Part 4

Threats to Radio Astronomy

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The Future of Radio Astronomy: Options for Dealing with Human Generated Interference

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Abstract. Radio astronomy provides a unique window on the universe, allowing us to study non-thermal processes (e.g. galactic nuclei, quasars, pulsars) at the highest angular resolution using VLBI, with low opacity. It is the most interesting waveband for SETI searches. To date it has yielded three Nobel prizes (microwave background, pulsars, gravitational radiation). There are both exciting possibilities and substantial challenges for radio astronomy to remain at the cutting edge over the next three decades. New instruments like ALMA and the SKA will open up new science if the challenge of dealing with human generated interference can be met. We summarise some of the issues and technological developments that will be essential to the future success of radio astronomy.

1. Telescope Sensitivity

Moore's law for the growth of computing power with time (i.e. a doubling every 18 months) is often quoted as being vitally important for the success of the next generation of radio telescopes (working at cm wavelengths) such as the Square Kilometre Array (SKA). It is worth noting that radio astronomy has enjoyed a Moore's law of it own, having exponentially improved in sensitivity with time as shown in Figure 1. In fact the doubling time is approximately 3 years, and has been in progress since 1940, giving an overall improvement in sensitivity of 10^5 to the present time. New instruments and planned upgrades, listed in Table 1, will continue this improvement into the next century. However, we are approaching the fundamental limits of large mechanical dishes and the noise limits of broadband receivers systems. We need to look to other means of extending this growth further into the future.

Why do we want to be on this exponential growth curve? Fields of research continue to produce scientific advances while they maintain an exponential growth in some fundamentally limiting parameter. For radio astronomy, sensitivity is definitely fundamentally limiting. An interesting question is whether there are other parameters for which an exponential growth could be maintained for a period of time. The first and most obvious point about exponential growth is that it cannot be sustained indefinitely. Can we maintain it for sometime into the future? There are two basic ways to stay on the exponential curve:

1. Spend more money, and
2. Take advantage of technological advances in other areas.

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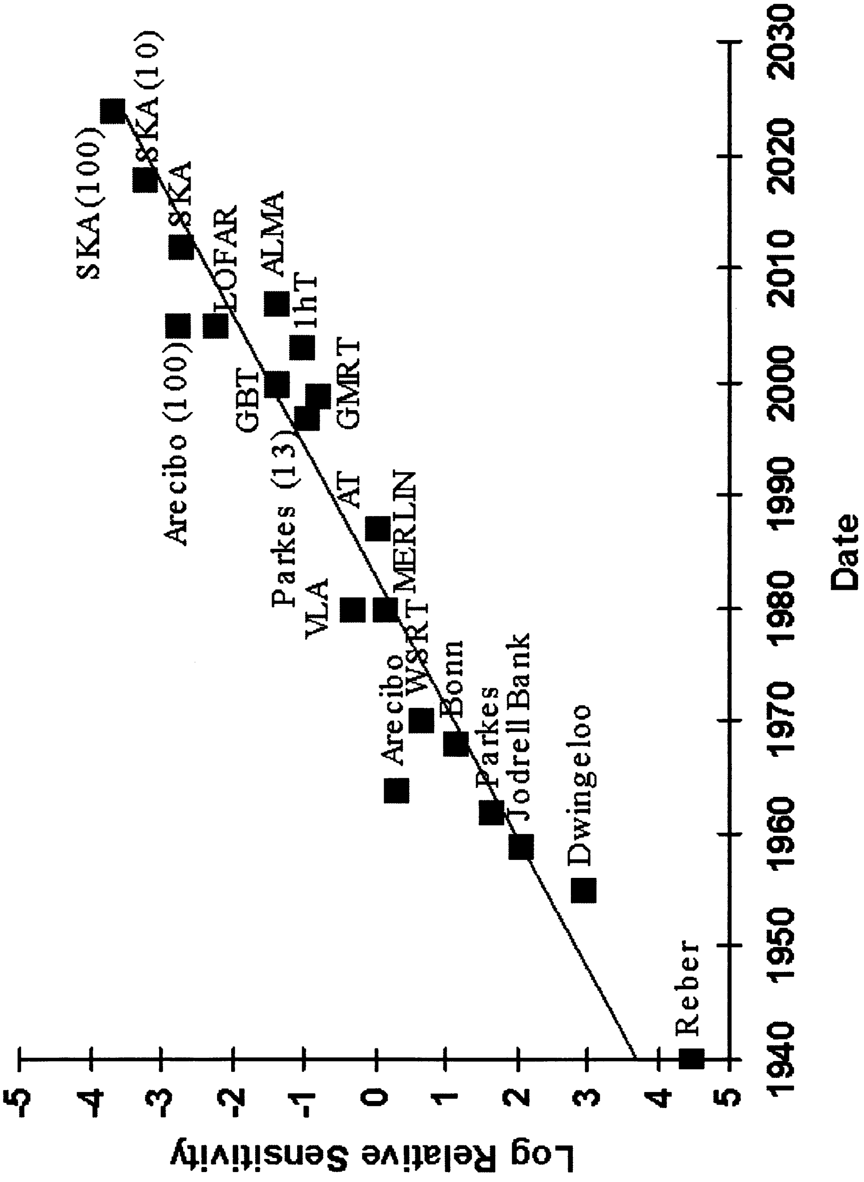

