INTERFERENCE REDUCTION FACTORS AND TECHNIQUES APPLICABLE TO SPACE RADIOASTRONOMY

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ABSTRACT

A number of space radio astronomy missions with space telescopes operating at observing band frequencies below < 3 THz have been flown or are currently under development or in the planning stage. With the advance of space radio astronomy it has become necessary to consider radio regulatory and frequency protection issues for this branch of radio astronomy. Location of a radio telescope in space potentially makes it easier to avoid the detrimental interference from man-made radio emissions. Still, these radio emissions can be a problem that requires applying additional measures (RFI mitigation) to suppress its negative impact.

INTRODUCTION

Radio astronomy observations with space-based telescopes may be the only means to provide answers to certain fundamental questions of modern astronomy. Astronomical discoveries resulting from such observations may reveal unexpected new physical and astronomical phenomena. A few dozen space radio astronomy experiments and dedicated telescopes have flown already. The first results from these missions have provided significant breakthroughs in our understanding of the nature of celestial radio radiation. These first successes of space radio astronomy led to significant efforts by the major space agencies and administrations in developing the successors to these experiments. Radio astronomers plan to deploy more Earth orbiting radio telescopes, radio telescopes in the vicinity of the L_2 Sun-Earth Lagrangian point, and, in the more distant future, in the shielded zone of the Moon. Among the several major "drivers" behind these advances in space radio astronomy are the science needs: i) to achieve an extremely high angular resolution, ii) to achieve superior sensitivity, iii) to observe outside the designated radio astronomy bands, iv) to observe in bands which are not accessible from the surface of the Earth, and v) to avoid unwanted radio emissions produced by ever expanding technological development.

Radio frequency interference which threatens radio astronomy observations from the surface of Earth will also degrade radio astronomy observations with space-based radio telescopes. However, any resulting interference could be different than for ground-based telescopes due to several conditions. Such factors as the location of the space-based radio telescopes in orbit, their distance from the Earth, and their orientation relative to man-made emissions as well as the use of appropriate RFI mitigation techniques will reduce the effect of these emissions on space radio astronomy observations. Also, because of this, space radio telescopes will be able to exploit the radio spectrum outside of the frequency bands allocated to the Radioastronomy Service by the ITU Radio Regulations.

MAN-MADE RFI REDUCTION FACTORS

In general, the impact of man-made radio emissions on space radio astronomy missions will depend upon the mission configuration (e.g., location of telescopes, space antenna type) and the type of radio astronomy observations to be performed (e.g., VLBI, radiometry, spectroscopy). Table 1 summarizes some important features for space radio astronomy experiments and dedicated missions with regard to the protection of these observations from man-made RFI.

Spatial Distribution RFI Sources Relative to a Space Radio Telescope

There are a few preferable locations/orbits where the space-based radio telescopes could be placed. They are a) Earth orbits, b) Shielded Zone of the Moon, c) Halo orbits around the Sun-Earth L_2 point, d) Earth's trailing orbits. Depending on the relative position of the space radio telescope and the potential sources of unwanted man-made (human generated) radio emissions, it is convenient to divide these sources into four classes: i) the sources of radio emissions located on earth and earth's surroundings (distance from the earth smaller than about 100 000 km), ii) the radio emissions from deep space exploration spacecraft (distance from the earth more than 2 000 000 km), iii) the radio emissions from Moon exploration spacecraft (located in the Moon's orbit and Moon's surface), and iv) the radio emissions from spacecraft located in the Sun-Earth L_2 point halo orbits.

