After receipt of such applications, the Commission will allow the Arecibo Observatory a period of 20 days for comments or objections in response to the notification indicated. The applicant will be required to make reasonable efforts in order to resolve or mitigate any potential interference problem with the Arecibo Observatory, and to file either an amendment to the application or a modified application, as appropriate. If the Commission determines that an applicant has satisfied its responsibility to make reasonable efforts to protect the Observatory from interference, its application may be granted.

(3) The provisions of this paragraph do not apply to operations that transmit on frequencies above 15 GHz.

Further, all amateur radio stations are excluded within a 10 mile radius, with the exception of repeaters and beacon station modifications or installations.

The majority of the license requests concern variations on the original license. The Observatory currently receives upwards of 400 requests a year, many of which have 20 to 30 entries. Approximately 70% of the license coordination requests are new. Processing and responding appropriately amounts to about 0.3 FTE (full time equivalent). Only a very few require coordination, though an important percentage with line-of-sight access require a warning that harmonics or errors in alignment of antennae can result in problems for the Observatory.

Coordination with the Arecibo Observatory is still required after the collapse of the 305-m platform in December 2020 as active scientific observations continue with the 12-metre telescope on site and the National Science Foundation is not closing the Observatory.

d) Outreach

The maintenance of a world-class radio Observatory on a crowded island depends on coordination and cooperation. This has always been forthcoming. It has been explicitly fostered over the last decade by the formation of an informal group, the Puerto Rico Spectrum Users Group (PRSUG). This convenes two meetings a year to foster cooperation and the exchange of information between public broadcasters and federal agencies on the island. The Observatory plays an active role in maintaining and supporting this group, and as a result has personal contact with many of the users. It has been particularly helpful in garnering concessions on the blanking of radar signals in the direction of the Observatory, and in coordination with frequency-agile radars on the island.

Annex 5

Radio notification zones around radio astronomical facilities in southeastern Australia

1 Introduction

This Annex describes protection measures for six radio astronomy sites, which are the major radio telescopes in Australia other than those at the Murchison Radio-astronomy Observatory (MRO), which is addressed in Annex 6. These six facilities are in the southeast region of Australia, have been operating for some decades and are close to population centres. The protection measures are therefore based on a consultation and negotiation process, in contrast to more stringent measures for the remote site of the MRO.

In 2006, the Australian Communications and Media Authority (ACMA) introduced "*Radiocommunications Assignment and Licensing Instructions (RALI) MS 31:* Notification zones for apparatus licensed services around radio astronomy facilities"[2], which provides for consultation between these radio astronomy telescopes and radio communication operators in their vicinity. The notification zones define a series of frequency bands and regions around each radio astronomy facility, where active use of spectrum has the potential to interfere with radio astronomy.

This Annex not only describes the notification zone measures in place, but summarises the calculations that were undertaken to define the notification zone sizes and thresholds.

2 Applicability

The frequency bands covered by RALI MS 31 are identified in footnote AUS87 of the Australian Radiofrequency Spectrum Plan (ARSP)[3]: 1 250-1 780 MHz, 2 200-2 550 MHz, 4 350-6 700 MHz, 8 000-9 200 MHz and 16-26 GHz. See Attachment 1 to this Annex for the text of AUS 87 and the location of the key radio astronomy facilities.

The notification process in RALI MS 31 applies to apparatus licensed, coordinated terrestrial service stations or earth stations only. No consideration is given, for example, to space or aeronautical services.

The process does not apply to continuing apparatus licences which were in place before the 2006 implementation of RALI MS 31. N or do they apply to transmitters that may be authorised for use by spectrum licences (for example, cellular phone networks) or class licences (for example, WiFi or Bluetooth devices).

The process does not apply to assignments whose details would be kept confidential under Australian legislation.

3 Background

The ITU Radio Regulations allocates some bands of scientific importance to the radio astronomy service, which are then reflected in the Australian Radiofrequency Spectrum Plan. In Australia, operators of radio astronomy facilities may obtain radiocommunications licences in allocated bands, giving them rights to protection from interference from other spectrum users. Radio astronomers also conduct observations in other bands on a fortuitous basis, but cannot take out licences in these bands. In these other bands, radio astronomy receivers are particularly vulnerable to interference from transmitters operating in the same spectrum bands.

Radio astronomy is regarded by the Australian Government as an important scientific undertaking with value for the broader community. Considerable investment has been made in a number of radio astronomy and support facilities around Australia, and there is strong international involvement in

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2 https://www.acma.gov.au/-/media/Spectrum-Engineering/Information/pdf/Radiocommunications-Assignment-and-Licensing-Instruction-Notification-Zones-for-Apparatus-Licensed-Services-around-Radio-Astronomy-Facilities-MS31.pdf?la=en

3 https://www.acma.gov.au/Industry/Spectrum/Spectrum-planning/About-spectrum-planning/australian-radiofrequency-spectrum-plan-spectrum-planning-acma and https://www.legislation.gov.au/Details/F2016L02001

radio astronomy science in Australia. There is therefore a benefit to the Australian community in protecting radio astronomy facilities from interference that would otherwise diminish their capacity.

In recognition of this commitment, the Australian Radiofrequency Spectrum Plan includes a chapter about radio astronomy spectrum[4]. The use of key bands for radio astronomy is also described in footnote AUS87 which lists specific locations of radio telescopes and notes their sensitivity to interference.

4 Impetus for developing notification zones

In 2002 the Australian Productivity Commission (APC) conducted a public inquiry on the Radiocommunications Acts and related market-based reforms undertaken by the national regulator[5].

A submission by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), which manages the Australia Telescope National Facility (ATNF), argued that footnote AUS87 was not effective in managing interference in bands where there is no allocation to the radio astronomy service. The CSIRO proposed designating major radio astronomy facilities as 'radio sensitive zones', within which it would be mandatory to notify radio telescope facilities that another user has applied for a transmitter licence. This would provide the radio astronomy community an opportunity to assess the potential for interference and propose alternatives. The proposal did not prevent other services from using spectrum, and made the radio astronomy community responsible for finding solutions.

The APC did not receive any opposition to this proposal and their report[6] made the following recommendation:

"Radio astronomy facilities should be designated as 'radio sensitive sites' under the Australian Radiofrequency Spectrum Plan. These facilities must be notified that another user has applied for a transmitter licence wholly or partially within the bands specified in footnote AUS87."

The ACA agreed with the recommendation but advised the APC that the ARSP, which partitions the radio spectrum into bands and defines the general allocation for each band, is not an appropriate vehicle to trigger a notification of a licence application. However, the ACMA maintains a suite of documents called Radiocommunications Assignment and Licensing Instructions (RALIs), that establish and codify processes to avoid interference and make successful frequency assignments. These instructions are carried out by accredited persons who have the power to assign frequencies for new radiocommunications transmitters.

A RALI, therefore, has the ability to trigger notification to radio astronomy facilities of potentially interfering transmitters before they are turned on.

5 Notification zone determination

A notification zone should be large enough to capture most potential interference sources without unduly inconveniencing other spectrum users. A time percentage of 10% interference is typically used for radio astronomy facilities, as described in Recommendation ITU-R RA.1031.

The following methodology was used to determine the size of the notification zones. Details are provided in the following sections.

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[4] Australian Radiofrequency Spectrum Plan General Information Chapter 1 Part 4 Section 14.

[5] In 2002, the Australian Communications Authority (ACA); in 2005 the ACA merged with the Australian Broadcasting Authority to form the ACMA.

[6] https://www.pc.gov.au/inquiries/completed/radiocommunication/report

– Define characteristics of potentially interfering transmitters, i.e. service type and quantity, antenna height, bandwidth and e.i.r.p.. From this information, estimate power spectral density (PSD) from the most representative transmitter class in each band.
– Define characteristics for radio astronomy receivers, i.e. location, antenna (gain, beam pattern, effective height), bandwidth and receiver performance parameters.
– Calculate the required propagation loss so that the level of a potentially interfering signal falls below that which could degrade a radio astronomy receiver beyond an agreed value. Apply an appropriate path-loss model to determine the corresponding minimum separation distances for each band and radio telescope.
– Use this analysis to estimate an appropriate zone radius.
– Analyse the potential number of affected frequency assignments within each zone.

a) Terrestrial transmitters – Technical characteristics

Technical characteristics of likely transmitters determined from existing assignments within the AUS87 bands, as well as the locations of transmitters relative to radio astronomy facilities.

For example, in the band 1 250-1 780 MHz, there were assignments to ten service types, including radiodetermination, amateur, and point-to-point. Radiodetermination assignments had the highest power spectral density, but these were based on six assignments at two locations, neither of them close to radio astronomy facilities. There were, however, over 4 200 assignments to point-to-point fixed services in this band, and therefore the PSD and average antenna height for these services was taken as representative. This approach was repeated for the other frequency bands, and in practice the point-to-point fixed service was consistently the most representative case.

The typical PSD and antenna height of the representative transmitters in each band are shown in Table 4.

TABLE 4

Indicative interferer parameters

Band (MHz)	Power spectral density (dBm/Hz)	Antenna height (m)
1 250-1 780	0.6	30
2 200-2 550	−8.1	30
4 350-6 700	0.0	20
8 000-9 200	0.5	20
16 000-26 000	−6.0	20

b) Radio astronomy receivers – Technical characteristics

A value of 0 dBi is usually assumed for the gain of the radio astronomy antenna in the direction of the horizon, as per the advice in Recommendation ITU-R RA.769. However, it was considered that −10 dBi for Parkes and −15 dBi for Narrabri would more accurately reflect the antenna pattern[7].

Table 5 gives the effective antenna height for each of the radio telescopes described in AUS 87.

[7] The Parkes antenna has an effective elevation limit of 30 degrees from the horizon, so the gain towards the horizon is −10 dBi from Recommendation ITU-R S.1428.

TABLE 5

Effective antenna heights

Effective antenna height (m)					
Narrabri	**Parkes**	**Mopra**	**Mt Pleasant**	**Ceduna**	**Tidbinbilla**
18	30	13	15	12	30

The levels in Recommendation ITU-R RA.769 were used as the threshold interference levels of radio astronomy receivers.

For the Parkes telescope, the interference thresholds for spectral line observations were applied in the 1 250-1 780 MHz band and the continuum observation thresholds were applied for the other bands. For the Narrabri telescope, the the continuum specification was used for all bands. For the remaining telescopes, the thresholds applicable to VLBI observations were used.

Converting to power spectral density (dBm/Hz) and accounting for the antenna gain yields the receiver threshold limits in Table 6.

TABLE 6

Threshold levels

Band (MHz)	**Threshold levels (dBm/Hz)**								
	Recommendation ITU-R RA.769			**Narrabri**	**Parkes**	**Mopra**	**Mt Pleasant**	**Ceduna**	**Tidbin-billa**
	Cont	***Spec***	***VLBI***	***+15 dB***	***+10 dB***	***VLBI***	***VLBI***	***VLBI***	***VLBI***
1 250-1 780	–249	–233	–204	–234	–223	–204	–204	x	–204
2 200-2 550	–247	x	–204	–232	–237	–204	–204	–204	–204
4 350-6 700	–247	–235	–204	–232	–237	–204	–204	–204	–204
8 000-9 200	–250	x	–204	–235	–240	–204	–204	–204	–204
16 000-26 000	–251	–234	–200	–236	–241	–200	–200	–200	–200

c) Propagation model

A number of propagation models as given in the Recommendations of ITU-R Study Group 3 were considered for use in the analysis.

While Recommendation ITU-R P.452 would be the most suitable, as it includes all propagation mechanisms including troposcatter and anomalous propagation, in practice it leads to a very large zone size, which is logistically unhelpful. It was therefore decided to use the method for calculating diffraction loss over terrain (in addition to free space loss) as described in Recommendation ITU-R P.526 to determine the geographic zones, while noting the potential effect of other propagation modes.

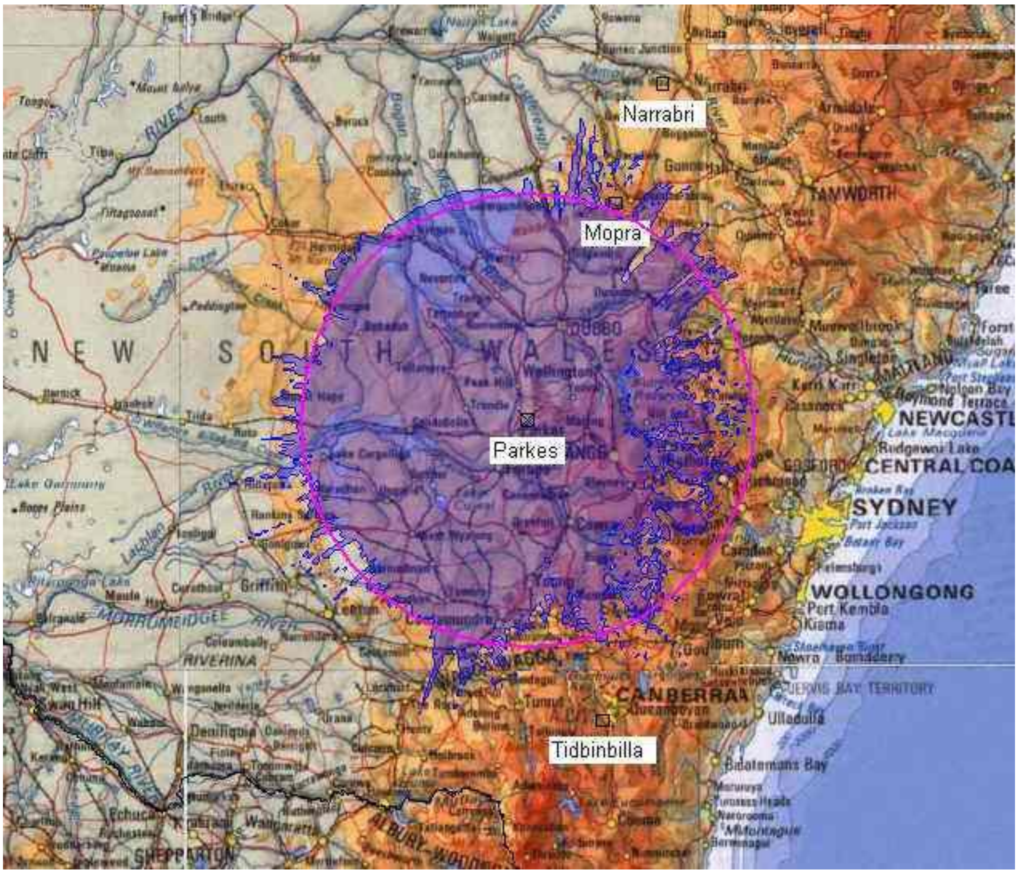
Terrain data for the diffraction calculation was taken from GEODATA 9 Second DEM, Version 2, a gridded digital elevation model with a grid spacing of 9 seconds in longitude and latitude (approximately 250 metres).

d) Interference analysis

Figure 10 shows results for the Parkes telescope at the 1 250-1 780 MHz band. The purple area represents the zone within which a transmitter with the characteristics of Tables 4 and 5 would exceed the thresholds in Table 6. A 200 km circle is a good approximation of the area and was chosen as the radius for this notification zone.

FIGURE 10

Parkes 1 250 MHz and 200 km circle



This was repeated for the frequency bands and the other radio telescope locations to obtain a notification zone size for each case.

e) Impact of zones

Before finalizing the zone sizes determined by the analysis described above, the impact of these zones on future spectrum use was considered. The apparatus licensing activity over the period 2000-2004 was used to estimate future activity. Frequency assignments approved within each of the zones for each frequency band was tabulated. Table 7 shows, as an example, the results for Tidbinbilla.

TABLE 7

Tidbinbilla area – Assignment activity

Band (MHz)	***D* (km)**	**2000**	**2001**	**2002**	**2003**	**2004**
1 250-1 780	120	1	0	3	6	12
2 200-2 550	80	0	0	0	0	0
4 350-6 700	70	0	3	0	5	1
8 000-9 200	50	0	0	4	4	0
16 000-26 000	30	18	10	16	22	12

Assignment activity was considered to be low for all the telescope/frequency combinations, with the exceptions of the 4 350-6 700 MHz band around Mt Pleasant and the 16-26 GHz band around Tidbinbilla.

Specifically there was high assignment activity around Mt Pleasant in the 5 GHz band, the 6 GHz band and the 6.7 GHz band. There was also high assignment activity near Tidbinbilla in the 18 GHz band and the 22 GHz band. It was therefore decided to exclude these sub-bands from the notification zone process to minimize the impost on the radiocommunications community around Mt Pleasant and Tidbinbilla.

f) Final notification zones

The notification zones as specified in RALI MS 31 are given in Table 8.

TABLE 8

Summary of notification zones

Band (MHz)	**Notification zones (km radius)**					
	Parkes	**Narrabri**	**Mopra**	**Mt Pleasant**	**Ceduna**	**Tidbinbilla**
1 250-1 780	200	250	150	100	n/a	120
2 200-2 550	180	180	130	80	120	80
4 350-6 700	160	160	120	70[8]	120	70
8 000-9 200	150	110	100	50	120	50
16 000-26 000	110	90	80	30	80	30[9]

6 Notification zone process

RALI MS 31 provides the threshold levels in Table 7 above, the zone sizes in Table 8 above, and advice on applying the propagation model of Recommendation ITU-R P.526. The process described in RALI MS 31 requires that an applicant for a terrestrial apparatus licence within the relevant frequency and notification zone must advise CSIRO before submitting the application to the ACMA.

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[8] Excluding the 5 GHz band (4.4-5 GHz), the 6 GHz band (5.925-6.425 GHz) and the 6.7 GHz band (6.425-7.11 GHz).

[9] Excluding the 18 GHz band (17.7-19.7 GHz) and the 22 GHz band (21.2-23.6 GHz).

The applicant can either supply the technical details of the proposed transmitter, in which case CSIRO will carry out an analysis, or the applicant can do the analysis and advise CSIRO of the results. If the power spectral density as estimated at the telescope is below the threshold, no further action is required. However, if the PSD exceeds the threshold, CSIRO can try to negotiate an acceptable alternative (for example, frequency channel, location) with the applicant. The applicant has no obligation to accept an alternative; therefore the 'notification zone' approach simply creates an opportunity for discussion.

In practice, this has been quite successful. Many transmitters in the notification zones have been found to meet the threshold without any modification. In other cases, the applicant has agreed to a change (generally a frequency channel) to reduce the impact on radio astronomy.

Attachement 1
to Annex 5

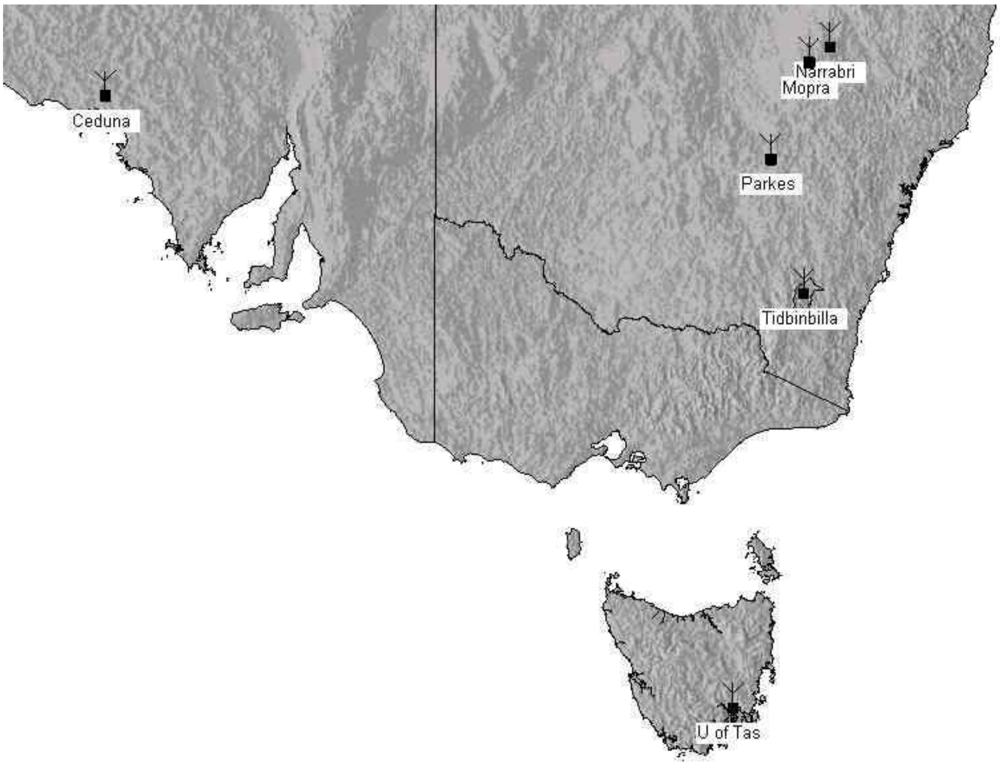
Australian radio-frequency spectrum plan footnote AUS87

AUS87 Radio astronomy facilities operated by the CSIRO at the Paul Wild Observatory Narrabri (latitude 30° 59' 52.048" S, longitude 149° 32' 56.327" E), the Parkes Observatory (latitude 32° 59' 59.8657" S, longitude 148° 15' 44.3591" E), and the Mopra Observatory Coonabarabran (latitude 31° 16' 4.451" S, longitude 149° 5' 58.732" E) and by the University of Tasmania at the Mount Pleasant Observatory Hobart (latitude 42° 48' 12.9207" S, longitude 147° 26' 25.854" E) and the Ceduna Observatory (latitude 31° 52' 08.8269" S, longitude 133° 48' 35.3748" E), and at the Canberra Deep Space Communication Complex (latitude 35° 23' 54" S, longitude 148° 58' 40" E) conduct passive observations in the frequency bands 1 250-1 780 MHz, 2 200-2 550 MHz, 4 350-6 700 MHz, 8 000-9 200 MHz and 16-26 GHz using receivers that are highly sensitive to interference.

Figure 11 shows the locations of these facilities.

FIGURE 11

AUS87 radio astronomy facility locations



Annex 6

The Australian Radio Quiet Zone Western Australia

1 Introduction

This Annex describes the measures defining the Australian Radio Quiet Zone Western Australia (ARQZWA) which protects radio astronomy activities on the Murchison Radio-astronomy Observatory (MRO). The ARQZWA was established to provide world-class radio quiet protection for new radio telescopes, including the Australian component of the Square Kilometre Array (SKA). As of 2019, the MRO hosts the Murchison Widefield Array telescope (MWA), the Australian SKA Pathfinder telescope (ASKAP) and the Experiment to Detect the Global EoR Signature (EDGES). Construction of the SKA is expected to start before 2022.

During the development of RALI MS 31 (as described in Annex 5) the Australian Communications and Media Authority (ACMA) recognised that their ability to protect radio telescopes near population centres was limited by the need to consider the wider needs of the community for radiocommunication services. The ARQZWA was established in a region of very low population density, where more stringent measures could be introduced.

2 Protection from individually licensed radiocommunications

This section considers controls on those radiocommunication transmitters which, in Australia, are covered by ‘apparatus licences’. These are issued to an applicant on an individual basis. This is in contrast to ‘spectrum licences’ and ‘class licences’ described in §§ 3 and 4, respectively.

a) Embargo 41, 2005

The initial step in establishing the ARQZWA was the introduction of an embargo on new terrestrial licensed transmitters. Embargo 41[10] was issued in April 2005 (and revised in November 2005 and April 2007). It specifies that no new radiofrequency assignments are to be made within 150 km (for the frequency range 100–230 MHz) and within 100 km (for frequencies from 230 MHz to 25.25 GHz) of the centre of the radio quiet zone. The revision in 2007 set the centre point at 26° 42’ 15” South, longitude 116° 39’ 32” East (GDA94 datum). The embargo did not cancel assignments that were already in place, and allowed for exceptions to new assignments on a case-by-case basis.

b) RALI MS 32, 2007

Embargo 41 was followed in 2007 by a Radiocommunications Assignment and Licensing Instruction (RALI) MS 32 which defined a process to assess potential licences in the region[11]. RALIs are policy documents defining ACMA procedures in deciding how to issue radiofrequency licences. Unlike the embargo which was a blanket restriction, RALI MS 32 provides a mechanism to consider applications on a case-by-case basis.

RALI MS 32 specified an inner ‘restricted zone’ of 150 km or 100 km within which licences would only be allowed on an exceptional basis. This was consistent with Embargo 41. Beyond the restricted zone, coordination zones are specified with a radius dependent on frequency, up to 260 km for the lowest frequency band. The zone sizes and PSD thresholds were derived in a similar manner to that described in Annex 5 for the notification zones. A summary is given in Attachment 1 to this Annex.

Within these coordination zones, applicants for licences are required to consult with CSIRO (as the site entity). If the proposed system exceeds the threshold level defined in RALI MS 32, CSIRO works with the applicant to consider modifications (e.g. location, frequency, power). If a solution is not found, CSIRO consults with science representatives for the MRO telescopes to assess whether the excess interference is acceptable. The outcome of this consultation is communicated to the ACMA along with the licensee’s application, and the ACMA then decides on whether to issue a licence.

