Radio astronomical use of the electromagnetic spectrum at Onsala Space Observatory

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Summary

Radio astronomy is a vigorous science which provides both astrophysicists and geodesists with invaluable data for studies of the Universe and the Earth. In Sweden, Onsala Space Observatory operates radio telescopes on its site south of Göteborg and is involved in several large international radio astronomical projects. Most of the observations with the telescopes in Onsala are made simultaneously with other telescopes in Europe and elsewhere.

An increasing source of concern in radio astronomy is Radio Frequency Interference (RFI), i.e., man-made radio signals which disturb the sensitive radio observations. The problem was recognized long ago by the International Telecommunication Union (ITU), which regulates the use of radio frequencies internationally and allocates radio frequencies to different services, including the Radio Astronomy Service (RAS). Frequency bands with protection for the Radio Astronomy Service are listed in Appendix A. In Sweden, the use of radio frequencies are handled by Post- och telestyrelsen (PTS). Onsala Space Observatory has a very good cooperation with PTS.

It is not possible to accurately predict which frequency bands will be scientifically the most interesting in the future. Still, based on international cooperation and planned observations with other telescopes, the following frequency bands have a high priority at Onsala Space Observatory:

- *10 – 90 MHz and 110 – 270 MHz (LOFAR)*
- *2.2 – 2.5 GHz and 8.1 – 9.0 GHz (geo-VLBI)*
- *2.2 – 14 GHz (four 1 GHz bands in this interval will be used for geo-VLBI)*
- *1.2 – 1.8 GHz, 4 – 9 GHz, 22 – 24 GHz, 43 – 44 GHz and 86 – 87 GHz (astro-VLBI)*
- *1.3 – 1.8 GHz, 4 – 8 GHz and 22 – 24 GHz (intended observations with eMERLIN)*

Several of the frequency bands mentioned above overlap, i.e., will be used for different purposes. In the future, astro-VLBI observations in the 22, 43 and 86 GHz bands will be made with larger bandwidths than today, possibly up to 4 GHz.

Many frequency bands are allocated to the Radio Astronomy Service (or have some kind of protection) through decisions by the International Telecommunication Union (ITU). For Onsala Space Observatory, the protection of these frequency bands, defined by ITU and listed in Appendix A, has a high priority. Single-dish observations with the telescopes in Onsala at frequencies in the 18 – 50 GHz and 70 – 116 GHz bands will continue to be important.

The frequency bands used or to be used in the near future at Onsala Space Observatory are summarized in Appendix B.

It is important to note that observations outside the allocated Radio Astronomy Service bands will always be needed, due to Doppler shift or cosmological redshift of spectral lines. There is also an increased need for observations with higher bandwidths (spanning several GHz).

Introduction

Radio telescopes are used for research in both astronomy and geodesy. The cosmic radio signals are very weak and sensitive equipment is needed to detect them. In Sweden, radio astronomical observations are performed at Onsala Space Observatory.

An increasing problem for radio astronomy is disturbances from man-made radio signals, so called Radio Frequency Interference (RFI). Several of the most important radio astronomical frequencies have different levels of protection from RFI, but the increased use of the radio spectrum for services like communication, radar, etc., is a growing problem and poses a threat to the radio astronomy service.

This document gives an introduction to radio astronomy and radio telescopes in general and the Swedish National Facility for Radio Astronomy, Onsala Space Observatory, in particular. It gives an overview of frequencies used in radio astronomy, and describes current developments in the field. The problem with RFI and international agreements to protect radio astronomy from RFI is introduced. The document is intended to serve as a basis for discussions of protection of frequency bands important for radio astronomy.

The origin of cosmic radio emission

Radio waves are emitted by most astronomical objects. Observations in the radio region of the electromagnetic spectrum are important for research on, e.g., comets, planets, star and planetary system formation, evolved stars, supernovae, the interstellar medium, the nucleus of the Milky Way, nearby and distant galaxies, active galactic nuclei, the cosmic microwave background and the Big Bang.

Continuum radiation

Radio continuum radiation can be thermal radiation from charged particles in hot gases, or synchrotron radiation from electrons spiraling around magnetic field lines with velocities close to the speed of light. Also dust emits continuum radiation, in particular at sub-mm wavelengths. Observations of continuum radiation are used to study, e.g., young and evolved stars and their environments, supernovae, regions around supermassive black holes in active galactic nuclei, and the origin of the Universe. The intensity of continuum radiation is frequency dependent in different ways depending on its origin. Therefore it is important to observe continuum radiation at different frequencies, but the exact value of these frequencies is less important.