Figure 1. Exponential growth of Radio Telescope sensitivity. Boxes indicate the sensitivity attained when the systems were first commissioned. This diagram does not indicate their present capabilities. Projected capabilities are shown for ALMA, LOFAR, SKA (with 1, 10 and 100 beams) and Arecibo (with 100 beams). The current 13-beam system on Parkes is also shown.

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Table 1. Summary of New Facilities

	D(m)	Area(m^2)	Freq(GHz)	Date
ALMA	64 x 12m	7.2 x 10^3	30.0 - 900	2007
GBT	100m	7.8 x 10^3	0.30 - 86	2000
1hT	512 x 5m	1.0 x 10^4	1.00 - 12	2003
VLA	27 x 25m	1.3 x 10^4	0.20 - 50	2002
GMRT	30 x 45m	4.8 x 10^4	0.03 - 1.5	1999
SKA	undecided	1.0 x 10^6	0.20 - 20	2015
LOFAR	10^6 x 1m	1.0 x 10^6	0.03 - 0.2	2003

1.1. International Mega Science Projects

International cooperation is now needed for dramatic improvements in sensitivity, because no one country can afford to do it alone. ALMA, the Atacama Large MM Array being developed by the USA, Europe and Japan is an example. It will cost around $US700M spread over 1999-2007 and will provide an unprecedented opportunity to study redshifted molecular lines. The Square Kilometre Array (SKA) which will work at centimetre wavelengths is likely to be a collaboration of ten or more nations, spending $US500M over 2008 to 2015.

There are two basic approaches to funding such large projects:

1. User pays, where member countries pay for slices of the time, or
2. The member countries build the facility and make it openly accessible to all.

Optical astronomy has moved very much down path 1, as the Keck, VLT and Gemini type facilities demonstrate. Radio astronomy has traditionally followed path 2, as have projects like CERN. For future facilities there may be pressure to move more into the user pays regime, possibly bringing about substantial change in the dynamics of the radio astronomy community.

In the past, considerable extensibility of instruments was attained because each country learned from the last one to build a telescope. That evolution is very clear from Figure 1. Since we are likely to be moving to internationally funded projects, that path to extensibility is much more restricted and designers must think very carefully about designing extensibility into the next generation telescopes.

1.2. Extensibility Through Improved Technologies

For a given telescope, past and present extensibility have been achieved by improvements in three main areas:

System Temperature: Reber started out with a 5000 K system temperature. Modern systems now run at around 20 K, meaning that if everything else were kept constant, Reber's telescope would now be 250 times more sensitive than when first built. There are possibilities of some improvements in future, but nothing like what was possible in the past.

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Bandwidth: Telescopes like the GBT (Green Bank Telescope) having bandwidths some 500 times greater than Reber's, will give factors of 20–25 improvement in sensitivity. Some future improvements will be possible, but again they will not be as large as in the past.

Multiple Beams: Whether in the focal or aperture plane, multiple beam systems provide an excellent extensibility path, allowing vastly deeper surveys than were possible in the past. Although multiple beam systems have been used for a number of experiments, the full potential of this approach is yet to be exploited. A notable example that has made a stride forward in this direction is the Parkes L-band system (Stavely-Smith et al. 1996). The fully sampled focal-plane phased array system being developed at NRAO by Fisher and Bradley highlights the likely path for the future.