In 2014, RALI MS 32 was revised to reduce the restricted zone to 70 km due to government concerns over the effect on some major mining projects. The revision also changed the lower frequency bound from 100 MHz to 70 MHz due to scope changes for the SKA. Finally, the revision introduced thresholds on received power over an area 50 km in radius, to protect against stronger signals which might produce non-linear effects in radio astronomy receivers.

c) Mid-West RQZ Band Plan, 2011

In 2011, the core protections of RALI MS 32 were incorporated in Australian legislation through the Radiocommunications (Mid-West Radio Quiet Zone) Frequency Band Plan[12]. As legislation rather than policy directions such as RALIs, a Band Plan has the same legal status as the Australian Radiofrequency Spectrum Plan.

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[10] https://www.acma.gov.au/-/media/Spectrum-Engineering/Regulation/pdf/Embargo-No-41.pdf?la=en

[11] https://www.acma.gov.au/-/media/Spectrum-Engineering/Information/Word-Document/RALI-MS32-ARQZWA.docx?la=en

[12] http://www.comlaw.gov.au/Details/F2011L01520

The Band Plan creates a primary allocation for radio astronomy in the frequency range 70 MHz-25.25 GHz for the Inner RQZ with a radius of 70 km, and a co-primary allocation (with the other services already allocated) for the Outer RQZ in the region between 70 and 150 km from the RQZ centre. The conditions of RALI MS 32 apply to the Outer RQZ.

While not changing the technical requirements of RALI MS 32, the Mid-West RQZ Band Plan gives more visible legal status to the radio quiet zone measures.

3 Protection from spectrum licensed radiocommunications

Spectrum licences authorise the licensee to deploy radiofrequency equipment operating in a specific frequency band and geographic area without requiring a licence for each installation. A typical application is mobile broadband network base stations.

The ACMA has placed restrictions on spectrum licences which generally are technically aligned with the conditions of RALI MS 32. For historical reasons, the manner in which this has been implemented varies; in some cases the geographic region around the ARQZWA is excised from the licence area. In other cases the licensee is required to consult under the terms of RALI MS 32 before installing transmitters within the same geographic zone covered by the RALI. In practice, this gives radio astronomy the same protection from spectrum licensed systems as from apparatus-licensed transmitters.

4 Protection from class licensed radiocommunications

Under Australian legislation, all transmitters must be licensed. Equipment for which individual licences would be impractical, such as ubiquitous consumer grade devices, are covered by class licences which specify frequency bands, EIRP limits and other technical constraints to minimize the potential for interference to other spectrum users. These licences are not issued individually, and in practice, most users of WiFi, garage door openers, CB radios and other such systems are unaware that a licence exists. In most cases, the requirement to comply with a class licence falls on the manufacturer, for example, by ensuring that EIRP limits are met.

However, with the introduction of the Mid-West Radio Quiet Zone Band Plan in 2011, the ACMA also placed conditions on three class licences. These were the licences covering satellite phones and the one for mobile CB radios (CB repeaters are individually licensed with apparatus licences) as well as the ‘Low Interference Potential Devices’ class licence. The last one covers many consumer grade and low power devices, including WiFi, Bluetooth, remote controls, remote monitoring and RFID. In general, class licences contain a requirement that users must not cause interference to licenced users of spectrum, and in conjunction with the Band Plan, this would provide legal protection. However, these three class licences were considered to be most likely of concern in the MRO region, and so explicit protection was included.

The conditions in the class licences apply to the Inner RQZ (70 km radius) and state that the user of the class-licensed device is in breach of the licence if they are notified that they are causing interference to radio astronomy observations.

In practice, enforcement of the class licence conditions is variable. CSIRO, as site entity, has briefed the local community on the requirements, and is available to provide advice before significant investments are undertaken (for example, new remote monitoring networks). Roadside signage has been erected at the 70 km boundary to advise travellers to turn off their radio devices. The class licence conditions give the site entity the legal basis to find interfering equipment and require that it be deactivated, although this has rarely been necessary.

5 Protection from mining activities

Apart from pastoral activity, which consists of large, very sparsely stocked cattle stations, the major industry in the Mid West region is mining. Radiocommunication equipment used by the mining industry is subject to the requirements described in §§ 2, 3 and 4 above. However, additional radio quiet measures have been introduced by the Western Australian government. These place restrictions on new mining activities in some areas, as well as providing for consultation about incidental emissions from mining operations.

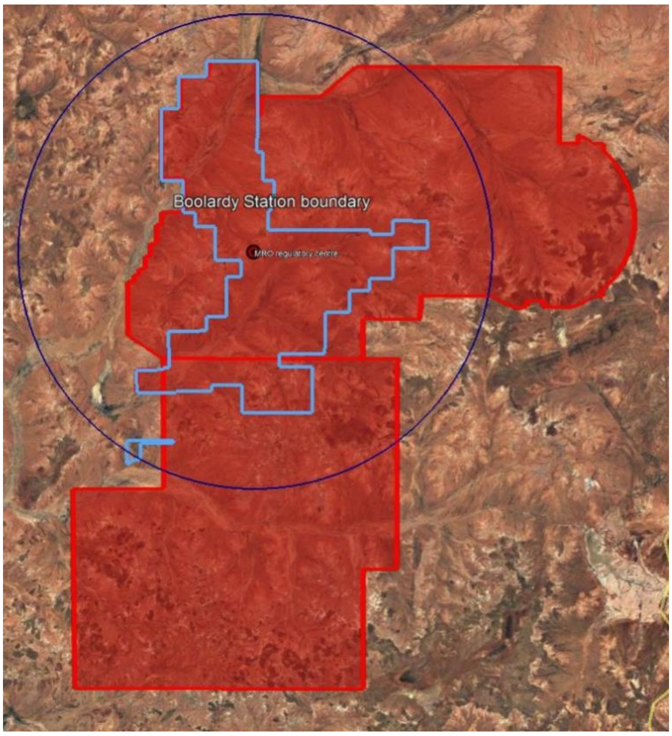
An irregular shaped region of land, with the boundaries based on existing operations and future prospectivity, has been identified under Section 19 of the *Mining Act 1978*. This identification prevents any new mining exploration or mine establishment. The “Section 19” zones are shown in red in Fig. 12. The outline of Boolardy Station, where the MRO is located, and a 70 km circle are shown for reference. It can be seen that the whole of Boolardy Station is covered, as is much of the 70 km Inner RQZ.

For the remaining part of the Inner RQZ not protected by Section 19, the Western Australian government, through its Department of Mines, Industry Regulation and Safety (DMIRS), has introduced measures to control interference from incidental emissions. Prior to filing a program of works or mining proposal (including for exploration activities) with DMIRS the proponent must file a Radio Emissions Management Plan (REMP). This plan must contain information about any electrical equipment, including vehicles,to be used for the mining work, as well as the location and time schedule of use. This should provide a sufficient basis to determine whether electromagnetic emissions from the activities will meet the radio-quiet requirements of the MRO (defined as the RALI MS 32 levels). CSIRO provides advice to DMIRS about the REMP as input to the approval process for the program of work.

In practice, some mining applicants, when advised of the REMP process as well as the restriction on radiocommunications under the ACMA measures, have decided not to proceed with mining exploration in the vicinity of the MRO.

FIGURE 12

Western Australian "Section 19" zones where mining is prohibited



6 Self protection from telescope operations

a) Telescope equipment

It is well known that electrical equipment used by a radio astronomy observatory is a major RFI concern. It is therefore important to have guidelines for equipment installed on the MRO itself.

However, assessment of interference from observatory equipment differs from that of telecommunication users or mines in two key respects. First, the distances are quite short, and propagation loss will vary quite significantly with specific geographic placement. Secondly, interference from observatory equipment is typically incidental emissions rather than deliberate radiocommunications, and may be harder to characterise.

In 2010, the MRO established basic guidelines for equipment to be deployed by the radio telescope users. It was deliberately designed to be very simple to assess and very conservative. An assumption was made that equipment could comply with (or be tested against) a well known US Military Standard, MIL-STD-461 (category RE102, Navy Mobile and Army). The emission levels from this standard, converted to a power spectral density, were then compared to the threshold levels of RALI MS 32. The difference therefore represents a loss which can be achieved by distance (only free space loss was assumed) and by shielding. The distance is defined as that between the piece of equipment installed as part of one telescope or experiment, and another telescope or experiment. That is, the standard does not address interference from part of one telescope to itself.

For three broad distance categories: less than 1 km, 1 to 10 km, and more than 10 km, the additional shielding was calculated as 80 dB, 20 dB, and 0 dB, respectively. All telescope operators are expected to comply with these limits, and non-compliant equipment which causes interference may be required to be removed.

Work is underway on a more sophisticated standard implemented in Matlab software. This will allow a user to choose from a list of industrial standards (for example, the CISPR series for commercial equipment) and identify the location of the proposed equipment (latitude, longitude, height). The software would then calculate any additional shielding required to ensure that emissions from the equipment do not exceed the RALI MS 32 levels at any of the other telescope receivers on the MRO. The output will be a plot of shielding as a function of frequency.

b) Short-term activities and discretionary equipment

It is recognized that some activities on the MRO, including construction, maintenance and publicity, may create RFI for a short time. Further, there may be a request to install other equipment not directly associated with radio astronomy observations, for example, for the use of staff on site.

A ‘Radio Emissions Management Plan’ process, based on the one described for mining in Section 5, has been implemented to address this. Proponents submit a REMP form describing the time and location of the activity, the proposed equipment (including vehicle, aircraft, or radio transmitters) and the purpose of the activity or equipment. The REMP is initially assessed by CSIRO to estimate the radio interference potential, and this is then advised to science representatives for the telescopes on the MRO. If there is no objection from the science representatives, the proposal is agreed and the applicant is informed. If there is concern that the activity will compromise astronomy observations, a consultation is undertaken to consider rescheduling or otherwise changing the activity.

In addition to telescope staff, this process has been used by local government (for example, in relation to roadworks or animal control) and a university (in relation to a geology field trip). A web-based version of the REMP is currently in testing.

Attachment 1
to Annex 6

Dimensioning the ARQZWA

The balance in dimensioning a radio quiet zone is between being sufficient to provide realistic protection of the site but not so large as to cause too great an impost on the community through denial of radiocommunications services.

1 Determining an appropriate geographic zone

RALI MS 32 recognizes that it is unlikely that any transmitter within the Inner RQZ of 70 km would be approved, so that coordination and consultation apply in the region beyond 70 km. Similar to the methodology described in Annex 5, the following approach was used to determine the size of the frequency-dependent coordination zones. Details are provided in the following sections.

– Divide the frequency range of the ARQZWA into frequency bands, based on allocations to other services which will potentially cause interference.
– Define characteristics of potentially interfering transmitters and estimate power spectral density (PSD) from the most representative transmitter class in each frequency band.
– Define characteristics for radio astronomy receivers.
– Calculate the required propagation loss. Apply an appropriate path-loss model to determine an appropriate zone radius for each band.
– Analyse the potential number of affected frequency assignments within each zone.

2 Terrestrial transmitters – Technical characteristics

Table 9 presents the relevant technical parameters of the most likely interferer, based on power spectral density and the number of existing assignments, for bands in the range 100 MHz to 25 GHz. Band divisions have been created so that transmitters with similar technical parameters are grouped together. (In the 2014 revision of RALI MS 32, the band 70-100 MHz was added, and the band edge at 820 MHz was changed to 694 MHz due to digital television replanning.)

TABLE 9

Indicative interferer parameters

Band (MHz)	e.i.r.p. (dBm/Hz)	Service	Antenna height (m)
100-230	20.1	FM and TV broadcasting	50
230-400	9.2	Land mobile	10
400-470	7.1	Land mobile	30
470-520	7.1	Land mobile	30
520-820	25	TV broadcasting	50
820-890	10.7	P-P	30
890-1 000	13.8	P-P	30
1 000-2 300	6.8	P-P	30
2 300-6 000	19.7	Earth station	10
6 000-10 000	7.9	P-P	30
10 000-25 000	−5.2	P-P	20

3 Radio astronomy receivers – Technical characteristics

An effective antenna height of 15 metres was used, based on proposals for the ASKAP telescope and early plans for the SKA. In the 2014 revision, a height of 1 m is used in the assessment for frequencies less than 300 MHz, based on updated designs for low frequency arrays.

A value of −15 dBi was assumed for the gain of the radio astronomy antenna in the direction of the horizon, based on expected elevation limits for dish antennas.

The levels in Table 3 of Recommendation ITU-R RA.769-1 were used as the threshold interference levels of radio astronomy receiving systems.

This results in the interference threshold values shown in Table 10.

TABLE 10

Interference threshold levels dBm/Hz

Frequency (MHz)	Interference threshold (dBm/Hz)
70	−211
100	−214
230	−222
400	−224
470	−224
520	−224
820	−228
890	−228
1 000	−230
2 300	−232
6 000	−232
10 000	−236

4 Propagation model

The ACMA chose to use a software package implementing DETVAG-90/FOA. This model was developed by the Swedish Defence Research Establishment and includes options to use several diffraction models, including Vogler's method for the calculation of multiple knife edge diffraction. It is suitable for frequencies between 10 kHz and 10 GHz. A time percentage of 10% was used, as per Recommendation ITU-R RA.1031.

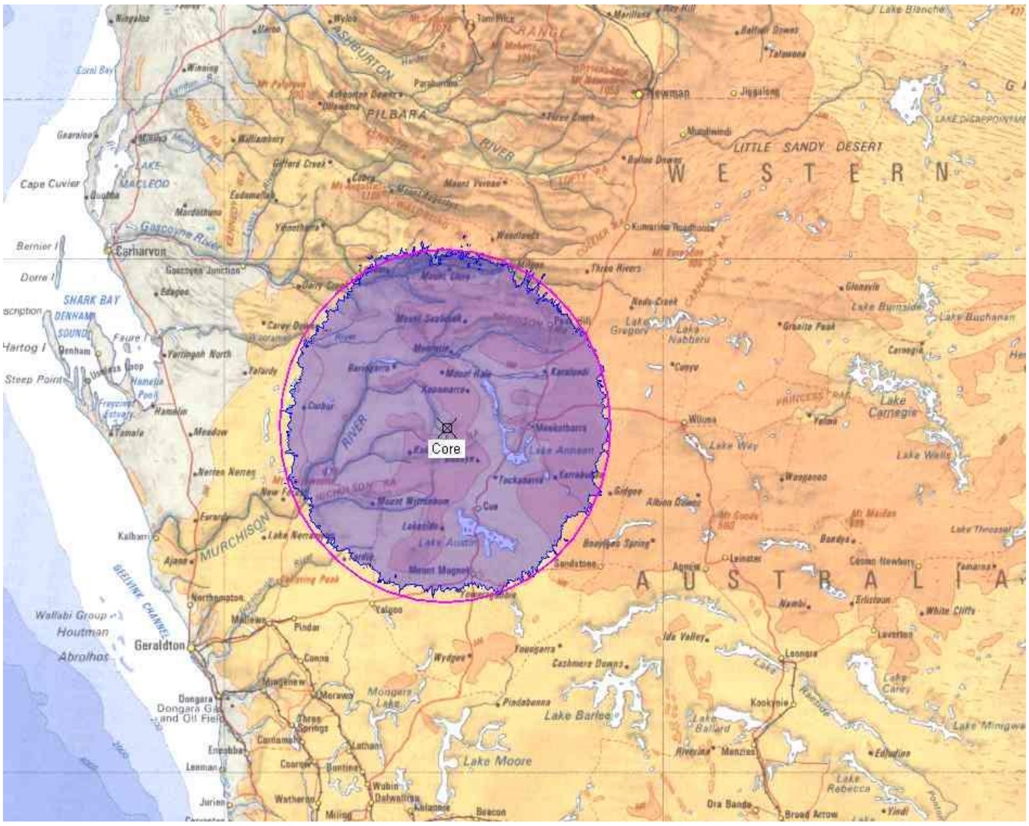
Terrain data for the diffraction calculation was taken from GEODATA 9 Second DEM, Version 2, a gridded digital elevation model with a grid spacing of 9 seconds in longitude and latitude (approximately 250 metres).

5 Interference analysis – centre criterion

Figure 13 shows results for the 520-820 MHz band. The purple area represents the zone within which a transmitter with the characteristics of Table 9 would exceed the thresholds in Table 10 at the centre point of the radio quiet zone. A 190 km circle is a good approximation of the area and was chosen as the radius for this frequency band.

FIGURE 13

Zone for 520-820 MHz (circle radius: 190 km)



This was repeated for other frequency bands to obtain the set of coordination zones.

6 Interference analysis – area criterion

For the 2014 revision of RALI MS 32, it was recognized that (a) the above analysis only evaluated interference received at the centre of the RQZ, while the telescopes at the MRO would be spread out over a larger geographic area and (b) in some cases, for coexistence with industry, there would be some need to allow transmissions that exceeded the centre theshold. A second criterion was introduced: a power level that represented the point at which radio telescope receivers would be driven to a non-linear point, and therefore astronomy signals could not be recovered. This criterion was defined in power (dBm) and evaluated not just at the centre of the RQZ, but over an area 50 km in radius around that centre.

A Monte Carlo analysis, using typical transmitter characteristics but random placement, showed that there was less than a 1% chance of meeting the centre threshold but failing the area test. These only occurred at microwave frequencies (and accounted for less than 3% of the microwave cases). It was therefore considered that this additional criterion did not introduce a significant new barrier, but provided a useful hard backstop if it is necessary to relax the centre threshold in some cases.

7 Results

Table 11 provides the size coordination radius, centre threshold and area threshold as a function of frequency bands as in the 2014 revision of RALI MS 32.

TABLE 11

ARQZWA zone parameters

Frequency range (MHz)	Coordination radius (km)	Threshold at ARQZWA centre (dBm/Hz)	Maximum allowable power level within 50 km (dBm)
70-100	260	−211	−90
100-230	260	−214	−90
230-400	180	−222	−95
400-520	165	−224	−95
520-694	190	−224	−95
694-1 000	145	−228	−95
1 000-2 300	140	−230	−95
2 300-6 000	120	−232	−95
6 000-10 000	100	−232	−95
10 000-25 250	100	−236	−95

8 Impact of zones

To assess the impact of the zones on the local community, the number of existing apparatus licences (at 2000) and new licences (in the period 2000-2005) were examined. This is shown in Table 12.

TABLE 12

Zone survey

Band (MHz)	Radius of zone (km)	Assignments within zone in 2000	New assignments by year					
			2000	2001	2002	2003	2004	2005
100-230	260	220	2	14	4	18	9	2
230-400	180	0	0	0	0	0	0	0
400-520	165	71	8	3	0	2	6	2
520-820	190	48	3	12	0	12	0	0
820-890	145	9	1	0	0	0	0	2
890-1 000	145	5	0	0	0	0	0	2
1 000-2 300	140	61	0	1	7	4	0	0
2 300-6 000	120	1	0	0	0	0	0	0
6 000-10 000	100	0	0	0	0	0	0	0
10 000-25 000	100	2	0	0	0	0	0	0

The survey of frequency assignments and trend shows a low level of activity, indicating that the. RQZ would have a low impost on the radiocommunications community.

Annex 7

Characteristics of radio quiet zones: protection of the radio telescopes in Spain

1 Actions taken by the administration of Spain to protect the IRAM 30 m radio telescope operating in the Sierra Nevada near Granada

a) Introduction and description

The Instituto de Radioastronomía Milimétrica (IRAM), in collaboration with the (Spanish) National Geographic Institute (IGN), operates a radio astronomy observatory station at Pico Veleta (Veleta Peak-Loma del Dilar), Sierra Nevada, Granada, at WGS coordinates: N 37º 03’ 58”, W 03º 23’ 34”, 2 904.0 m The radio astronomy instrument there is a 30 m telescope (The IRAM 30 m telescope) with surface accuracy of 70 microns, operating in the frequency range 70-275 GHz. Further information about the telescope is available at http://www.iram.es/.

The observatory is in the midst of a large ski resort, above the resort buildings, hotels, *etc.* but somewhat below the ski trail peaks. When the ground is bare it is possible to drive directly to the telescope on paved roads (but only by authorized vehicles) and the area sees occasional hikers and sightseers. When the ground is snow-covered, access is by a specialized snow vehicle. The telescope is visible both from the city of Granada (a 50 minute drive; see Fig. 14) and the nearby ski resort base camp.

b) Specific protections

Spanish National State Secretariat for Telecommunications and the Information Society, in its Order 1679 of June 18, 2009, “In order to ensure the efficient reception of signals from outer space and to provide protection of the instrument from radio interference”, established various limitations on nearby property rights and electromagnetic emissions. The limitations created by Order 1679 may be summarized as follows:

i) Geographic reference point for establishing the limitations

This are defined by WGS coordinates: N 37º 03’ 58”; W 03º 23’ 34”; 2904.0 m

ii) Limitations on property rights

The proprietors or occupants under any title of any of the lots adjacent to the observatory shall be inhibited from building or modifying buildings not in accordance with the limitations and bounds established in the present resolution.

Within a radius of 1000 m from the radio astronomy station, no construction should appear above an elevation of 3 degrees as viewed by the telescope.

The minimum separation between an industrial facility, high voltage power line or railway, and any of the receiving antennas of the observatory will be 1 000 m.

To determine the minimum distance from the observatory at which radio transmitters may be located, taking into account that the station operates at frequencies above 3 000 MHz, the limitations set out in Table 13 shall apply:

TABLE 13

Range of frequencies (f) (MHz)	Interfering service	Apparent radiated power of the transmitter in the direction of the station to be protected (kW)	Maximum distance limitation that may be applied between the transmitting antenna and the station to be protected (km)	Maximum distance limitation and radio electric conditions (CRE)* that may be demanded (km)
$f > 3\,000$	Radiolocation Space Research (Earth-to-space)	$0.001 < P \leq 1$	1	
		$1 < P \leq 10$	2	
		$P > 10$	5	
	Other services	$0.001 < P \leq 0.01$	0.6	02, and CRE
		$0.01 < P$	1	

* The radio electric conditions that may be demanded (CRE) will be understood, in accordance with those established in Royal Decree 1066/2001, of 28 September.

iii) Limitations on the intensity of the electric field

To protect the frequency bands used by the observatory which are allocated to the Radio Astronomy Service on a primary basis in the National Table of Allocations in force, the intensity of the electric field in the above referenced bands will be limited to the following values, when measured at the observatory, independently of where the transmitter is located:

TABLE 14

Frequency band	Pfd (dB(W/m^2))	Equivalent intensity of the electric field (dB(µV/m))
76-77.5 GHz	–130	15.8
79-86 GHz	–129	16.8
86-94 GHz	–125	20.8
94.1-116 GHz	–124	21.8
130-134 GHz	–124	21.8
136-158.5 GHz	–124	21.8
164-167 GHz	–123	22.8
182-185 GHz	–121	24.8
200-231.5 GHz	–119	26.8
241-248 GHz	–118	27.8
250-275 GHz	–117	28.8

For all other frequencies, the intensity of the electric field shall be limited to +88 dB(µV/m) (–57 dB(W/m^2)), also measured at the site of the Radio Astronomy Station.

iv) Radio coordination zone

Prior to assigning frequencies to radiocommunication stations with an apparent radiated power that exceeds 25 Watts in the direction of the observatory, within a 10 km radius of the same, studies will be carried out to determine that the intensity of the electric field at the reference point of the Observatory shall not exceed the appropriate values given in *iii)*. A theoretical model will be employed to calculate the electric field intensity, and the radiation pattern of the station and the terrain attenuation will also be taken into account.

Should the theoretical calculations result in an electric field intensity in excess of the limits stipulated in section b, electric field intensity measurements may be carried out at observatory using trial signals, and in collaboration with observatory and State Secretariat for Telecommunications and the Information Society staff. Under no event will the outcome of such measurements exempt the definitive transmitter of the obligation to comply with the limits given in *iii)* above.

v) Supervision and control

The State Secretariat for Telecommunications and the Information Society will exercise the functions attributed to it in order to conduct inspections on compliance with the limitations and bounds established.

vi) Appeals

A brief period (one-two months), was granted after publication of the decree, during which appeals or lawsuits against the decree could be filed.

FIGURE 14

Location of the IRAM 30 m telescope in the Sierra Nevada near Granada, Spain, shown on a relief map

2 Actions taken by the administration of Spain to protect the Yebes radio telescope

a) Introduction and description

The Spanish National Geographic Institute (IGN) is a governmental institution that operates three radio telescopes in Yebes Observatory (Guadalajara, Spain) whose sizes are 40-m, 13.2-m and 14-m in diameter. They allow to conduct radio astronomy observations, either single-dish or VLBI, in the range 2 to 116 GHz in different bands. The location of each radio telescope is the following:

- 40-m: 40º 31' 28.83" N, −3º 5' 12.68" E
- 13.2-m: 40º 31' 24.51" N, −3º 5' 18.71" E
- 14-m: 40º 31' 26.97" N, −3º 5' 21.8" E

The mean altitude of the site is 980 m above sea level. Snow is present only 2-3 days per year. Further information can be found in: http://astronomia.ign.es/web/guest/telescopios

The observatory located on the top of a hill in the country-side, but it is surrounded by nearby towns and there is a high speed train station at 6.5 km, approximately. It is only 70 km to the east of Madrid and the closest airport is at 30 km.

