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Protecting Space-Based Radio Astronomy

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Abstract. This paper outlines some of the radio frequency interference issues related to radio astronomy performed with space-based radio telescopes. Radio frequency interference that threatens radio astronomy observations from the surface of Earth will also degrade observations with space-based radio telescopes. However, any resulting interference could be different than for ground-based telescopes due to several factors. Space radio astronomy observations significantly enhance studies in different areas of astronomy. Several space radio astronomy experiments for studies in low-frequency radio astronomy, space VLBI, the cosmic microwave background and the submillimetre wavelengths have flown already. The first results from these missions have provided significant breakthroughs in our understanding of the nature of celestial radio radiation. Radio astronomers plan to deploy more radio telescopes in Earth orbit, in the vicinity of the L_2 Sun-Earth Lagrangian point, and, in the more distant future, in the shielded zone of the Moon.

1. Introduction

The explosive development of radio techniques in response to various commercial and scientific applications has resulted in a wealth of data about the Universe obtained through radio astronomy. But it has also created "radio frequency interference" (RFI) that threatens radio astronomy observations from the surface of Earth. This man-made radio noise will also degrade radio astronomy observations taken with space-based radio telescopes. However, any resulting interference could be different than for ground-based telescopes, because of different factors, such as the location of space radio telescopes at relatively large distances from the Earth (the source of man-made radio noise) or even (in the future) on the far side of the Moon, as well as the telescope's orientation relative to Earth.

The frequency sharing and protection considerations associated with space radio astronomy are, in general, more complex than in ground-based radio astronomy because of the requirements not only for observing bands but also for communication links needed to support spacecraft and space radio telescope operations. Moreover, unlike ground-based radio telescopes, space-based radio telescopes are located in close proximity to transmitters and receivers used for spacecraft operations and for data transmission.

The subject of this paper is radio interference to radio astronomy observations originating from man-made systems transmitting radio waves for broadcasting, communications, navigation or other radio "active" services. From the point of view of an astronomer observing with a radio telescope, this man-made 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 inaccurate interpretation of an observation. Even more threatening, the powerful interfering radio signals from "active" services may damage the sensitive receivers of a radio telescope. As a result of such harmful interference, loss of radio astronomy data may occur.

Similar to ground-based radio astronomy, radio frequency interference from other services must be taken into account when the space radio astronomy missions and experiments are designed and operated. However, the basic principles of frequency sharing and protection commonly used in ground-based radio astronomy are not always applicable to space-based radio astronomy. In addition, in order to realize the full scientific potential of space radio telescopes, their designers tend to build space receivers with the receiving bands much wider than assigned to radio astronomy by radio regulations. Because of this, the need to minimize a loss of data due to interfering radio signals may have an impact on the mission design (e.g., orbit selection, antenna type).

Space radio astronomy, by its nature, requires international spectrum coordination. Space radio astronomy developments are truly an international effort. International cooperation is driven by the need to share the cost of the mission. International spectrum coordination is also needed because of the orbital location of the space radio telescope as well as the need to provide ground operations support through a significant part of its orbit.

2. Radio Astronomy Observations with Space-Based Telescopes

Space radio astronomy observations are defined as those astronomical measurements conducted in the radio band $f < 3\times 10^3$ GHz (Radio Regulations 1994, S1.4, S1.5) by coherent (radio) detection techniques (Kitchin 1991) with a space-based radio telescope or network of radio telescopes at least one of which is located in space. Space radio astronomy observations already significantly enhance such radio astronomy fields as:
(i) studies of natural radio sources with the Space Very Long Baseline Interferometry (SVLBI) technique with an angular resolution not achievable with ground-based interferometry,
(ii) studies of the cosmic microwave background radiation with satellite-based observations achieving unprecedented sensitivity by avoiding atmospheric noise and terrestrial RFI,
(iii) studies of natural radiation below approximately 10-30 MHz that are difficult or impossible with ground-based radio astronomy due to the Earth's ionosphere,
(iv) astronomical studies in millimetre and submillimetre wavebands where the Earth's atmosphere significantly attenuates (or completely blocks) the radiation of astronomical sources from reaching the surface.

