



MASTERARBEIT / MASTER'S THESIS

Titel der Masterarbeit / Title of the Master's Thesis

„Monitoring and Analysis of Electromagnetic Interference in Radio Astronomy“

verfasst von / submitted by

Ing. Harald Chmela, BSc

angestrebter akademischer Grad / in partial fulfilment of the requirements for the degree of
Master of Science (MSc)

Wien, 2018 / Vienna, 2018

Studienkennzahl lt. Studienblatt /
degree programme code as it appears on
the student record sheet:

A 066 861

Studienrichtung lt. Studienblatt /
degree programme as it appears on
the student record sheet:

Astronomie

Betreut von / Supervisor:

ao. Univ. Prof. Dr. Franz Kerschbaum

Monitoring and Analysis of Electromagnetic Interference in Radio Astronomy

Ing. Harald Chmela, BSc

Institute for Astrophysics, University of Vienna, Türkenschanzstraße 17, A-1180 Vienna

Abstract

Our modern world uses more and more electronic devices with constantly increasing computing power and clock frequencies. These devices tend to emit electromagnetic radiation into frequency bands which are reserved for radio astronomy and protected by international regulations. To investigate this growing problem monitoring of these electromagnetic interferences is necessary.

A small radio telescope with 2.3 meter dish diameter is modified so that it stays operational in an environment with strong signal sources like mobile phones. The side lobe sensitivity of the radio telescope to the interferences is analyzed.

A low noise amplifier with large signal immunity and a broadband receiver for electromagnetic radiation in the two main radio astronomy frequency bands 1420 MHz and 1665 MHz is developed. A software defined radio is used to record the interfering signals. The structure of the interference in the frequency and time domain is analyzed. A generic model is presented which can produce similar spectra.

An omnidirectional antenna is mounted at the site of the radio telescope to monitor emissions coming from inside the institute's building. The radio telescope and other low gain antennas are used to locate the sources of the interference. The emitted electrical field strength of different electronic devices which are used in the vicinity of the radio telescope is measured and compared to the limits defined in the standard for electromagnetic compatibility. Shielding measures are implemented at the devices and the reduction of the emission is documented.

For a more comprehensive investigation of the electromagnetic interference situation in an urban environment a proposal for a large area monitoring project is given. This project would enable one to analyze the spectral and time structure of a large amount of electronic devices located in the city of Vienna. A directional antenna is pointed to the Vienna city center and first measurements are presented.

Überwachung und Analyse von elektromagnetischen Störungen in der Radioastronomie

Ing. Harald Chmela, BSc
Institut für Astrophysik, Universität Wien, Türkenschanzstraße 17, A-1180 Wien

Zusammenfassung

In unserer modernen Welt sind immer mehr elektronische Geräte mit ständig steigender Rechenleistung und Taktfrequenz in betrieb. Diese Geräte emittieren elektromagnetische Strahlung in Frequenzbänder, die für die Radioastronomie reserviert sind und die durch internationale Vorschriften geschützt werden. Um dieses akute Problem zu untersuchen, ist eine Überwachung der elektromagnetischen Störungen notwendig.

Ein kleines Radioteleskop mit einem Spiegeldurchmesser von 2.3 Metern wird so modifiziert, dass es in einer Umgebung mit starken elektromagnetischen Störungen weiter funktionsfähig bleibt. Die Empfindlichkeit dieses Radioteleskops gegenüber den Störungen wird analysiert.

Es werden ein rauscharmer, großsignalfester Vorverstärker und ein breitbandiger Empfänger für elektromagnetische Strahlung in den beiden radioastronomischen Frequenzbändern 1420 MHz und 1665 MHz entwickelt. Ein digitaler Empfänger wird verwendet um die Störsignale aufzuzeichnen und deren Struktur im Frequenz- und Zeitbereich zu analysieren. Ein allgemeines Modell zur Erzeugung von ähnlichen Spektren wird vorgestellt.

Eine isotrope Antenne wird am Standort des Radioteleskops montiert, um Störemissionen aus dem Inneren des Institutsgebäudes aufzuzeichnen. Das Radioteleskop und andere Richtantennen werden verwendet, um die Störquellen zu lokalisieren. Die emittierte elektrische Feldstärke verschiedener elektronischer Geräte, die in der Nähe des Radioteleskops betrieben werden, wird gemessen und mit den Grenzwerten in den Normen für die elektromagnetische Verträglichkeit verglichen. An den Geräten werden Abschirmungsmaßnahmen durchgeführt und die Reduzierung der Störemissionen wird dokumentiert.

Für eine umfassendere Untersuchung der Störsituation in einem großen städtischen Umfeld wird ein Überwachungsprojekt vorgeschlagen. Dieses Projekt würde es ermöglichen, die elektromagnetischen Störungen von einer großen Anzahl an Geräten innerhalb der Stadt Wien im Spektral- und Zeitbereich zu analysieren. Eine Richtantenne wird auf die Wiener Innenstadt gerichtet und erste Messungen werden präsentiert.

Acknowledgements

First and foremost I would like to thank Professor Franz Kerschbaum for giving me the opportunity to modify the radio telescope and to use the existing receiving equipment for this project. Thank you also for the opportunity to work as a tutor in the internship radio astronomy, and geometric optics where I found a new area of interest.

I would like to especially thank Armin Luntzer, who helped me in endless long discussions to better understand the topic of radio astronomy and who always helped me out with problems at the radio telescope.

My thanks also goes to Wolfgang Zelinka who helped me in many working hours to modify the radio telescope and to bring it to the best possible performance and who has documented the improvements.

I would also like to thank my former colleagues at the Austrian Broadcasting Corporation, who trained me in high frequency technology. Without that knowledge this project would not have been feasible.

Lastly I would like to thank Hans Dominik and Stefan Denaerde two authors of science fiction books who wrote about a better world we could live in, which has always inspired me in my whole scientific work.

Content

1	Introduction	3
1.1	Radio Wave Emission Processes	4
1.1.1	HI Spectral Line Emission	4
1.1.2	OH Maser Emission	5
1.1.3	Free - Free Radiation	6
1.1.4	Synchrotron Radiation	6
1.2	Frequency Bands in Radio Astronomy	7
1.3	Frequency usage by Telecommunication	8
1.4	Electromagnetic Compatibility	10
1.5	Expected EMI Power Density	11
2	The Small Radio Telescope (SRT)	14
2.1	Modification of the SRT Frontend	15
2.1.1	Can Antenna used as Dish Feed	17
2.1.2	Frontend Bandpass Filter	18
2.2	Sensitivity of the SRT	20
2.3	Synthesized Antenna diagram of the SRT	23
2.3.1	Comparing different dish Diameters for EMI immunity	26
3	EMI Monitoring Equipment	27
3.1	Frontend Amplifier	27
3.2	Receiver	31
3.3	Recording Device	33
3.4	Calibration	33
3.5	Receiver sensitivity	34
3.6	Monitoring Antenna	36
3.6.1	Omnidirectional Antenna	37
3.6.2	Directional Antenna	38
4	Recorded Data	40
4.1	Frequency usage at the SRT site	40
4.2	EMI Measurements with the SRT	42
4.2.1	Method for identifying single spectral line emissions	43
4.2.2	Localizing a EMI source with the SRT	45
4.3	EMI Spectra of electronic Devices	49
4.4	EMI shielding Measures	56
4.5	Analysis of the spectral Structure of the EMI	60
4.5.1	Generic Model for producing digital Noise	63
4.6	Analysis of the Time Structure of the EMI	66
4.6.1	Measurements at the IfA	66

5	Proposal for a EMI monitoring Project	70
5.1	Range of the EMI monitoring Project	71
5.2	Measurements of the EMI arising from Vienna	72
6	Appendix	78
6.1	Conclusion	78
6.2	Intermodulation Products.....	79
6.3	Power matching and reflected Power	81
6.4	Summary.....	82
6.5	Kurzfassung	82
6.6	List of Figures.....	83
6.7	List of Tables.....	85
6.8	Abbreviations	86
6.9	References.....	87

1 Introduction

The Institute for Astrophysics (IfA) operates a Small Radio Telescope¹ (SRT) with 2.3 meter dish diameter for educational purposes. The location of the IfA in the city of Vienna cannot be compared to any modern radio observatory, where usually a radio quiet zone around the site is defined.