The site can be reached by car and visitors usually arrive by bus.

b) Specific protections

The Spanish National State Secretariat for Telecommunication and the Information Society, in its order CTE/1444 of May 22, 2003, establishes radio electric protection of the Yebes Observatory (Guadalajara, Spain). This protection has been updated in the new Law of Telecommunications, published in the Spanish Official Bulletin the 10th of May, 2014.

i) Limitations on property rights

Within a radius of 1000 m from the radio astronomy station, no construction should appear above an elevation of 3 degrees as viewed by the telescope.

The minimum separation between an industrial facility, high voltage power line or railway, and any of the receiving antennas of the observatory will be 1 000 m.

Electric intensity field measured in the observatory within the restricted bands used for any of the radiotelescopes has to be limited to the values given in Table 15.

TABLE 15

Electric intensity restricted frequency bands at Yebes Observatory [(1)]

Frequency band	Pfd (dB(W/m^2))	Equivalent intensity of the electric field (dB(μV/m))
1 400-1 427 MHz	−180	−34.2
1 419.99-1 420.01	−196	−50.2
1 610.6-1 613.8 MHz	−181	−35.2
1660-1 670 MHz	−181	−35.2
2 690-2 700 MHz	−177	−31.2
49 990-5 000 MHz	−171	−25.2
10.6-10.7 GHz	−160	−14.2
15.35-15.4 GHz	−156	−10.2
22.19-22.20 GHz	−162	−16.2
22.21-22.5 GHz	−148	−0.2
23.69-23.70 GHz	−161	−15.2
23.6-24 GHz	−147	−1.2
31.3-31.8 GHz	−141	4.8
42.5-43.5 GHz	−137	8.8
72.75-80.75 GHz	−130	15.8
78.5-86.5 GHz	−129	16.8
88.59-88.60 GHz	−148	−2.2
86-92 GHz	−125	20.8
101.05-109.05 GHz	−124	21.8

(1) This Table has been extracted from the values given in Spanish Law of Telecommunications, Boletín Oficial del Estado 10 Mayo 2014, Sec.I page 35905”.

The remaining frequencies have a limitation of +88.8 dB(uV/m) measured at the location of the radioastronomy station.

Radioelectric transmitting stations located in the proximities of the observatory have to comply with the following power limitations:

TABLE 16

Range of frequencies (f) (MHz)	Apparent radiated power of the transmitter in the direction of the station to be protected (kW)	Maximum distance limitation that may be applied between the transmitting antenna and the station to be protected (km)
$f \leq 30$	$0.01 < P < 1$	2
	$1 < P \leq 10$	10
	$P > 10$	20
$f > 30$	$0.01 < P \leq 1$	1
	$1 < P \leq 10$	2
	$P > 10$	5

When a frequency band has to be allocated to a station located at less than 20 km from the radioastronomy station, if the power radiated is over 25 watts, some measurements has to be carried out at the radioastronomy station. At first, some theoretical calculation has to be done in order to have a first approximation of the electric intensity field level that will be received at Yebes Observatory. This value has to be below the one shown in Table 14. In case these calculations shown an intensity level higher than that, some test measurements could be performed at radioastronomy centre by observatory personal staff along with Spanish National State Secretariat for Telecommunication and the Information Society staff, in order to check it. In any case, transmitter has to satisfy the restriction given in Table 14.

ii) Supervision and control functions

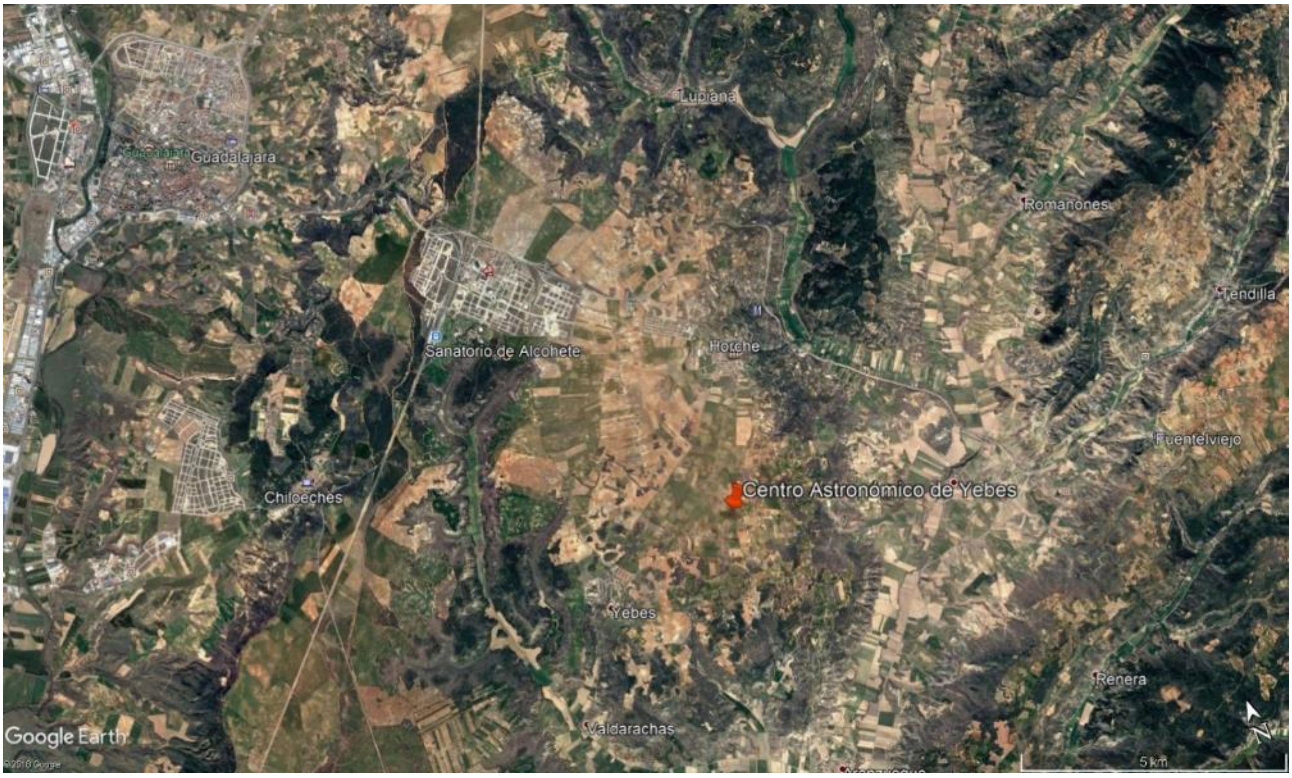
The State Secretariat for Telecommunications and the Information Society will exercise the functions attributed to it in order to conduct inspections on compliance with the limitations and bounds established in the law

iii) Appeals

A brief period (one-two months), was granted after publication of the decree, during which appeals or lawsuits against the decree could be filed.

FIGURE 15

Satellite view of the location of the Yebes Observatory near Guadalajara (Spain) and surroundings



Annex 8

Spectrum protection criteria for the Square Kilometre Array (SKA)

1 Introduction

The Square Kilometre Array (SKA) is the next generation radio telescope, designed as a global endeavour involving 14 countries and more than 600 professionals. The SKA will be constructed by the SKA Observatory, the first intergovernmental organisation dedicated to radio astronomy.

The breadth of science that the SKA will cover is truly remarkable, and includes:

– Penetration of the earliest stages of the Universe (Cosmic Dawn) as it transformed from a sea of neutral hydrogen to the first stars and galaxies.
– Mapping the evolution of galaxies from their earliest formation until the present day using high-sensitivity observations of huge samples of galaxies.
– Strong tests of Einstein’s theory of gravity in the regions around black holes.
– Discovering long-period gravitational waves, which have emanated from the big bang itself.
– Understanding how cosmic magnetism has shaped the Universe.
– Tracing the star-formation history of the Universe.
– Discovering the earliest stages of the formation of disks around stars before planet formation.
– Finding the astronomical origin of mysterious bursts of radio emission.

To explore this extensive range of science objectives, and at the same time provide the flexibility for unexpected discoveries, the SKA will bring up to two orders of magnitude increase in sensitivity within the frequency range of 50 MHz to 25.5 GHz. This enhancement results from a hundred-fold increase of collecting area at centimetre wavelengths, combined with an increase of the operating bandwidth for continuum observations, as compared with existing radio telescopes.

SKA will observe the faintest signals arriving from cosmic sources, with power levels up to seven orders of magnitude lower than a typical communication signal. This makes radio frequency interference (RFI) one of the highest risks for the SKA, where the effect of RFI on radio telescope receivers can range from lost data in frequency and time domain, up to damage of a front end in extreme cases.

The active use of the radio spectrum is continuously increasing due to technological advances and increased demand for wireless services. Continuum access to the radio spectrum, as needed for SKAO’s scientific goals, will result in overlap with numerous frequency bands allocated to active radiocommunication services. Radio transmissions from such stations will constitute RFI for the SKA, which is a growing concern in the radio astronomy community.

The SKA will deal with RFI by the combination of:

1) choosing remote locations with a low population density;
2) having RFI resilient receivers, with as high a dynamic range as possible;
3) incorporating RFI mitigation technology into the telescope signal chain; and
4) by establishing a Radio Quiet Zone around the telescopes.

This Annex describes the protection that the SKA requires to ensure the envisioned scientific output of the instruments.

2 The SKA Observatory

The SKA Observatory (SKAO) will comprise two telescopes on two sites, SKA-Low in Australia and SKA-Mid in South Africa, as well as the SKAO Global Headquarters in the United Kingdom. Science data products of SKA will be distributed around the globe by a network of regional science centres located in various SKAO member countries.

Both telescopes are designed as interferometers, providing a higher resolution on the sky than a single-dish telescope. SKA1-Low, located in the Murchison Shire in Western Australia, will comprise 131 000 log-periodic antennas arranged in 512 stations of 256 antennas. SKA1-Mid, located in the Karoo area of South Africa, will comprise 197~15 m dish antennas (including the 64 dishes of the MeerKAT precursor telescope). After the initial deployment of SKA1, it is expected that SKA2 will extend both telescopes throughout most of Australia/New Zealand and the African continent respectively.

FIGURE 16

SKA-MID, (a) location with respect to Cape Town, (b) central area, and (c) core

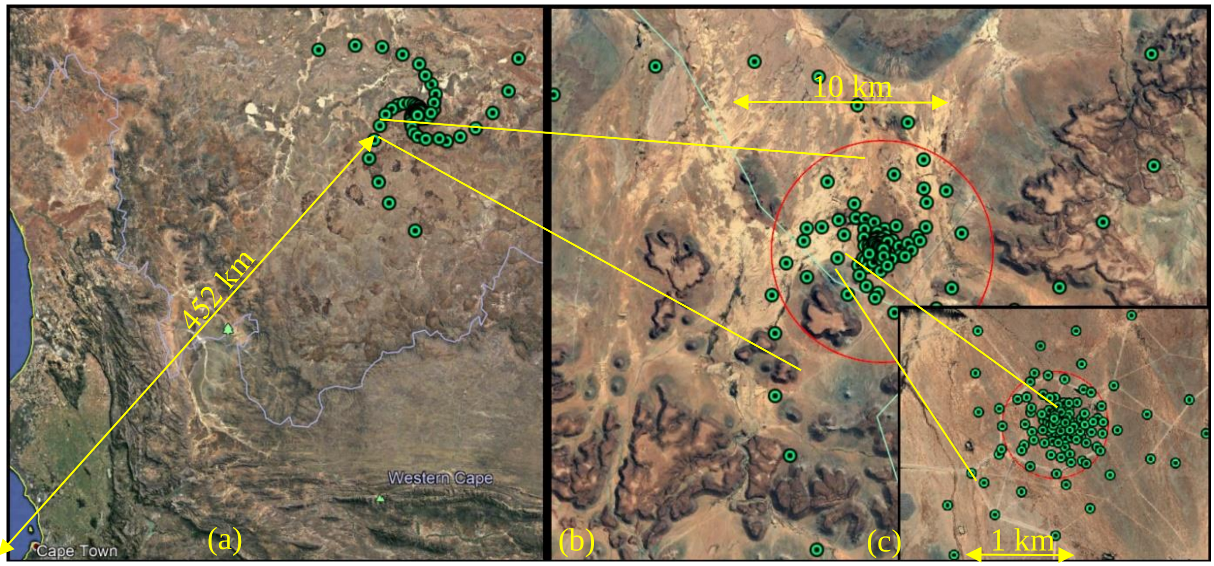
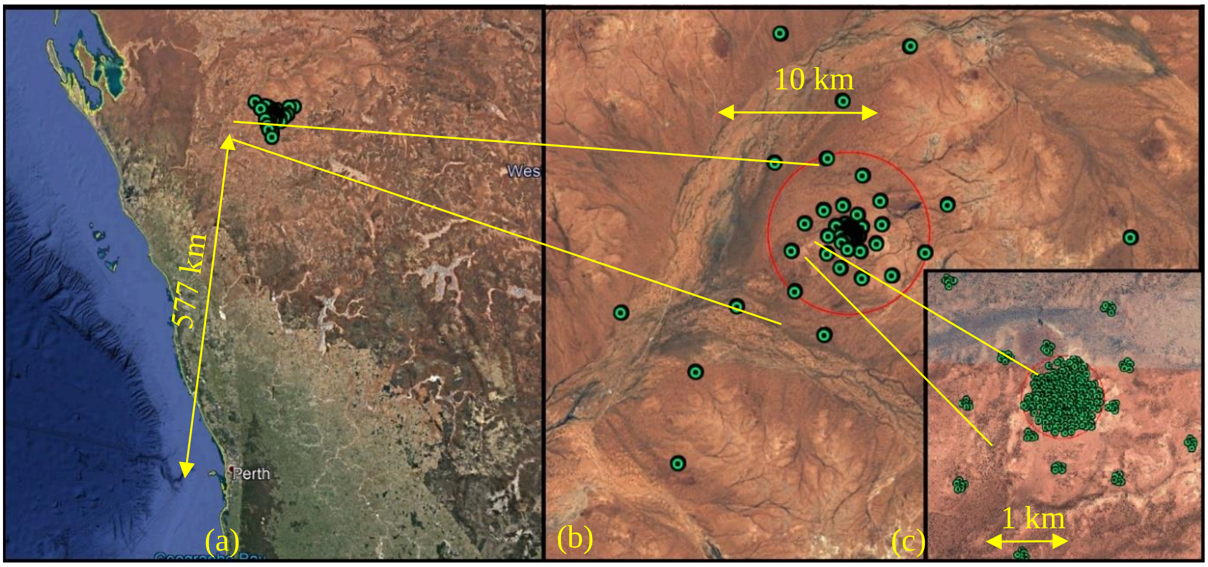


FIGURE 17

SKA-LOW, (a) location with respect to Perth, (b) central area, and (c) core



The core and central area of each telescope can be defined as a circle with an approximate radius of 0.5 km and 5 km respectively, where most of the collecting area will be located in a densely packed configuration. Outside of the central area, three spiral arms reach up to 38 km from the array centre in SKA1-Low (90 km for SKA1-Mid), which provides the rest of the total collecting area. The separation of individual antennas along the spiral arms is increased logarithmically from a few km to up to 20 km for the outermost. The expansion of SKA2 will deploy stations (dishes) located further away than the spiral arms, extending into the east of Australia for SKA1-Low and to other African countries in the case of SKA1-Mid.

3 Protection Thresholds for the SKA

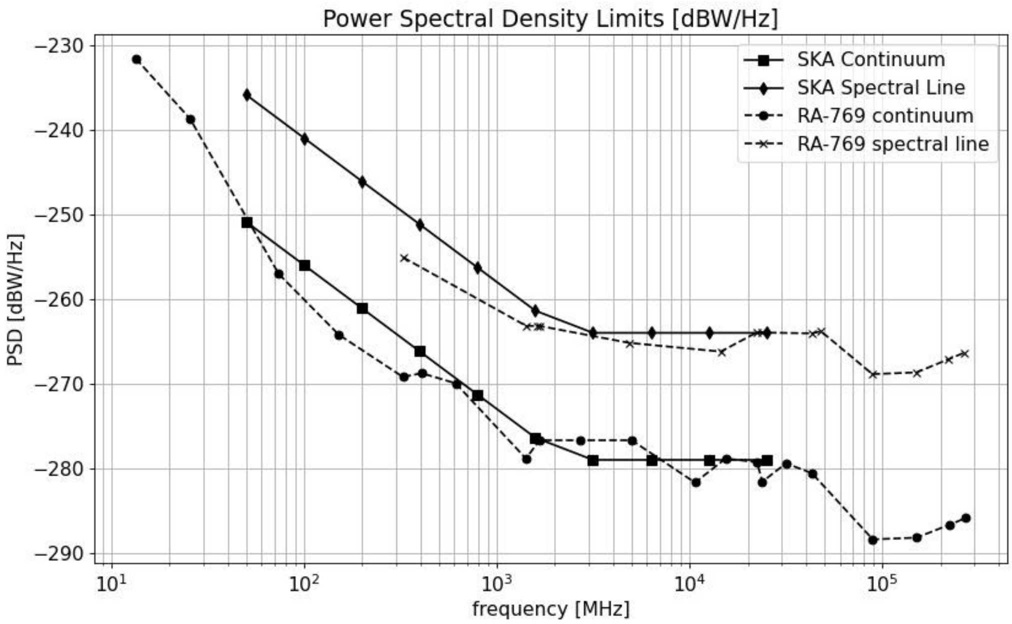
Recommendation ITU-R RA.769 defines the interference thresholds for single telescope observations and more relaxed thresholds for Very Long Baseline Interferometry (VLBI) observations. While the SKA will benefit from RFI mitigation as an interferometer, the densely packed central area will require protection levels in the same order as that of single antenna telescopes. For the spiral arms and remote stations, the interferometric effect will provide a level of mitigation dependent on the antenna baselines and the characteristics of the RFI source. Terrestrial RFI that is only present at one antenna will be mitigated by the interferometric effect, as long as it is not saturating the receiver. Very distant RFI sources such as air- or space-systems could generate a quasi-planar wave towards the antenna pairs, diminishing the attenuation effect of the interferometer.

3.1 Telescope Protection Levels

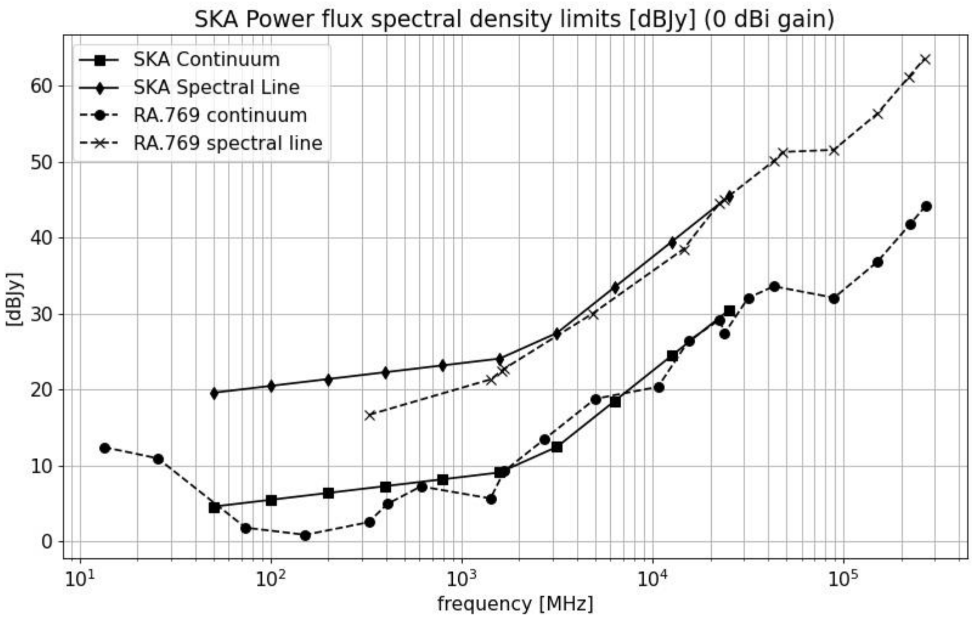
Based on Recommendation ITU-R RA.769, the SKAO has defined its own *SKA protection levels* as a limit for internally and externally generated RFI deemed harmful to SKA observations. A distinction between Recommendation ITU-R RA.769 and the SKA protection levels is that the latter covers the frequency range from 50 MHz up to 25.5 GHz continuously. In frequency bands where thresholds are not defined in Recommendation ITU-R RA.769, the SKA protection levels were derived by interpolation. This resulted in a compromise where in some frequencies the SKA limits are more stringent than Recommendation ITU-R RA.769 and others the opposite. Figure 18 shows both the SKA protection levels and Recommendation ITU-R RA.769 continuum and spectral line limits.

FIGURE 18

Comparison of SKA and RA.769 thresholds in (a) power spectral density [dB(W/Hz)] and in (b) power flux spectral density [dBJy]. Note: 1 Jy is equal to −260 dB(W/m²/Hz)



(a)



(b)

3.2 Interferometric effect

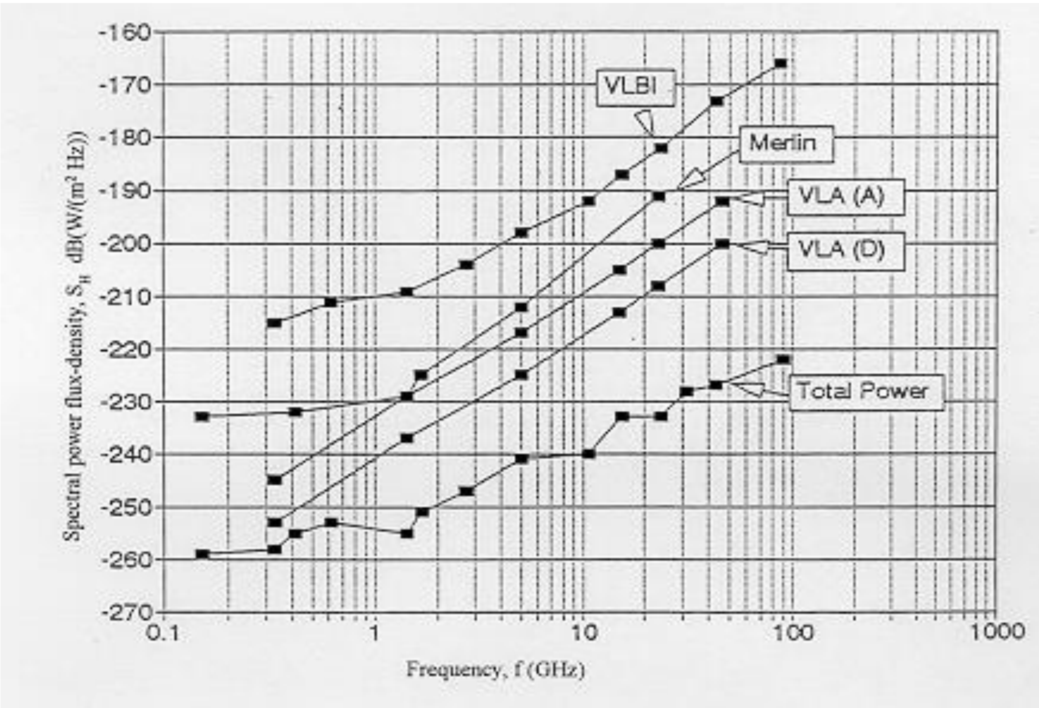
An aperture synthesis telescope, such as the SKA, provides greater discrimination against interfering signals than a single-dish (total power) radio telescope. In any interferometer pair, separation of the stations causes relative changes in the phases of the incident signals, and this results in *fringe rotation* associated with the sidereal motion of the cosmic source being observed. The response of a radio telescope array can thus be seen as a weighted response of a large number of antenna pairs with different spatial orientation and separation distances.

In the case of broadband interfering signals, further rejection occurs because of inequalities in the time delays from one side of the observing band to the other, which results from *delay tracking* of the signal paths via the individual antennas and results in de-correlation of the RFI signals. The magnitude of the de-correlation depends on the position of the RFI source on the sky and the projection of the baseline on this direction. A detailed explanation of these effects can be found in Chapter 15, "Interferometry and Synthesis in Radio Astronomy" by Thompson, A.R., Moran, J.M. and Swenson, G.W. (1986).

The ITU-R Handbook on Radio Astronomy shows the detrimental interference levels computed for interferometers such as the VLA-D and VLA-A configurations and MERLIN. These are compared to the single-dish continuum and the VLBI levels in Fig. 19. The lower threshold levels for these arrays, compared to those for single-dish telescopes, result from the separation of the stations of the array, observing bandwidths and integration times.

FIGURE 19

The curve marked as Total Power is for single dish telescopes. The ordinate is given as spfd (from ITU-R Handbook on Radio Astronomy)



The VLA-D configuration has the densest core of all compared arrays. Its RFI protection requirements are approximately 15 dB less stringent than those of single-dish (total power) telescopes (Table 1 of Recommendation ITU-R RA.769). The spacing of the stations/dishes of the SKA1 central area will be even less than the closest VLA-D spacing. Therefore, the protection of the SKA central area should be to the same as that of the single-dish values given in Recommendation ITU-R RA.769. The protection requirements for the stations beyond the central area will start with the most stringent single-dish values decreasing with an interferometric factor up to the threshold levels for VLBI observations at the outermost stations.