Using these three methods, a small telescope like the Parkes 64-m has remained on the exponential curve and the forefront of scientific discovery for 35 years (shown in Figure 1 in 1962 and in 1997). Other telescopes have of course undergone similar evolution and we only highlight Parkes as an example. Scope for continuing this evolution looks good for the next decade, but beyond that more collecting area will be needed. A 64-beam system installed in 2010, would allow Parkes to stay on the curve for some time. The technology to do this is probably only 3-4 years away from providing a realisable system, making it possible to jump well ahead of the curve. Putting a 100-beam system on Arecibo by 2005 is possible and would allow Arecibo to jump way out in front of the curve as it did when first built in 1964.

The relevance of Moore's law in this context is that, if it continues to hold true for the next 1-2 decades, it will provide the necessary back-end computational power to realise the gains possible with multiple beams.

2. Key Technologies, Driving Future Developments:

HEMT receivers which are wide-band, cheap, small and reliable, allowing us to build low-noise systems with many elements.

Focal plane arrays giving large fully-sampled fields of view will allow rapid sky coverage for survey applications and great flexibility for targetted observations, including novel possibilities for calibration and interference excision.

Interference rejection allowing passive use of spectrum outside the bands allocated to passive uses. High dynamic range linear systems, coupled with high temperature superconducting or photonic filters will allow use of the spectrum between communication signals. Adaptive techniques may allow some co-channel experiments, by removing the undesired signals, so that astronomy signals can be seen behind them.

More computing capacity may result in much more of the system being defined in software rather than hardware. This may lead to a very different expenditure structure, where software is a capital expense and computing hardware is a considered as a consumable or running cost.

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Fibre/photonic based beamforming and transmission of recorded signals will revolutionise bandwidths and signal quality, especially for high resolution science.

Software radio and smart antenna techniques which will allow great flexibilty in signal processing and signal selection.

3. Interference Sources and Spectrum Management

It is important to be clear of what we mean when we talk about interference. Radio astronomers make passive use of many parts of the spectrum legally allocated to communication and other services. As a result, many of the unwanted signals are entirely legal and legitimate. We will adopt the working definition that interference is any unwanted signal, getting into the receiving system.

If future telescopes like the SKA are developed with sensitivities up to 100 times greater than present sensitivities, it is quite likely that current regulations will not provide the necessary protection. There is also a range of experiments (eg redshifted hydrogen or molecular lines) which require use of the whole spectrum, but only from a few locations, and at particular times, suggesting that a very flexible approach may be beneficial. Other experiments require very large bandwidths, in order to have enough sensitivity. Presently only 1-2% of the spectrum in the metre and centimetre bands is reserved for passive uses, such as radio astronomy. In the millimetre band, much larger pieces of the spectrum are available for passive use, but the existing allocations are not necessarily at the most useful frequencies.

3.1. Terrestrial Sources of Interference

Interference can arise from a wide variety of terrestrial sources, including communications signals and services, electric fences, car ignitions, computing equipment, domestic appliances and many others. All of these are regulated by national authorities and the ITU (International Telecommunication Union). In the case of Australia, there is a single communcations authority for whole country and therefore for the whole continent. As a result there is a single database containing information on the frequency, strength, location, etc. of every licensed transmitter. This makes negotiations over terrestrial spectrum use simpler in principle.

3.2. Space and Air Borne Sources of Interference

Radio astronomy could deal with most terrestrial interfering signals by moving to a remote location, where the density and strength of unwanted signals is greatly reduced. However with the increasing number of space borne telecom and other communications systems in low (and mid) Earth orbits, a new class of interference mitigation challenges is arising - radio astronomy can run, but it can't hide! The are several new aspects introduced to the interference mitigation problem by this and they include: rapid motion of the transmitter, more strong transmitters in dish sidelobes and possibly in primary beam, and different spectrum management challenges.

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There is also an upside to the space borne communication systems in that they help to develop the technology that makes space VLBI possible, which leads to the greatest possible resolution.

A classic example of the problems that can arise is provided by Iridium mobile communications system, which has a constellation of satellites transmitting signals to every point on the surface of the Earth. Unfortunately in this case, there is some leakage into the passive band around 1612 MHz, with signals levels up to 10^{11} times as strong as signals from the early Universe.