Radio telescopes work at the edge of the technological possible sensitivity, which makes them very sensitive to electromagnetic interferences (EMI). Due to the urban environment the SRT users very often have to deal with artificial signals. In education this is very disturbing for the unexperienced user who might get confused by artificial signals appearing at random sky positions with different strength and frequencies. It also means additional work in the data reduction process.

Figure 1 shows two typical observations of the galactic plane of the Milky Way galaxy at different galactic longitudes (GLON) done with the SRT. The broad spectral feature of neutral hydrogen (HI) around 1420.5 MHz is overlaid with two narrow band artificial signals. On some sky positions the EMI can get so strong that the HI signal nearly disappears in the full scale of the spectrum, as shown in Figure 1 right. This is very annoying for students who work for their first time with a radio telescope. They might think that the EMI lines are the HI emissions of the Milky Way.

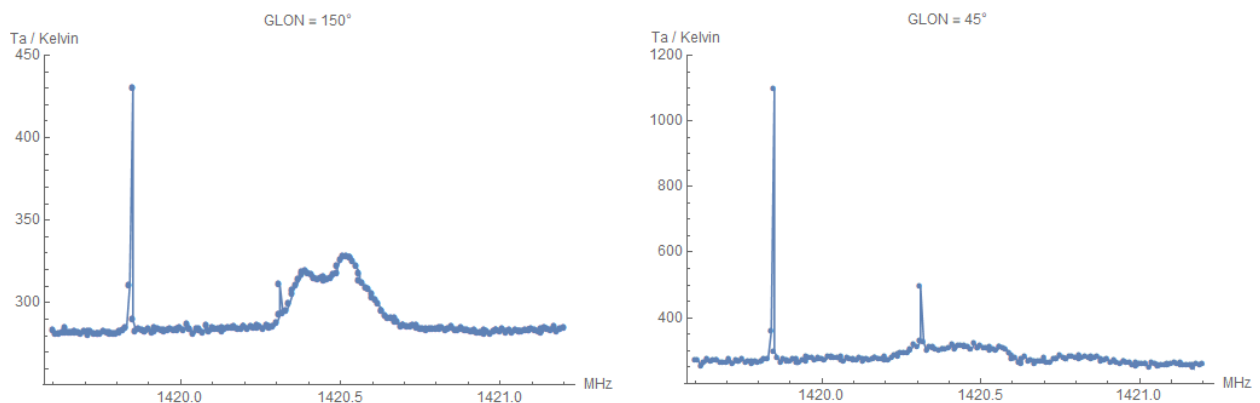


Figure 1: Two HI observations of the Milky Way galaxy disturbed by EMI of different strength

In an environment with nearby strong signal sources like mobile phones the biggest problem is saturation of the first amplifier which then creates intermodulation products by the process described in appendix 6.2. After equipping the SRT with a bandpass filter as described in chapter 2.1.2, intermodulation could be excluded as the source of interference. Nevertheless artificial signals were still present in the recorded spectra. The interest fell then on to signal sources, which directly radiate into the frequency bands which are reserved for passive radio astronomical observations.

Most artificial signals arise from electronic devices like computers or flat screens inside the IfA, but there are also some signals, which are radiated from the city of Vienna. The location of the IfA makes it ideal to study EMI from the large urban area of Vienna. A low gain antenna at the roof of the IfA was pointed to the city center of Vienna. The EMI situation is recorded over a longer period of time to study the time structure of the arising EMI.

¹ First version of Small Radio Telescope, www.haystack.mit.edu/edu/undergrad/srt/
MIT Haystack Observatory, 99 Millstone Road Westford, MA 01886

1.1 Radio Wave Emission Processes

The lowest part of the electromagnetic spectrum up to 300 GHz is the regime of radio waves. There exist different physical processes which can produce radio waves. They are differentiated between continuum emissions and spectral line emissions. Continuum emissions produce a broadband noise in the radio spectrum, while spectral line emissions are narrow spectral features which can be broadened by the Doppler shift.

1.1.1 HI Spectral Line Emission

First of all to mention is the most important spectral line in radio astronomy, the 1420.4 MHz or often called 21 cm emission of the neutral hydrogen atom. It gives radio astronomy the ability to see the coldest and not ionized hydrogen gas in the universe.

In the ground state of the hydrogen atom there exists two hyperfine levels caused by the different orientation of the magnetic moments of the proton and the electron. The lowest energy level is realized if the magnetic moments are aligned antiparallel, comparable with two bar magnets attracting each other as shown in Figure 2 right. Directly connected to the orientation of the magnetic moment is the direction of the spin.

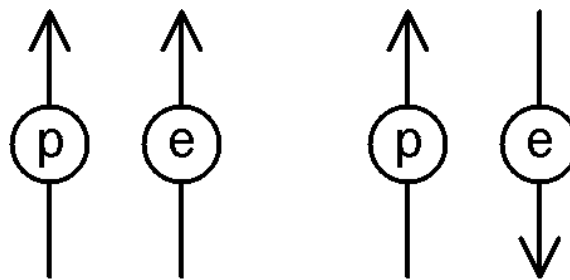


Figure 2: Alignment of the magnetic moments of the proton and the electron in the hydrogen atom in the excited energy state (left) and in the ground state (right)

By collisional excitation the electron can flip its spin direction and with it the orientation of its magnetic moment. In the parallel orientation of the magnetic moments a slightly higher energy is stored in the hydrogen atom, comparable with two bar magnets repelling each other. When the hydrogen atom is returning to the ground state, meaning the electrons magnetic moment is flipping to its natural orientation, a radio photon at 1420.4 MHz is emitted.

This transition is often called a forbidden one, as the excited state has an extremely long lifetime of millions of years. This transition can only be observed in a large amount of hydrogen atoms and cannot be produced in the laboratory. The extreme long lifetime leads to a very small emission line width. This makes it ideal for analyzing the motion of hydrogen clouds by evaluating the Doppler shift.

Observing the 21 cm line emission is the best way to study the structure of galaxies, as most of the hydrogen gas is concentrated in a thin disk around the galactic plane. By probing the Doppler shift of the hydrogen line the rotation profile can be revealed far beyond the optical visible part of the galaxy.

1.1.2 OH Maser Emission

The hydroxyl (OH) molecule is a radical which can be produced by dissolving a hydrogen atom from a water molecule. It was one of the first molecules discovered in the universe by its maser emission around 18 cm wavelength. Maser stands for Microwave Amplification by Stimulated Emission of Radiation. A maser works in the microwave regime using the same principal of stimulated emission as a laser does in the optical regime.

Masers can occur naturally if photons with the right frequency are travelling from a background source through a medium with excited molecules. In a gaseous medium where the excited energy state is overpopulated a passing photon can cause a stimulated emission of another photon at the same frequency. This leads to an amplification of the background source seen as a negative opacity in the medium. A sufficient long lifetime of the excited energy state is necessary to achieve the overpopulation.