3.3 Telescope Saturation Level

It is reasonable to expect that no environment will ever be 100% RFI free. As a minimum, a sub-set of frequencies will always be needed for essential services deployed on the sites or the surrounding communities. For these cases it is important to ensure that the interference levels on SKA receivers do not produce non-linear effects that could result in a contamination of a wider bandwidth than that of the RFI signal. The power level at which an LNA starts to produce non-linear products up to the level that it can impact RAS observations in another frequency band depends on the characteristics of each receiver, and in the case of the SKA1 there are seven different receivers to consider. As a conservative value, an input power of −100 dBm is defined as the saturation threshold. This value simplifies interference studies and the regulatory processes that can be applied on SKA sites.

4 Classification of RFI Sources

RFI affecting a radio telescope can be classified by several dimensions such as the type of source, frequency or time signatures, amplitude, time occupancy, long term periodicity, affected parts of the array, and many others. For the purpose of this discussion, it is divided into intentional and unintentional RFI. Unintentional sources of RFI are considered to originate from electrical equipment generating radio emissions as a secondary product of its operations (e.g. cars, microwave ovens, electric motors, etc). The intentional sources or transmitters group can be further classified into ground based (e.g. mobile phone networks, hand-held radios, broadcasting stations, point to point links, earth stations communicating with satellites, etc) and non-ground based RFI (e.g. airplanes, high altitude platforms, Earth satellites, interplanetary spacecraft, etc). As a general rule, ground based radio communication users are exclusively managed by the national entity in charge of the radio spectrum, while the regulation of aerial and space usage includes an important aspect of international agreements at the ITU-R.

The SKA-Mid antennas will have a minimum elevation of 15 degrees, therefore RFI coming from ground-based stations (or unintentional radiation from electrical equipment) will enter the antennas though its 0 dBi side lobes. Each SKA-Low antenna will have a broad fixed beam pointing towards the nadir, where for elevations less than 15 degrees the same 0 dBi assumption holds. This is the same assumption that is used for the derivation of the Recommendation ITU-R RA.769 limits and can be used to find the necessary separation distance for terrestrial RFI sources. As an example, an IT equipment certified to CISPR22 standards will require an extra shielding of 60 dB (average in frequency) to comply to the SKA protection levels if located at a distance of 1km from an antenna.

For the case of air- or space-borne RFI sources, there is a probability that an SKA antenna will be pointing towards it with a gain level larger than 0 dBi. A reference antenna pattern for radio astronomy has an average gain above 0 dBi for boresight angles of less than 19 degrees (see Recommendation ITU-R RA.517). This effectively means that an RFI source in the sky, in compliance with Recommendation ITU-R RA.769 levels, should be avoided by an angle of up to 19 degrees from the boresight direction of the radio astronomy antenna. The recent development of very large satellite constellation deployments has increased the satellite density in the sky, increasing the probability of beam-to-beam coupling but also increasing the total received power by aggregation of many visible sources simultaneously.

5 Protection from ground-based RFI

Protection from ground-based RFI can be granted to the SKA telescopes by its host countries through the establishment of Radio-Quiet Zones (RQZ) as protected areas under national legislation and regulations facilitating radio astronomical research. The radio-quiet characteristics of the SKA sites was an important criterion for the site selection process, including commitments to improve and maintain it over the 50 years lifetime of the observatory.

In the central area the interferometric effect will have little impact on interference due to its relatively short baselines. Therefore, the central areas of both SKA telescopes can be considered as single-antenna telescopes and will require the highest level of protection as defined in § 3. Interference received by baselines in the spiral arms will be mitigated though the interferometric effect, as a function of projected baseline distances, location, and other characteristics of the RFI source and observational parameters. The required protection level of the spiral arms should start with the SKA protection levels for short baselines, with a relaxation towards the dishes/stations in the extremes of the spirals. Dishes or stations of SKA2, located further away than the spiral arms, can be considered as pure VLBI stations due to their large baselines. Protections for these remote stations can be established as local areas around each dish/station where the SKA protection levels (adjusted for VLBI levels as per Recommendation ITU-R RA.769) are respected.

5.1 Restriction Zones

To achieve the highest level of protection from intended transmissions from licensed or unlicensed transmitters, a restriction zone around each antenna shall be defined. The extension of these restriction zones could be defined by calculating the necessary attenuation that an unlicensed device (like a Wi-Fi, Bluetooth, remote control transmitter, etc.) would require in order to comply to the SKA protection levels at each SKA receiver (with little or no extra shielding) taking into account the geographic characteristics of each area. Restriction zones for antennas in the central area will naturally overlap with each other, resulting in a quasi-circular area centered at the centroid of the array. In the case of the spiral arms and remote antennas, restriction zones will be centred on each antenna individually.

5.2 Coordination zones

Outside of each restriction zone, a coordination zone shall be defined where the site entity will be involved in the licensing process of active services to ensure that any licensed transmitter is in compliance with the SKA protection levels for all antennas in the telescope. For the outermost antennas of the array, a relaxation of the protection levels is accepted considering the RFI mitigation effect of long baselines. Within a coordination zone the use of unlicensed (or license exempt) devices is typically allowed.

5.3 Exempted frequencies

Any intentional transmitter within the RQZ, operating under the exempted frequency bands defined in the RQZ regulations, should not generate interference levels that can saturate any SKA receiver. This will enable the SKA to excise the exempt transmitter frequency band from the observation data without losing extra spectrum.

5.4 Restricted access zones (RFI zones)

RFI Zones (RFIZ) under direct control of the Observatory will be established to protect the telescopes from RFI from electrical and electronic equipment (intentional and unintentional radiators) from within the SKA Observatory, other instruments on site, or any supporting equipment or activity. Access controls, considering the equipment to be used/installed, the type of activity to be conducted, and the operational condition of the telescopes at the time scheduled for the activity will be used to minimize the generation of EMI that could compromise SKA observations.

6 Protection from aerial and space-borne RFI

While protected in the radio astronomy bands by national and international regulation, as well as in the complete telescope frequency range, from terrestrial transmissions by the RQZ regulations, the wideband SKA receivers will still be exposed to strong interfering signals from aerial and space-borne transmitters. Radio Quiet Zones seldom have control over transmitters onboard air or space platforms, as these systems are usually internationally coordinated amongst countries. The large line-of-sight distances and antenna footprints on the ground make it very difficult to restrict their operation in a small geographic area such as an RQZ. Furthermore, terrain shielding is not effective against these sources and the possibility of beam-to-beam coupling increases. All of these strong moving sources in the sky pose an increasing risk on the SKA's ability to perform radio astronomical observations in its full frequency range.

While tracking the sidereal position of astronomical sources, the SKA antennas might interact with such transmitters in two scenarios: 1) stationary transmitters in the local sky like GEO satellites or High Altitude Platform Systems (HAPS) and 2) moving transmitters like airplanes and low-orbit satellites. Apart from the transmitted power and the transmitter beam pattern, the difference between these situations is mainly the relative angular speed of the source with respect to the astronomical source being tracked by the telescope. The power and beam pattern of the transmitter will define the maximum received interference power, and the angular speed will determine the time variation. A direct beam encounter with an aerial or space source can easily drive the receiver of the SKA antennas into a non-linear regime, which for a slow moving source could take much more time to clear. In the case of high density systems such as the large LEO constellations (with thousands of satellites), the aggregated received power from all visible satellites can also play an important part in the overall interference level.

Possible approaches to SKA protection from aerial and space-borne emitters include:

– Modification of airplane routes away from the telescope site as far as practically possible.
– Include protections of the RQZ in licensing arrangements of HAPS.
– Enforcing controls on ground stations, therefore removing the necessity to illuminate the RQZ area in certain applications.
– Advocating for the advancement and utilisation of steerable beam antenna technology that could help minimize the power flux density generated in the RQZ.

7 Conclusions

The SKA telescope protection levels required to define a RQZ have been outlined with definitions of restriction zones and coordination zones to protect observations. Attachment 1 to this Annex describes a general description of the spatial structure of the RQZ using the concepts of restriction zone, coordination zones and restricted access zones.

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[1] Gergely, T, 2004, in Proceedings of RFI2004 Workshop on "Mitigation of RFI in Radio Astronomy", http://www.ece.vt.edu/swe/RFI2004.

[2] ITU-R Handbook on Radio Astronomy, 1995, International Telecommunication Union, Geneva (Section 2.3).

[3] Thompson, A.R. 1982, The response of a radio astronomy synthesis array to interfering signals, IEEE Trans. Antenna Propagation, AP-30, 450-456.

[4] Thompson, A.R., Moran, J.M., & Swenson, G.W., 1986, Interferometry and synthesis in radio astronomy, (John Wiley, New York, NY), reprinted by Kreiger press, Melbourne FL (Chapter 15).

[5] Otto, B and Van der Merwe, C, 2020, RFI zone definitions for MeerKAT and SKA1, SSA-0008N-01A-001

Attachment 1
to Annex 8

General example of an RQZ implementation

This Attachment describes the combination of different Zones to provide the required levels of protection against unintentional and intentional transmitters for the whole SKA system. The general structure of the RQZ comprises three structural components to achieve the required radio quietness at all the array stations:

a) Restricted Zones (RZ) within which all emissions in a frequency range are prohibited. These are directed at non-licensed transmitters.

b) Coordination Zones (CZ) where the pfd levels at the core and the remote stations, as well as the transmission power determines the coordination distances using appropriate propagation studies.

c) RFI Zones (RFIZ) are areas under total control of the observatory, where all activities and equipment used have to be approved by the site entity responsible. These areas protect the telescopes from unintentional radiation from electronic equipment (EMI) and assist in the control of RFI.

1 Restricted Zones

Restricted zones around SKA antennas/stations will provide protection from unlicensed devices up to the SKA telescope protection levels. Three type of EZ can be identified, the central area (a circle of 10 km diameter), the spiral arms as any station located outside of the central area and less than 200 km away from the core, and the remote stations that are still relatively close to one another so that if individual restriction zones would be established, they would be touching or near enough touching. To define the extension of the EZ, a propagation calculation can be done considering a 100 mW transmitted power from a license-exempted transmitter (this is considered an average transmit power for such devices). The minimum coupling loss can then be calculated using as threshold the SKA protection levels and the relaxed VLBI levels for the central area and remote stations respectively. Using the propagation model described in Recommendation ITU-R P.452-16 (considering free space loss and diffraction loss), the minimum separation distance needed is obtained for each case as a function of frequency.

TABLE 17

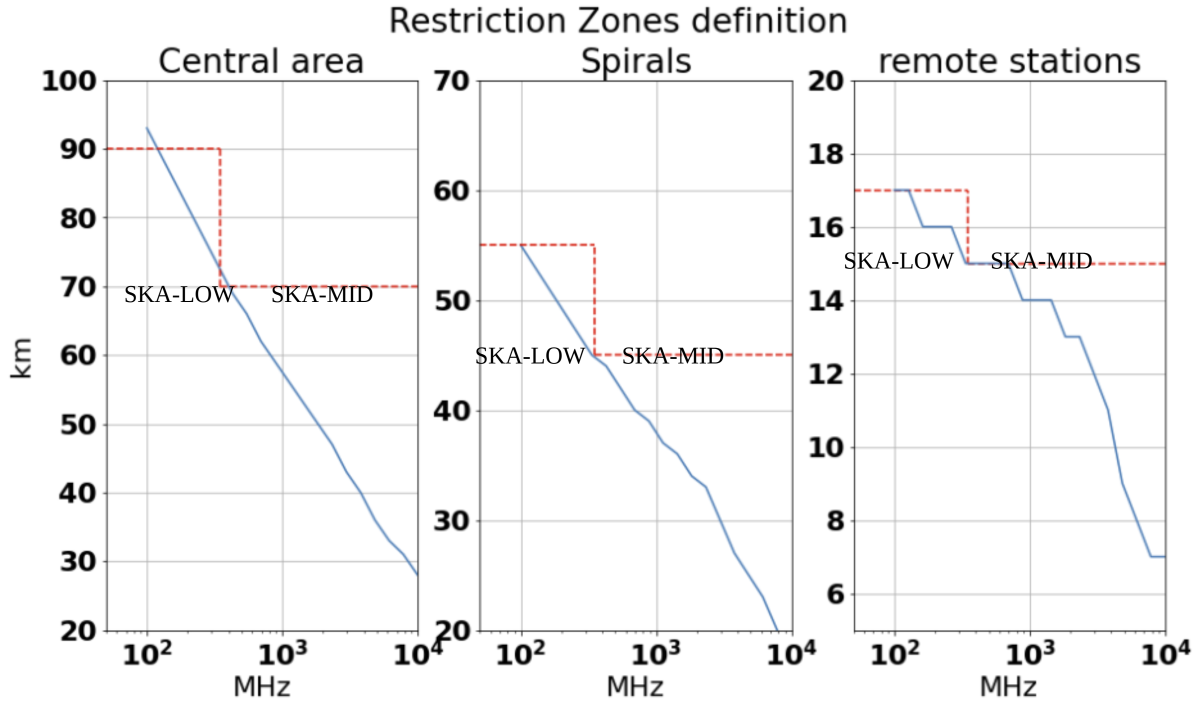
Proposed radial structure of the SKA restriction zones

	Station radial distance	**Restriction zone radius (EZ)**	**pfd levels for Coordination Zone (CZ)**
Central Area	Inside 5 km	SKA-LOW 90 km SKA-MID 70 km	SKA protection levels
Spiral arm stations / antennas	Annulus 5-200 km	SKA-LOW 55 km SKA-MID 45 km	SKA protection levels + 15 dB
Remote stations / antennas	Beyond 200 km	~15 km radius*	Recommendation ITU-R RA.769 VLBI thresholds

* NOTE – The size of the restriction zones around remote stations will be determined by local conditions and are expected to be around 10-20 km.

FIGURE 20

Dimensions of restriction zones for central area and remote stations of the SKA



The central restriction zone should provide the stated protection against short range, portable and mobile transmissions and fixed low power transmissions which are not on high sites or high masts. No transmission facilities should be allowed within the RZ unless they have been specifically cleared. Restriction zones defined in the spiral arms antennas/stations will probably overlap with the central restriction zone, except for the outermost ones.

2 Coordination Zones

Establish appropriate Coordination Zones with procedures to determine coordination distances with the objective to provide both the stations in the central area and outer locations with a radio quiet environment with the following levels:

- For antennas in the core and central areas, up to 5 km radius, *coordination* must ensure that the *SKA protection levels* are met.
- For the spiral arms antennas (beyond 5 km up to 200 km from the centre), *coordination* must ensure that the requirements are met for the *Continuum Threshold plus 15 dB*, equivalent to requirements for *Spectral Line Thresholds*, as defined in section 3.
- For the outer antennas the VLBI protection levels must be met.

The size and shape of the coordination zones will be determined by the characteristics of the terrain in each location and the RFI source being considered.

3 RFI originating beyond the RQZs

Many transmissions from outside the RQZs will also have an adverse impact on the SKA. Existing transmissions that have a significantly adverse impact, as determined according to agreed standards, could be identified in the National Regulatory Database and could be subjected to an improvement scheme in conjunction with National Policy for the SKA and in collaboration with the National Regulatory Authority. From the National Regulatory Database it would become apparent what the geographical area is, beyond the RQZ, in which regulatory scrutiny and coordination is generally required, and also, which specific RFI sources beyond that must remain under scrutiny. Any changes to these sources that may increase RFI need to be coordinated with the SKA.

Any new transmission facilities that are planned within the coordination range referred to above need to be approved by the national regulatory authority in conjunction with the SKA. Any high-power and high-site transmission facility planned outside of the RQZ zones should ideally be subject to scrutiny. Reference power levels and effective site heights need to be determined.

4 Establishment of RQZs

The RQZs need to be established in terms of the appropriate national and local legislation, not only in terms of communications statutes but also other applicable statutes, for example, with respect to land surveying including demarcation on official maps, land use and rights and civil aviation.

5 RFI management within the site

To effectively manage RFI generated by SKA equipment and activities (or any other telescope on the site), RFI Zones are defined within the land owned by the SKAO or by the entity responsible of the telescope site. The use of any electrical equipment (intentional transmitter or not) and any activity within these zones is internally regulated by controls and processes defined by the Observatory and the Site Entity. This internal regulation does not mean prohibition of equipment use or transmissions, but an effectively managed use of such, to minimize the impact on telescope observations.

These RFIZ are defined by different RFI risk levels, looking at the minimum propagation loss from any existing telescope to any point in the map as a function of frequency. This zones allows for certain equipment that can generate radiated emission to be located/used at X m distance from an antenna or an activity to be conducted at Y m distance to avoid RFI harmful to observations. Also, critical areas (*RFI Zone 0*) can be defined, where no intentional transmitter is permitted to avoid damage to the very sensitive receivers. An example of this zone definitions is provided by the South African Radio Astronomy Observatory in the SKA-MID site in [5], the zones definitions and figures are reproduced here.

TABLE 18

RFI zones definition in SKA-Mid site

Zone ID	Zone Title	Notes
RFI Zone 0	Receptor (Dish)	100 m radius circle around each of the MeerKAT, MK+ or SKA1 telescope receptors. For SKA1 spiral arms, this will be within the 100 m x 100 m security fences.
RFI Zone 1	Inner Core	5 km radius circle around the SKA virtual core / centre: 30.71292°S, 21.44380°E [4].
RFI Zone 2	Outer Core	25 km radius around the SKA virtual core / centre: 30.71292°S, 21.44380°E [4].
RFI Zone 3	Spiral Arms	10 km corridor centred around the spiral arm telescope locations.

FIGURE 21

RFI Zone 0 (Dish)

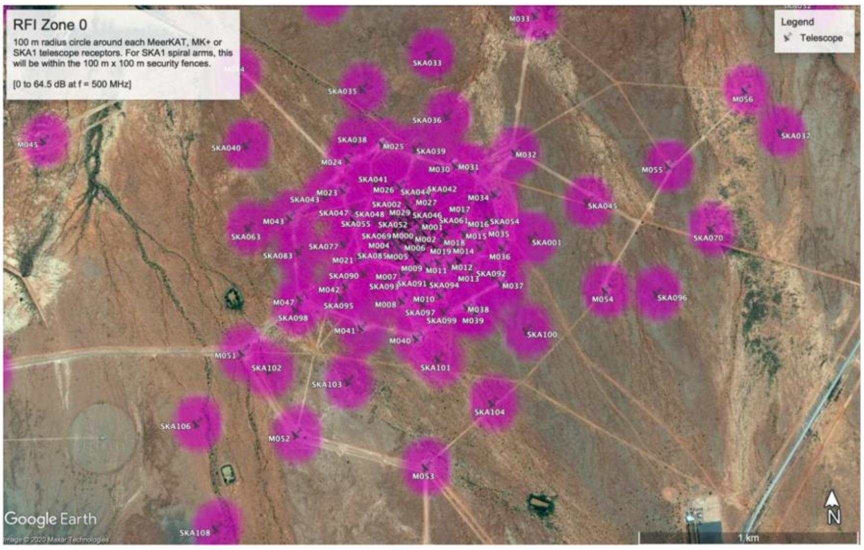


FIGURE 22

RFI Zones 1 and 2 (inner and outer core)

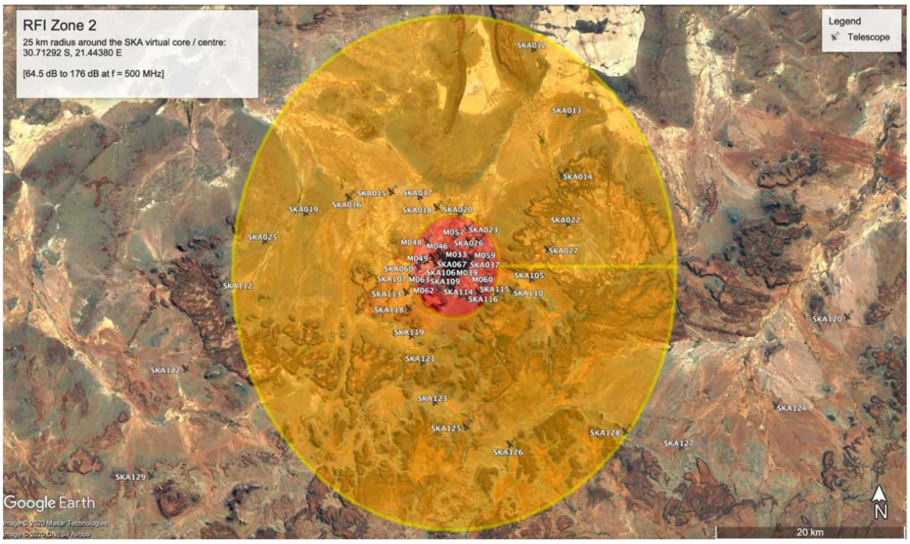
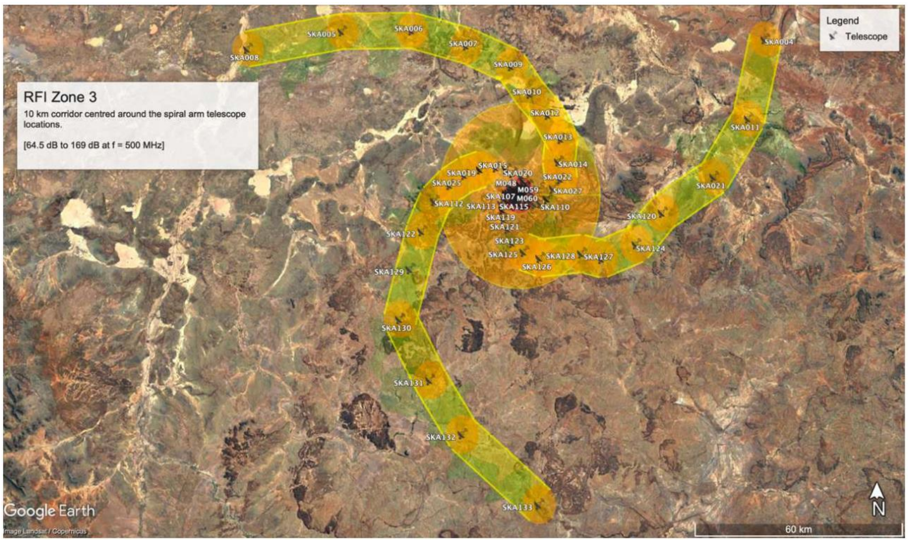


FIGURE 23

RFI Zone 3 (spiral arms)



Access to the observatory, use and installation of electrical equipment is subjected to approval from the SKAO and the site responsible. All activities must be accompanied by an EMC Control Plan (EMCCP) providing proof of compliance to the SKA protection levels. The level of emissions of the activities/equipment in the EMCCP will define the RFI Zone in where they can be conducted/installed.

Naturally, these processes recognize the need for deviations (like with construction activities or temporary testing equipment) where it is not practical to require the equipment to be "radio quiet", in this cases coordination with the telescope observations mitigates the impact of the generated RFI.

6 Safety critical situations

Due to the remoteness of the SKA sites, safety of personnel and equipment takes precedence over RFI considerations. In the case of a safety critical event all RFI restrictions are lifted from the site.

Attachment 2 to Annex 8

Propagation studies, RFI characterisation and data acquisition

1 Propagation studies

The translation of the threshold levels for the spatial array components towards actual separation distances need to be established using propagation studies with various levels of complexity.

To evaluate the effect of a distant transmitter on a radio telescope, the effects of radio propagation must be taken into account. This is a very complex area and has been the subject of extensive studies. In the ITU-R there are about 80 recommendations in the propagation area.

Propagation models vary from simple, accounting only for fundamental effects (free space propagation, diffraction), to very complex, that account for many effects such as ionospheric and tropospheric factors, and terrain obstacles.

As an example, the propagation loss calculated per the model in Recommendation ITU-R P.452-16 are presented in Figs 24 and 25 below as Path loss (dB) vs Distance (km). For all plots the following additional parameters were set:

– Flat terrain was assumed, and no specific terrain information was used.

– The antenna heights were set to 15 m for the receiver (indicative for the SKA) and 90 m for the transmitter (a typical radiocommunications tower).

– The curves labelled 'total loss' considers scattering and ducting effects modelled in Recommendation ITU-R P.452-16 which effectively decrease the propagation loss.

Figures 24 and 25 present two plots for different time percentages, labelled 2% and 50%. These percentages refer to the time that the propagation loss can be less than the calculated and represent a measure of the probability of interference.

