Conservation of spectrum for scientific services,- the radio astronomical perspective

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Abstract

Scientific services are indispensable for a technical society, but by their nature they have more stringent protection requirements. They are efficient in their use of allocated bandwidth and utilise the highest possible detection sensitivity, but any detectable man-made signal in their band jeopardizes their operation. There is no free choice of frequencies, these are given by natural molecular transition frequencies. As a consequence, only the scrupulous regulatory protection of core frequencies for science can ensure the viability of scientific use of radio spectrum for the benefit of all.

1. Introduction

Any undertaking, be it commercial (where it is natural), political, social, scientific, even cultural and educational, is nowadays viewed under economic aspects and depending on the intention and thoroughness of the scrutiny, this will not only include the internal and direct costs and benefits to those who are involved but also what is externalised to other sectors of society, other countries, future generations or even the global environment. Pollution and energy generation are classical examples known to everyone. There is a tradition of highlighting only the short term direct benefits when we are dealing with the privatisation and liberalisation of use of common and by their nature limited resources, at the same time the proponents are often neglecting the externalised costs of higher economic efficiency (i.e. pollution), and the long-term benefits public use of resources has given to society. The radio spectrum, and in particular its use for scientific purposes is just another example for this: Nobody denies that i.e. accurate weather forecasts are a means of improving the yields of agriculture, the forecast of natural disasters and the efficiency of transport. The benefits of meteorological earth sensing are common for everybody and the direct costs are borne by the taxpayer. The same is also true for other scientific use of the radio spectrum where there is often a considerable delay between scientific research and its impact on society or the economy. But even for weather forecasts the economic impact can only be partially quantified, but nevertheless no one would deny their significance and benefit. The same is true for the overall impact of the scientific radio spectrum use, as outlined in the recent RSPG report[1] and the draft ITU report on scientific use of spectrum[2]. Purely economic arguments quickly lose their objectivity when their metrics become ill-defined and become a matter of definition by vested interests. In that context, it becomes clear that efficient use of spectrum may mean very different things to different people.

2. Spectrum efficiency as seen by a radio astronomer:

Large radio telescopes are highly sensitive and routinely detect minute signals that have flux densities of the order of $1\,\mathrm{mJy} = 10^{-29}\,\mathrm{Wm^{-2}Hz^{-1}}$, which corresponds to what one would receive from a UMTS mobile phone radiating 1 W at a distance of 40 million km (roughly 100 times the Earth-Moon distance).

In 2008, scientists detected water vapour emissions at 6.1 GHz in a distant quasar[3,4]. With 305dBW the narrow band signal emission had 10000 times the total power of the sun, but after it had travelled for 11.1 Gigayears, it was attenuated by 555dB which resulted in a spectral flux density of S_ν=2.5 mJy or a spectral power density S= -323 dB(W/Hz) for 6.1 GHz at the radio telescope. The system noise level of a radio astronomical receiver at a system temperature of T_{sys}=37 K is N = kT_{sys} = -213 dB(W/Hz). Using Shannon's theorem for the channel capacity $C_S = \Delta\nu \cdot \log_2(1+S/N)$ bits/s for a channel bandwidth of $\Delta\nu$=78kHz we get a bit rate of 10^{-6} bit/s. Detecting a spectral line in about t_{int}=50000 seconds (= 14 hours) is indeed a sign of good technical spectrum efficiency,- thanks mainly to the high gain of a 100m diameter radio antenna and the radio astronomical

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measurement technique. The sensitivity of a radio astronomical antenna is the accuracy with which the mean noise power can be determined in a given time and bandwidth which is given by the radiometer equation[5,6]:

$$\Delta S_{\nu} = \frac{2 \cdot k \cdot T_{sys}}{\varepsilon_{ant} A_{ant}} \frac{1}{\sqrt{\Delta\nu \cdot t_{int}}} \qquad (1)$$

where the aperture efficiency for the 100m Effelsberg antenna is ε_{ant}=0.53. With the aperture A_{ant} of 7854 m^2 we get a ΔS_{ν}= 0.4 mJy for the described observation. The effective link spectral efficiency ($C_s/\Delta\nu$) for these numbers is $\log_2(1 + S_{\nu} / \Delta S_{\nu}) = 2.9$ (bit/s)/Hz which is similar to WiFi (IEEE 802.11a/g) or digital TV (DVB-T)[7]. From a technical point of view, radio astronomy has a good spectral efficiency and is making good use of the allocated band.