The OH molecule has a lot of rotational and vibrational degrees of freedom which produce different microwave emissions. According to [1] the excitation levels with quantum numbers and the emission frequencies in the ground state $^2\Pi_{3/2}$ and in the first excited state $^2\Pi_{1/2}$ of the OH molecule are summarized in Table 1. For astrophysical masers the transitions in the ground state are the most important ones. The strongest emission is observed at 1612 MHz.

According to [2] the excitation of the OH molecule is due to infrared radiation of 35 μm wavelength. OH masers are typically found in gas outflows from stars at velocities from 10 to 20 km/s. The maser action is located within a thin shell which is expanding with the outflow. By the Doppler shift this leads to a symmetric spectral pattern around the rest frequency of the maser. This is caused by simultaneously seeing the red and blue shifted part of the shell at the same time.

Transition	Frequency [MHz]
$^2\Pi_{3/2} \ J=3/2 \ 1^+ \rightarrow 2^-$	1612
$^2\Pi_{3/2} \ J=3/2 \ 1^+ \rightarrow 1^-$	1665
$^2\Pi_{3/2} \ J=3/2 \ 2^+ \rightarrow 2^-$	1667
$^2\Pi_{3/2} \ J=3/2 \ 2^+ \rightarrow 1^-$	1720
$^2\Pi_{1/2} \ J=1/2 \ 0^- \rightarrow 1^+$	4660
$^2\Pi_{1/2} \ J=1/2 \ 1^- \rightarrow 1^+$	4751
$^2\Pi_{1/2} \ J=1/2 \ 1^- \rightarrow 0^+$	4766

Table 1: Maser emission frequencies in the ground state and first excited state of the OH molecule from [1]

The OH maser emission can only be triggered if the photons from the background source are traveling along the line of sight through an area with a sufficient low Doppler shift, otherwise the emission cannot be excited. If there is a radial velocity gradient in the gas outflow the longest line of sight occurs at the edges of the gas cloud. Under these circumstances a ring of OH masers can be seen. OH masers are observed in stellar jets or in accretion disks. They can reach a very high luminosity in the order of the solar luminosity.

1.1.3 Free - Free Radiation

In contrast to the spectral line emissions described in the previous chapters there exist other radiation processes which are producing continuum emission. In a continuum no discrete spectral lines can be distinguished. This kind of radiation is detected as broadband noise similar to the thermal noise which is always present in radio receiving systems.

In an ionized medium, for example in an HII region, the electrons are separated from the protons. The charged particles are moving around by their thermal motion at random distributed velocities. During an encounter of two particles they are accelerated by the electrostatic force between each other. According to Maxwell's equations accelerated charges produce electromagnetic radiation. As the protons are much heavier than the electrons nearly all radiation is produced by the electrons.

This emission process is called free – free radiation as the electrons are free before the scattering process as well as afterwards. As the electron loses energy during this scattering process it is often called thermal bremsstrahlung.

1.1.4 Synchrotron Radiation

Synchrotron radiation is produced when charged particles are spiraling around magnetic field lines. This leads to a constant acceleration of the charged particle which is then emitting electromagnetic radiation. As the particles lose energy during this process synchrotron radiation is also called magneto bremsstrahlung.

The radiation is emitted in the forward direction of the path of flight of the electron. Because of the spiral motion the direction of the emission is constantly changing. It can be seen from the observer only for a very small amount of time. Therefore synchrotron radiation consists of a series of very narrow spikes. The total of all emissions and their harmonics are summing up to a continuum as the single radiation processes are uncorrelated. This produces a very broadband continuum emission.

Synchrotron radiation can be found wherever magnetic fields and charged particles are involved. According to [3] for example it is produced in solar flares where both ingredients for synchrotron radiation are present. The ionized particles are caught by the strong magnetic field lines which make the particles spiraling around the magnetic field lines. This leads to a very high brightness temperature of the sun's corona around one million Kelvin at a wavelength of 1.5 meter. This is way beyond the temperature of the surface of the sun and therefore called non thermal radio emission.

1.2 Frequency Bands in Radio Astronomy

Nearly all information we can get from the universe is transported to the earth via electromagnetic radiation. Especially in the radio regime exists a very high competition with telecommunication systems. For future scientific research it is very important to keep this window to the universe open.

Interesting frequency ranges for radio astronomy are allocated all over the electromagnetic spectrum. Starting in the short wave range with the decametric emissions from planets or from the sun and ending up in the highest microwave regime where molecular lines from various substances are observable.

Most frequency ranges are used by telecommunication and very often interference from artificial produced signals cannot be avoided. Essential frequency ranges for radio astronomy are protected worldwide from active transmissions by international regulations.

Table 2 shows a selection of very important spectral lines in the low frequency range between 1 GHz and 2 GHz. The International Astronomical Union (IAU) pointed out in [4] the need to protect these frequencies from the use by telecommunication.

The IAU suggested a minimum required bandwidth which should be kept free of any transmission. In Austria the usage of the HI band at 1420 MHz is limited by [5] to a narrower bandwidth. It has been shrunk from 1400 MHz to 1427 MHz.

Substance	Rest frequency [MHz]	Suggested bandwidth [MHz]
Hydrogen (HI)	1420.406	1370.0 - 1427.0
Hydroxyl radical (OH)	1612.231	1606.8 - 1613.8
Hydroxyl radical (OH)	1665.402	1659.8 - 1667.1
Hydroxyl radical (OH)	1667.359	1661.8 - 1669.0
Hydroxyl radical (OH)	1720.530	1714.8 - 1722.2

Table 2: Important spectral lines in radio astronomy and reserved bandwidth between 1 GHz and 2 GHz

For the observation of highly redshifted objects it is necessary to extend the reserved frequency bands to even lower limits. Collisions with telecommunication bands cannot be avoided at this point as the lower frequency range is highly occupied by telecommunication.

The most important band from 1370 MHz to 1427 MHz is reserved for the 21 cm emission of neutral hydrogen (HI) which has an emission frequency ν_e of 1420,406 MHz. Using the equation for the redshift $z=(\nu_e-\nu_o)/\nu_o$ the starting frequency 1370 MHz of the reserved bandwidth equals only to a very small redshift of 0.037.

Higher redshifts of z around 13 which are interesting for cosmology shifts the hydrogen line down into the 100 MHz range. This is the band of ultra short wave (UKW) radio transmissions and is usually highly occupied with very strong signals from radio stations. This is a huge problem in the Low Frequency Array (LOFAR) network of radio telescopes which operate in that range and cannot observe between 85 MHz and 108 MHz.

1.3 Frequency usage by Telecommunication

The International Telecommunication Union² (ITU) coordinates on scale of national laws the use of the electromagnetic spectrum by the different services and generations of telecommunication systems. The usage of radio frequencies in Austria is coordinated by the Austrian Regulatory Authority for Broadcasting and Telecommunications³ (RTR).

The occupation of the spectrum shown in Figure 3 has got denser over the years by the increasing use of wireless technology. The frequency bands spread out with each new generation of mobile communication systems.

From special interest for radio astronomy is the recently assigned LTE band at 1500 MHz. The lowest channel in this band abuts directly on to the HI frequency band from 1400 MHz to 1427 MHz. Special limitations to the out of band emissions are defined in [6] for the lowest two channels of the LTE 1500 MHz band, shown in Figure 4, to protect the HI radio astronomy frequency band.

The maximal leakage of transmitted power into the whole radio astronomy band from 1400 MHz to 1427 MHz is defined in [6] as -72 dBW at the antenna port of the base station. This is equivalent to a total power of 63 nW and is very hard to reach when transmitting in the lowest block. On the other hand a source emitting a single spectral line with 63 nW in a distance of 10 km would produce 5×10^9 Jansky and would be brighter than any radio astronomical object.