A few dozen space radio astronomy experiments and dedicated telescopes for studies in low-frequency radio astronomy, space VLBI, and the cosmic microwave background have already flown, while the first submillimetre mission, SWAS, was successfully launched in December 1998. The results from these missions have provided significant breakthroughs in our understanding of the nature of celestial radio radiation. Among them, for example, is the discovery of the cosmic microwave background radiation anisotropy by the COBE satellite in 1993, which provided insights on the Universe as it was about 1 million years after the Big Bang. These first successes of space radio astronomy led to significant efforts to develop the successors to these experiments.

The following subsections summarize some important features of space radio astronomy experiments of the past, present and future. This list does not include early experiments performed mainly in the field of low-frequency radio astronomy, or the solar system radio astronomy experiments performed with interplanetary spacecraft.

2.1. Space VLBI

Space Very Long Baseline Interferometry (SVLBI) potentially can provide a microarcsecond or better angular resolution at radio wavelengths. This can be achieved if the radio interferometer consists of antennas separated by a distance exceeding the Earth's diameter. Today's first generation of SVLBI missions use only one antenna in space, located in relatively low orbits (apogee 20,000 - 100,000 km) and operate simultaneously with a ground-based network of VLBI telescopes. Radio astronomers envision a future where networks of space radio telescopes are located in high-Earth orbit or at the Sun-Earth L_2 point, as well as VLBI radio telescopes located on the Moon.

Table 1. Space VLBI missions / experiments.

Mission / Experiment	Dates	Orbit	Frequency bands (GHz)	References
TDRSS	1986-1988	Geosynchronous 38,000 km	2.271 - 2.285 15.35 - 15.43	Levy et al. 1986 Linfield et al. 1990
VSOP	12 Feb 1997 (launch)	Elliptical Apogee =20,000 km Perigee = 500 km	1.6-1.722 4.8-5.0 22.2-22.3	Hirabayashi 1998(a)
Radioastron	2002 - 2006	Elliptical Apogee = 78,000 km Perigee = 2000 km	0.32-0.328 1.633-1.697 4.8-5.0 22.2-22.3	Kardashev 1997
VSOP - 2	2005 - 2008	Elliptical Distance from Earth up to 100,000km	4.8-5.0 22.2-22.3 42-44	Hirabayashi 1998(b)
ARISE	2010 - 2015	Elliptical Distance from Earth up to 80,000km	8.0-9.0 21-23 42-44 84-88	Ulvestad et al. 1998
Millimetron	2010 - 2015	Earth-Sun system L_2 point, $1.5\text{x}10^6$ km from Earth	18-26 45-53 104-112 217-225 266-274	Kardashev 1995

SVLBI astrophysical objectives include studies of the physics of the most compact and remote objects known in the Universe, associated with such energetic events as the nuclear activity in galaxies (compact continuum extragalactic radio sources, megamasers, the compact radio source in the centre of the Milky Way). The SVLBI technique is also useful for studies of the birth, life and death of stars (masers in protostar disks, flaring radio emissions from stars, neutron stars (pulsars), and X-ray binaries associated with the final stages of a star's evolution).

The list of space VLBI missions already flown or in the preparation/planning stage is given in Table 1. The current generation of Space VLBI missions and future missions will also rely heavily on ground support. Radio interference in SVLBI observing bands as well as in SVLBI communication and data channels (phase reference signal transfer, data transfer, and spacecraft operations) can jeopardize SVLBI observations.

2.2. Microwave Studies of the Early Universe

The microwave background radiation discovered in the mid 1960s is crucial to understanding the origin and evolution of the Universe. In fact, it is the only way so far to see what the Universe "looked like" when it was about a million years old (the current age of the Universe is estimated to be about 15 billion years). No electromagnetic radiation can come from the earliest stage of the Universe's evolution because the Universe was so dense and ionized at this stage that all electromagnetic radiation was absorbed by matter.