Spectral lines

Many molecular spectral lines fall in the radio region of the electromagnetic spectrum, from dm to sub-mm waves. More than one hundred different molecules have been observed in cosmic sources. There are also a few important atomic spectral lines in the radio region. Often, emission lines from cold gas is observed, but also absorption lines are sometimes studied. Particularly important spectral lines are the following:

- The HI line: The single most important radio spectral line is the "21 cm line" from neutral atomic hydrogen with a rest frequency of 1420.4 MHz. Hydrogen is the most common element in the Universe.

- The CO lines: Molecular hydrogen is abundant in the Universe, but it hardly emits any radio waves. Molecular gas is instead traced by observations of the CO molecule, which emits strongly in radio at a frequency of 115 GHz and multiples thereof (230 GHz, 345 GHz, etc.).

Both the HI line and the CO lines can be observed in the Milky Way as well as in distant galaxies.

Observations of spectral lines from different molecules is of prime importance in radio astronomy, and provides data for modeling the astrophysics and astrochemistry of many cosmic objects.

The Doppler effect and cosmological redshift

In the Milky Way, orbital velocities are on the order of 200 km/s, leading to observed Doppler shifts of less than 0.1 % of the rest frequency. The expansion of the Universe causes significantly larger redshifts of spectral lines. For example, the famous radio galaxy Cygnus A, about 600 million light-years distant, has a redshift of about 6 % (corresponding to a recessional velocity of 17000 km/s). More distant galaxies have larger redshifts, according to Hubble's law. The observed wavelengths of emission from objects at "cosmological distances" can be several times the rest wavelength (and the frequency correspondingly smaller).

Radio telescopes and observations

Single dish observations

The classical and still very important radio astronomical technique is to use a single radio telescope in the form of a parabolic antenna. The 20 m telescope at Onsala Space Observatory is partly used for single dish observations.

Very Long Baseline Interferometry (VLBI)

The technique to simultaneously and coherently observe the same cosmic radio source with several radio telescopes (typically located in different countries or even on different continents) is called Very Long Baseline Interferometry, VLBI. Onsala Space Observatory is a pioneer in developing the VLBI technique.

In astronomy, the VLBI technique is used to increase the spatial resolution (the current record is 28 microarcseconds, corresponding to 5 cm on the Moon as seen from the Earth). Both spectral line and continuum radiation is observed.

In geodesy, VLBI is used to measure, e.g., changes in distances between tectonic plates and in Earth's rotation. Geodetic VLBI needs cosmic sources as point-like as possible and emitting continuum radiation, like distant quasars (a type of active galactic nuclei).

Arrays

Antennas located at the same site can be connected together electronically to form an array. Two examples are ALMA in Chile for mm and sub-mm waves, and LOFAR stations in Europe for meter waves.

Sensitivity of radio telescopes

The radio signals from cosmic sources are extremely weak due to the large distances they travel, which is reflected by a commonly used unit for spectral power flux density (spfd):

1 jansky (Jy) = 10^{-26} W m^{-2} Hz^{-1}. (A mobile phone emitting isotropically 1 W of power at the distance of the Moon with a bandwidth of 200 kHz gives an spdf of 270 Jy on the Earth – a very strong source by radio astronomical standards.) Many radio astronomical sources have flux densities much less than 1 Jy.

Because of the weakness of the cosmic signals, it is necessary to use radio telescopes with large antenna area, sensitive low noise receivers, large bandwidths for continuum observations (also important for spectral line observations), and to have frequency bands free from RFI.

Directivity of radio telescopes

Typical radio telescopes are parabolic antennas with large diameters, leading to small main lobes (for example, at 100 GHz, a 20 m diameter telescope has a main lobe only about 0.01° wide). It is important to note that the signal strength of RFI is often much larger than that of the cosmic source observed, so RFI entering the system through side lobes can be a severe problem. In general, pointing the telescope away from the RFI source is not enough to avoid problems.

Frequency resolution and bandwidths

The frequency resolution needed for spectral line observations depends on the cosmic object observed, the purpose of the observations, and the frequency used. For sources in the Milky Way (e.g., evolved stars and molecular clouds), frequency resolutions corresponding to velocity resolutions less than 1 km/s are often used (for example, a resolution of 10 kHz corresponds to a velocity resolution of 0.3 km/s at 10 GHz using Doppler's equation). For extragalactic sources, the need for frequency resolution is often an order of magnitude less.

Spectrometers typically have several thousand frequency channels. A large total bandwidth is necessary in order to, e.g., cover several spectral lines or study the shapes of emission lines. Emission lines from galaxies can be very broad due to the velocities present (several hundred km/s). It is also necessary to have parts of the spectrum free from emission, in order to find a so-called baseline for the spectrum. Spectrometers used in radio astronomy have total bandwidths of up to several GHz.