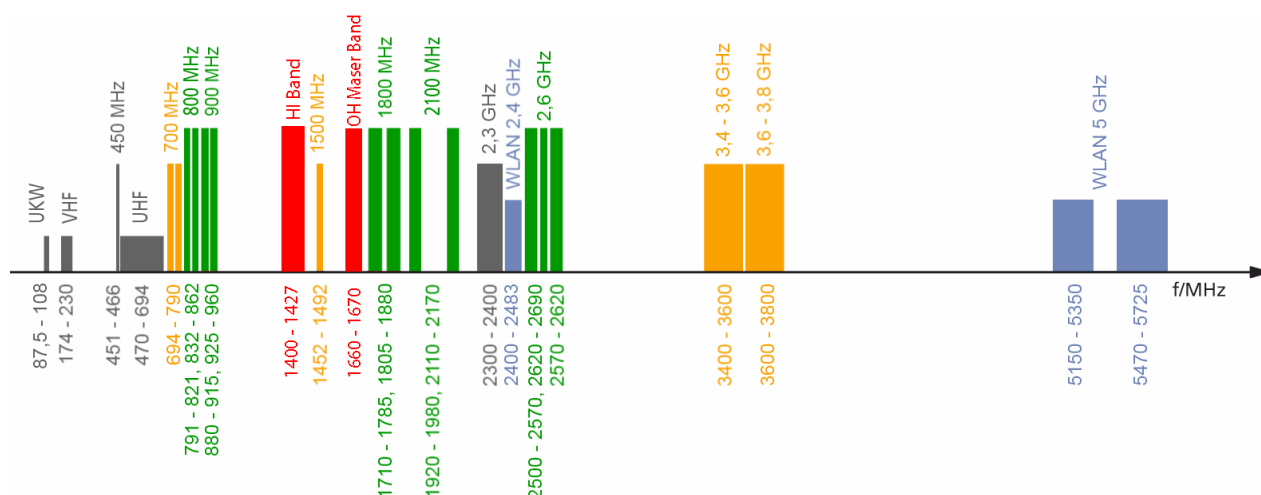


Figure 3: Frequency usage by telecommunication in Austria 2018. Radio astronomy frequency bands are marked in red, GSM and UMTS in green, LTE in orange, WLAN in blue (reprinted and modified from [2])

1427 MHz														1518 MHz				
1427 - 1432*	1432 - 1437	1437 - 1442	1442 - 1447	1447 - 1452	1452 - 1457	1457 - 1462	1462 - 1467	1467 - 1472	1472 - 1477	1477 - 1482	1482 - 1487	1487 - 1492	1492 - 1497	1497 - 1502	1502 - 1507	1507 - 1512	1512 - 1517*	1517 - 1518
Downlink (base station transmit)																		Guard band
90 MHz (18 blocks of 5 MHz)																		1 MHz
*Block conditions and **Restricted power:																		

*Block conditions and **Restricted power:

Figure 4: Block assignment in the LTE 1500 MHz band (reprinted [7])

² International Telecommunication Union, Geneva, Switzerland, www.itu.int

³ Rundfunk und Telekom Regulierungs-GmbH, A-1060 Wien, www.rtr.at

In Austria the frequency assignment up to 3000 GHz is regulated by the BMVIT⁴. In [5] is listed which frequencies may be used for active transmissions and which frequencies may only be used for passive observations.

A selection from [5] of reserved frequency bands for radio astronomy is shown in Table 3. Even some of these reserved bands have to be shared with other uses like satellite or aeronautical communications. In comparison to Table 2 not all of the suggestions of the IAU are fulfilled. Some frequency bands are limited to a smaller bandwidth.

Frequency range		Frequency usage
Start [MHz]	Stop [MHz]	
13.36	13.41	Fixed Radio Astronomy
25.55	25.67	Radio Astronomy
37.5	38.25	Radio Astronomy
73	74.6	Radio Astronomy A01
406.1	410	Radio Astronomy 5.149
608	614	Radio Astronomy 5.149
1400	1427	Radio Astronomy 5.340 , HI line emission
1610.6	1613.8	Radio Astronomy, OH maser emission
1660	1670	Radio Astronomy, OH maser emission
2655	2700	Radio Astronomy
4800	5030	Radio Astronomy
10600	10700	Radio Astronomy
14470	15400	Radio Astronomy
22000	22500	Radio Astronomy
23600	24000	Radio Astronomy
31300	31800	Radio Astronomy

Table 3: A selection from [5] of frequency ranges reserved for passive use by radio astronomy

The limits for spurious emissions of broadcasting radio systems are usually very strict and provide some level of protection for radio astronomy. But not all EMI in radio astronomy are resulting from broadcasting devices. Nearly every modern electronic device uses processor systems with constantly increasing computing power and clock frequencies. The harmonics of these frequencies reach up into the radio astronomy frequency bands.

The emission limits for these devices summarized under the term multimedia equipment (MME) are much more lenient than for active transmitting devices. The emission limits are not divided into small distinct frequency ranges. Only an upper limit for the maximal allowed emission for a very large frequency range is defined in the standards for electromagnetic compatibility (EMC). Therefore some devices may be very strong EMI sources and other ones produce nearly no emission in the radio astronomy frequency bands.

⁴ Bundesministerium für Verkehr, Innovation und Technologie, Radetzkystraße 2, A-1030 Wien

1.4 Electromagnetic Compatibility

The ability of a device not to disturb other devices by unwanted electromagnetic emissions or to be disturbed itself by other devices is called electromagnetic compatibility (EMC). The confirmation of sufficiently low emission and the immunity to interference are regulated by EMC guidelines. There exist various EMC standards and limits for the maximal emitted electric field strength for different kinds of devices and for different working environments.

Special standards need to be applied to radio communication systems with transmitting functionalities to enable the proper function of these devices in the first place. That means higher limits and stronger restrictions to the emitted frequencies. For transmitting devices this is regulated separately in the electromagnetic environmental compatibility, which protects nature and humans from high electromagnetic fields.

The typically used electronic equipment in the surrounding of the SRT is multimedia equipment (MME) like computers, laptop or flat screen monitors. For these devices the European standard EN 55032 [8] is applied, which defines the electromagnetic emission requirements for MME.

In that standard two different classes of devices are defined. Class A applies to industrial use and class B applies to home use. The limit for the electric field strength is defined in a distance of 3 meter from the device. For the measurement in an anechoic chamber it is sometimes useful to measure the field strength in 1 meter distance as it was done in [9].

Two different limits are given for the measurement with an average detector and with a peak detector. For different frequency ranges different limits are defined. Table 2 shows the limits for MME in the frequency range from 1 GHz to 3 GHz.

EMC standard for MME	Detector type	Field strength
Class A, industrial use	Peak	76 dB μ V/m
Class A, industrial use	Average	56 dB μ V/m
Class B, home use	Peak	70 dB μ V/m
Class B, home use	Average	50 dB μ V/m

Table 4: Limits for the electric field strength in a distance of 3 m for the frequency range 1 GHz to 3 GHz

The limits defined in the EMC standards are set to prohibit mutual interference from commonly used MME devices. But when comparing these limits to the sensitivity of a radio telescope the emission limits appear to be incredibly high. This is because radio telescopes works with the maximum of technological possible sensitivity to reach the faintest signals from distant astronomical objects.

For example the typical radio emission of the sun at 21 cm wavelength is in the size of 100 solar flux units (SFU) or 10^6 Jansky (Jy). A MME device emitting the maximum allowed electric field strength of 76 dB μ V/m in a single spectral line would produce 10^6 Jy in a distance of 10.000 kilometer.