Table 2. Missions to study the microwave background

Mission / Experiment	Dates	Orbit	Frequency bands (GHz)	References
Prognoz-9 / Relict 1	07/01/1983-01/1984	Highly elliptical Apogee = 750,000 km Perigee = 1000 km	37 -37.4	Strukov et al. 1984 Klypin et al. 1992
COBE / DMR	11/18/1989-12/23/1993	Circular distance from Earth = 900 km	31.25-31.775 52.631-53.458 90.909-91.777	Smoot et al. 1990 Mather et al. 1991
MAP	2000 - 2003	Earth-Sun system L_2 point, 1.5x10^6 km from Earth	18-96	Bennett 1997
PLANCK	2005 - 2010	Earth-Sun system L_2 point, 1.5x10^6 km from Earth	27-33 39.6-48.4 63-77 90-110 122-178 177-257 287.5-418.5 444-646 698.5-1015.5	Bersanelli et al. 1996

This relic radiation has almost an isotropic character and the spectrum of a blackbody with a temperature very close to 2.7 K, with the maximum intensity at millimetre wavelengths. Extremely small variations in the temperature of this radiation (on the order of $\delta T/T = 10^{-5}$), with characteristic angular sizes in degrees to tens of degrees, are believed to contain information on the "primordial seeds" from which all the galaxies in the Universe evolved. Observations of this phenomenon require extraordinary sensitivity which is achieved through the use of wideband cryogenic receivers and hours of integration time for measurement of one data point. Though microwave background studies are also performed from the ground, ground-based observations are ultimately constrained by amplitude and polarization fluctuations due to propagation in the atmosphere. Also, a full-sky mapping of the microwave backround radiation is required for these studies. Ground-based observations with different instruments observing different parts of the sky incorporate calibration and other systematic errors. Only observations from space are free from these constraints. The most spectacular results in this area of astronomy research have been obtained with space-based radio telescopes.

A list of space radio astronomy missions for the study of the cosmic microwave background emissions which have already flown or are under development is given in Table 2.

2.3. Low-Frequency Radio Astronomy from Space

Observations at frequencies below approximately 10-30 MHz are difficult or impossible to conduct from the ground due to the Earth's ionosphere. Information on radio emissions from astronomical objects at frequencies below the ionospheric cutoff (about 6 MHz) has come entirely from spacecraft observations. The first space radio astronomy low-frequency experiments have given us just a glimpse of the wealth of astronomical phenomena expected to be manifested in this band. Key astronomical information has already been obtained on the Sun and the planetary radio emissions, as well as the background radio emission of our Galaxy. It is expected that the next generation of low-frequency space radio astronomy experiments/missions will allow us to better forecast the impact of solar activity on the Earth, to understand the late stages of the evolution of radio galaxies (to discover galaxy "fossils"), and perhaps to discover radio emissions from Jupiter-like planets in extrasolar planetary systems.

Table 3. Low-frequency radio astronomy missions

Mission / Experiment	Dates	Orbit	Frequency bands (MHz)	References
RAE-1	Jul.4, 1968-Jul. 1972	Earth orbit Circular, 5800 km	0.45 - 9.18	Weber et al. 1971
RAE-2	Jun.15, 1973-Feb. 1976	Lunar orbit 360,000 km from Earth	0.25 - 13.1	Alexander et al. 1975
WIND/WAVES	Jan.11, 1994 (launch)	Halo orbit around L_1 point, 1.5×10^6 km from Earth	0.02-13.85	Bougeret et al. 1995
ALFA	2003 - 2006	10^6 km from Earth	0.03 - 30	Jones et al. 1998

Numerous low-frequency radio astronomy experiments have been performed with spacecraft since 1960. A few of these experiments are listed below (see Table 3). A new mission, Astronomical Low Frequency Array (ALFA), consisting of 16 spacecraft, is being studied by NASA. It will study low-frequency natural radio emissions with a sensitivity and angular resolution orders of magnitude greater than previous experiments.