FIGURE 24

Propagation loss at 500 MHz

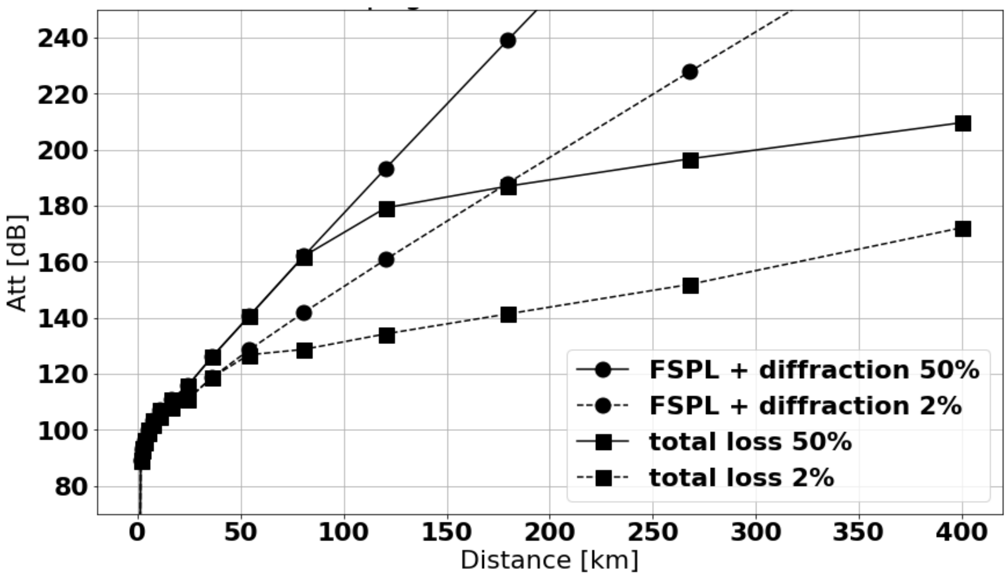
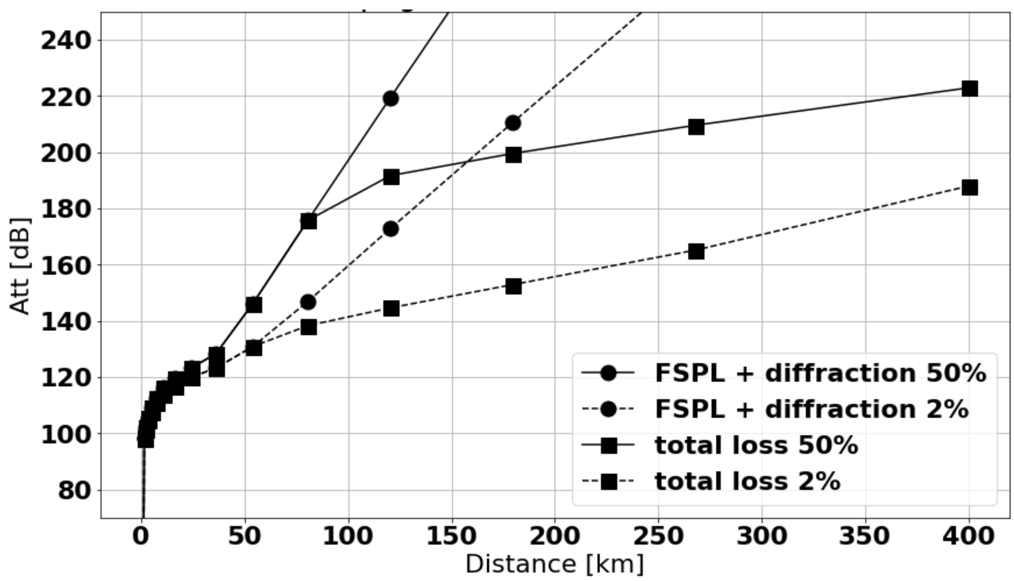


FIGURE 25

Propagation loss at 1400 MHz



Path loss (dB) at different distances (km) calculated with the propagation model from Recommendation ITU-R P.452-16, for the low frequencies of 500 MHz (top) and 1.4 GHz (bottom). The solid lines are at 50% and the dashed lines at 2% probability of interference.

2 Computerized Predictions

Due to the very low threshold levels and the long distances over which such signals can be produced, the number of RFI sources across the SKA frequency spectrum, from 50 MHz to 25 GHz, will be quite large - even in remote sparsely populated areas.

To produce and maintain a comprehensive characterization of the SKA sites with respect to RFI it is necessary to use a computerized signal level prediction system. Such a system needs to be based on ITU-R propagation models, must be accredited, and incorporate topographical models with sufficient accuracy.

3 Location and Characterization of Potential RFI Sources

The next step is the characterization of the present and future RFI environment in the SKA sites, which includes:

– Creating a database of all existing transmitters that produce signals exceeding the threshold levels which will include the geographical and topographical transmitting site data and the transmission characteristics.

– The prediction of the signal levels produced by all these transmitters at the candidate SKA sites.

– Long term measurements of the actual RFI environment with regards to statistical data.

– An assessment of future radiocommunication developments in the region.

4 RFI Database

A database of existing licensed transmitters is usually maintained by national radiocommunication or communications regulatory authorities. From this, the density and characteristics of potential RFI sources near an SKA site can be determined. However, this information is sometimes incomplete and often does not accurately represent operating facilities.

The building of an SKA database for potential RFI sources is very important and needs to take the following into account:

1) The character and impact of the potential RFI sources will vary greatly due to the individual power and radiation characteristics, transmitting site characteristics, distance and the intervening topography. It includes high power sources on high sites with up to 1 MW effective radiated power and low power sources on average sites with less than a 100 W effective radiated power. The directionality of the radiation pattern needs to be taken into account. High power RFI sources may be up 1 000 km (even more) distant.

2) Data should be obtained from the Communications Regulatory Authorities and, although it is unlikely to be complete or the most accurate, it will be useful for crosschecks. The telecommunication network operators will have the most accurate data which they need for their network planning and operations. For certain applications, usually service networks, frequency spectrum blocks are allocated with different blocks to different operators. The frequency assignment to particular transmitters is then done by the operators to optimize network operations and frequency use. Direct interaction with operators can be established and their cooperation obtained.

3) Signal predictions (calculations) need to be carried out with computerized systems to obtain a complete picture of the radio environment and to determine the spectrum availability (conversely, the spectrum occupancy) at the various threshold levels. Although measurements need to be carried out, it cannot produce a complete picture due to the high cost of measurements and the difficulties of measuring at these very low levels without actually having the SKA.

   If the data acquisition process and the prediction process are combined, then only the data for those RFI sources that exceed the threshold levels can be selected to be stored in the database.

4) It is useful to have the predicted RFI available when measurements are made. Transmissions have to comply with ITU recommendations with respect to out-of-band (channel) radiation. Under normal circumstances, there will not be out-of-band transmissions. If it should occur, a valid complaint can be made to the regulator. However, operators usually will respond quickly to rectify the matter if the matter is taken up directly with them.

Many transmitters produce strong ‘out-of-band’ unintended emissions. Although such emissions may fall within the limits set within the ITU Radio Regulations, they can still strongly affect sensitive radio telescopes like the SKA. Thus, radiocommunication services in bands even hundreds of MHz away from the telescope operating frequency should often be considered in RFI evaluations.

5 Field Measurements

Field measurements and identification of RFI sources is extremely important in characterizing the current “radio quietness” of the SKA sites and identifying any change in it. The SKA sites are already equipped with RFI monitoring systems that will be expanded by the SKA1. However, achieving sensitivity levels equivalent to those described in Recommendation ITU-R RA.769 is very difficult. RFI monitoring does not aim to measure up to this very stringent levels but to provide a sensitive enough measurement that allows for fast detection of RFI environment change. Ultimately the most sensitive instrument to detect RFI is the telescope itself, but it is not good in source identification, making these two systems complementary.

6 Potential future RFI

Likely future radio transmitters are much harder to determine. Obvious areas of population and development are probably the best indicators of future activities. Thus, SKA are selected as remote as possible.

Telecommunications operators do not do long term network planning anymore. They much rather respond to market demand which is often coupled to technological developments.

Potential future RFI should rather be controlled through regulatory processes coupled to the SKA.

Annex 9

Characteristics of the radio coordination zone around the Itapetinga radio telescope

1 The coordination zone around Itapetinga radio telescope

a) Introduction and description

The Itapetinga radio telescope is located at latitude 23°11’ 05.77”S, longitude 46°33’ 28.429” W with 805 m elevation, in Itapetinga, city of Atibaia, São Paulo state, Brazil. It was built in 1973 what was then a remote site. It is protected from the neighbourhood by hills having average altitude of 100 m above the telescope level. The current population of Atibaia is around 144 000 inhabitants (refer to the last year verification) and population density is about 301 people / km^2. Its main economic resources come from agriculture and tourism, having very small industrial activity. During the last ten years, the urban area of the city grew closer to boundary of the Electric Silence Zone created around the radio observatory.

FIGURE 26

The large yellow circle shows the electric silence zone around the Itapetinga radio telescope

Itapetinga was the first radio telescope built by ESCO in 1972. It is a 13.7 m single dish telescope optimized to operate in 18 GHz to 50 GHz band and to operate with smaller aperture efficiency in the band of 70 to 100 GHz. Due to the weather conditions at the observatory site, it has been used mainly in the lower frequency band. The diameter of the large yellow circle shown in Fig. 26 is about 4 km and the radome of the radio telescope is seen in centre as a white dot. Top left shows an urban area on the border of the Silence Zone. The small circles show areas of illegal deforestation.

Radio-frequency spectrum measurements between 80 MHz to 3 GHz and from 3 GHz to 8 GHz have been conducted using discone and horn antennas, respectively, in the radio telescope site and on the top of the hills.

Figures 27 and 28 shows the average of one-day measurements. It shows uncalibrated amplitude (dBm) versus frequency.

FIGURE 27

Average daily spectra observed on the top of the hill

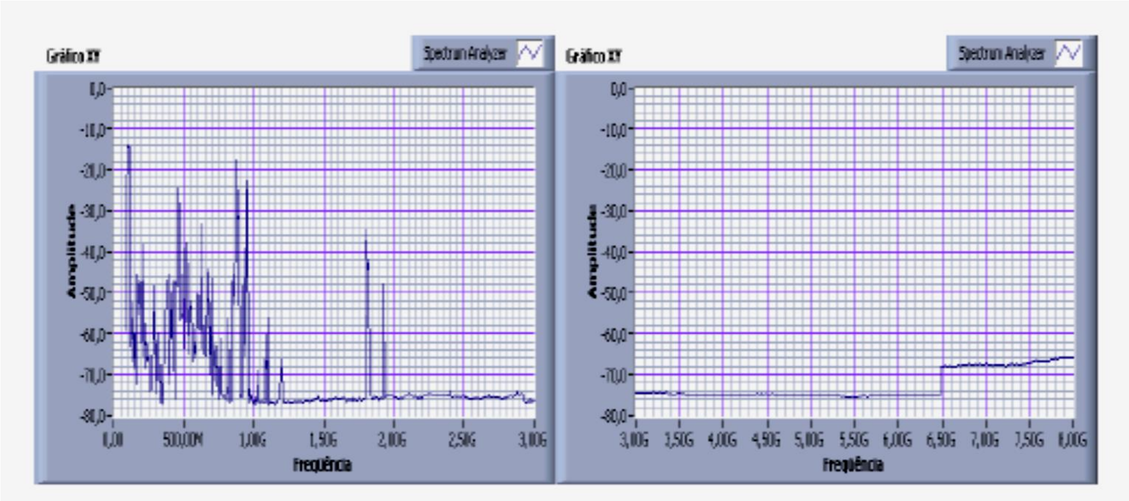
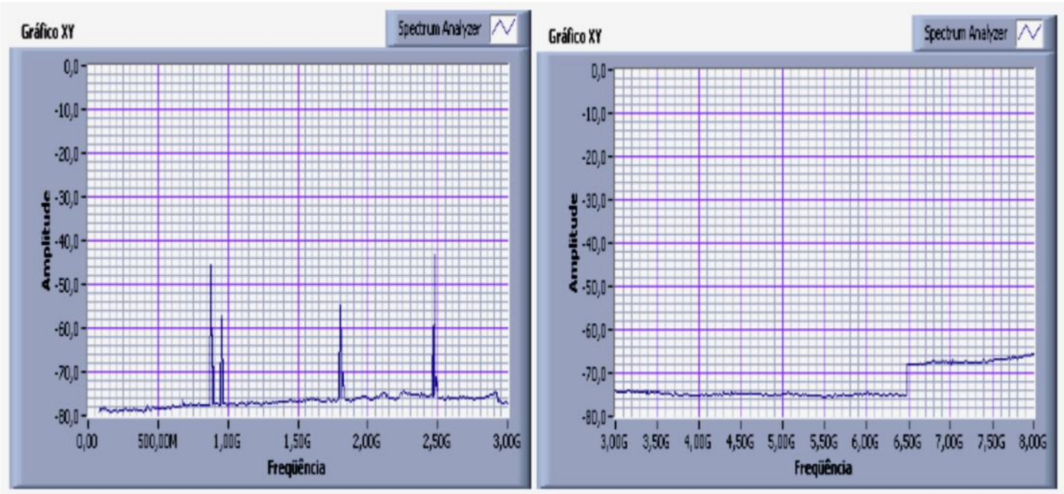


FIGURE 28

Average daily spectra observed on the site of the observatory



b) Local legislation

In order to protect the operation of the radio telescope and passive experiments operating in the observatory area from local radio interference, the municipal law 1285/1972 was created in 1972 defining an Electrical Silence Zone adjacent to the Itapetinga observatory. In 1975 this law was modified to law 1503/1975 defining a circle of 4 km diameter, centered at the observatory, as the Electrical Silence Zone.

According to the definition of electrical silence adopted, no urban expansion is allowed in this area to avoid interferences due to power line transmission, microwave oven, radio control devices, neon signs, and all kind of devices capable of producing radio interference. The few people already living in this area receives instructions in order to avoid generate harmful interferences to the observatory.

This area is also protected from urbanization and deforestation since it is classified as a Permanent Protection Area (PPA), according to the federal laws 4771 stated in 15/09/1965 and 7803 stated in 08/08/1993.

In this particular case, the preservation of the Silence Area increased strongly the value of the land motivating the landlords to propose projects to divide their areas in small lots for sale. The laws above are impeding this kind of business. However a lot of effort is still necessary to preserve this silence zone.

Annex 10

Characteristics of radio quiet zones: protection of the MeerKAT / SKA radio telescope in South Africa

1 Actions taken by the administration of the Republic of South Africa to protect the MeerKAT/SKA radio telescope operating in the Karoo area in the Northern Cape Province

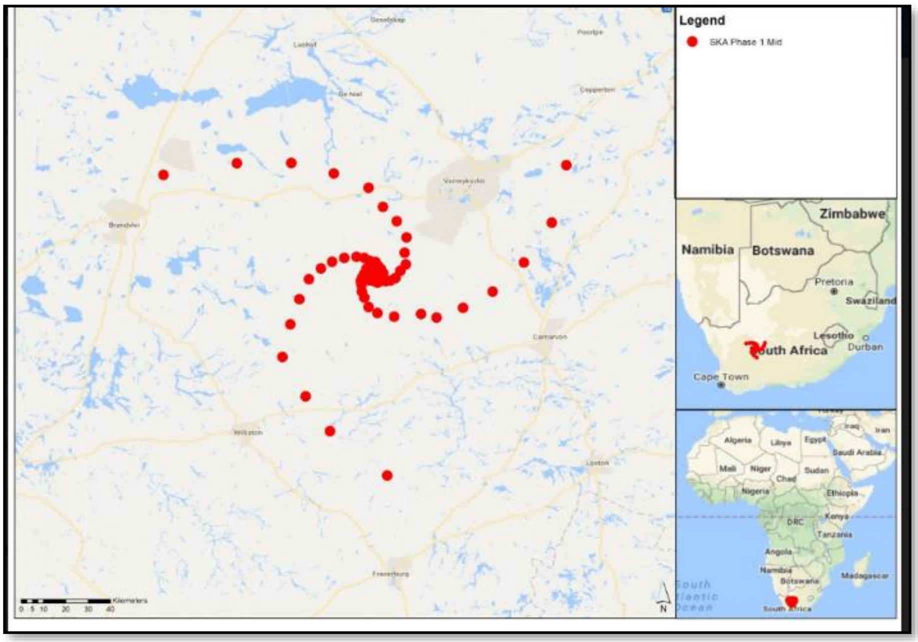
1.1 Introduction and description

MeerKAT telescope is an astronomical interferometer that combines an array of 64 radio telescope antennas formally recognised as a precursor to the SKA radio telescope. The 64 MeerKAT radio telescope antennas form part of the mid-frequency component of SKA telescope, which will undertake observations in the 100 MHz-25.5 GHz frequency band. Figure 29 identifies the location of antennas for the SKA phase 1, and Table 19 lists the names of the MeerKAT antennas and their geographical location.

The full scope of receiver deployment for MeerKAT will include receivers in 1 750 MHz-3 500 MHz and 8 GHz-14.5 GHz frequency bands. However, at this stage the existing deployment is comprised of receivers and digitizers in the 900 MHz-1 670 MHz and 580 MHz-1 015 MHz frequency band. The MeerKAT antenna has a diameter 13.5 m for the main reflector and a 3.8 m diameter sub-reflector of the offset Gregorian dish.

FIGURE 29

The location of antennas for the SKA phase 1



Note to Fig. 29: The SKA Phase 1 telescope to be located in South Africa consists of 133 spirally distributed parabolic dishes of 15 m diameter. Sixty-Four (64) MeerKAT dishes are also located at the center of the SKA, bringing the total number of SKA dishes to 197.

TABLE 19

MeerKAT antennas and their geographical location

Antenna	Latitude			Longitude		
	deg	min	sec	deg	min	sec
M000	-30	42	46.53	21	26	37.69
M001	-30	42	45.38	21	26	38.04
M002	-30	42	47.08	21	26	36.8
M003	-30	42	46.37	21	26	35.5
M004	-30	42	48.01	21	26	33.36
M005	-30	42	48.99	21	26	34.17
M006	-30	42	49.39	21	26	37.31
M007	-30	42	52.88	21	26	34.64
M008	-30	42	57.17	21	26	34.49
M009	-30	42	51.85	21	26	39.22
M010	-30	42	56.42	21	26	41.31
M011	-30	42	51.23	21	26	41.16
M012	-30	42	51.76	21	26	43.26
M013	-30	42	52.58	21	26	46.9
M014	-30	42	49.08	21	26	48.55
M015	-30	42	46.91	21	26	45.92
M016	-30	42	45.84	21	26	48.83
M017	-30	42	43.45	21	26	45.5
M018	-30	42	47.78	21	26	41.97
M019	-30	42	49.06	21	26	44.42
M020	-30	42	49.53	21	26	41.65
M021	-30	42	50.43	21	26	26.88
M022	-30	42	44.42	21	26	25.89
M023	-30	42	39.78	21	26	23.99
M024	-30	42	34.93	21	26	24.81
M025	-30	42	32.48	21	26	31.16
M026	-30	42	39.25	21	26	34.28
M027	-30	42	40.55	21	26	39.52
M028	-30	42	42.63	21	26	36.08
M029	-30	42	43.83	21	26	34.67
M030	-30	42	36.1	21	26	44.44
M031	-30	42	36.76	21	26	47.27
M032	-30	42	34.1	21	26	55.33
M033	-30	42	11.75	21	26	59.82
M034	-30	42	40.72	21	26	51.45
M035	-30	42	45.67	21	26	52.51
M036	-30	42	49.24	21	26	52.59
M037	-30	42	54.71	21	26	52.29
M038	-30	42	58.28	21	26	46.02
M039	-30	42	59.03	21	26	47.54
M040	-30	43	2.92	21	26	36.99
M041	-30	43	1.28	21	26	27.2
M042	-30	42	54.74	21	26	24.41
M043	-30	42	43.97	21	26	14.33
M044	-30	42	20.3	21	26	4.33
M045	-30	42	31.14	21	25	29.13
M046	-30	41	42.92	21	25	42.87
M047	-30	42	56.6	21	26	16.27
M048	-30	41	12.56	21	24	52.6
M049	-30	42	25.61	21	24	22.51
M050	-30	43	7.19	21	25	20.88
M051	-30	43	4.78	21	26	6.05
M052	-30	43	17.09	21	26	15.71
M053	-30	43	22.15	21	26	38.35
M054	-30	42	56.03	21	27	10.77
M055	-30	42	36.66	21	27	23.16
M056	-30	42	24.64	21	27	38.06
M057	-30	40	53.96	21	26	49.07
M058	-30	41	12.56	21	28	23.4
M059	-30	42	15.14	21	28	56.51
M060	-30	43	39.54	21	28	46.52
M061	-30	43	55.25	21	26	37.38
M062	-30	44	1.08	21	25	43.86
M063	-30	43	39.54	21	24	29.49

2 Means to achieve the Radio Quiet Zone for MeerKAT/SKA

To protect radio astronomy observations undertaken by MeerKAT/SKA from detrimental radio frequency interference, a national legislative and regulatory framework has been developed for the specific purpose of establishing radio quiet zones. South Africa has adopted a multi-pronged approach to achieve a radio quiet zone (RQZ), which includes:

i) Site characteristics including topographical shielding;

ii) Legislative and regulatory controls, which includes limitation and prohibition of sources of detrimental radio-frequency interference (RFI), Electromagnetic Interference (EMI); and

iii) Policy controls, which result in improved spectrum efficiency in and around the RQZ; and

iv) Maintenance of RQZ.

2.1 Geographic location and site shielding

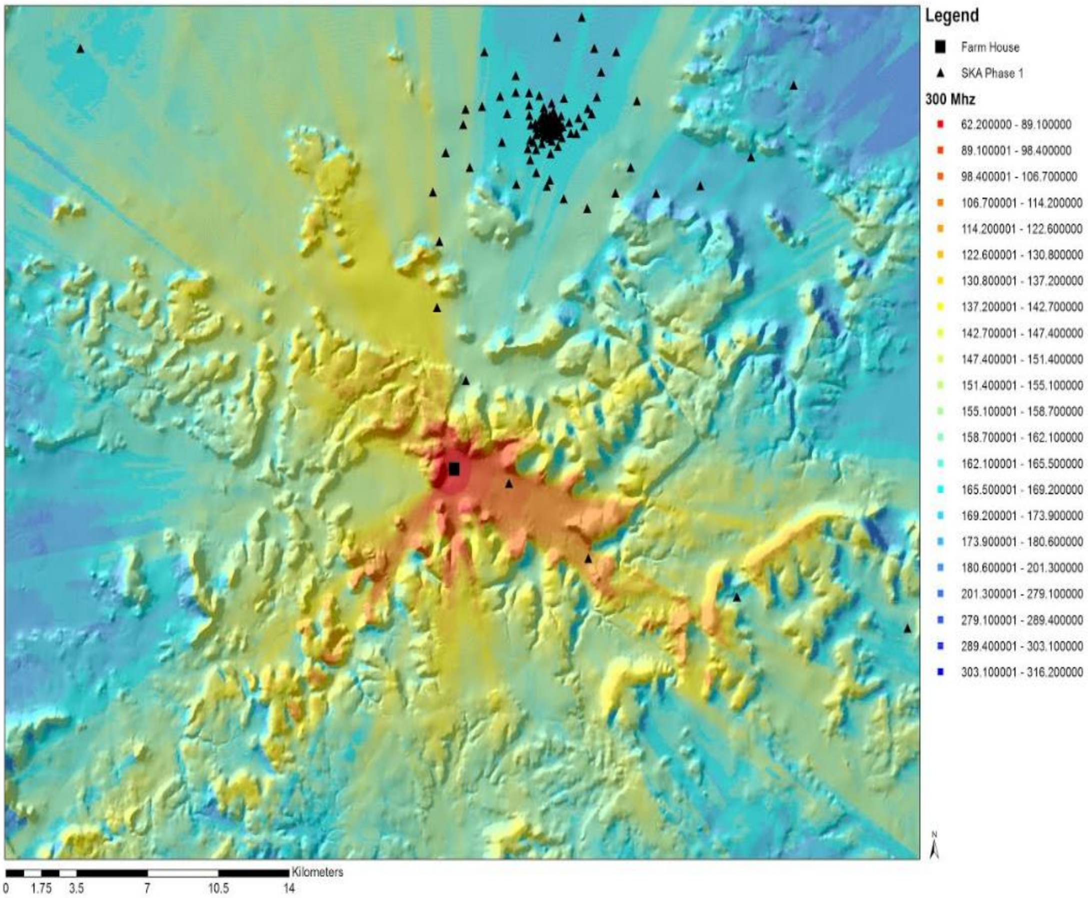
The observatory is located in the Karoo area of the Northern Cape Province. Its location takes advantage of two factors that influence the existing radio-frequency environment as measured at the site:

i) the area is sparsely populated, with an average population density of less than one person per square kilometre outside of the small communities; and

ii) The prevalence of hills provides natural topographical shielding against distant sources of RFI as illustrated in Fig. 30.

FIGURE 30

Natural shielding of the MeerKAT/SKA telescope shown through a 300 MHz pathloss profile from a nearby Farm House



2.2 Legislative and Regulatory control

On 17 June 2008, the Parliament of the Republic of South Africa (RSA) enacted the Astronomy Geographic Advantage Act (AGA Act) into law to provide for the preservation and protection of areas within the Republic that are uniquely suited for radio astronomy.