1.5 Expected EMI Power Density

In the EMC standards only the electrical field strength in a distance of 3 meter is given as a limit for the emission of electromagnetic energy. To calculate the emitted electromagnetic power of the source the characteristic vacuum impedance Z_0 has to be used. According to [10] Z_0 is defined as the square root of the magnetic field constant μ_0 divided by the electric field constant ϵ_0 and has the value of 376,73 Ω .

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 376,73 \Omega$$

(1)

Z_0 describes at which voltage to current ratio electromagnetic energy is transported in the vacuum and it also has nearly the same value in air. For a conductive energy transport on coaxial cables the characteristic impedance is much lower, usually 50 Ω .

The power density S in watt per square meter at a certain point in space can be calculated using the electrical field strength E at this point and the characteristic vacuum impedance Z_0 by following equation (2).

$$S = \frac{E^2}{Z_0}$$

(2)

The electric field strength in the EMC standards is given in the unit dB μ V/m, which is a logarithmic unit referring to a electric field strength of 1 μ V/m.

$$E_{[dB\mu V/m]} = 20 \text{ Log} \left(\frac{E_{[\mu V/m]}}{1 \mu V/m} \right)$$

(3)

Assuming an isotropic emission the source power P_s in watt can be calculated out of the power density S by following equation (4). Hereby r is the distance in which the EMI measurement was done, usually defined in the EMC standards by 3 meter or for an easier measurement 1 meter as done in [9].

$$P_s = 4 \pi S r^2$$

(4)

This leads to the maximal allowed electromagnetic source power which may be radiated by an EMI device into the frequency interval from 1 GHz to 3 GHz. Table 5 shows the limits for the field strength and source power for the different EMC standards and detector types.

EMC standard	Electric field strength	Source power
Class A, peak	76 dB μ V/m	12 μ W
Class A, average	56 dB μ V/m	120 nW
Class B, peak	70 dB μ V/m	3 μ W
Class B, average	50 dB μ V/m	30 nW

Table 5: Maximum allowed electric field strength in 3 meter distance to the device and maximal allowed source power for the different EMC standards for MME.

As the source power P_s is known the power density S_d produced at a given distance d from the device can be calculated as follows, when assuming a completely isotropic radiation of the EMI.

$$S_d = \frac{P_s}{4 \pi d^2} \quad (5)$$

When monitoring EMI emissions in the distance d the power density S_d reaches the measurement antenna with gain g and effective antenna area A_{eff} . The antenna area depends on the aperture of the antenna and for an isotropic antenna also on the wavelength λ . The measurement antenna draws the electric power P_r out of the power density S_d . According to [11] this is described by the Friis transmission equation (6). Due to the frequency dependence of the Friis equation (6) the received power of an isotropic antenna drops down by 6 dB when the frequency is doubled.

$$P_r = g \cdot S_d \cdot A_{eff} = g \cdot S_d \cdot \frac{\lambda^2}{4\pi} \quad (6)$$

The antenna gain g is usually given in the logarithmic unit dBi which is defined by equation (7). This unit dBi is referring to a theoretical completely isotropic radiating antenna. When referring to a dipol antenna the unit dBd is given and then a correction factor of 2.15 dB has to be added to reach dBi.

$$g_{[dB]} = 10 \text{ Log } (g) \quad (7)$$

The received electric power is usually measured in the logarithmic unit dBm which is defined in relation to a power of 1 mW according to equation (8).

$$P_{[dBm]} = 10 \text{ Log } \left(\frac{P_{[mW]}}{1 \text{ mW}} \right) \quad (8)$$

In a receiving system with the characteristic impedance Z (normally 50 Ω) the electric power P can be expressed in terms of voltage measured in dB μ V by using Ohm's law. The logarithmic unit dB μ V is referring to a voltage of 1 μ V according to equation (9).

$$U_{[dB\mu V]} = 20 \text{ Log } \left(\frac{U_{[\mu V]}}{1 \mu V} \right) = 20 \text{ Log } \left(\frac{\sqrt{P \cdot Z}}{1 \mu V} \right) \quad (9)$$

It is important to mention that the definition of the logarithmic units for voltage and power are different by a factor of two as can be seen when comparing equation (3) and (8). A linear factor of two in the logarithmic unit means the power of two in the corresponding linear unit. This definition is accounting for the quadratic dependence of the power P from the voltage U as it is expressed by Ohm's law $P = U^2 / Z$. This means when doubling the voltage the power is increased by a factor of four.

When talking about power densities as defined by equation (5) the source power P_s seen in the distance d is diluted to a sphere with surface area $A = 4 \pi d^2$. For example when doubling the distance d to a source the power density drops by a linear factor of four. As a result of Ohm's law the voltage and the electric field strength in the distance d drop only by a linear factor of two. But when using logarithmic units for voltage and power they both drop by the same amount of 6 dB caused by the different definitions of the units.

As a consequence of this all logarithmic units for the power density, the received power, the electric field strength, the magnetic field strength, as well as the received voltage and current drop down by 6 dB when the distance to the source is doubled. This makes it very easy to compare field strength, voltage current and power with the same scaling relation just by adding a constant in dB. But one always has to keep in mind that these are different linear factors depending on which unit the 6 dB are referring to.

For example the received power at the port of an antenna measured in dBm can be converted directly into the output voltage measured in dB μ V just by adding a constant in dB. For a system with $Z = 50 \Omega$ this constant is 107 dB. Further on the electric field strength at the location of the antenna can be calculated from the output voltage as well as from the output power of the antenna just by adding an antenna specific constant in dB/m.

2 The Small Radio Telescope (SRT)

The SRT shown in Figure 5 was designed by MIT Haystack Observatory⁵ to teach students and amateur astronomers in radio astronomy. It uses a 2.3 meter dish from a television satellite receiving system. The dish is attached to a motorized altazimuth mount which allows a complete remote control via the client software. The receiver is mainly designed to operate at 1420 MHz for the observation of HI emissions but it works up to 1800 MHz where the OH maser line emissions are and it can also be used for continuum emissions in this frequency range. The low frequency and the small dish size leads to a very poor angular resolution of only 6°.

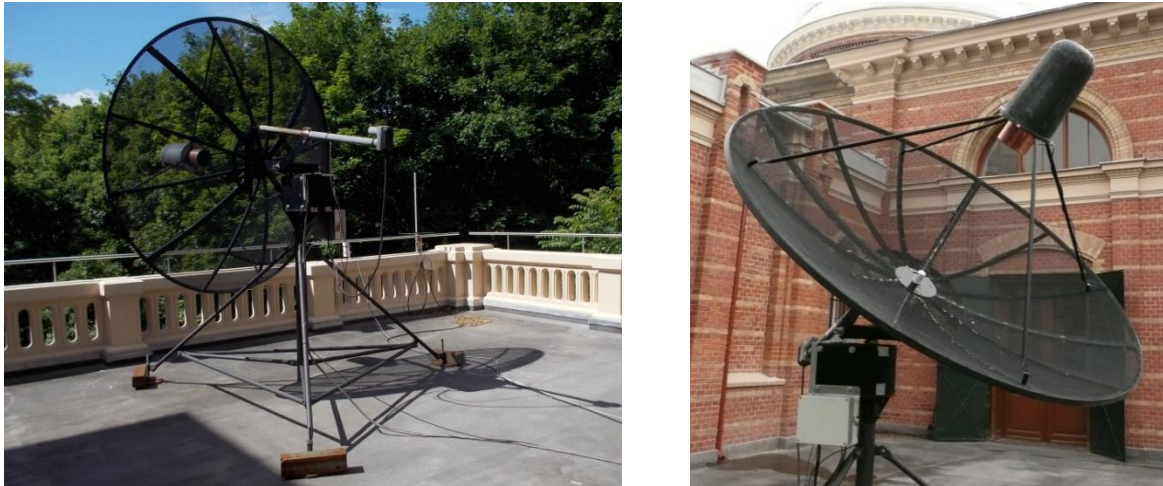


Figure 5: The small radio telescope operated by the institute for astrophysics at the Vienna university

The SRT is located at the west side balcony of the institutes building as shown in Figure 5 right, where it is surrounded by very high building walls. This means it can only see a very small part of the sky. Figure 6 shows the horizon at the site of the SRT in pink and the clear sky in white. This site also exposes the SRT to many potentially EMI sources which are located inside the nearby building where for example mobile phones are used frequently.