3. Spectrum requirements today

Spectrum allocation to radio services is a purely human convention, resulting from a long complex political process. There is however no free choice of frequency for observations of many of the celestial objects. The radiation from molecular clouds and interstellar gas occurs in particular frequency bands determined by the natural molecular transitions of the matter that is observed by a radio telescope. The cosmological redshift causes these lines to be shifted to lower frequencies as a function of distance from the observer (an example is the 22 GHz water vapour line mentioned above). The detection of faint spectral lines requires very long long integration times ($\approx 10^4$ s), but some of the most energetic processes observed by radio astronomers occur on the shortest possible timescales: Transient giant radio pulse emission detected in some pulsars lasts only a few microseconds and shows peak flux structures shorter than the nanosecond resolution of the Nyquist-limited detector[8]. Peak fluxes from the Crab pulsar (6000 light years away) exceed 50 kJy (≈70000 K for the Effelsberg 100m telescope). Bandwidths of more than a GHz are needed around 8 – 15 GHz to resolve the time structure of the giant pulses which may hold the key to the understanding of the still enigmatic pulsar radio emission process. Transient interference, even of very short duration, must be avoided for an efficient detection of the occasional giant pulses and the recently discovered weak rotating radio transients (RRATs). Astronomers strive for an understanding of physical processes of the celestial sources, and for that they require the knowledge about the full spectrum of radio emission, spanning eleven octaves from < 30 MHz to 90 GHz in the case of pulsars.

At the lower end the LOw Frequency ARray multi-purpose sensor array (LOFAR) covers the band 10-90 MHz and 110-250 MHz using large phased-array antennas. LOFAR is already operating, although only partially finished. 44 stations in the Netherlands, Germany, France, United Kingdom and Sweden are planned to be finally connected with optical fibres to a central correlating BlueGene/P supercomputer the Netherlands.

At the upper end of the frequency range, the Atacama Large Millimeter/submillimeter Array (ALMA) which is being built in Chile will observe from 31 GHz up to 1000 GHz.

The sky background temperature has its minimum in L-band around 2.3 GHz, consequently radio telescope will have their greatest natural sensitivity per given band with here. All of the current large radio telescopes use that band as the core of their observational activity and the Square Kilometre Array (SKA), planned for the next decade will also operate in the cm to dm regime.

The activity of the sun is investigated by solar radio observers. Information about plasma processes at the surface, solar flares and shock acceleration of particles, as well as monitoring for coronal mass ejection which can result in violent disturbances of the earth's ionosphere requires regular wide band imaging of the sun from 150 MHz to 34 GHz.

Access to UHF frequencies between 300 and 700 MHz is vital for the measurements of interstellar dispersion which causes a frequency dependent delay of distant radio signal. Radio astronomy has Pulsar researchers strive to determine the structure of space-time and try to discover very low frequency gravitational waves by measuring the precise arrival times of pulsar signals. Knowledge of the slowly changing interstellar dispersion delay is of great importance here. Highly red-shifted Hydrogen lines from distant galaxies fall into the range 700-1400 MHz which is heavily used by other radio services.

When radio astronomy became a recognised and protected radio service in 1959, the valve based analogue technology of the time allowed the use of only very small bandwidths and simple detection methods. Most of the spectrum allocations below 30 GHz were sufficient in those days and the later revisions have not significantly improved the situation or kept pace with technical progress. Digital signal processing has provided not only a 'digital dividend' for broadcasting and mobile services, but at the same time also enhanced and widened the scope of radio astronomical investigations with respect to sensitivity, bandwidth, as well as time and frequency resolution. Radio astronomers already make astronomy observations using cognitive radio and software defined radio (CR+SDR) techniques and opportunistically access even those small and dispersed parts of the spectrum that are not allocated to radio astronomy and are locally free from interference. LOFAR, which operates in bands allocated to many other services is a good example of that. As one has control over the modulation schemes of man-made radio links one can reduce their bandwidth requirements ('digital dividend') using more efficient encoding methods, however this is control is not given over natural sources at great distance. For astronomy the 'digital dividend' is a double edged sword: We obtain higher frequency agility, higher sensitivities, bandwidths, and resolution, but the higher sensitivity also implies a higher vulnerability to interference. Sadly but unavoidable, the same technical progress has also increased the number and power of interference sources.

4. Interference protection and regulation

The sensitivity of a radio antenna is not only proportional to the collecting area, but also to square root of the receiver bandwidth multiplied by the time duration of the measurement. In order to detect distant cosmic radio sources, radio observatories require sufficient bandwidth which is free of man-made radiation for sufficiently long time (and that includes even weak and distant sources). Modern signal processing can provide some interference mitigation in the form of compensation for a few steady local sources as well as flagging and excision in cases where interference is clearly detectable and not too strong to saturate the receiver. But that comes at a cost: Data loss and loss of sensitivity is an inevitable consequence and anathema to the desire to obtain the highest sensitivity and signal to noise ratio. It also increases the requirements for computer- and man-power and can result in research not being undertaken for sheer lack of resources. Irrespective of the technical and financial efforts that may be made by radio astronomers, their radio vision can be blinded by simple equipment that emits on their frequencies and operates in the vicinity of the observatory.