2.4. Millimetre and Submillimetre Radio Astronomy from Space

Millimetre and submillimetre astronomy observations from the ground are restricted to a few atmospheric windows due to absorption by water vapor and oxygen. Even in these "atmospheric windows" the sensitivity of observations is degraded by the influence of the atmosphere, forcing astronomers to build millimetre and submillimetre telescopes at high altitudes. A space location entirely eliminates these atmospheric effects and also offers access to the frequency bands where the ground-based observations are not at all possible.

The millimetre and submillimetre wavebands are essential to the study of the "cold matter" in the Universe -
(i) cold molecular and dust clouds in our Galaxy, which are the site of the origin of stars,
(ii) dust and molecules in young galaxies at high redshifts in the early Universe, and
(iii) the microwave background radiation, which at the equivalent temperature 2.7 K has its maximum intensity at 150 GHz.
Space-based millimetre and submillimetre radio telescopes will significantly enhance the ability of astronomers to conduct research in these bands and may lead to fundamental astronomical discoveries. This is recognized by the space agencies, which are developing an impressive set of space missions for millimetre-submillimetre studies of the Universe. Table 4 contains a full list of such missions that have been or are expected to be launched in the next two decades.

Table 4. Millimetre and submillimetre radio astronomy missions

Mission	Dates	Orbit	Frequency bands (GHz)	References
SWAS	1998 - 2000	Earth orbit, Circular, 600 km from Earth	487-493 547- 557	Melnick 1993
ODIN	1999 - 2001	Earth orbit, Circular, 600 km from Earth	118.25-119.25 486-502 541-579	Scheele 1996
FIRST	2005 - 2010	Highly elliptical Earth orbit / 70,600 km, or halo orbit about Sun - Earth L_2 point / $1.5\text{x}10^6$ km	490 - 642 640 - 802 800 - 962 960 - 1122 1120 - 1250 1600 - 1800 2400 - 2600	Pilbratt 1997
ARISE (single dish mode)	2005 - 2010	Elliptical, Apogee = 100,000 km	50-70	Ulvestad 1998

Most of the past and current experiments have been flown on Earth-, Moon- or Sun-orbiting spacecraft. It is planned that the new generation of space radio telescopes are to be deployed in the vicinity of the L_2 Sun-Earth Lagrangian point. In the more distant future, radio astronomers plan to place radio telescopes in the shielded zone of the Moon.

2.5. Radio Astronomy from the Sun-Earth Lagrangian Point

Quasi-stable (halo) orbits can be established for spacecraft around five special libration (Lagrangian) points in the gravitational field of the Sun-Earth system.

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Two of them, the L_1 and L_2 points, are located along the Sun-Earth line at distances of about 1.5x10^6 km from each side of the Earth - the L_1 point is between the Sun and the Earth and the L_2 point is on the other side, furthest from the Sun. Halo orbits having radii up to about 250 000 km are possible in the vicinity of the L_2 point. Favourable conditions for maintaining and operating space telescopes near the L_2 point (e.g., efficient radiative cooling of a telescope and receivers) have led to proposals for a number of such astronomical missions (see Tables 1-4). Because of the great distance from the Earth, the orbits around the L_2 point are expected to be "quiet" in terms of radio interference.

2.6. Radio Astronomy from the Shielded Zone of the Moon

The far side of the Moon offers excellent conditions for the location of astronomical observatories including radio observatories. The advantages and opportunities for radio astronomy on the Moon have been discussed in numerous studies describing a wide range of projects from low-frequency arrays (Landecker et al. 1991), to highly-sensitive radio astronomy observations at centimetre wavelengths and SETI (Heidmann 1998), to submillimetre radio interferometers (Mahoney 1991). One of the most important advantages to radio astronomy is an environment relatively free from terrestrial radio transmissions provided by the natural shielding of the Moon.

> "The shielded zone of the Moon comprises the area of the Moon's surface and an adjacent volume of space which are shielded from emissions originating within a distance of 100 000 km from the centre of the Earth" (Radio Regulations 1994, S22.22.1).

In recognition of the great scientific potential of the location of radio telescopes on the shielded zone of the Moon, international radio regulations prohibit any emissions in this zone causing harmful interference to radio astronomy observations in the *entire* frequency spectrum, except in the bands allocated to space research and required for the support of space research services (Radio Regulations 1994, S22.22 Section V).