2.2.1 Declaration of the Karoo core and central astronomy advantage areas

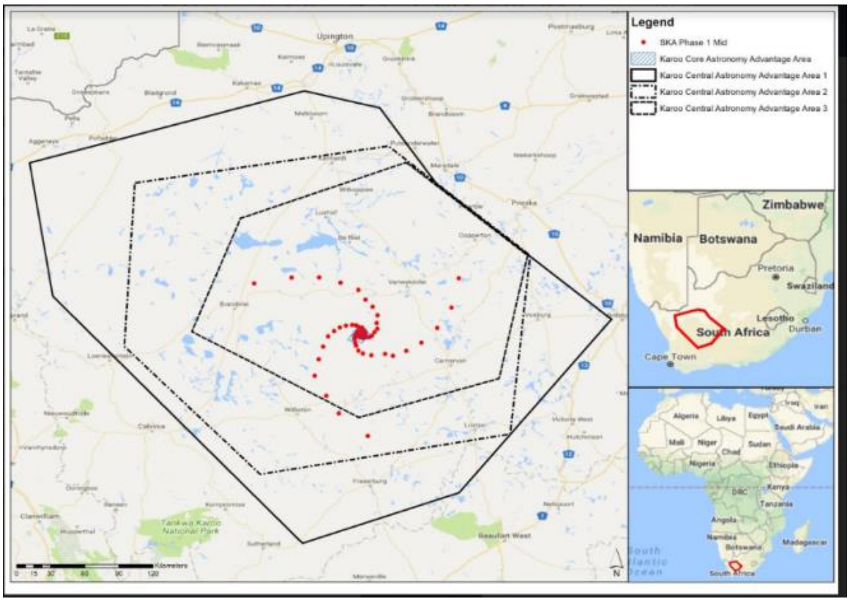
After the enforcement of the AGA Act, the following Astronomy Advantage Areas were declared for the purposes of radio astronomy and related scientific endeavors, which are also shown in Fig. 31. The protected area is bounded by the meridians of longitudes at 18˚48′ 54.65″ E and 23˚25′ 40.44″ E and latitudes of -28˚46′ 44.4″ S and 32˚22′ 10.56″ S:

i) The Karoo Core Astronomy Advantage Area (KCoreAAA), which covers an area of about 13 406 hectares; and the

ii) Karoo Central Astronomy Advantage Areas (KCAAAs), which covers an area of about 10 705 284 hectares.

FIGURE 31

Declared Karoo Core and Karoo Central Astronomy Advantage Areas



Regulations were published for both the KCoreAAA and KCAAAs, which includes varying levels of prohibitions and restrictions to protect the radio astronomy. The regulations are summarised as follows:

i) KCoreAAA Regulations – all the radio transmissions within the regulated radio-frequency spectrum are prohibited, unless for the purposes of radio astronomy;

ii) KCAAA Regulations – provides for an impact assessment and permitting framework that enables radiocommunication so long as the assessed impact complies with relevant conditions and restrictions.

The AGA Act makes provision for the declaration of Coordinated Astronomy Advantage Areas. Most of the area that lies outside the KCAAA 1 within the Northern Cape Province is designated to be declared as the Karoo Coordinated Astronomy Advantage Area to limit the impact of high-powered transmitters on the KCoreAAA and KCAAAs. The Regulations governing restrictions and prohibition of radio transmissions within the Karoo Coordinated Astronomy Advantage Area is still being developed

Since the coming into force of the AGA Act, several other radio telescopes have been established within the declared KCAAA 1, including 180+ Hydrogen Epoch Reionisation Array (HERA) receivers operating in the 50-250 MHz frequency band. The number of HERA telescopes will increase to 360 in the next two years. One C-Band All Sky Survey (CBASS) (7.6 m paraboloid) telescope operates in the 4.5-5.5 GHz frequency band and HIRAX dishes operate in the 400-800 MHz frequency band. The SKA Phase 1 telescope will operate in the 350 MHz - 14 GHz frequency band. The KCAAA Regulations makes provision for the frequency bands of the SKA Phase 2 radio telescope. Radio astronomy instruments including HERA, CBASS and HIRAX are declared to be astronomy and related scientific endeavors in terms of the AGA Act and make opportunistic use of the infrastructure provided for the MeerKAT telescope. MeerKAT and HERA telescopes, which are recognized to be SKA precursor instruments, are located within the KCoreAAA and other guest instruments are located within the KCAAA 3 that preserve the spectrum from 100 MHz to 25.5 GHz in terms of the AGA Act.

2.2.2 Prohibition of spectrum usage

Unless otherwise authorised in terms of relevant regulatory provisions, spectrum usage as prescribed for the Karoo Core and Central Astronomy Advantage Areas in Table 20 is prohibited. A list of frequency bands that will be exempted from the prohibition in Table 20 for delivery of radiocommunication services to communities in the Karoo is still being developed. The basis of identifying exempted frequency bands is one of spectrum efficiency – to deliver essential services within the available spectrum resource. Authorisation to operate radiocommunication equipment within the declared KCAAAs is subject to obtaining an appropriate permit.

TABLE 20

Protected Area and prohibited frequency range

Declared area	Prohibited band
KCoreAAA	9 kHz to 3 000 GHz
KCAAA 1	100 MHz to 2 170 MHz
KCAAA 2	100 MHz to 6 GHz
KCAAA 3	100 MHz to 25.5 GHz

2.2.3 Management of the Karoo Core and Central Astronomy Advantage Areas

An Astronomy Management Authority (AMA) has been assigned by the Minister for Science and Technology with the responsibility to administer the processes and procedures to: implement the protection requirements; to conduct compliance assessment and to issue permits with appropriate radio transmission specifications.

2.2.4 Conditions for spectrum use within the KCAAAs

Any radio-frequency spectrum usage and radiocommunication transmissions shall comply with conditions prescribed in the regulations. Penalties are imposed in cases where these conditions are transgressed as stated below:

a) the received power level shall not exceed a saturation level of (minus) −100 dBm at any radio astronomy station within the MeerKAT/SKA protection corridors or within 20 km of the SKA Virtual Center. The SKA Virtual Centre is a compliance assessment point for the applicable protection levels for radio astronomy as defined under (b) and it is located at the geographic coordinates 30.71292 S and 21.44380 E; and

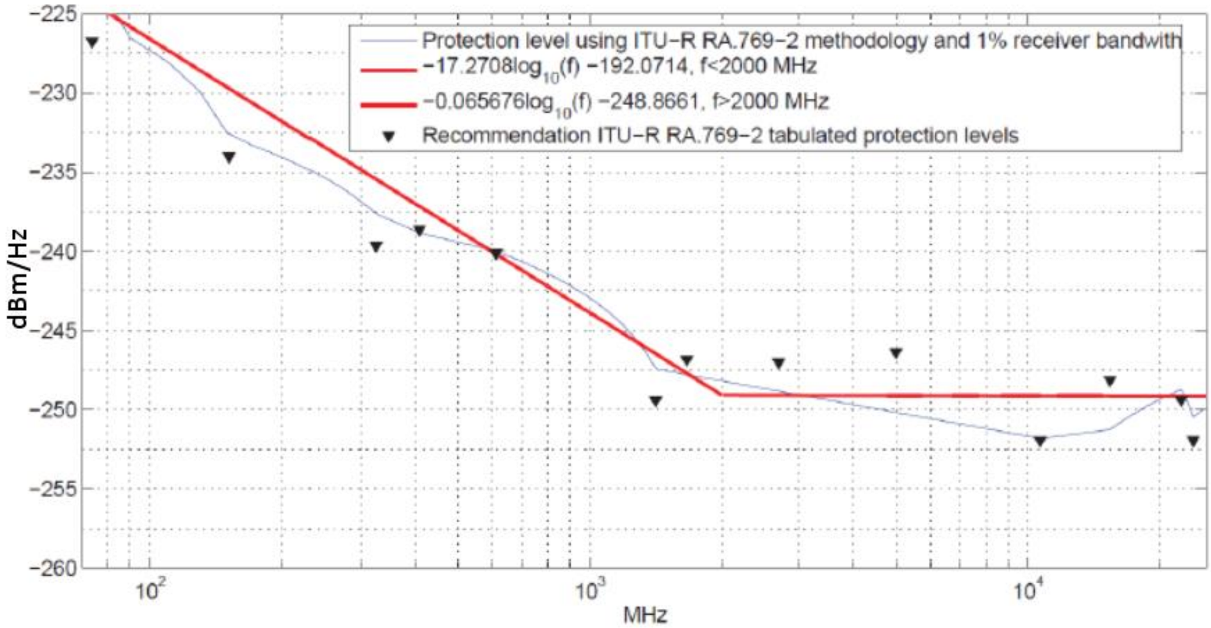
b) the protection levels to be applied in astronomy advantage areas, and used as a basis for all impact assessments, is illustrated in Fig. 32. Radio transmissions shall not exceed the protection levels applied at the SKA Virtual Centre. The protection levels are derived using methodologies described in Recommendation ITU-R RA.769-2, and are designated as the South African Radio Astronomy Service (SARAS) protection levels and it is described by the following equations in the regulation published in terms of the AGA Act:

SARAS (dBm/Hz) = $-17.2708 \log(f) - 192.0714$ for $f < 2$ GHz, the values of (f) in MHz

SARAS (dBm/Hz) = $-0.065676 \log(f) - 248.8661$ for $f \geq 2$ GHz, the values of (f) in MHz

FIGURE 32

South African radio astronomy service protection levels



2.2.5 Restriction of spectrum use

2.2.5.1 Licensed spectrum use

Licensed transmitters that operate in exempted frequency bands (see § 2.2.2) are restricted, by way of a permitting process, to prevent detrimental impact from RFI at pre-defined locations occupied by MeerKAT/SKA receptors. Radio transmission on the frequency band not exempted is prohibited. The special section in the South African Table of Frequency Allocation also prescribes that all licensed spectrum users in the declared areas are to be subjected to authorization in a procedure prescribed under the AGA Act.

2.2.5.2 Unlicensed Spectrum Use

The Independent Communication Authority of South Africa (ICASA) has prescribed a list of radio equipment (short-range devices) and their technical standards and specifications for which spectrum licenses have been exempted. Such equipment shall not be operated within 50 km of the SKA Virtual Centre unless a permit has been issued by the astronomy management authority.

Outside the 50 km radius, certain unlicensed transmitters emitting e.i.r.p. of 250 mW or less will be exempted from the requirements of obtaining a permit in terms of the AGA Act for operation within license exempted spectrum, unless such transmission interferes with the radio telescope.

2.2.5.3 Unintentional radio emissions

The location and configuration of the MeerKAT and the SKA telescope receiver was identified after consideration of existing electromagnetic interference sources. New electrical equipment and electrical infrastructure with power rating of greater than 100 kVA and within 30 km from the nearest SKA infrastructure requires a permit to be issued by the management authority after assessing the interference level and determining the separation distance required to minimize interference. For electricity generation by means of wind turbines, the distance is 50 km. If a permit to operate is granted, it will include all the conditions that the operator must comply with relating to the electrical infrastructure and equipment. The avoidance of interference by the electrical equipment shall be achieved by separating it from the nearest SKA infrastructure by a separation distance where RFI level due to electromagnetic emissions comply with the SARAS protection level.

2.3 Spectrum policy controls for broadcasting services

To protect the MeerKAT and the SKA radio telescopes, all terrestrial television broadcast transmissions in the KCAAAs have been prohibited. Television broadcast transmissions may only be via direct-to-home satellite transmissions in the frequency band 10.7 to 12.5 GHz.

2.4 Maintenance of RQZ

The RQZ in the KCAAA is maintained by routine measurements of the radio frequency environment using four fixed spectrum monitoring installations near the four closest towns and two fixed spectrum monitoring installations at the MeerKAT and SKA core. Provision is made to have a spectrum monitoring equipment on each spiral arm. Fixed spectrum monitoring equipment is strategically placed at nine geographic locations around and within an array of SKA Phase 1 telescope receivers. The Astronomy Management Authority (AMA) and ICASA entered into a Memorandum of Agreement to provide the framework and mechanism for cooperation between the two parties in cases of identified interference and compliance enforcement.

Annex 11

Radio quiet zone – Pushchino Radio Astronomy Observatory of the Astro Space Centre in the Physics Institute of the Russian Academy of Sciences

The Pushchino Radio Astronomy Observatory is one of the two largest observatories on the territory of the Russian Federation according to the number of radio-telescopes and to their common wavelength range. Three radio telescopes now in operation occupy an area of approximately 150 hectares. The DKR-1000 telescope is a cross-type radio-telescope of size 1000 by 40 m. Its operational frequency range is 30-120 MHz. There is also a large phased array (LPA), consisting of 16 384 dipoles with a central frequency of operation of 111.5 MHz and bandwidth of 4 MHz. A paraboloidal reflector of diameter 22 m (RT-22) completes the telescope list, its operational frequency range being from 327 MHz to 37 GHz. The telescopes of the observatory may thus conduct observations over a wavelength range from 10 m down to 8 mm.

The observatory uses both superheterodyne and a new generation of digital receivers. Observations using the DKR-1000 and RT-22 radio-telescopes are carried out using the frequencies which are allocated to the RAS. They are also carried out in a number of frequency bands not allocated to the RAS, but which are still free of other signals, thus enabling high sensitivity radio observations leading to the solution of certain astrophysical problems.

Interference from mobile tele-communication systems, radio navigation systems, satellite communications, television and also random signals arising from natural sources (thunderstorm discharges, hoar-frost on the dipoles, etc.) limit the observing time of the Pushchino radio telescopes across the frequency range to 20-80% of the whole time. Well-known methods of interference reduction are applied depending on the type and power of the interference. Examples of these are tuning-out of the interference by shifting the frequency of the observations, and the use of digital (for digital receivers) and analogue (for superheterodyne receivers) signal filters. Work is underway on monitoring of interference from radiocommunication stations. In the long-wave part of the radio astronomy waveband the interference situation is improved by the fact that the nearest buildings are situated no closer than 500 m from the telescopes.

When observations are conducted in bands not allocated to the RAS, protection from emission from radio communication stations is assured by the Administration of the Russian Federation. Thus the area covered by the Pushchino Radio Astronomy Observatory can be considered as a RQZ and it is possible to carry out observations in the frequency band 109.5-113.5 MHz using the LPA radio telescope.

Annex 12

Studies of the emission management zone around the Dominion Radio Astrophysical Observatory, Penticton, Canada

1 Introduction

Radio astronomy involves making observations close to or at the sensitivity limits attainable with currently available technologies. In addition, the more spectrum available at a radio astronomy station, the more productive that observatory can be. In the case of new, major international facilities, such as the Square Kilometre Array or the Atacama Large Millimetre Array, sites have been chosen that are almost unpopulated. However, there are many major scientifically valuable radio astronomy stations in the world that are located in environments of increasing population and spectrum use. Maintaining the effectiveness of these facilities is a complicated issue in spectrum management, but is nevertheless essential. Moreover, there is no guarantee in the medium to long term that the currently isolated locations of the new instruments will remain as electromagnetically isolated as they are now. It is therefore useful to look at the task of evaluating the environments of radio observatories and the tools needed for managing the areas around them. In these cases, perhaps the use of the term "Radio Quiet Zone", is not really accurate, and using the term "Emission Management Zone" (EMZ) would be more appropriate.

Maintaining an EMZ involves efforts at the international, national, regional and local level, and of course the radio astronomy station in question. The collaboration between these bodies comprises the development of relationships and lines of communication, measurement programmes and development of propagation modelling tools. In addition, it is necessary to understand the interference problems particularly relevant for that particular EMZ. These fall into three broad categories:

a) unwanted emissions from transmitters operating in designated radio services in bands allocated to those services;

b) signals and unwanted emissions from licence-exempt devices operating in domestic environments (e.g. wireless networks and other wireless devices, garage door openers, ultra-wideband devices and BPL systems);

c) emissions from computers and other domestic devices using digital systems or radio-frequency oscillators.

Category (a) falls in the domain of conventional spectrum management processes. However, categories (b) and (c) fall outside these processes, and the only practical approach found so far is to manage population growth in the EMZ. Finally, the protection measures used to ensure the continuing viability of the observatory must not burden other spectrum users unduly.

This report is a case study, describing work in progress to review and tighten the definition of the EMZ surrounding the Dominion Radio Astrophysical Observatory (DRAO), located near Penticton, British Columbia, Canada. DRAO is Canada's National Facility for radio astronomy, operated by

National Research Council Canada (NRC), a Federal agency, through its Herzberg Astronomy and Astrophysics Research Centre (HAA). The study comprises measurements and modelling of path attenuation around the observatory, measurements and modelling of background noise and estimating interference levels from potential housing developments.

2 The Dominion Radio Astrophysical Observatory

FIGURE 33

The Dominion Radio Astrophysical Observatory, looking east-south-east from the west end of the Synthesis Telescope

Note to Fig. 33: The CHIME telescope is on the right in the middle distance, and the John A. Galt (26-m) Telescope and CHIME pathfinder are in the far distance (see text for details).

Since opening in 1960, DRAO has been home to a number of radio telescopes and related experiments, operating from decametre to centimetre wavelengths. These include (operated by NRC-HAA except where noted otherwise):

- 1960 – present: a 26-m single antenna (known as the John A. Galt Telescope since 2014) that has historically operated between 400 MHz and 6.7 GHz, and is currently being upgraded to make sensitive Zeeman measurements in the 900-1 800 MHz band;
- 1965 – 1969: a pair of interferometric dipole arrays operating at 10 MHz and 22 MHz;
- 1974 – present: the Synthesis Telescope, an interferometer of 9-m antennas (currently seven) that has operated in the radio astronomy bands at 408 and 1 420 MHz, and is currently undergoing an upgrade to operate over simultaneous bands spanning 400-800 MHz and 900-1800 MHz;
- 1990 – present: a redundant pair of 2-m diameter Solar radio flux monitors that measure the F10.7 Solar activity index at 2.8 GHz, plus a 30 MHz riometer (relative ionospheric opacity meter, operated by Natural Resources Canada);
- 2012 – present: a 4-m diameter, wide-band Solar radio flux monitor that operates simultaneously at 1.4, 1.6, 2.8, 3.3, 4.9 and 8.3 GHz;

- 2014 – present: a pathfinder instrument for the Canadian Hydrogen Intensity Mapping Experiment (CHIME, see below), a 400-800 MHz transit interferometer comprising two 20×37 m cylindrical reflectors, operated by a consortium led by University of British Columbia;
- 2015 – present: the Dish Verification Antenna Mk 2 (DVA2), an 18-m offset Gregorian antenna designed and built to demonstrate single-piece composite antenna fabrication, currently fitted with a 350-1 050 MHz receiver (the Onsala SKA Band 1 prototype), but capable of operating up to 40 GHz;
- 2017 – present: CHIME, a 400-800 MHz transit interferometer comprising four 20×100 m cylindrical reflectors, operated by a consortium led by University of British Columbia.

At the time of writing, two new projects are in final stages of design, with construction expected in the near future:

- The Canadian Hydrogen Observatory and Radio-transient Detector (CHORD), a 512-element, highly-redundant array of 6-m antennas that will operate from 300-1 500 MHz, a collaboration between NRC-HAA, McGill University, University of Toronto, University of Calgary, and Perimeter Institute for Theoretical Physics;
- The Canadian Galactic Emission Mapper (CGEM), a 4-m single antenna expected to operate around 10-15 GHz, a collaboration between NRC-HAA and University of British Columbia.

Other nascent projects could see the site occupied by instruments operating below 300 MHz and as high at 116 GHz.

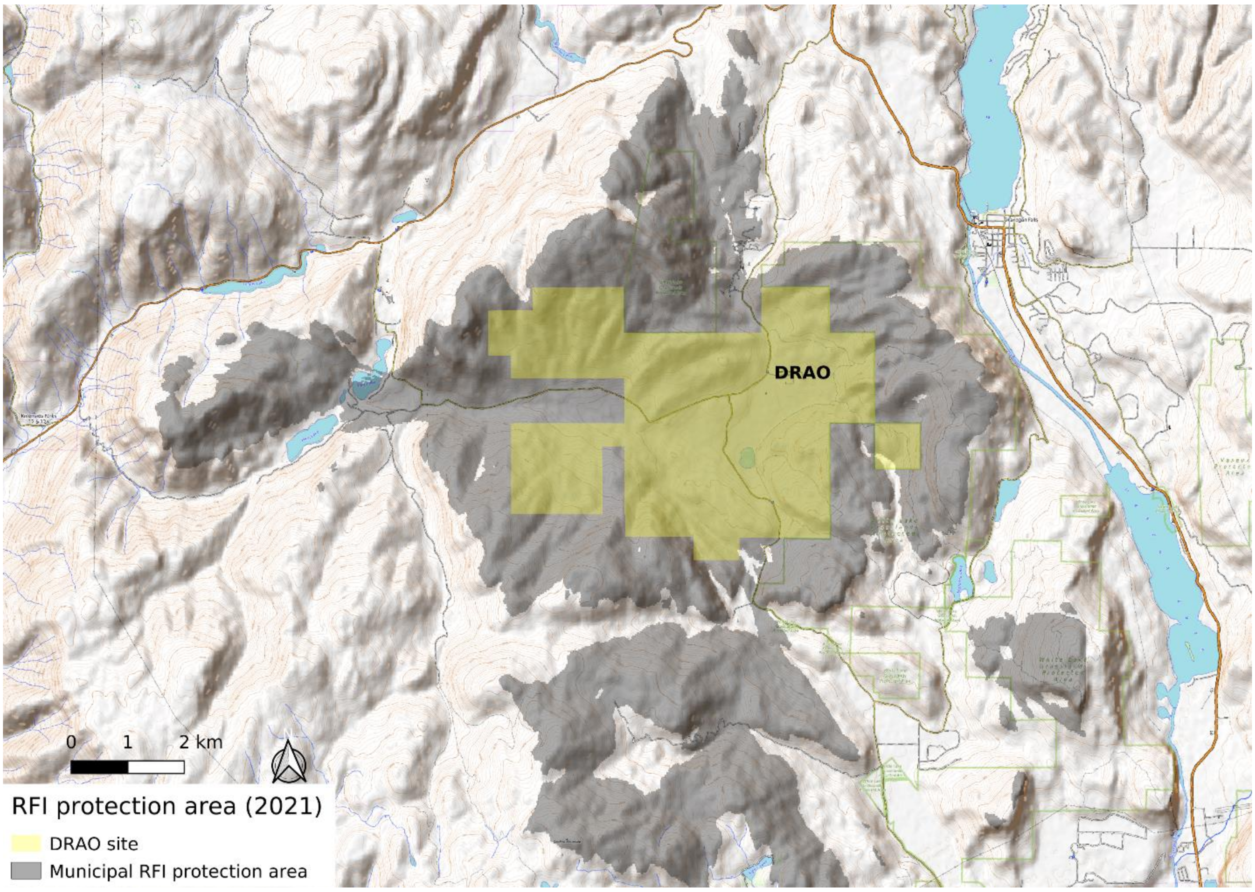
DRAO is located at 540 m elevation in a mountainous rural region in the southern interior of British Columbia. This location was selected after extensive nation-wide RFI surveys in the late 1950s, exploiting a natural ‘bowl’ surrounded by mountains that stand ~300-900 m above the floor, and provide natural RFI shielding from nearby communities. Land reserves granted by the Province of British Columbia form a 469 ha core site. Adjacent farming lands were acquired by NRC to prevent them from being developed, comprising an additional 1 781 ha lands, for a total of 2 250 ha in the DRAO site, covering most of the ‘bowl’. The low level of development in the area has drawn interest from both public and private conservation groups, which have together acquired 4 730 ha of neighbouring lands. Combined with the DRAO site, a total of nearly 7 000 ha (70 square-kilometres) is thus protected from development.

A number of regulatory measures have been taken by all levels of government to help protect DRAO from RFI. These include:

- Federal spectrum management and enforcement activity conducted through Industry, Science and Economic Development Canada (ISED);
- Federally-regulated designated airspace over DRAO (1 nautical mile radius to 1000 ft above ground level), administered by Nav Canada;
- Provincial restrictions on vacant lands in DRAO’s vicinity:
  – “Notation of Interest” to ensure consultation in land use planning;
  – “No Registration Reserve” to restrict mineral exploration and extraction;
- Municipal by-laws that limit subdivision and development in an area defined by lines-of-sight to DRAO (see Fig. 34).

FIGURE 34

The Municipal RFI protection area at DRAO, which includes lands that are ≤60 m vertically of a direct line-of-sight to selected locations within the DRAO site



DRAO is about 20 km south of the city of Penticton, the largest community in the region, home to 34 000 of the 83 000 regional population (2016 census). The average population density is 8 people per square-kilometre across the whole region, with development largely confined to low-elevation valleys. The closest town to DRAO is Okanagan Falls (population 2 100), which is 4 km to the east, but on the other side of a 300 m tall ridge, and a further 200 m lower in elevation. The smaller communities of Willowbrook and Twin Lakes are ~7 km south and west of DRAO, respectively, but – like Okanagan Falls – are well-shielded by terrain and have not been a significant source of RFI to date.

A more serious RFI threat is the neighbouring community of St Andrew's, a residential development and golf course just 1 km north of DRAO, with little terrain shielding. It was established in 1974, with approval for 150 houses, of which 96 have been constructed to date. A Land Use Contract between the developer and the Municipal government contains clauses to protect DRAO from RFI, including restrictions on devices and technologies known to cause RFI at the time. It remains in force today, but a process is now in place to modernize this arrangement.