Time resolution

Some cosmic radio sources show time variations. One example is pulsars, which can have variations as short as microseconds. The study of such variability requires very large bandwidths.

Radio astronomy in Sweden

Onsala Space Observatory, the Swedish National Facility for Radio Astronomy hosted by Chalmers University of Technology and financed by the Swedish Research Council, is the only professional radio astronomical observatory in Sweden. There are also small radio telescopes for educational purposes in several other places.

Onsala Space Observatory currently operates the following radio telescopes in Onsala, 45 km south of Göteborg:

- The **20 m** diameter telescope, a parabolic antenna for 2–120 GHz, used for single-dish astronomy, and astronomical and geodetic VLBI.

- The **25 m** diameter telescope, a parabolic antenna for 1–7.5 GHz, used for astronomical VLBI.
- The **LOFAR** station, an array for 10–90 MHz and 110–270 MHz and part of the International LOFAR Telescope, used for astronomy and space science, mainly through simultaneous observations with other LOFAR stations in Europe.

Most of the astronomical VLBI observations are performed within the European VLBI Network (EVN) and the geodetic VLBI observations within the International VLBI Service for Geodesy and Astrometry (IVS).

A **twin telescope** system for geodetic VLBI is being planned in Onsala for 2014. It will consist of two 12 m diameter parabolic antennas and operate at frequencies between 2 and 14 GHz.

In addition, Onsala Space Observatory is one of three partners in the **APEX** sub-mm wave telescope in Chile, hosts the Nordic ALMA Regional Centre node for supporting Nordic scientists using the **ALMA** array in Chile and builds receivers for ALMA, and is involved in the development of **SKA**, the Square Kilometre Array, to be built in southern Africa and in Australia.

Almost all astronomical observations with the telescopes in Onsala are made after a proposal procedure: Scientists apply for time on a telescope or telescope system by submitting a proposal which describes the project and the observing time and frequency bands needed. The proposals are evaluated, and those with highest scientific rating are scheduled for observations. Proposals for observing time are typically accepted two or three times per year. Onsala telescopes are open for scientists from all countries.

Radio astronomical frequencies

Important radio astronomical frequencies

Two examples of important radio astronomical frequencies for spectral line observations were mentioned above (the HI line at 1420 MHz and the CO lines at 115, 230, … GHz). Other often observed spectral lines are those from the hydroxyl radical (OH; several lines at 1612–1721 MHz), methanol (CH_3OH; lines at, e.g., 6.7 and 12.2 GHz), and silicon monoxide (SiO; several lines at about 43 and 86 GHz). Observations of many more spectral lines and molecules are needed to study the physics and chemistry of, e.g., the interstellar medium and evolved stars. The Committee on Radio Astronomy Frequencies (CRAF) lists astrophysically important spectral lines on its web site (see http://www.craf.eu/iaulist.htm).

At Onsala Space Observatory, observations of continuum radiation are made together with other radio telescopes using the VLBI technique or the International LOFAR Telescope, and must therefore be performed at internationally agreed frequencies.

Some of the most important frequency bands for the Radio Astronomy Service (RAS) are protected or partly protected from harmful interference through regulations by ITU (International Telecommunication Union), see Appendix A. The frequency bands used at Onsala Space Observatory are listed in Appendix B.

Frequencies for geodetic VLBI

Onsala Space Observatory currently perform geodetic VLBI observations with the 20 m telescope at S-band (2.2–2.5 GHz) and X-band (8.1–9.0 GHz).

General developments

Two general trends concerning radio astronomical frequency bands can be noted. The first is that observations are extended to higher frequencies (sub-mm astronomy with, e.g., APEX and ALMA at frequencies of on the order of a THz). Frequencies much higher than 100 GHz cannot be observed from Onsala due to the atmosphere. The second is to build powerful instruments for low frequencies (e.g., LOFAR for 10–270 MHz and SKA for 70 MHz – 10 GHz).

Another trend is that technical developments make observations with higher band-widths possible. This leads to better sensitivity for continuum observations, or the possibility to observe many spectral lines simultaneously (which has several advantages, including reduced calibration problems).

Geodetic VLBI will move from the current S/X band system to the 2.2–14 GHz range (see below).

Radio Frequency Interference (RFI)

Unwanted man-made radio signals received by radio telescopes, disturbing the observations of cosmic radio sources, are called Radio Frequency Interference (RFI). Common sources of RFI are communication systems and radars, but also, e.g., industrial workshops can cause interference. Transmitters can be located on the ground, on ships, aircraft and other vehicles, including satellites.