3. Radio Frequency Interference in Space Radio Astronomy

At the present time, the radio frequency spectrum from 9 kHz to 275 GHz is completely allocated to one or more radio services. Because of the fast progress in utilizing even higher radio frequencies, efforts have begun for allocation of the frequencies from 275 GHz to 1000 GHz. The radio spectrum is allocated by the International Telecommunication Union in blocks of frequencies to provide the necessary frequency bands for operations of different radio services. There are currently two dozen bands below 275 GHz, with relative bandwidth $\delta f/f$ between 0.2 to 10 percent, allocated for radio astronomy observations on a primary basis. Three of them are effective only in one of three ITU geographical areas. Additionally, a few allocations exist on a secondary basis. Ground-based radio astronomy observations are conducted actively in all of these bands. Moreover, radio astronomers are in the forefront of developments at even higher frequencies, conducting observations with ground-based radio telescopes at frequencies as high as 900 GHz. Thus, ground-based radio astronomy utilizes practically the entire frequency spectrum available at which cosmic radio waves are not absorbed or reflected by the Earth's atmosphere and ionosphere. For observations with space radio telescopes, radio astronomers intend to use the existing radio astronomy frequency allocations plus the parts of the spectrum at which the atmosphere is opaque. Moreover, they hope to be able to observe in the entire radio frequency spectrum, not just in the frequency bands designated by the radio regulations, to fully realize the potential of the space missions and to explore the frequency bands which it is impossible to study on Earth because of emissions from other radio users.

3.1. RFI in Space-Based vs. Ground-Based Radio Astronomy

There are important factors regarding radio frequency sharing and protection for space radio astronomy missions that are different from such considerations for ground-based radio astronomy.

Firstly, the space telescope's location away from the Earth means that RFI sources, which are contained mainly within the distance of 100,000 km from the centre of the Earth (Radio Regulations S22.22.1, 1994), will occupy only a portion of the sky. A space radio telescope equiped with a high-gain antenna can avoid observations in the direction of Earth. The main disadvantage is that such limitations will constrain the scientific operations by removing from any potential observations a significant portion of the sky. Evidently, such a constraint is more severe for Earth-orbiting space telescopes with apogees smaller than the distance to the Moon. From the L_2 point, however, the angular size of the noisy area will be just a few degrees across. Also, radio astronomy observations with a low-gain space antenna (e.g. the dipole type used for low-frequency radio astronomy) will be more affected by RFI since they have low selectivity to the direction of the upcoming signals.

In addition to the RFI from the vicinity of the Earth, transmissions from deep space probes as well as transmissions required to support space research operations on the Moon and other planets can affect space radio astronomy observations. Careful coordination between radio astronomy, space research, and space operation services is required to protect space radio astronomy.

Secondly, geographical spacing between ground-based radio observatories and ground stations supporting active radio services allows simultaneous operations by both of these services in same the same frequency band. This has allowed the co-allocation of bands to both radio astronomy and active radio services transmitting from the Earth towards space-based receivers. Geographical sharing may work for a ground-based telescope, but an orbiting telescope may go right above the source of the RFI and be completely unprotected. Also, since the space-based radio telescope is likely to observe at any point in its orbit, different criteria of sharing and protection may apply while it is above the different ITU frequency allocation regions.

Thirdly, such radio services as inter-satellite communications are in general compatible with ground-based radio astronomy because they tend to use bands which ground-based telescopes cannot use due to the atmosphere's opacity. In turn, however, such intersatellite links may interfere with space-based radio astronomy experiments which will be designed to observe also in the bands not accessible to ground-based telescopes.

Finally, it is well known that because of the extremely high sensitivity of the radio telescopes, sharing of the radio astronomy bands with an active service with a transmitter located within line-of-site of the ground-based radio telescope at a distance even as far as that to the geostationary orbit is practically impossible (Handbook 1995). Estimates show that the level of detrimental interference from such transmissions in radio astronomy bands exceeds the threshold of the interference required to protect the radio astronomy observations. But the remote location of space radio telescope will help to reduce line-of-sight RFI from the emissions of these active services.