Table 1. Space radio astronomy missions requirements and characteristics

Type of mission	*Radio astronomy technique*	*Science requirements*	*Preferable location / orbit*	*Preferred range of frequencies*	*Antenna type/size*	*Type of Front-end amplifier*
Space VLBI	Very Long Baseline Interferometry	Extremely high angular resolution ~ 10^{-3} -10^{-6} arcseconds, high sensitivity <mJy	HEO[1] Earth orbit: Appogee ~10^5 km; Perigee ~ 10^3 km	From 300 MHz to 300 GHz	High gain paraboloid, 10-25 m diameter	HEMT[3], cooled to 20-100 K
Low Frequency Space Radio Astronomy	Radiometry, Interferometric arrays	Moderate angular resolution ~ 10-100 arcseconds, the sensitivity is limited to about a few Jy due to the Galactic radio emission	Earth trailing orbit at ~ 10^6 km from the Earth, Shielded Zone of the Moon	From 0.03 to 30 MHz	Array of low gain (dipole type) antennas	HEMT
Cosmic Microwave Background Radiation studies	Precision radiometry, polarimetry	High sensitivity and high thermal stability ~ mK, moderate angular resolution ~ 0.1 deg to a few degrees	Sun-Earth L_2 point halo orbits, Shielded Zone of the Moon	From 10 GHz to 1 THz	High gain paraboloid antenna ~ 1-3 m diameter	HEMT, cooled to a few degrees K
Millimeter and Sub-millimeter wavelength Space Radio astronomy	Spectroscopy, Continuum, single dish and interferometric arrays	High spectral resolution up to Df/f < 10^{-7}, moderate angular resolution ~ a few arcseconds to subarcsec, sensitivity ~ a few Jy,	NEO[2] orbits (~1000km), Sun-Earth L_2 point orbits, Shielded Zone of the Moon	From 300 GHz to 3 THz	High gain paraboloid, 1-8m diameter	SIS[4], HEB[5], cooled to a few degrees K
Extremely Sensitive Space Radio Astronomy	Precision radiometry, Spectroscopy, Single dish and interferometric arrays, VLBI	Extremely high sensitivity, high angular resolution, high spectral resolution	Shielded Zone of the Moon	All radio spectrum	Arrays of antennas	HEMT, SIS, HEB, cooled to a few degrees K

[1] Highly Elliptical (HEO) orbit; [2] Radio Regulations do not define the term Near –Earth orbit (NEO). For the purpose of this paper we adopt the working definition that the NEO orbits are the earth orbits with the apogee below ~ 100.000 km; [3] HEMT - High Electron Mobility Transistor, [4] SIS - Superconductor-Iinsulator-Superconductor, [5] HEB -Hot Electron Bolometer mixers.

From the point of view of a radio astronomer observing with a ground-based radio telescope, the RFI is often sporadic in position, intensity, or frequency. This makes it difficult to distinguish sources of natural radio emissions from RFI, and may lead to the inaccurate interpretation of an observation. The space telescope's location away from the Earth provides that the sources of man-made radio emissions located on the Earth and its vicinity will occupy just a part of the sky. Further, the space telescope located on the distant L_2 point or Earth trailing orbit will see the Earth as a relatively small, localized radio source. Hence, a space radio telescope equipped with a high-gain antenna could avoid observations in the direction of Earth. The main disadvantage of this is that such a limitation will constrain the scientific operations. Also, radio astronomy observations with a low-gain space antenna (e.g., the dipole type which is used for low frequency radio astronomy) will be more affected by RFI since they have low selectivity to the direction of the upcoming signals from the earth.

Space radio telescopes located in the Shielded Zone of the Moon (SZM) will be protected from Earth-based radio emissions and emissions from spacecraft in orbits with apogee as high as 10^5 km. The Space Research (active) and Space Operation services (e.g. active sensors and communication channels on the Moon and solar system exploration spacecraft/vehicles as well as communication channels from the space telescopes located in the Sun Earth L_2 point) could be the main source of unwanted radio emissions for the radio telescopes located in the SZM. One can expect that in some conditions the commercial satellites can be placed in highly elliptical orbits with an apogee above 10^5 km or may use the Moon perturbed orbits in order to be placed on the operational earth's orbit (e.g. the Hughes telecommunication satellite in June 1999). However, since the position of satellites/vehicles and their operational frequencies will be well known, the radio telescopes could attain acceptable rejection of the unwanted radio emissions applying operational constraints.