Communication systems include, e.g., WiFi-equipment, mobile telephones and base stations, radio links, and radio and TV broadcasting. The use of radio frequencies for mobile communication is increasing. Radars are used for many applications: air traffic control, navigation at sea, remote sensing, etc. Collision-avoidance radars on cars can be a problem for the radio astronomy service in the near future.

Some RFI problems require a local solution (e.g., the placement of radio links), while others need a national or global solution (e.g., radar and communication systems on satellites).

A special problem for the radio astronomy service is out-of-band emission, i.e., when transmitters emit radio signals outside the allocated band. This can be due to improperly designed equipment. Even if these signals are much weaker than the wanted in-band emission, they can be a source of RFI since modern radio astronomical systems are so sensitive. Since radio astronomy is a passive service, the problem cannot be solved by increasing the transmitted power. The development of ultra-wideband equipment is a particular source of concern for the radio astronomy service.

The terrain and the curvature of the Earth gives some protection from RFI: transmitters which are below the horizon as seen from the radio telescope are smaller problems than those within the line-of-sight (but the problem is more complex than that, and frequency dependent). Large structures can reflect signals from transmitters which would otherwise not be "seen" by the radio telescope and can thus cause RFI problems. An increasing problem for the radio astronomy service in this respect is wind turbines. These are tall structures (up to about 150 m including the rotor) and have a very large reflecting area. Wind turbines can therefore reflect radio signals (from, e.g., mobile telephone systems or radars) into a radio telescope, causing RFI.

The following two figures can serve as illustrations of the effects of RFI on radio astronomical observations. In Figure 1, a spectrum analyzer shows the spectrum at about 2 GHz observed with the 20 m diameter telescope at Onsala Space Observatory. The width of the green curve is due to unavoidable noise. The large peaks in the spectrum to the left are due to nearby mobile phone base stations – this RFI is thousands of times larger than the cosmic signal which hides in the noise. The spectrum to the right shows the situation without RFI. Figure 2 shows the spectrum of the star CW Leo at about 86 GHz, observed with the 20 m diameter telescope in Onsala. Three of the peaks in the spectrum look like normal spectral lines, but are in fact due to RFI entering the system and disturbing the so-called IF band. This is a very problematic type of RFI, difficult to distinguish from the real cosmic signal, in this case from the C_4H molecule.

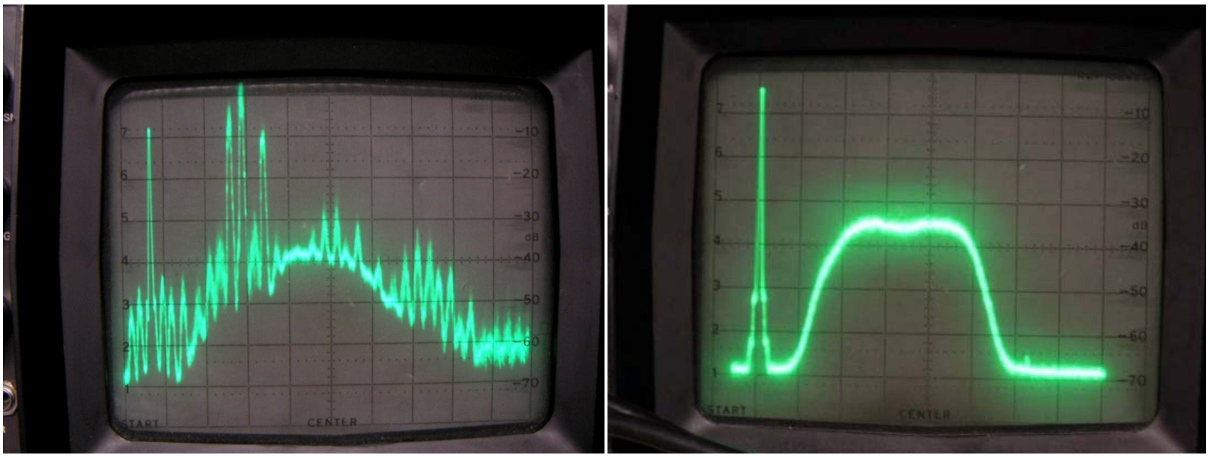

Figure 1. A spectrum analyzer showing the spectrum at about 2 GHz observed with the 20 m telescope in Onsala. *Left:* Large peaks in the spectrum due to RFI from mobile phone base stations. *Right:* The spectrum without RFI. The cosmic signal is much smaller than the width of the green curve. Note that the vertical scale is logarithmic in both pictures (the unit is dB): one square up means ten times stronger signal. RFI peaks more than 10 000 times stronger than the RFI-free spectrum can be seen.