3.3. Radio Quiet Reserves

Radio quiet reserves have been employed in a number of places, with Green Bank being a notable success. For future facilties such as the SKA and ALMA, the opportunity exists to set radio quiet reserve planning in process a decade before the instruments are actully built. Radio quiet reserves of the future may take advantage not only of spatial and frequency orthogonality to human generated signals, but also time, coding and other means of multiplexing. These later parameters may be particularly important for obtaining protection from space borne undesired signals, a number of which illuminate most of the Earth's surface.

4. Radio Wavelength Fundamentals

Undesired interfering signals and astronomy signals can differ (be orthogonal) in a range of parameters:

- Frequency
- Time
- Position
- Polarisation
- Distance
- Coding

It is extremely rare that interfering and astronomy signals do not possess some level of orthogonality in this 6-dimensional parameter space. We therefore need to develop sufficiently flexible back-end systems to take advantage of the orthogonality and separate the signals. This is of course very similar to the kinds of problems faced by mobile communication services, which are being addressed with smart antennas and software radio technologies.

5. Interference Excision Approaches

There is no silver bullet for detecting weak astronomical signals in the presence of undesired human generated signals. Spectral bands allocated for passive use provide a vital window, which cannot be achieved in any other way. There is a

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range of techniques that can make some passive use of other bands possible and in general these need to be used in combined or complementary ways.

Screening to prevent signals entering the primary elements of receivers.

Front-end filtering (possibly using high temperature superconductors) to remove strong signals as soon as they enter the signal path.

High dynamic range linear receivers to allow appropriate detection of both astronomy (weak signals below the noise) and strong interfering signals.

Notch filters (digital or analogue) to excise particularly bad spectral regions.

Decoding to remove multiplexed signals. Blanking of periodic or time dependent signals is a very succesful but simple case of this more general approach.

Calibration to provide the best possible characterisation of interfering and astronomical signals.

Cancellation of undesired signals before correlation, using adaptive filters and after taking advantage of phase-closure techniques (Sault et al. 1997).

Adaptive beam-forming to steer nulls onto interfering sources. Conceptually, this is equivalent to cancellation, but it provides a way of taking advantage of the spatial orthogonality of astronomical and interfering signals.

5.1. Adaptive Systems

Of all the approaches listed above, the nulling or cancellation systems (which may be adaptive) are the most likely to permit the observation of weak astronomical signals that coincide in frequency with undesired signals. These techniques have been used extensively in military, communications, sonar, radar, medicine and other fields (Widrow & Stearns 1985, Haykin 1995). Radio astronomers have not kept pace with these developments and in this case need to infuse rather than diffuse technology in this area. A prototype cancellation system developed at NRAO (shown in Figure 2) has demonstrated 70 dB of rejection on the lab bench and 30 dB of rejection on real signals when attached to the 140-foot telescope at Green Bank (Barnbaum & Bradley 1998). Adaptive Nulling systems are being prototyped by NFRA in the Netherlands. However their application in the presence of real radio astronomy signals is yet to be demonstrated and their toxicity effects on the weak astronomical signals need to be quantified. Arguably the best prospect for testing cancellation schemes in the near future lies in recording baseband data from exisiting telescopes, containing both interfering and astronomy signals (Bell et al. 1999). A number of algorithms can then be implemented in software and assessed relative to each other.

6. The Telecommunications Revolution

We cannot (and do not want to) impede the telecommunications revolution, but we can try to minimise its impact on passive users of the radio spectrum and

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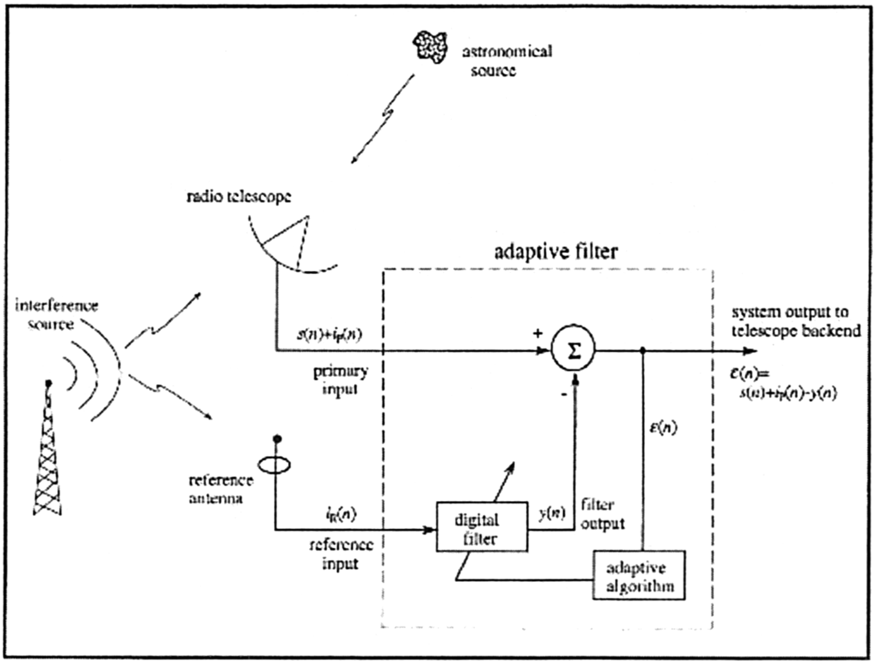