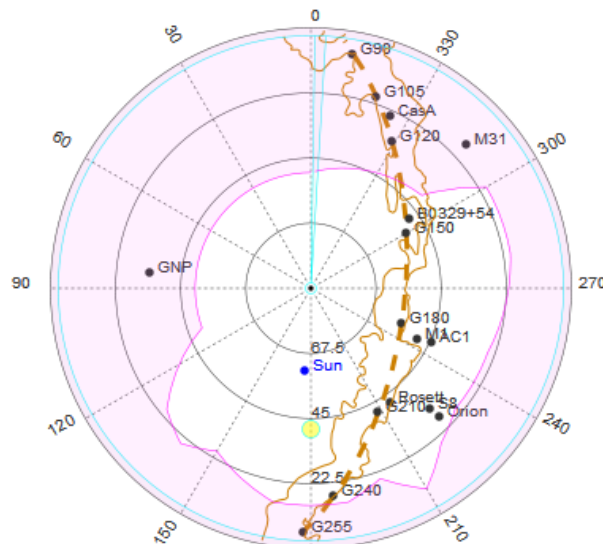


Figure 6: Sky map at the SRT site with the horizon line in pink and the clear field of view in white. The contours of the Milky Way galaxy are shown in orange and the mechanical pointing limit in light blue.

⁵ MIT Haystack Observatory, 99 Millstone Road Westford, MA 01886, www.haystack.mit.edu

2.1 Modification of the SRT Frontend

As a first measure to avoid EMI the original design of the SRT has been modified as it could not deal with strong signals. A lot of spurious signals could be identified as intermodulation products (see appendix 6.2) in the first amplifier stage which gets saturated by strong signals like nearby mobile phones. It is common practice in radio astronomy to connect the first amplifier directly to the feed horn to get as much of the signal as possible. But in an environment with strong out of band signals a bandpass filter is required before the first amplifier to avoid saturation and unwanted intermodulation products.

The original frontend amplifier showed a very poor input matching (see appendix 6.3) of only 3 dB. This means that half of the signal is lost due to back reflection to the antenna. Also it could not be used at the OH maser frequency as it contains an internally bandpass filter at the output tuned only for HI observations. Therefore the original amplifier was replaced by a specially designed amplifier for the use in radio telescopes.

Figure 7 shows the circuit diagram of the modified frontend assembly. The signal coming from the dish feed enters at the SMA connector X1 and passes through the bandpass filter F1. The characteristic of this filter are described in detail in chapter 2.1.2. The filtered signal is amplified by 35 dB in the amplifier U1. The WLA15-3525A is a quasi-superconducting low noise amplifier from WanTcom⁶. Its performance characteristics are summarized in Table 6. The 5V supply voltage for the amplifier is provided by the receiver on its input and extracted by a bias tee out of the coaxial cable at the BNC connector X2. Therefore no additional power supply cable is necessary.

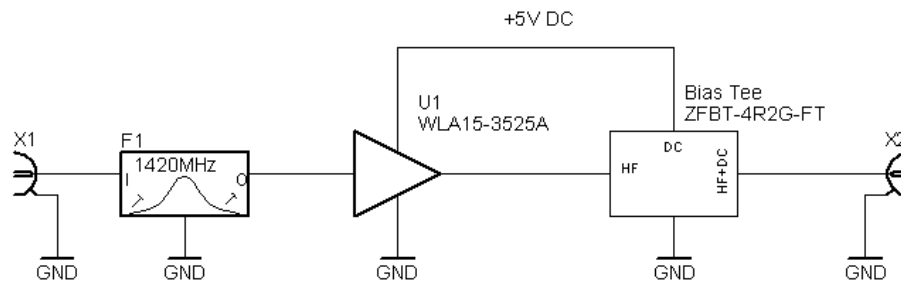


Figure 7: Circuit diagram of the modified frontend assembly of the SRT

Frequency range	1420 - 1670 MHz
Gain	35 dB
Input return loss	14 dB
Noise figure	0.3 dB
Reverse isolation	40 dB
Power supply	5 V / 45 mA

Table 6: Performance characteristics of the WLA15-3525A low noise amplifier

To get as much of the signal as possible from the feed into the amplifier a very short coaxial cable connection is necessary. For the shortest possible cable length the complete frontend assembly was mounted directly at the back side of the can antenna used as dish feed as shown in Figure 8. The characteristics of the can antenna are described in detail in chapter 2.1.1. Also

⁶ WanTcom, Inc. 1420 Lake Drive West, Chanhassen, USA, www.wantcominc.com

the interconnection between the amplifier, the bias tee and the filter are as short as possible using nearly no additional coaxial cables.

The amplified signal coming out from X2 is lead via a coaxial cable to the receiver. In the original design the receiver was placed directly in front to the dish. As the receiver is connected via a data connection to the server potentially EMI signals could travel back from the server room to the antenna. Therefore the receiver was placed at the supporting structure of the azimuthal mount to depart it from the antenna system as shown in Figure 5 right.

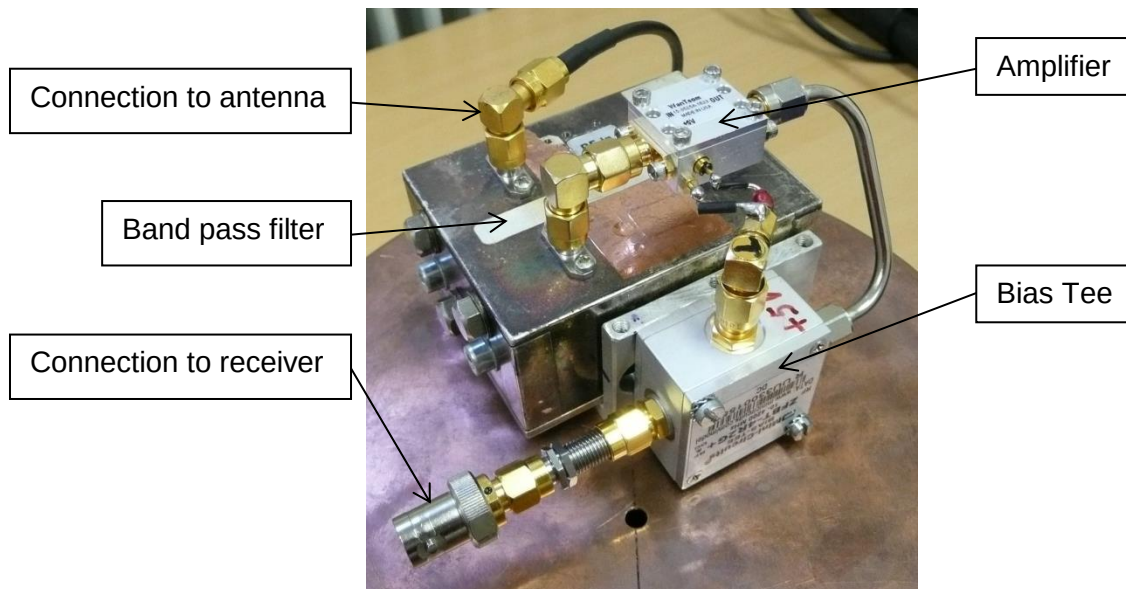


Figure 8: Modified frontend assembly of the SRT with WLA15-3525A low noise amplifier mounted at the backside of the can antenna

The WLA15-3525A amplifier has a limited frequency range which is specially matched for HI and OH maser observations. This means it collects less additional noise from other frequency ranges which leads to a very low noise figure and it makes it less vulnerable for creating intermodulation products by strong out of band signals as described in appendix 6.2. This limits the usable frequency range of the SRT to the values given in Table 7.