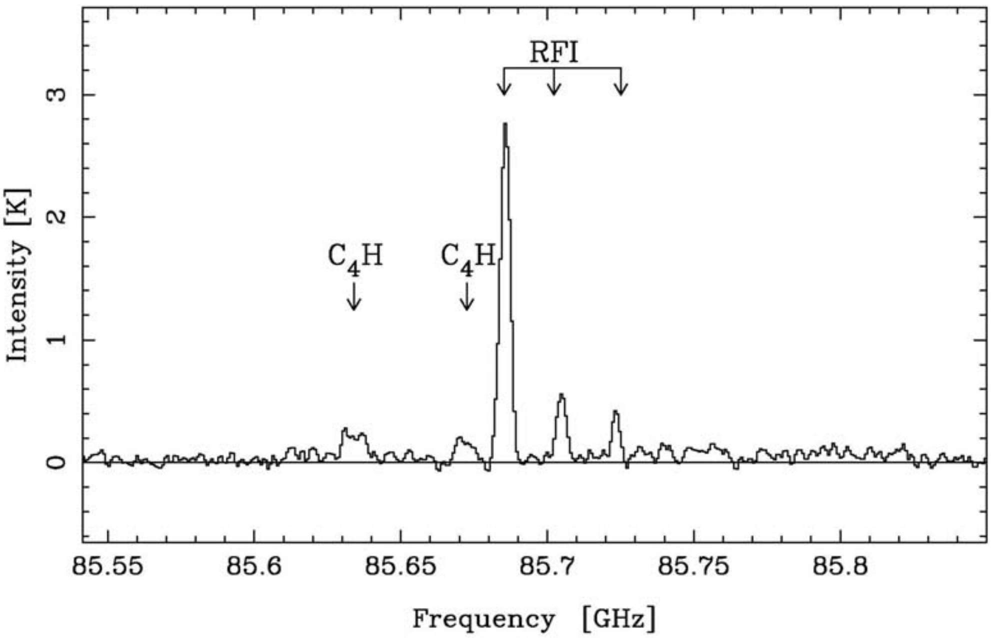

Figure 2. The spectrum of the star CW Leo at about 86 GHz observed with the 20 m telescope in Onsala. Three "spectral lines" due to RFI are marked.

Protection of radio astronomical frequencies

Internationally, the use of radio frequencies is regulated by the International Telecommunication Union, ITU, in particular through its Radio Regulations (RR). The ITU organizes World Radiocommunication Conferences (WRCs) which allocate radio frequencies to different services, such as broadcasting, aeronautical radionavigation and mobile services. Radio astronomy is recognized as such a service (the Radio Astronomy Service, RAS), but differs from other services in that it is a passive service, i.e. not involved in transmission of radio signals. On a national level, in Sweden the use of radio frequencies are handled by Post- och telestyrelsen (PTS). Onsala Space Observatory has a very good cooperation with PTS, which has resulted in different forms of local protection of some radio astronomical frequencies.

On behalf of European radio astronomers, the Committee on Radio Astronomy Frequencies (CRAF) of the European Science Foundation (ESF) coordinates activities to keep the frequency bands used by radio astronomy and space sciences free from interference. The CRAF Handbook for Radio Astronomy is a very useful source of information on the needs of radio astronomy and the regulatory process. The Handbook contains a summary (see its Table 3) of frequency allocations to the Radio Astronomy Service and the allocations to other services in bands adjacent to radio astronomy bands, according to the ITU Radio Regulations.

ITUs recommendation ITU-R RA.769 tabulates thresholds for interference at different frequencies for spectral line and continuum observations (see CRAF Handbook for Radio Astronomy, section 3.6, from which Figure 3 below is taken). In the ITU-RR frequency allocations, some frequency bands of radio astronomical interest are protected in footnotes. In particular, ITU-R Footnote 5.340 prohibits emission in some bands, and ITU-R Footnote 5.149 gives some protection to the radio astronomy service in other bands (see Appendix A).