Figure 2. Example of an adaptive cancellation system. From Barnbaum & Bradley (1998).

maximise the benefits of technological advances. The deregulation of this industry has had some impact on the politics. Major companies now play a prominent (dominant?) role in the ITU (International Telecommunication Union). Protection of the bands for passive use must therefore addressed and promoted by government.

7. Spectrum Pricing

There may be some novel ways in which spectrum pricing could evolve in order to provide incentives for careful use of a precious resource. Radio astronomy and other passive users cannot in general afford commercial rates and therefore need government support. One possibility would be to have a 'green tax' which could be used to fund interference management and research.

Such strategies do not come without cost. While the long term economic cost may be relatively small, upfront R&D costs to an individual company may compromise their competitiveness. This issue must therefore be addressed at national or international policy level.

Unlike many other environmental resource-use problems, spectrum overuse is both reversible and possible to curtail. This leads to certain political advantages because politicians like to have problems which they can solve and this is a more soluble problem than many other environmental problems.

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8. Remedies

Siting Radio Telescopes Choosing remote sites with natural shielding helps, but doesn't protect against satellite interference. We can establish radio quiet zones, using National government regulations. This is easier for fixed than for mobile transmitters. The far side of the Moon and the L2 Lagrangian point are naturally occurring radio quiet zones but are very expensive to use.

OECD Megascience Forum: Task Force on Radio Astronomy The goals of the OECD Megascience Forum are complementary to IAU efforts, providing a path for top-down influence of governments which would otherwise not be possible. This task force aims to promote constructive dialogue between regulatory bodies, the international radio astronomy community, telecommunications companies and government science agencies. It will investigate three approaches favoured by the Megascience Forum: technological solutions, regulation and radio quiet reserves.

Environmental Impact In the meter and cm bands <2% of the spectrum is allocated to passive use! 98% is already used: resource use has been extravagant. Almost all the spectrum at wavelengths longer than 1cm is now polluted, and the situation is rapidly deteriorating at shorter wavelengths. However, the situation is reversible and shareable in more creative ways! in contrast to most other pollution problems.

9. Funding of Radio Astronomy

University-based radio astronomy research in the USA has suffered relative to astronomy at other wavelengths for two reasons:

1. The centralised development at NRAO has made it difficult for many universities to remain involved in technical developments.

2. Space-based programs in infrared, optical, UV, X-ray, and Gamma-ray bands have a rather different funding structure, where access to research funds is based on successful observing proposals. Radio astronomy has no access to such funds and therefore is a relatively uneconomical pursuit for astronomers. This method of funding is being taken up in other countries and radio astronomy needs to find a way to join the scheme.

More globally, radio astronomy has suffered relative to other wavelengths, because data acquisition, reduction and analysis is unnecessarily complex. Researchers have to spend a lot more effort in data processing than in other areas of astronomy. For example, in many other bands, fully calibrated data lands on the researcher's desk a few days after the observations were taken. Radio astronomy needs to finds ways to move into this regime (as Westerbork have done to some degree), but at the same time preserve the vast flexibility that can be derived from measuring the electric field at the aperture.

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10. Conclusions

The possibilities for the future of radio astronomy are good, but there are some challenges issues for the community to consider and address:

- The whole radio spectrum is needed for redshifted lines
- About 2% of spectrum below 50 GHz is reserved for passive use by regulation, so we must develop other approaches
- We cannot (and don't want to) impede the telecommunications revolution
- Radio astronomy has low credibility until we use advanced techniques
- It is essential to influence government policy
- Astronomers should have a uniform position
- Threatening language doesn't help
- Is interference harmful?

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