This is particularly true for license free industrial equipment where CISPR emission standards are often less stringent than the radio regulations that cover ordinary radio equipment. The CISPR-11 emission standard prescribes a limit of 30 dBμV/m for $f < 230$ MHz and 37 dBμV/m for 230 MHz $< f < 1$ GHz measured from a distance of 10 m. No limits are given for frequencies above 1 GHz, but fast switching electronic equipment is quite capable of radio frequency interference (RFI) above 1 GHz. The required path loss for compatibility with the ITU-R RA-769[5] interference limit pertaining to a radio telescope is of the order of 120-130 dB and separation distances are correspondingly large.

A variety of ultra wideband (UWB) sensor equipment has been introduced into the mass market in car short-range radar, location tracking, and building tool applications, all these devices are unlicensed and uncontrolled. In its simplest form, it is just a source of fast rise-time pulses coupled to an antenna. Their frequency range spans 1 – 10 GHz and the (CEPT) permitted e.i.r.p. spectral density -90 to -41 dBm/MHz is low enough not to affect most communication systems. However that is not true for sensitive passive services and that the principal incompatibility has been recognised in CEPT reports[8]. Nevertheless, not enough was done by regulators to enforce a consistent protection. The single interferer protection distances are of the order of a few km, with aggregate emission of licence free equipment being even more unpredictable. Here one is just hoping for the best. It is clear that modern, but quite ordinary and legal household, farming or building site equipment can be the source of significant interference and that is indeed what has been observed in a multitude of cases.

Governments of Australia, Chile, South Africa and the US have created radio quiet zones for their current or future sites of radio observatories in order to achieve some degree of protection. This is of course not feasible in densely populated European countries and of only limited effect against air-borne and space-borne transmitters. These are not shielded by topography and therefore present one of the biggest problems. Because big antennas are highly directional, they are much less sensitive to radiation from local sources in directions the telescope is not pointed towards, but they still receive them with little or no extra gain. That means that a hypothetical 1 W transmitter broadcasting on 2.7 GHz from a geostationary orbit 36000 km above the site of a radio telescope could be seen with a strength similar to a weak cosmic radio source, even when the antenna is not pointing at that transmitter! Radio astronomy has suffered from interference caused by out-of-band emissions of broadcasting satellites (ASTRA-1D), navigation satellites (GLONASS) and is still badly affected by interference from the IRIDIUM mobile satellite system. Modern and very powerful earth sensing radar satellites (CLOUDSAT, Terra-SAR) with a ground level peak power density of 0.035 mW/m^2 are even capable of destroying a radio astronomical receiver frontend in the case of direct beam coupling. Radio observatory sites should not be imaged by these satellites, without sufficient prior notice to the technical staff of the observatory.

4. Conclusions

Scientific use of radio spectrum, including radio astronomy is *ipso facto* of public interest: It is paid for by the taxpayer as a result of political consensus. It is also clear that spectrum protection for radio astronomy transcends national borders and is a truly long-term global issue. The protection requirements are exceptionally stringent and vital bands are protected by a 'no emissions permitted' clause in the radio regulations. These regulations do not account for short time variable (TDMA or UWB) interference sources, but *peak pulse energy limits* are nowadays also required for interference free observations of transient sources and even for protection of equipment from accidental damage. The spectrum allocations, which give radio astronomy only 0.7% exclusive use below 30 GHz, had been a compromise in the sixties and seventies and are clearly insufficient now as they do not reflect the technical progress and scientific discoveries. Radio astronomers try counter that by being flexible and try to observe in unused parts of the spectrum allocated to other services. Being a passive use of spectrum, this creates no interference for anyone, but the inevitable greater spectrum utilisation by active services in the future will soon close that escape route. It is very difficult, if not impossible to increase the allocations to scientific services or adapt their protection to modern developments in the current climate of high commercial exploitation of radio spectrum. But even something like the fully efficient use of spectrum by active services or low level emissions from industrial or consumer equipment near a radio observatory will impose crippling constraints on its scientific research portfolio. A *laissez faire* or 'market approach' to spectrum management is particularly inappropriate for scientific services, as the protection requirements are given by nature and therefore not negotiable, they are also long-term and global, instead of short-term and local and the 'returns' are unpredictable. We have also seen the spectacular failure of the market paradigm many times before, even on its home ground in recent time, when applied by professionals in the banking sector. Science is part of a the infrastructure of a society and it was already known to Adam Smith in 1776 that non-profit endeavours for public benefit have to be undertaken by the state. That clearly applies to scientific spectrum use which can only be safeguarded by robust and wide ranging regulatory protection measures. These ought to be guided only by the inherent technical and scientific practicalities and should make no difference for the nature of interference, be it from industrial equipment, consumer goods or in-band or out-of-band emissions from other radio services. CRAF for radio astronomy in ITU region 1 and IUCAF for radio astronomy in all regions cooperate with other scientific users of radio spectrum (such as EUMETNET, ESA, WMO) and engage with spectrum regulators on national, European and global scale to explain the very special regulatory requirements of scientific services.

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5. Literature

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