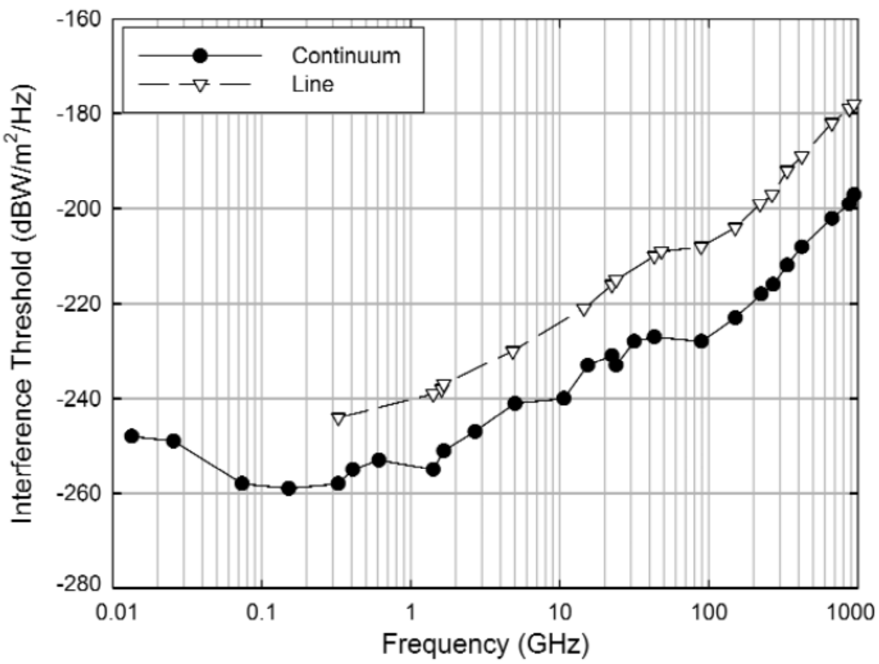

Figure 3. Thresholds of interference versus frequency for radio astronomy spectral line and continuum observations. From ITU-R Recommendation RA.769.

On a European level, the Radio Spectrum Policy Group (RSPG), a high-level advisory group, assists the European Commission in the development of radio spectrum policy. The RSPG recognizes the importance of protecting frequency bands for scientific use (Document RSPG06-144, see http://rspg.groups.eu.int/).

A special problem for radio astronomy is interference from transmitters operating in frequency bands outside those allocated to the Radio Astronomy Service (i.e., out-of-band emission).

In Sweden, the importance of protecting research from interference has been recognized by the Parliament in the law "Act on Protection of Research Sensitive to Disturbance, 2006:449". The County Administration of Halland has in accordance with this law decided about restricted access to the Onsala Space Observatory area.

Onsala Space Observatory: developments and priorities

Now and in the foreseeable future, much of the observational activities at Onsala Space Observatory will be performed together with other telescopes (LOFAR, geo-VLBI, astro-VLBI, and eMERLIN). It is therefore vital that radio astronomical frequency bands have international protection.

The future of geodetic VLBI is outlined in the VLBI2010 plan developed by the International VLBI Service for Geodesy & Astrometry (IVS). According to VLBI2010, observations will be performed in four 1 GHz bands in the 2.2–14 GHz range (the upper limit will possibly in the future be extended to 18 or 32 GHz). Relatively small (12 m or larger) and fast slewing antennas will be used. As mentioned above, Onsala Space Observatory is planning to build two new 12 m diameter antennas for geodetic VLBI in 2014 (a twin telescope system) and equip them with receiver systems for 2.2–14 GHz.

Single dish observations, in particular of spectral lines, will continue to be important. An increase in observations in the 70/80 GHz bands is expected. Several important deuterated molecules (one or more hydrogen atoms exchanged for deuterium) have spectral lines in these bands. Observations of deuterated molecules are important for several reasons, e.g., measurements of the cosmic deuterium abundance put constraints of cosmological models.

Concerning the protection of frequency bands for research at Onsala Space Observatory in the coming years, priorities can in principle have different grounds: purely scientific priorities, priorities based on planned observations with other telescopes (structural priorities), and priorities based on other international agreements (other priorities).

Scientific priorities: We can only know what has been considered important observations in the past, but we cannot know what will be important in the future. Several years from now, spectral lines which have rarely been observed before could turn out to be very interesting, and redshifted objects in the distant Universe will be observed at frequencies impossible to predict. Discoveries lay in the heart of science, and cannot be predicted. Purely scientific priorities of frequency bands are thus not possible, or can only be guesses. For the near future, an increase in observations of deuterated molecules in the 70/80 GHz bands is expected, as mentioned above.