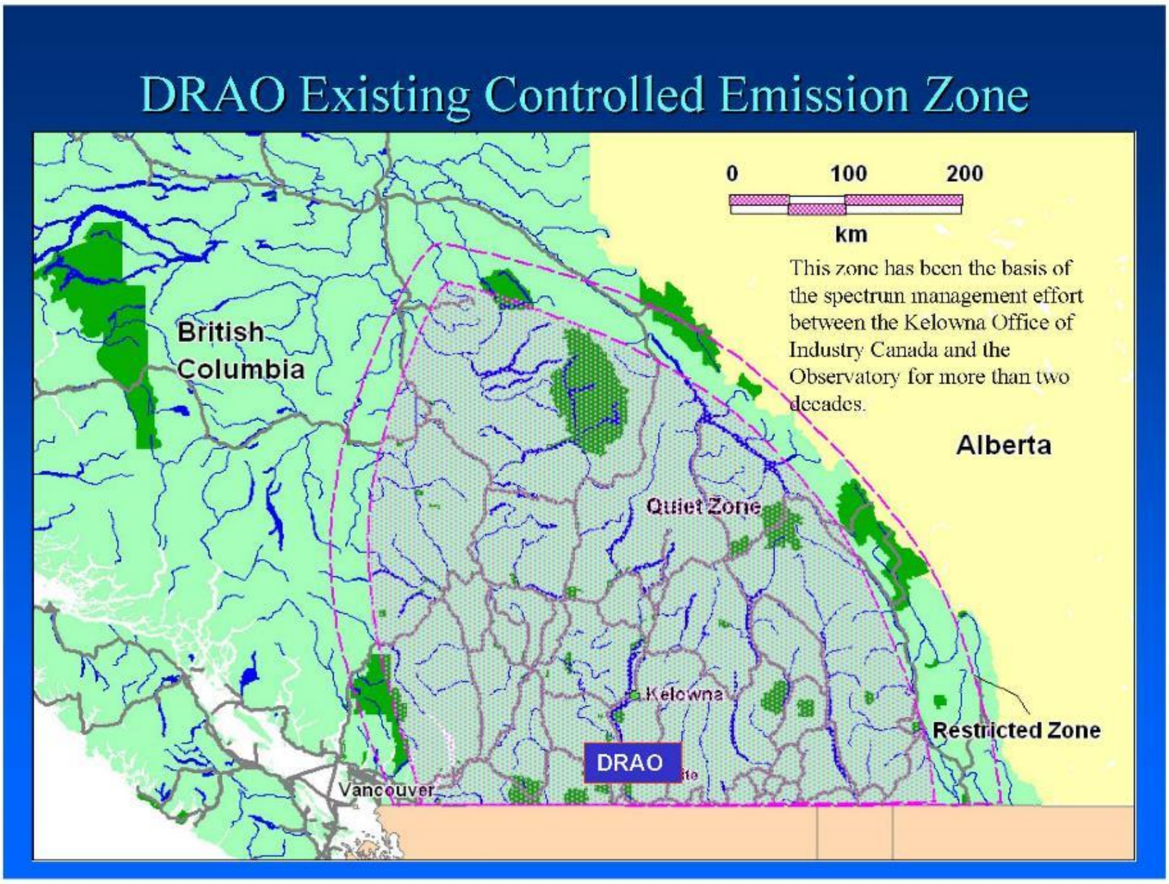
3 The need for a study

Within Canada, the guideline for managing the radio spectrum to protect the observatory is an EMZ, which has been in effect for more than two decades. The zone is shown in Fig. 35. Although satisfactorily large, it contains many communities. On the plus side, the interior of British Columbia comprises a series of mountain ranges running mainly North-South. Most of the populated areas lie in the valleys between these ranges, which provides significant topographic protection for the observatory from unwanted emissions from these communities, along with intended transmissions in shared bands.

The need to review this EMZ arose from the increasing pressure to provide additional spectrum to communities that are located within the EMZ. The need for additional spectrum is driven by the constantly evolving and increasingly sophisticated radio applications as well as by the emergence of new radio applications, including consumer devices. Another contributing factor was that the EMZ was established based on radio technologies and spectrum usage dating back to the 1970s, which does not reflect today’s reality. This shortcoming turned every licensing request addressed by ISED and DRAO working together into a case study, which led to a lot of efforts and time being invested by all parties.

FIGURE 35

The existing emission management zone



What was needed was a map of path loss between points on the map and the observatory, and for providing community planning information, estimates of domestic emissions and their potential impact upon observatory operations.

4 The study

The study comprises two separate projects:

a) theoretical calculations of path loss between points in the EMZ and a test antenna at the observatory, using the Predict and Longley-Rice propagation models and a digitized terrain map, and measurements made using a test transmitter at as many modelled points as possible;

b) estimates of the emissions produced by an average house.

The project is a joint one between the national, regional and local offices of Industry Canada, and staff at DRAO.

4.1 Path loss measurement and calculations

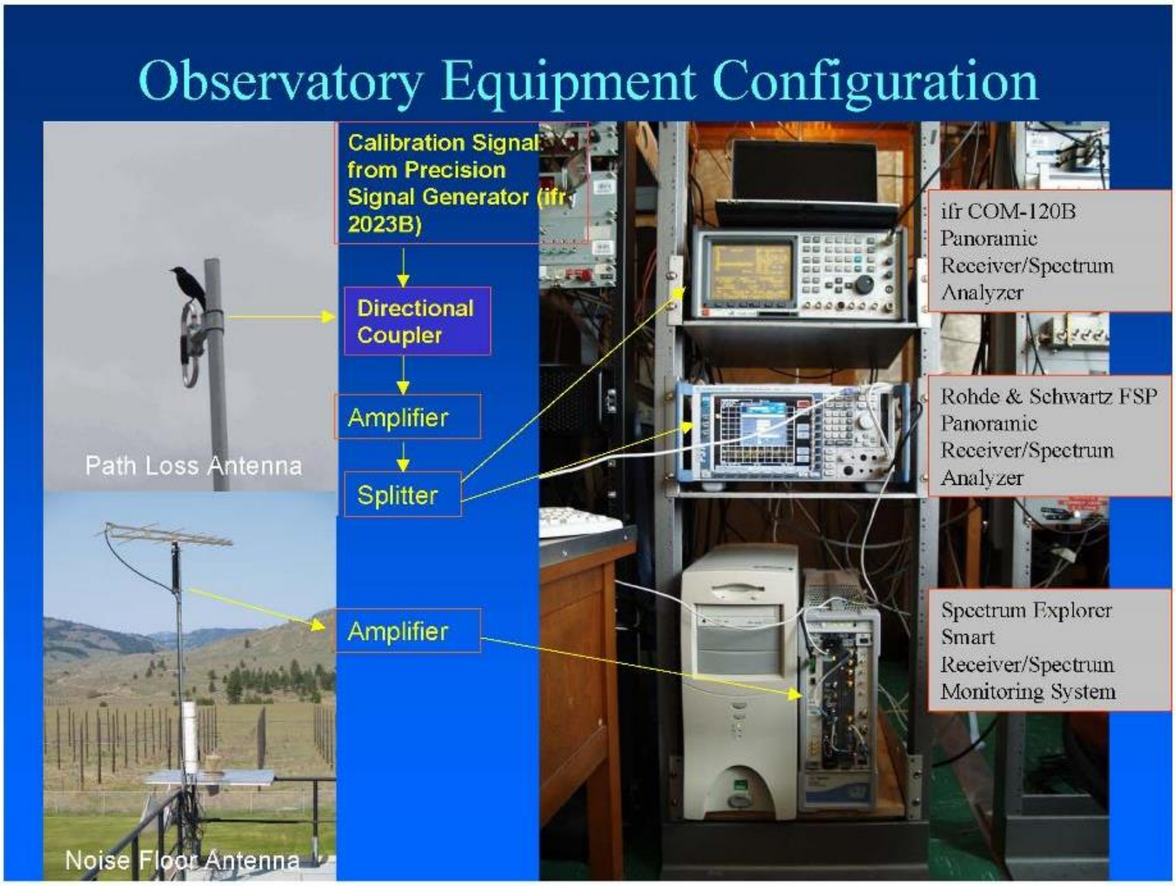
Because of unpredictable access problems in highly mountainous terrain, the experiment was done in the reverse order. Test transmissions were made from points around the observatory in the EMZ, the path losses estimated, and then the path losses between those points and the observatory estimated using both the Predict and Longley-Rice propagation models.

4.1.1 The hardware

The hardware at the observatory is shown in Fig. 36. The test transmissions in the 406.1-410 MHz band were received using a calibrated dipole and measured and recorded using two spectrum analysers. The log periodic antenna was used for an ongoing programme of noise floor measurements. The outputs from the lower spectrum analyser and the Spectrum Explorer system were directly accessible over the DRAO computer network, and in the Vancouver and Ottawa offices over the internet.

FIGURE 36

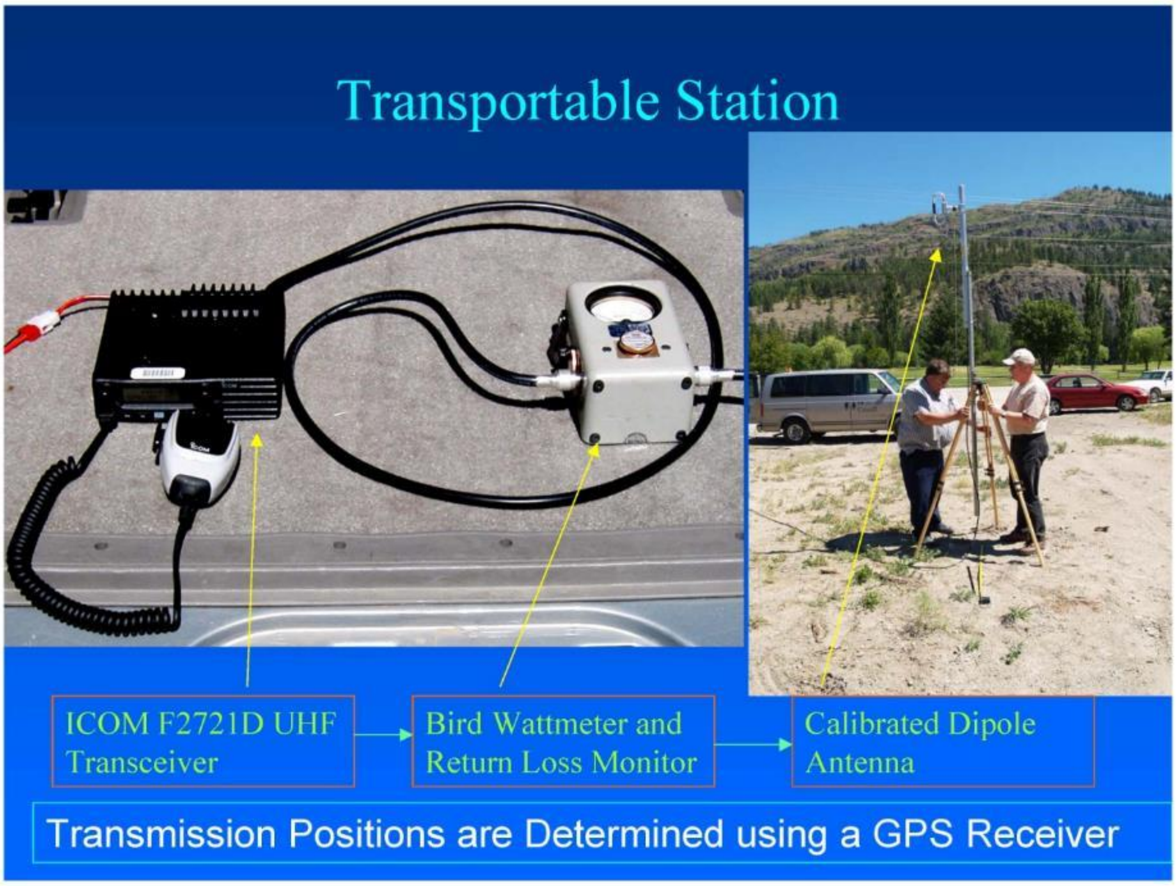
Observatory hardware. The dipole was used for the path loss transmissions and the log-periodic antenna for noise floor measurements



The mobile transmitter arrangement, as shown in Fig. 37, consists of an identical calibrated dipole, mounted on a tripod. A commercial transmitter provided the signals and a power meter and calibrated length of coaxial cable ensured it was possible to estimate the power radiated.

FIGURE 37

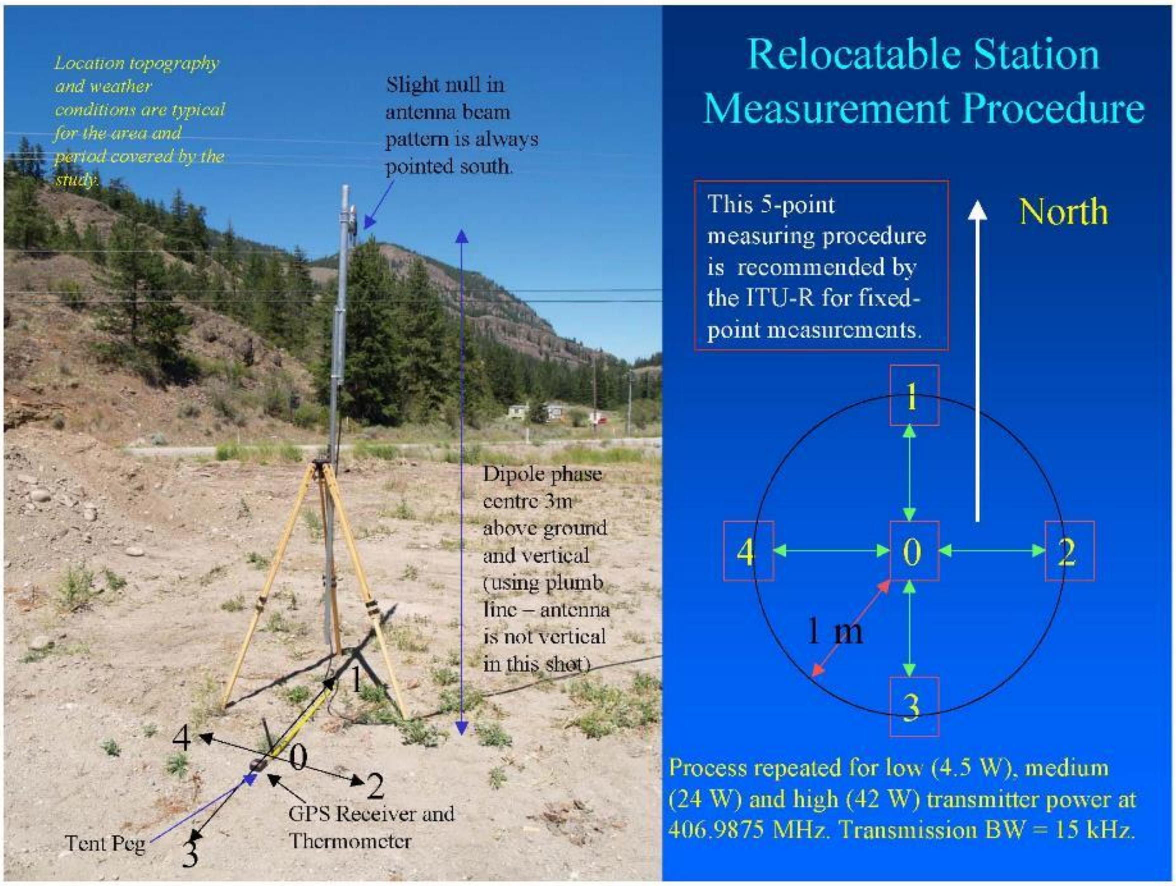
The mobile transmitter system, comprising a commercial transmitter, a power meter and an identical dipole to that used at the receiver, together with a calibrated length of coaxial cable



The measurement method used here reduces somewhat the errors induced in path loss measurements by local reflections. Transmissions are made from five points: the main point, and then at points North, East, South and West of this point at a distance of 1 metre from the main point. The path loss is measured for each point and the average of all five points used in the study. In order to accommodate the need for high power in some cases, and lower powers in other cases in order to avoid overloading the receiver, for each point, transmissions were made at three power levels: low (4.5 W), medium (24 W) and high (42 W). The process is shown in Fig. 38.

FIGURE 38

Transmission procedure used for path loss measurements



4.1.2 Measurements

Path loss measurements were made from a variety of locations: at the tops of hills and in valley bottoms. However, more measurements were made around valley bottoms because of (a) accessibility, and (b) that is where housing developments and other concentrations of human activity usually occur. A GPS receiver was used to determine the coordinates of the locations where measurement were taken. Of course, hilltops are the chosen places for transmitters, so hilltops either already used for transmitters, or where more might be deployed, and hilltops that might be considered suitable sites for future transmitters were tested.

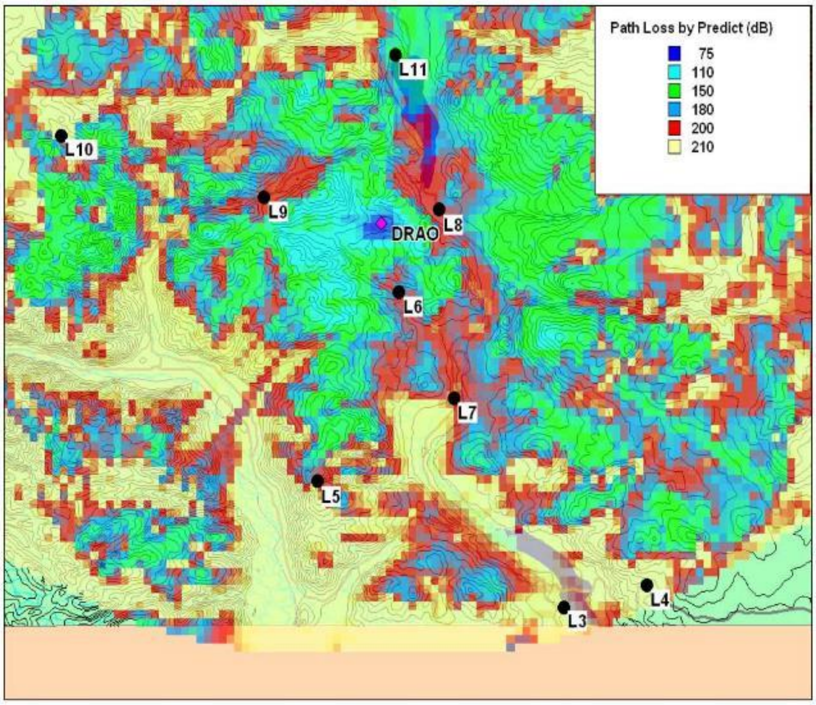
4.1.3 Modelling propagation path losses

Using a digitized terrain map (50-m resolution) and propagation modelling software, the propagation path losses between the test transmission location and the observatory test antenna were estimated. Two software packages were used: "Predict" and "Longley Rice". *Predict* is a commercially available package developed in Canada and widely used for propagation modelling. In urban, suburban and country terrain between flat and mildly hilly, it has been found to yield estimates within 10 dB of the measured values in most cases. The *Longley-Rice* propagation model is a widely available and used public software.

Figure 39 shows the local propagation loss map as estimated using the Predict software. In addition, the test sites are marked. Test point L11 was located in the centre of the housing development shown in Fig. 34.

FIGURE 39

**Propagation loss map for the DRAO environs estimated using the Predict software and a digitized terrain map
The left and right edges of the map run North-South with North at the top**



The measured losses from each of the test locations, together with the estimates obtained using the Predict and Longley-Rice propagation modelling software are tabulated below.

	Estimated path loss (dB)		Measured path loss (dB)	
Location	**Predict**	**Longley-Rice**	**Median**	**Standar deviation**
L3	208	187	160	3
L4	215	190	171	2
L5	184	165	154	3
L6	200	165	129	3
L7	208	172	145	3
L8	196	170	149	4
L9	191	175	160	4
L10	191	180	168	3
L11	176	170	153	5

The measured path losses from transmission sites to the observatory were in almost all cases significantly lower than estimates made for the same path using either the Predict or Longley-Rice propagation models. Therefore unless appropriate margins are allowed (these margins might be specific to the terrain surrounding the observatory), compatibility assessments regarding prospective deployment of devices or services that could possibly interfere with operations at the observatory should not be made without some measurements. The differences between modelled and measured propagation losses are almost certainly due to the rough terrain surrounding the observatory.

However, terrain properties are used to screen radio observatories from interference, so this particular case is applicable at other observatories.

Measurements made in high summer (hot and dry), and autumn (cooler and wetter) did not differ significantly from one another. However at this point it is not known whether this conclusion would apply to winter (cold and snow). Further measurements need to be done.

4.1.4 Conclusions

1) In assessing compatibility with proposed deployments of transmitters or housing developments, one cannot depend exclusively on modelled propagation losses without at least enough actual measurements to assess safe protection margins for making the estimates safely usable.

2) In the terrain surrounding DRAO, which comprises low mountains, forest and arid terrain, there was little difference between measurements made during hot dry summer weather and moister autumn conditions. However, as yet no measurements have been made under winter conditions (snow and ice). These need to be done.

3) In the case of housing developments or proposed transmitter deployments, specific path loss measurements need to be made. The general results in studies like this can safely be used only as guidelines during the initial evaluation process.

4) The collaborative effort here between spectrum managers in the Canadian Administration and DRAO radio astronomers in all stages of the study greatly improved the understanding of each other's problems in the spectrum management process and working together at all levels in the project promoted good working relationships and an excellent atmosphere for future studies.

4.2 Domestic radio emissions

4.2.1 The problem

An issue of growing concern is the rapidly increasing number of devices pervading both the commercial and domestic spheres that either use radio technology or electronics liable to make interference. In general, commercial applications are located in areas allocated for commercial use, but domestic applications arise everywhere there are people.

Radio telescopes such as the Atacama Large Millimetre Array, located on the Atacama Plateau in Chile, and the Square Kilometre Array, which will be built in Western Australia and South Africa, are far from population centres. However, there are many radio telescopes in the world, at sites such as Jodrell Bank (United Kingdom) and Effelsberg (Germany) that were reasonably isolated when they were built but are increasingly affected by encroaching housing and community development. In addition, the number of potentially interfering devices in common use is increasing and will continue to do so. In a world with a rapidly expanding population and pressures for resource development, there are no guarantees that currently isolated sites will remain so.

The Dominion Radio Astrophysical Observatory is a typical example of a site that was well isolated but is now faced with pressure to expand communities and build housing developments closer to the observatory. The local municipal land managers understand the observatory's concerns but need more quantitative information to help them better understand what can be permitted without causing undue risk to the observatory and what cannot.

4.2.2 Unwanted emissions from a single device

Consider the case of a single electronic device, producing radio emissions with power distributed over the spectrum given by $\xi(f)$, located at a distance, r, from the observatory, where the path loss to the radio telescope is $L(r)$. The loss is shown as a function of r but in rough terrain it will be a more complicated relationship involving additional variables. The total power at the radio telescope from all electronic devices is given by:

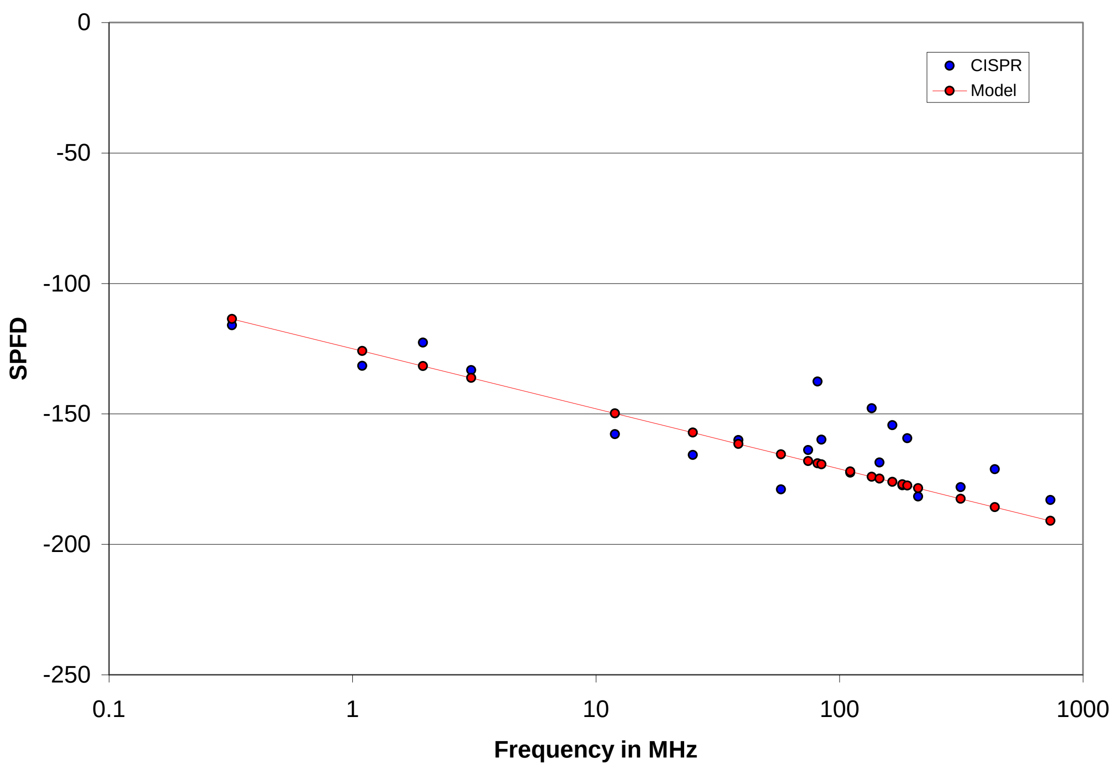
$$P = \sum_i \frac{\xi_i(f)}{L_i(r)}$$

It is assumed that all devices intentionally transmitting are doing so outside bands allocated to the RAS. Under these circumstances, all the emissions being considered are unwanted emissions. The upper limits for unwanted emissions from electronic devices are listed in documents produced by the Comité International Spécial des Perturbations Radioélectriques (CISPR) in standard documents CISPR-11 and CISPR-22.