Free-Space Transmission Loss

Due to free-space transmission loss, the man-made radio emissions concentrated around the Earth as well as radio emissions from deep space probes will be reduced significantly because of the large distance separation between the space radio telescopes and the source of the radio emission. The range of the expected losses depending on the relative distance between the sources of man-made radio emissions and space radio telescopes at different wavelengths varies from ~ 100 dB and more. Table2 summarizes the above considerations depending on the location of the space radio telescope and sources of the interfering man-made radio emissions.

Table 2

SRT orbit / location	*Dominating sources of unwanted man-made radio emissions*	*Distance between RFI source and Space Radio Telescope*	*Angular size of*		*Free-space transmission loss (dB) at*		
			the Earth (deg)	*the 10^5 km region (deg)*	*Observing frequency 10MHz*	*Observing frequency 1GHz*	*Observing frequency 1THz*
Near-Earth orbits	Earth and Earth's satellite based transmitters	~ 10^3-10^5 km	120 – 6.9		~ 112-152	~ 152-192	~ 212-252
Sun-Earth L_2 point	Earth and Earth's satellite based transmitters	~ $1.5x10^6$ km	0.5	7.6	~ 176	~ 216	~ 276
Earth trailing orbits	Earth and Earth's satellite based transmitters	> $30x10^6$ km (> 0.2 A.U.)	0.02	0.38	> 202	> 242	> 302
Shielded Zone of the Moon	Moon exploration satellites	~ 100-1000 km	N/A	N/A	~ 92-102	~ 132-152	~ 192-212
	Deep space spacecraft cruise	> $2x10^6$ km	N/A	N/A	> 178	> 218	> 278
	Spacecraft in Sun-Earth's L2 point orbits	~ $1.2x10^6$ km	N/A	N/A	~ 174	~ 214	~ 274
	Planetary exploration systems	> $40x10^6$ km	N/A	N/A	> 204	> 244	> 304

Absorption in the Earth's Atmosphere

Because of the space-based telescope location above the Earth's atmosphere, the influence of radio emissions generated by the Earth's surface or aircraft's transmitters will be significantly impaired at frequencies where propagation effects (absorption, refraction) in the ionosphere or troposphere are essential.

At frequencies lower than the maximum electron plasma frequency in the ionosphere, f_{max}, radio waves generated below the ionosphere are generally trapped and cannot escape into space. The value f_{max}, is highly variable. It varies depending upon the geographical location of the transmitter, day time, season and solar cycle. f_{max} can vary by as much as a factor of 2 or 3 reaching a maximum of 5-6 MHz at the equator at mid day and a minimum of about 1-2 MHz at the end of the local night. Radio waves at frequencies below f_{max} are attenuated by the ionosphere by thousands of decibels. Accordingly, radio astronomy observations with space-based telescope conducted at frequencies below 5-6 MHz above the earth's day side and 1-2 MHz above the earth's night side will be effectively shielded by the ionosphere from the man-made earth-based radio emissions. Signals at frequencies above the f_{max} experience dissipative attenuation due to collisions of free electrons with neutral atoms and molecules. Total attenuation is between 0.2 – 5 (dB) at the frequency 30 MHz depending on the level of solar activity (higher value correspond to the solar flare events) and decreases as the inverse square of the frequency.

Above ~ 1 GHz the ionosphere is essentially transparent. Absorption in the troposphere's gaseous content, primarily water vapor and oxygen, becomes a significant factor at frequencies above a few GHz leading to the restriction of the atmosphere transparency at millimeter and submillimeter wavelength to a few "windows." Space-based radio astronomy observations may be conducted in bands allocated to the Radio Astronomy Service and to the Space Research Service (passive) as well as outside of these bands. Existing ITU allocations for the Radio Astronomy service are chosen to minimize absorption in the earth's atmosphere, and, hence, to optimize performance of the ground–based telescopes. In many cases the active services (Earth-to-space) have been co-allocated at the same band or allocated to adjacent or nearby bands. Consequently, the transmissions by the ground-based and airborne systems belonging to these active services at frequencies below about ~ 100 GHz will not be suppressed significantly by the Earth's atmosphere absorption except transmissions at frequencies in the vicinity of the oxygen absorption line (~50-70 GHz). However, at frequencies above ~100 GHz, absorption in the atmosphere becomes significant, especially in and around the oxygen and water vapor lines. Radio astronomy observations from above the Earth's atmosphere at frequencies where the earth's atmosphere absorption is high will not only provide access to the new observing bands, but also will benefit from the reduction of the interference from earth-based and airborne transmissions.