Structural priorities: Observations using VLBI and similar techniques requires international cooperation and agreements, and that the frequency bands used are specified for very long periods of times. Moving to new frequencies would require huge investments at observatories in many countries. Onsala Space Observatory in involved in international cooperation using the following frequency bands, the protection of which has a high priority:

- 10 – 90 MHz and 110 – 270 MHz (LOFAR)
- 2.2 – 2.5 GHz and 8.1 – 9.0 GHz (geo-VLBI)
- 2.2 – 14 GHz (four bands in this interval will be used for geo-VLBI)
- 1.2 – 1.8 GHz, 4 – 9 GHz, 22 GHz, 43 GHz and 86 GHz (astro-VLBI)
- 1.3 – 1.8 GHz, 4 – 8 GHz and 22 – 24 GHz (intended observations with eMERLIN)

Several of the frequency bands mentioned above overlap, i.e., will be used for different purposes. In the future, astro-VLBI observations in the 22, 43 and 86 GHz bands will be made with larger bandwidths than today, possibly up to 4 GHz.

Other priorities: Many frequency bands are allocated to the Radio Astronomy Service (or have some protection) through decisions by the International Telecommunication Union (ITU). The bands are selected because they contain interesting spectral lines. See ITU-R Footnotes 5.149 and 5.340 in Appendix A for details. For Onsala Space Observatory, the protection of these frequency bands has a high priority. Single-dish observations with the telescopes in Onsala at frequencies in the 18 – 50 GHz and 70 – 116 GHz bands will continue to be important.

Some of the protected bands are narrower than actually observed bands. Protection is still important: bands totally free from RFI are needed for calibration purposes, and they also contain interesting spectral lines.

The frequency bands used or to be used in the near future at Onsala Space Observatory are summarized in Appendix B.

It is important to note that observations outside the RAS bands will always be needed, due to Doppler shift or cosmological redshift of spectral lines. Development of more sensitive receivers will facilitate observations of, e.g., molecular spectral lines from increasingly distant (and therefore more redshifted) objects. Such observations are of great cosmological value.

References and links

- Committee on Radio Astronomy Frequencies (CRAF): http://www.craf.eu
  - CRAF Handbook for Radio Astronomy, 3rd edition, 2005.
  - Information on ITU-RR allocations, important spectral lines, etc.
- Onsala Space Observatory: http://www.chalmers.se/oso
- Radio Spectrum Policy Group (RSPG): http://rspg.groups.eu.int/
  - Opinion Scientific use of Spectrum: Document RSPG06-144.
- VLBI2010 system for geodetic VLBI:
  - http://ivscc.gsfc.nasa.gov/technology/vlbi2010-general.html

Abbreviations used in this document

ALMA	The Atacama Large Millimeter/submillimeter Array in Chile
APEX	Atacama Pathfinder Experiment (telescope in Chile)
CRAF	Committee on Radio Astronomy Frequencies (www.craf.eu)
eMERLIN	an array of radio telescopes in England (www.e-merlin.ac.uk)
EVN	European VLBI Network (www.evlbi.org)
ITU	International Telecommunication Union
IVS	International VLBI Service for Geodesy & Astrometry (ivscc.gsfc.nasa.gov)
LOFAR	Low frequency array (www.lofar.org)
OSO	Onsala Space Observatory (www.chalmers.se/oso)
PTS	Post- och telestyrelsen
RAS	Radio Astronomy Service
RFI	Radio Frequency Interference
SKA	Square Kilometre Array
VLBI	Very Long Baseline Interferometry

Useful equations

Relation between frequency and wavelength

$$\lambda = \frac{c}{f}\ ,\ \ f = \frac{c}{\lambda}$$

$c = \text{speed of light} = 3 \cdot 10^8\ \text{m/s},\quad f = \text{frequency (Hz)},\quad \lambda = \text{wavelenght (m)}$

Examples: 10 MHz ↔ 30 m, 1 GHz ↔ 0.3 m, 100 GHz ↔ 0.003 m

Doppler effect

$$\frac{f_0 - f_{\text{obs}}}{f_0} = \frac{v_{\text{r}}}{c}$$ (non-relativistic case)

$f_0 = \text{rest frequency},\quad f_{\text{obs}} = \text{observed frequency},\quad v_{\text{r}} = \text{radial velocity}$

Hubble's law for the expansion of the Universe

$$v_{\text{r}} = H \cdot r$$

$H = \text{Hubble's constant}\ \left(\approx 70\,\frac{\text{km}}{\text{s}}/\text{Mpc}\right), r = \text{distance. } 1\ \text{Mpc} \approx 3\ \text{million lightyears.}$

Example: r = 1 billion lightyears ↔ v_{r} = 20 000 km/s (causes redshift of cosmic signals)

Appendix A: ITU-R Footnotes

ITU-R Footnote 5.149
For more information, see CRAFs web site: http://www.craf.eu/s5_149.htm.