Unfortunately the CISPR documents do not quote values for frequency bands allocated to the RAS on a primary or secondary basis. Therefore a curve was fitted to the CISPR values in order to estimate the values in bands in which radio astronomical observations are made.

FIGURE 40

The CISPR values (blue) show the maximum spfds for devices as measured 30 m from the device. The red dots and line are a fitted equation



The fitted equation is:

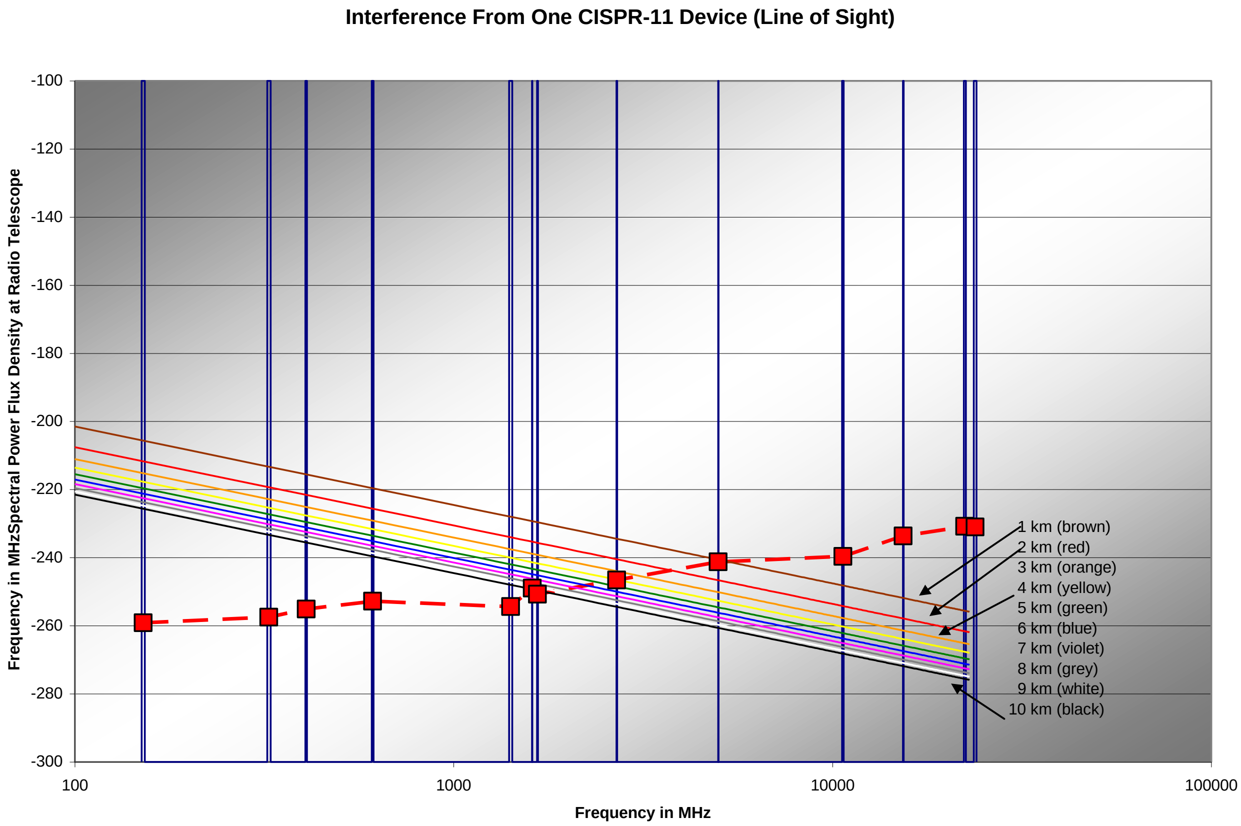
$$spfd = -10\ln(f) - 125$$

Where f is the frequency in MHz. The CISPR values show deviations of possibly 20 dB from the fitted line in some cases, but taking into account the deviations in real cases, plus devices actually hitting the CISPR values would be a worst case, the simplicity is justified.

Using the levels in Recommendation ITU-R RA.769 as the criterion for flagging compatibility issues, in combination with the equation above, the problem potential for a single device emitting at the CISPR limits as a function of frequency and distance in LoS of a radio telescope can be estimated. The results are shown in Fig. 41. It is clear that for radio astronomical observations at frequencies below about 2 GHz, a single device would be a problem if closer than about 10 km from the observatory, in LoS. If the device is located inside a house, it is assumed in standards calculations that this attenuates the signal by an additional 10 dB. One example of a device to which this discussion applies is the *energy saving light bulb*, some kinds of which use radiofrequency oscillators to excite the plasma. Since these are expected to be deployed in great numbers over the coming decade, they are a major issue for radio observatories located close to any significant population concentration.

FIGURE 41

Unwanted emissions from a single CISPR device at various distances from a radio telescope as a function of frequency



4.2.3 Unwanted emissions from a community

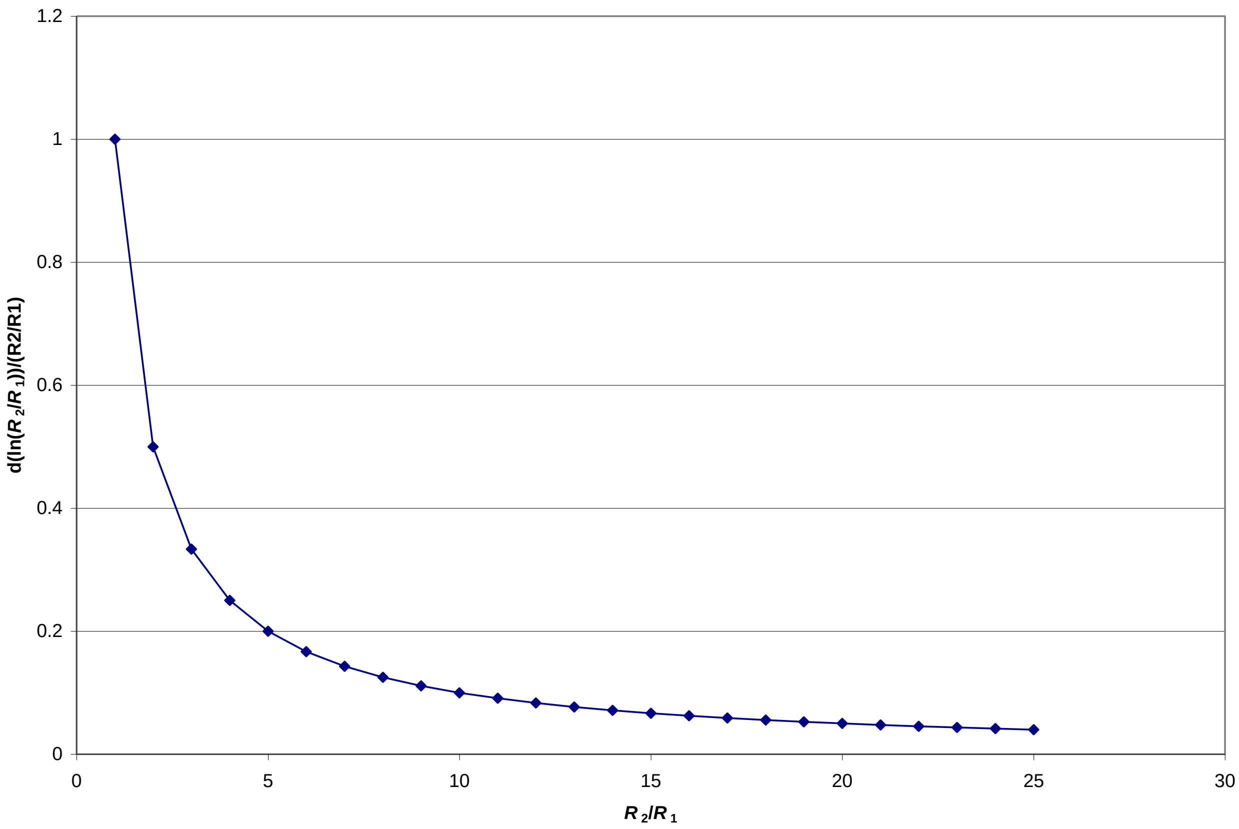
If there is a uniformly dense housing development containing *n* houses per square kilometre, and each of these houses is operating *m* electronic devices all radiating at the CISPR specified levels $\xi(f)$, the total power received at the radio observatory is:

$$S(f) = nm\xi(f)\int_{R_1}^{R_2} \frac{2\pi r}{4\pi r^2} dr = \frac{1}{2} nm\xi(f) \ln\left(\frac{R_2}{R_1}\right)$$

Where the development starts at a distance R_1 from the observatory and extends to R_2. The differential with respect to (R_2/R_1) of this function is shown in Fig. 42. This shows that in a uniform housing development in LoS of an observatory, extending a community outward, on the side furthest from the observatory has a far smaller effect than extending it closer to the observatory, even though fewer houses are involved in the latter case.

FIGURE 42

The rate of change of total unwanted emission as a function of size of the community or development



This preliminary discussion shows that unwanted emission from communities using an increasing number of electronic devices, such as energy-saving light bulbs could be a severe problem for a radio observatory if in LoS. Measurements at DRAO show that even small hills can give additional attenuation of more than 50 dB at 408 MHz, and much more at higher frequencies.

4.2.4 Conclusion

Expanding communities and encroachment of development around observatories, together with the increasing use of radio and other electronic devices in domestic use are a major issue in the management and continuing effectiveness of radio observatories. Since unwanted emissions from homes and support infrastructure is going to increase with time, but not in a predictable way, housing in LoS of an observatory should be avoided to the greatest practical extent. Terrain blocking is essential.

Annex 13

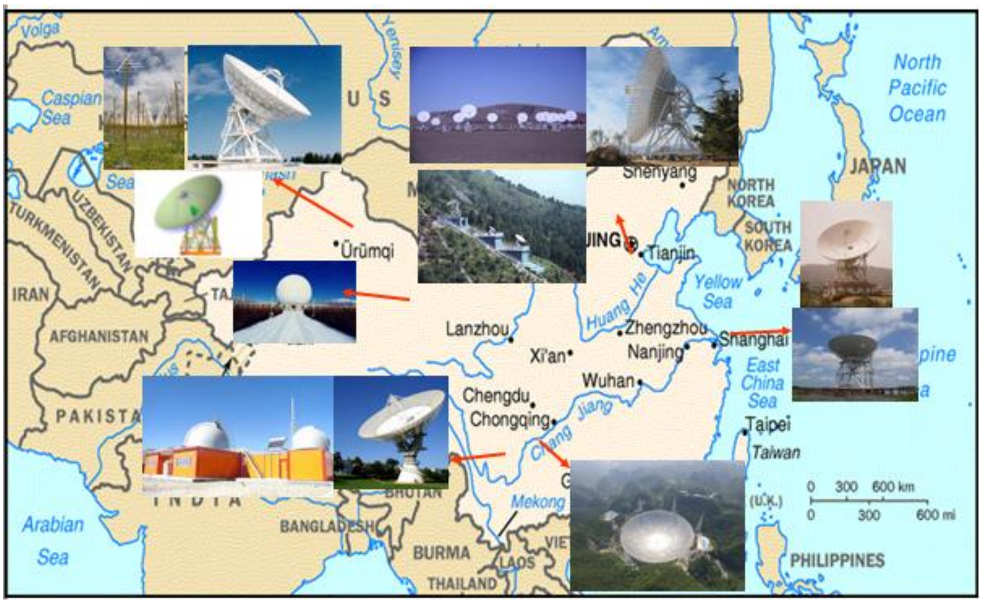
Characteristics of radio quiet zones: protection of the radio telescopes in China

1 Introduction and description

Radio astronomy in China has developed rapidly over the past decade. Several new radio telescopes have been built in the country (Fig. 43). The rapid progress of radio astronomy spurs the development of spectrum protection for telescopes. At present the Chinese astronomical community attaches great importance to the EMC measures of radio telescopes and has carried out a series of studies. Based on the studies on International Telecommunication Union (ITU) Radio Regulations and RFI measurements at radio astronomical stations, the RFI situation of the radio environment around the stations has been analysed, and the RFI measurement system has also been developed. Moreover, for several radio telescopes, especially large radio telescopes, the radio quiet zones have been established, which enable the protection of the astronomical observations from RFI and ensure the scientific output of the telescopes.

FIGURE 43

Some radio telescopes in China



2 Research activities

Due to the limitation of spectrum resources and increase of deterioration of the radio environment around the site of radio telescope, the continuous development of domestic radio astronomy has been adversely affected. It has led to the fact that the spectrum protection becomes more and more important. On the basis of the experiences from current radio astronomy stations, the radio interference monitoring methods suitable for various stations in China have been studied, including the scientific requirements, the frequency range of monitoring, the equipment used and performance indicators thereof, data storage and calibration. Meanwhile, other concerns, such as the domestic spectrum allocation, the location and characteristics of the known transmitters around each observing station, the spectrum regulations, the trends of the local spectrum usage, as well as the possible impact of population growth, are also taken into account.

By monitoring the radio environments of some existing and planned stations in China, the feasibility of the protection distance algorithms and radio interference monitoring methods for typical active services on the ground has been verified. At present, the National Astronomical Observatories of CAS and Shanghai Astronomical Observatory have developed radio environment monitoring systems suitable for astronomical requirements.

Research on interference reduction and coordination is actively carried out based on analysis and evaluation of the monitoring results, such as the interference test for the Mingantu Ultrawide Spectral Radioheliograph (MUSER) which was once called Chinese Spectral Radioheliograph (CSRH) during the site selection phase, electromagnetic environment measurement and analysis of radio telescopes in conjunction with radio regulators, testing and coordination work to cope with the complex radio environment for the Shanghai 65 m telescope (Tianma), assessment of interference from electronic equipment at stations, etc.

3 Legislative and regulatory control

In accordance with the development of domestic radio services, the standards for interference assessment of radio astronomy. By reference have been formulated to Recommendation ITU-R RA.769, the interference time evaluation criteria acceptable for domestic radio telescopes are given, and the interference protection rules for each radio astronomy station are proposed.

In order to protect the domestic radio environment around telescopes and preserve resources for the future development of the radio astronomy service, the footnotes CHN11 and CHN12 were amended to meet the increasing requirements of domestic radio astronomy during the process of revising the Regulations on the Frequency Division of the People's Republic of China. More frequency bands are assigned and more telescope sites are identified in the updated footnotes CHN11 and CHN12.

4 RQZs in China

Currently, four radio telescopes in China have established their own RQZs, which are the Five-hundred-meter Aperture Spherical radio Telescope (FAST) in Guizhou, the Mingantu Ultrawide Spectral Radioheliograph (MUSER) in Inner Mongolia, the Delingha 13.7 m radio telescope in Qinhai, and the Shanghai 65 m Radio Telescope (Tianma). The RQZ for the Qitai 110 m telescope (QTT) in Xinjiang is under coordination. More details are given below.

4.1 RQZ around FAST

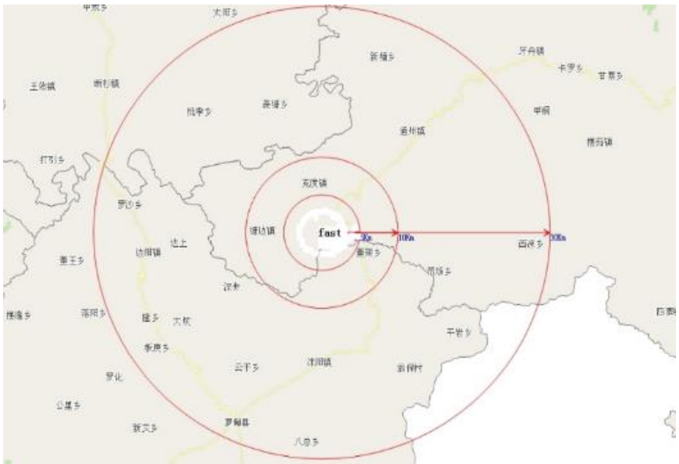
The Five-hundred-meter aperture spherical radio telescope (FAST), completed in 2016 and under commissioning, is the largest single-dish radio telescope in the world. Three outstanding features of the telescope are the unique karst depressions serving as the site, the active main reflector which corrects spherical aberration on the ground to achieve full polarization and a wide bandwidth without involving a complex feed system, and the lightweight focus cabin driven by the six steel cables.

Being the most sensitive radio telescope, FAST will enable astronomers to jumpstart many of the science goals, for example, the neutral hydrogen line surveying and detecting thousands of new pulsars etc.

The FAST site is a depression called Dawodang (East: 106°51′20″, North: 25°39′10″, Altitude: about 1 000 m) located in south Guizhou. To protect the radio quiet environment for FAST, the local government has established a RQZ up to 30 km radius, with the Dawodang depression as the centre (Fig. 44).

FIGURE 44

RQZ around FAST



The protection area is divided into three subsections, radius R < 5 km is the core area, also named as restriction zone; 5 km < R < 10 km is the central area and 10 km < R < 30 km is the remote area, named as coordination zone. Within the restriction zone, no transmitters may be stationed. Meanwhile, within the coordination zone, operators wishing to station transmitters are required to coordinate with the operators of the FAST telescope.

4.2 RQZ around MUSER

The Mingantu Ultrawide Spectral Radioheliograph (MUSER), which began construction in 2009, is located in Inner Mongolia (East: 115°14′44.7″, North: 42°12′31.3″). It operates at centimeter and decimeter wavelengths (0.40-15.00 GHz), and has 100 antennas with diameters of 2.0 and 4.5 m in a 3-arm spiral array.

MUSER can obtain full imaging observations of the solar chromosphere and corona by using aperture synthesis technology. It represents a new generation of solar radio telescopes that can generate observations with high spatial, temporal and spectral resolution.

The RQZ around MUSER is established with a radius of 10 kilometres (Fig. 45). No new radio transmitting stations should be set within the RQZ.

FIGURE 45

RQZ around MUSER (CSRH)

4.3 RQZ around Delingha 13.7 m radio telescope

The Delinha 13.7 m radio telescope in Qinhai Province is a radio facility working in the millimeter waveband in China. The telescope is equipped with an indigenously developed SIS superconductor receiver working in the band of 85-115 GHz. The observations of the spectral lines of CO isotopes, HCO+, SiO, CS, etc., and continuum spectra with the telescope are widely used for the study of molecular cloud structure, the physical and chemical environment of star formation regions, planetary nebulae, supernova remnants etc.

FIGURE 46

RQZ around Delingha 13.7 m radio telescope

The RQZ established by the local government in 2015 is of 26 km radius, with latitude 37°22′42.5″ and longitude 97°43′46.7″ as centre (Fig. 46). Within the protected area, radius R < 11 km is the core area, where transmitters in the protected band of the telescope are prohibited, and radius 11 km < R < 26 km is the coordination area, where transmitters in the protected band of the telescope are subject to the approval of radio regulatory department.

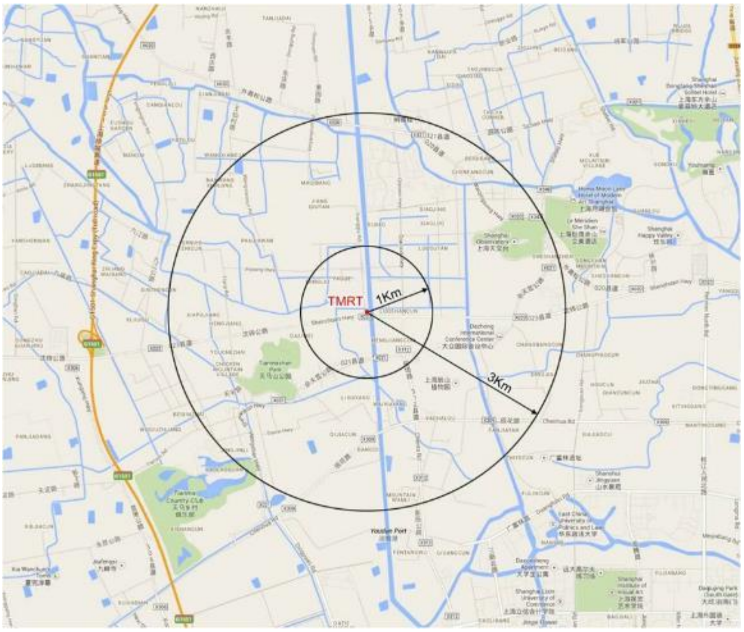
4.4 RQZ around Tianma telescope

The Shanghai 65 m Radio Telescope (Tianma) is a fully steerable radio telescope with a 65 m aperture. Its operating wavelengths from 7 mm to 21 cm in eight sections cover the entire centimeter and long millimeter range for radio astronomical observation. The main tasks include radio astronomy, lunar exploration and deep space detection.

The protection area for Tianma is within a circle of 3 km radius in Songjiang District with the center latitude 31°05′13.0″ and longitude 121°09′48.1″ (Fig. 47). Radius R < 1 km is the core area, where transmitters are forbidden. Radius 1 km < R < 3 km is coordination zone, where transmitters are strictly controlled.

FIGURE 47

RQZ around Tianma



4.5 RQZ for QTT 110 m telescope (proposed)

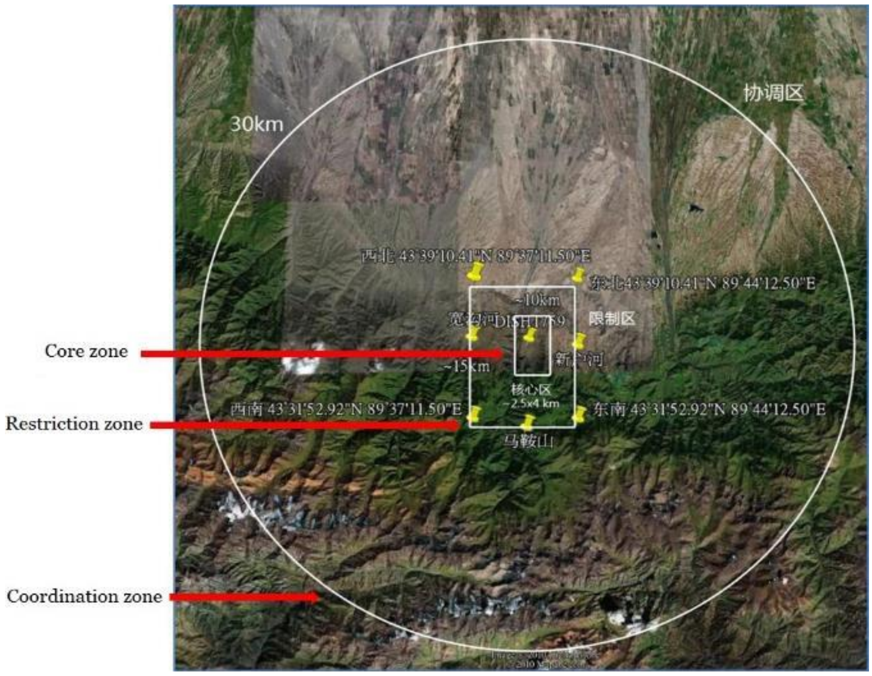
A steerable radio telescope of 110 m aperture (QTT) is constructing in Qitai Base which is located at the northern foot of Tianshan Mountain in Xinjiang province. The legislation of a RQZ has been completed.

The base, seated in a basin which is about 1.5 km from east to west and 2 km from south to north, and 1 730-1 830 m above the sea level, is surrounded by mountain ridges about 1 900 m above sea level. The place provides an enclosed environment for radio frequency interference.

The RQZ has been divided into core zones, restriction zone and coordination zone from the centre of the station to the outside (Fig. 48). Wherein, the centre of 2.5 × 4 square kilometres is the core zone, the range of 10 × 15 square kilometres is the restriction zone, and the radius of 30 kilometres around the telescope is the coordination zone. Within the core zone, any transmitter shall not be installed, all kinds of instruments and equipment with radio radiation that are not effectively shielded are forbidden to be used. Within the restriction area, no transmitters shall be stationed, and other large equipment and instruments to be installed should undergo strict inspections. Flexible measures might be adopted within the coordination area.

FIGURE 48

RQZ for QTT



Attachment
to Annex 13

Information summary of RQZs in China

	FAST	MUSER	Delingha	Tianma	QTT
Centre position (Lat. Long.)	25°39′ 10″, 106°51′ 20″	42°12′31.3″, 115°14′44.7″	37°22′42.5″, 97°43′46.7″	31°05′32″, 121°08′10″	43°36'04", 89°40'57"
Altitude	841 m	1 356 m	3 200 m	4 m	1 759 m
Date of policy (year)	2013	2007	2015	2012	2018
Restriction zone	~5 km radius	~10 km radius	~11 km radius	~1 km radius	Rectangle 10 × 15 km²
Coordination zone	5-30 km radius	-	11-26 km radius	1-3 km radius	~30 km radius
Note	-	-	-	-	In planning