RFI MITIGATION IN SPACE RADIO ASTRONOMY

RFI mitigation techniques are designed to take advantage of differences in the frequency, time and space domains between the useful and interfering signals. Ground-based radio telescopes are surrounded by sources of unwanted radio emissions that can enter the receivers, often unexpectedly, from any direction, at any frequency and any time. This makes the application of the RFI mitigation techniques often complicated and of minimal effectiveness. Spatial distribution of the sources of man-made radio emissions relative to the space-based radio telescopes significantly differs. Location of a radio telescope in space or in the Shielded Zone of the Moon potentially makes it easier to avoid the detrimental interference from the man-made radio emissions. Still, such radio emissions can be a problem that requires applying additional RFI mitigation measures to suppress its negative impact.

The ITU recognizes the special importance of the Shielded Zone of the Moon and orbits around the Sun-Earth Lagrange points which potentially provides the best locations for radio telescopes, by establishing a quiet zone in the Shielded Zone of the Moon and recommending to protect the coordination zone in the vicinity of the Sun-Earth L_2 point. This provides the opportunity for the developers of space radio astronomy missions to take advantage of such arrangements and design the telescopes with a sensitivity which will not be limited by the unwanted man-made radio emissions.

Many difficulties in RFI mitigation at the ground-based telescopes arise because of the great number of interfering sources, their random spatial distribution and some time fast motion. Because of the remoteness of the space radio telescopes locations, the sources of interfering radio emissions will be localized in well defined directions relative to the beam pattern of a space radio telescope or an array of telescopes. In addition, the relative movement of these sources of man-made RFI and a space radio telescope will be much slower than in the case of ground-based telescopes. The number of such sources of interference (e.g., deep space probes, the earth and planets), in the foreseeable future, shall not exceed a few dozens. It will provide an easier and more effective application of such RFI mitigation techniques as "Beam Forming" and "Adaptive Nulling" (steering of one or more nulls of antenna array onto interfering sources). This is especially important for the Low Frequency Space Radio Astronomy in which the low directional antennas or arrays of such antennas will be used. The same technique will also help to suppress the interfering signals from the space probes entering the radio telescopes located in the Shielded Zone of the Moon.

The effect of man-made radio emissions on observations with a space based radio telescope could be reduced through the appropriate orientation of the space radio telescope. The model for the envelope of sidelobes for the antennas with diameters greater than 100 wavelengths is given in ITU-R SA.509-2. The sidelobe level of 0 dBi, (level which is used to calculate possible interference effects for radio astronomy) occurs at 19^0 from the main beam. In most cases, space radio telescopes will be located far enough that the sources of radio emissions in the vicinity of the Earth will occupy the part of sky much smaller than circle with 19^0 radius. According to the same envelope model, the additional suppression of at least –10 dB can be obtained, if the telescope will be steered away the source of the emission for more than 48^0. Using special types of antennas like offset-feed reflectors with unblocked apertures or horn reflector antenna, the sidelobes level could be suppressed to > 10-15 dB lower than levels given by the ITU-R SA.509.2 sidelobe model.

Space VLBI is a special case. Since the contemporary Space VLBI missions configurations must include an extensive ground support including co-observing support with earth-based telescopes, observing bands at both earth-based and space-based telescopes shall be protected. However, sensitivity of the VLBI observations to RFI, in general, is lower than for other types of radio astronomy observations. In addition, the observations could be carefully designed in such a way that the space telescope maintains a preferable orientation with the Earth (location of the most RFI sources) located in the space antenna backlobe.

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