In making assignments to stations of other services to which the bands:

13.36 - 13.41 MHz	4990 - 5000 MHz	92 - 94 GHz
25.55 - 25.67 MHz	6650 - 6675.2 MHz	94.1 - 100 GHz
37.5 - 38.25 MHz	10.6 - 10.68 MHz	102 - 109.5 GHz
73 - 74.6 MHz (in Regions 1 and 3)	14.47 - 14.5 GHz	111.8 - 114.25 GHz
150.05 - 153 MHz (in Region 1)	22.01 - 22.21 GHz	128.33 - 128.59 GHz
322 - 328.6 MHz	22.21 - 22.5 GHz	129.23 - 129.49 GHz
406.1 - 410 MHz	22.81 - 22.86 GHz	130 - 134 GHz
608 - 614 MHz (in Regions 1 and 3)	23.07 - 23.12 GHz	136 - 148.5 GHz
1330 - 1400 MHz	31.2 - 31.3 GHz	151.5 - 158.5 GHz
1610.6 - 1613.8 MHz	31.5 - 31.8 GHz (in Regions 1 and 3)	168.59 - 168.93 GHz
1660 - 1670 MHz	36.43 - 36.5 GHz	171.11 - 171.45 GHz
1718.8 - 1722.2 MHz	42.5 - 43.5 GHz	172.31 - 172.65 GHz
2655 - 2690 MHz	42.77 - 42.87 GHz	173.52 - 173.85 GHz
3260 - 3267 MHz	43.07 - 43.17 GHz	195.75 - 196.15 GHz
3332 - 3339 MHz	43.37 - 43.47 GHz	209 - 226 GHz
3345.8 - 3352.5 MHz	48.94 - 49.04 GHz	241 - 250 GHz
4825 - 4835 MHz	76 - 86 GHz	252 - 275 GHz
4950 - 4990 MHz		

are allocated, administrations are urged to take all practicable steps to protect the radio astronomy service from harmful interference. Emissions from spaceborne or airborne stations can be particularly serious sources of interference to the radio astronomy service (see Nos. **4.5** and **4.6** and Article **29**).

ITU-R Footnote 5.340

For more information, see CRAFs web site: http://www.craf.eu/s5_340.htm.

All emissions are prohibited in the following bands:

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1400   - 1427  MHz,
2690   - 2700  MHz, except those provided for by No. 5.422,
 10.68 - 10.70 GHz, except those provided for by No. 5.483,
 15.35 - 15.4  GHz, except those provided for by No. 5.511,
 23.6  - 24    GHz,
 31.3  - 31.5  GHz,
 31.5  - 31.8  GHz in Region 2,
 48.94 - 49.04 GHz from airborne stations,
 50.2  - 50.4  GHz[1],
 52.6  - 54.25 GHz,
 86    - 92    GHz
100    - 102   GHz
109.5  - 111.8 GHz,
114.25 - 116   GHz
148.5  - 151.5 GHz,
164    - 167   GHz,
182    - 185   GHz,
190    - 191.8 GHz,
200    - 209   GHz,
226    - 231.5 GHz,
250    - 252   GHz.
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[1] The allocation to the earth exploration-satellite service (passive) and the space research service (passive) in the band 50.2 - 50.4 GHz should not impose undue constraints on the use of the adjacent bands by the primary allocated services in those bands.

Appendix B: Onsala Space Observatory frequency bands

The table below shows frequency bands used or to be used in the near future for observations at Onsala Space Observatory. The exact frequency bands used during a particular observing season depends on which of the proposed projects have been accepted and scheduled on the telescopes.

For more information on protected frequency bands for the Radio Astronomy Service at Onsala Space Observatory, see CRAF: http://www.craf.eu/sweon.htm.

Frequency band	Comments
10 - 90 MHz	LOFAR
110 - 270 MHz	LOFAR
0.8 - 1.8 GHz	Mainly astro-VLBI - obs. with eMERLIN at 1.3-1.8 GHz planned - occasionally also single dish
2.2 - 14 GHz	Single dish and VLBI - geo-VLBI: 2.2–2.5 & 8.1-9.0 GHz - geo-VLBI in four 1 GHz bands planned - astro-VLBI: 4.5-5.3 and 6.0-6.7 GHz - astro-VLBI at 4-9 GHz planned - observ. with eMERLIN at 4-8 GHz planned - single dish at many frequencies
18 - 50 GHz	Single dish and VLBI - astro-VLBI: 22 GHz - observ. with eMERLIN at 22-24 GHz planned - single dish at many frequencies
70 - 116 GHz	Single dish and VLBI - astro-VLBI at 86 GHz - single dish at many frequencies