3.2. Protecting Space Radio Astronomy from Man-Made Radio Interference

The impact of RFI 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, extended source, continuum, spectroscopy).

Although the sensitivity of VLBI observations to RFI, in general, is lower than for other types of radio astronomy observations (Handbook 1995), the effect of RFI on SVLBI observations may be different in a few aspects. Recent experience with SVLBI observations in L-band with the Japanese VSOP satellite HALCA has shown a high vulnerability to RFI entering through the space radio telescope sidelobes (Lioubtchenko et al. 2001). Particularly since sensitivity on the baseline between the space radio telescope and ground telescope is not very good (the space radio telescope has a modest size of 8-m diameter), RFI in the observing channels of both the ground and space telescopes makes the initial detection of interferometric fringes difficult. This may lead to the loss of precious observing time.

Space radio telescopes for cosmic microwave backround studies are also very sensitive to RFI. They have
(i) extremely high sensitivity (a few tenths of mK for an integration time of only 1 second),
(ii) very wide bandwidth of the radiometers ($\delta f/f$ = 0.1-0.2),
(iii) a need for extremely high stability of the receiver's gain and calibration accuracy, and
(iv) a need for continuous data collection during a long duration (about 1 yr).
Locating space radio observatories for such observations at the L_2 point or on the shielded side of the Moon is practically a mandatory requirement.

Low-frequency radio astronomy observations from space at frequencies below the ionospheric cut-off are partially protected from ground-based RFI by ionospheric shielding. However, observations from space at frequencies between 6 and 30 MHz, where ground-based observations are still very difficult due to the ionosphere, may be significantly affected by terrestrial RFI because
(i) these observations are usually conducted with low-gain antennas,
(ii) this part of the radio spectrum is heavily used by the broadcasting services,
(iii) a high dynamic range is required (the signal power of observing targets, ranging from solar radio phenomena to extragalactic radio sources, may differ

by more than 90 dB), and
(iv) these measurements require accurate calibrations.

It has been reported that man-made radio emissions introduce significant interference to low-frequency observations in the vicinity of Earth at distances up to 1.5x10^6 km (the L_1 Sun-Earth system Lagrange point) (Alexander et al. 1975; Kaiser et al. 1996). The future space observatories operating in these bands will need to be located on the shielded side of the Moon or far enough from the Earth that other means of suppression of the RFI can be used (Jones et al. 1998).

The RFI in the observing bands of a millimetre-submillimetre radio telescope can lead to at least three potential reasons for the loss of data. First, since the front-end devices based on SIS (Superconductor-Insulator-Superconductor) junctions have a very small level of destruction power, about 10 mW, these front-ends can be easily destroyed if powerful radar or intersatellite link signals are accidentally intercepted by the telescope antenna beam. Secondly, such interfering signals at the level of -90 dBW picked up, for example, in antenna sidelobes, can easily saturate the receiver. Thirdly, narrow bandwidth RFI appearing in the observing band by leaking through the sidelobes can lead to the spurious identification of a non-existent molecular line.

The ITU frequency allocations for radio services are currently limited to frequencies below 275 GHz. It is important for future allocations above 275 GHz to take into consideration the new developments in millimetre-submillimetre space radio astronomy.

Finally, preliminary studies show that the levels of radio emissions on the surface of the Moon even from the deep space probes (deep space is defined as the region beyond 2 x 10^6 km from the Earth) may exceed the thresholds for harmful interference established for total power continuum radio astronomy measurements (Gutierrez-Luaces 1997). This indicates that protection of Moon-based radio astronomy will require careful coordination of the frequency allocations for all permitted active services.

4. Conclusions

Space radio astronomy is an integral part of future developments in radio astronomy. Consideration of frequency protection and sharing for this field is urgent and timely because of the rapid growth. Initial steps to protect space radio astronomy have been made by establishing a quiet zone on the back side of the Moon. Efforts have also been made to establish a coordination zone to protect the radio observatories in the vicinity of the Sun-Earth L_2 point. Much more work needs to be done.

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