With that modification the SRT reaches a system temperature around 250 Kelvin as can be seen at the noise floor in Figure 50 right. This is already below the ambient temperature without cooling any component. For an even lower system temperature the amplifier could be cooled down to $-40\text{ }^{\circ}\text{C}$. This option was not realized as it means an additional power supply and a heat source in form of the waste heat of the cooling system near the antenna.

Dish diameter	2.3 m
3 dB main beam width	5.8°
1 st Sidelobe	8.5°
Antenna gain	27 dBi
System temperature	250 K
Receiver frequency range	1420 MHz – 1670 MHz

Table 7: Performance characteristics of the SRT after modification

2.1.1 Can Antenna used as Dish Feed

The original feed of the SRT was a C-band feed from satellite communication which has been adapted for 1420 MHz by inserting a quarter wavelength open coaxial cable. This antenna was not matched to the receiving frequency and therefore strong signals in other frequency bands could easily reach the amplifier and creating intermodulation products by the process described in appendix 6.2.



Figure 9: Primary focus assembly with original amplifier mounted at the SRT (left), inside view of the can antenna (middle) and attachable funnel for the can antenna (right)

To block unwanted frequencies the SRT frontend has been equipped with a matched can antenna and a bandpass filter in front of the first amplifier stage. Figure 9 shows the modified frontend assembly mounted at the primary focus of the SRT. It uses a can antenna as a simplified version of a feed horn. A funnel can be attached to the can antenna to increase its gain and tighten its antenna diagram. The can antenna is made out of a 0.5 mm copper metal sheet which dimensions are given in Figure 10.

Inside the can a standing wave pattern is formed by the incoming wave due to the reflection at the back end. A $\lambda/4$ stub made out of 4 mm² copper wire which is soldered directly to the 50 Ω SMA output connector collects the received energy. By choosing the right pickup point in relation to the back side a impedance transformation from the 376 Ω vacuum impedance to the 50 Ω cable impedance is achieved. Under these conditions all of the incoming energy is transferred to the cable. By using only one linear polarized pickup this antenna can receive radiation only in one polarization direction.

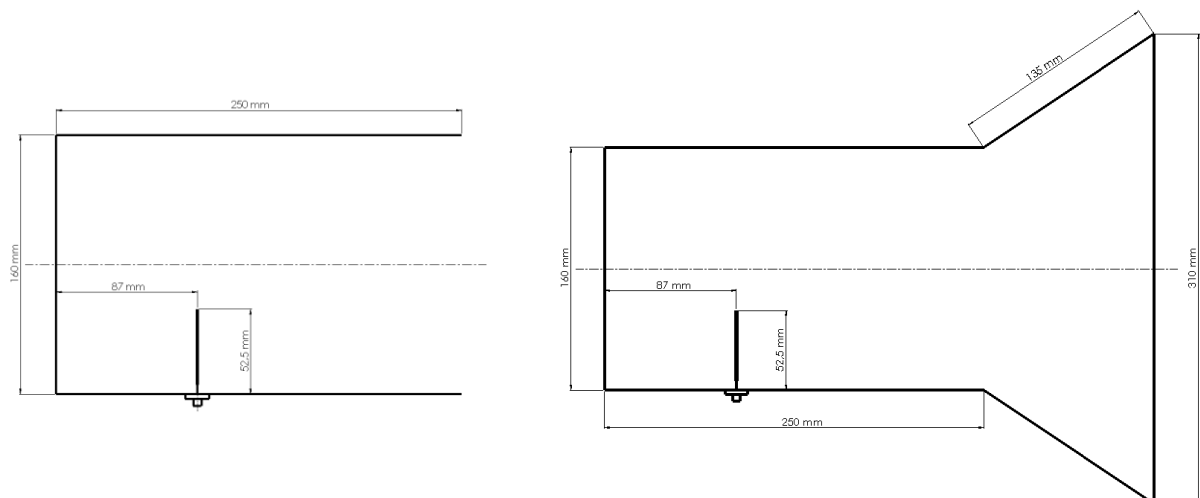


Figure 10: Dimensions of the can antenna used as a dish feed for the SRT without funnel (left) and with attached funnel (right)

2.1.2 Frontend Bandpass Filter

The received signal from the can antenna is feed directly into a two cavity bandpass filter. When using a filter before the first amplifier the SNR is increased by the insertion loss of the filter. A low loss design is needed, which means to use highly conductive materials and solid structures. This filter is made out of silver plated brass as shown in Figure 11 which leads to a high quality factor of the resonance circuits. A good matching at the input and output is required to avoid losing any signal through back reflection to the antenna.

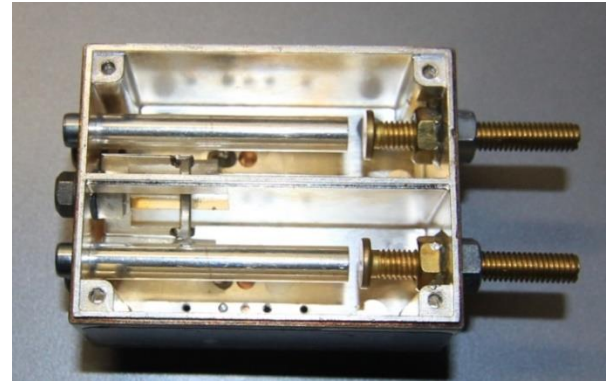
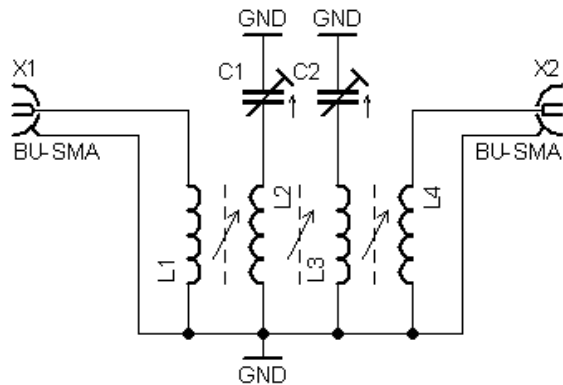


Figure 11: Circuit diagram and inside view of the two cavity bandpass filter for 1420 MHz

The circuit diagram in Figure 11 shows that this filter consists of two resonant circuits built with the coaxial inductors L2 and L3 and two adjustable capacitors C1 and C2 with which the passing frequency is set. The inductors L2 and L3 are coupled together with an adjustable inductive loop which is responsible for the bandwidth of the filter. The input and output matching at the 50 Ω ports X1 and X2 is adjusted with the inductive coupling loops L1 and L4. A proper function of this filter is achieved when both resonant circuits are tuned symmetrical to the center frequency and when the input and output matching shows two symmetric poles around the center.

By using the setups shown in Figure 26 and Figure 25 the forward transmission and the input matching of this bandpass filter was measured for a frequency range up to 1800 MHz. The results are given in Figure 12 and are showing the sharp transition steepness of this filter. The out of band suppression is greater than 30 dB for frequencies below 1420 MHz and better than 50 dB for higher frequencies. That is very crucial for suppressing mobile phone signals in the 900 MHz and 1800 MHz GSM band. The input matching only drops down at 1420 MHz proving that all other frequencies than the desired ones are reflected back at the input.

This bandpass filter reaches an insertion loss of 0.6 dB around the center frequency and is tuned to a 2 dB bandwidth from 1410 MHz to 1430 MHz. It reaches an input matching of at least 10 dB at the center frequency as shown in detail in Figure 13. Two clear poles appear in the input matching as it is expected for a two cavity bandpass filter and that also proves the correct tuning of the two resonance circuits and the three coupling loops.

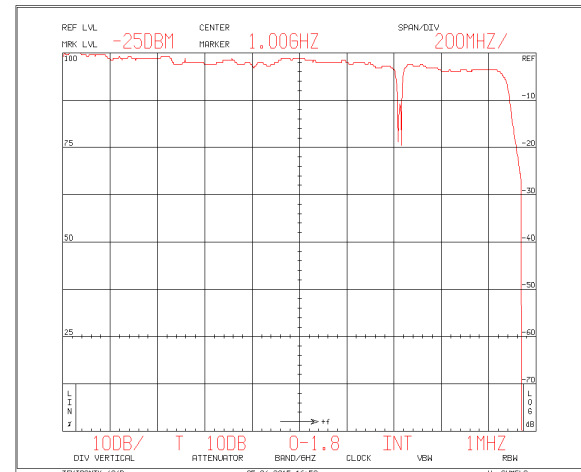
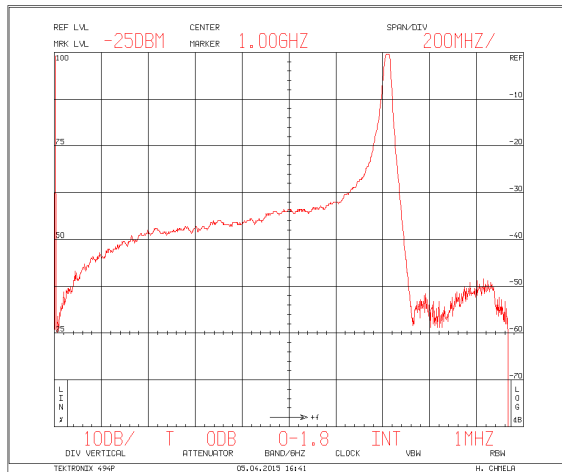


Figure 12: Forward transmission (left) and input matching (right) of the two cavity bandpass filter

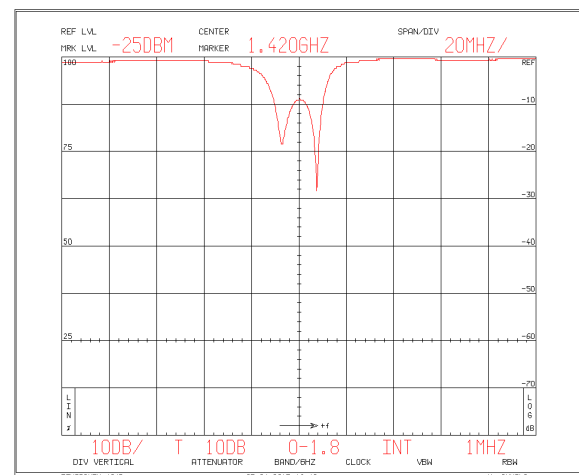
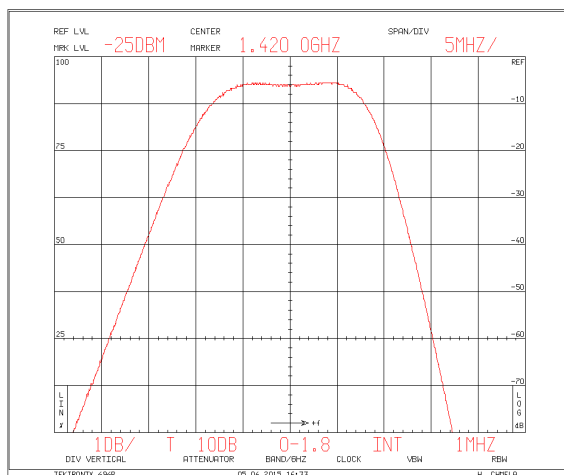


Figure 13: Detail of the forward transmission (left) and input matching (right) of the two cavity bandpass filter

Center frequency	1420 MHz
0.2 dB bandwidth	± 5 MHz
2 dB bandwidth	± 10 MHz
3 dB bandwidth	± 15 MHz
Insertion loss at ± 5 MHz	0.6 dB
Input matching at 50 Ω	> 10 dB
Connectors	50 Ω SMA

Table 8: Performance characteristics of the SRT frontend bandpass filter

The first amplifier is directly connected to the output port of the filter. The output matching of the filter has been optimized to the input impedance of the connected frontend amplifier WLA15-3525A by measuring the return loss at the filter input.

With this setup radio observations are possible even in an environment with strong out of band signal sources like mobile phones. It is also suitable for the detection of faint EMI signals which are emitting directly into the radio astronomy frequency band.

2.2 Sensitivity of the SRT

In radio astronomy the received power is expressed in terms of temperature by the linear Rayleigh Jeans approximation of the blackbody radiation. This is a suitable simplification only for low frequencies as they are used in radio astronomy. For the high frequency regime the Wien approximation can be used. A correct description for the whole frequency range can only be provided by the more complex Planck law.

According to [3] the Rayleigh Jeans law in equation (10) calculates the brightness B in watt per square meter per unit frequency and per solid angel. There is a linear dependency on the temperature T , a quadratic dependency on the wavelength λ and k_B is the Boltzmann constant.

$$B = \frac{2 \cdot k_B \cdot T}{\lambda^2} \quad (10)$$

The electric power per unit frequency P_v which is created by a resistor completely enclosed in a black body with temperature T can be calculated according to [3] by equation (11) using the Boltzmann constant k_B .

The same relation holds for a radio telescope which is pointing to a black body radiator at the temperature T when the beam is completely filled by the black body. The radio telescope receives then the electric power P_v .

$$P_v = k_B T \quad (11)$$

The system temperature of the SRT can be read out from Figure 50 right at a level of 250 Kelvin. It can be expected to see a single EMI line at a level around 260 Kelvin. By using equation (11) and (8) the sensitivity of the SRT at the input of the frontend amplifier can be calculated to an input power level of -174 dBm equal to 3.9×10^{-21} watt. In a 50Ω system this is equivalent to an input voltage of -67 dB μ V or 4.2×10^{-10} volt.

The SRT uses a 2.3 meter dish which gain can be calculated by following the Friis equation (6) and replacing the effective antenna area A_{eff} by the area of the parabolic mirror which leads to equation (12). An aperture efficiency η_A of 50 % is introduced, which is mainly caused by the tapering of the dish illumination due to the antenna pattern of the feed horn and by receiving only one polarization direction. Under these conditions the gain of the SRT dish is 27 dBi.

$$g = \frac{4 \pi A}{\lambda^2} \eta_A = \left(\frac{\pi d}{\lambda} \right)^2 \eta_A \quad (12)$$

Under normal observation conditions when the SRT is pointing into the sky a single EMI line can be expected to be seen when it is falling into one of the side lobes which are pointing toward the building. The side lobe pattern depends on the diameter of the dish and on the received wavelength. According to [12] it can be calculated using equation (13) which is representing the airy function of the diffraction limit $\arcsin(1.22 \lambda/D)$. J_1 is the first order Bessel function. $D_\lambda = D/\lambda$ is the ratio of the aperture A and the wavelength λ and Θ is the off axis angel in the antenna diagram in radiant.

$$F(\Theta) = \left[\frac{2 J_1(\pi \Theta D_\lambda)}{\pi \Theta D_\lambda} \right]^2$$

(13)

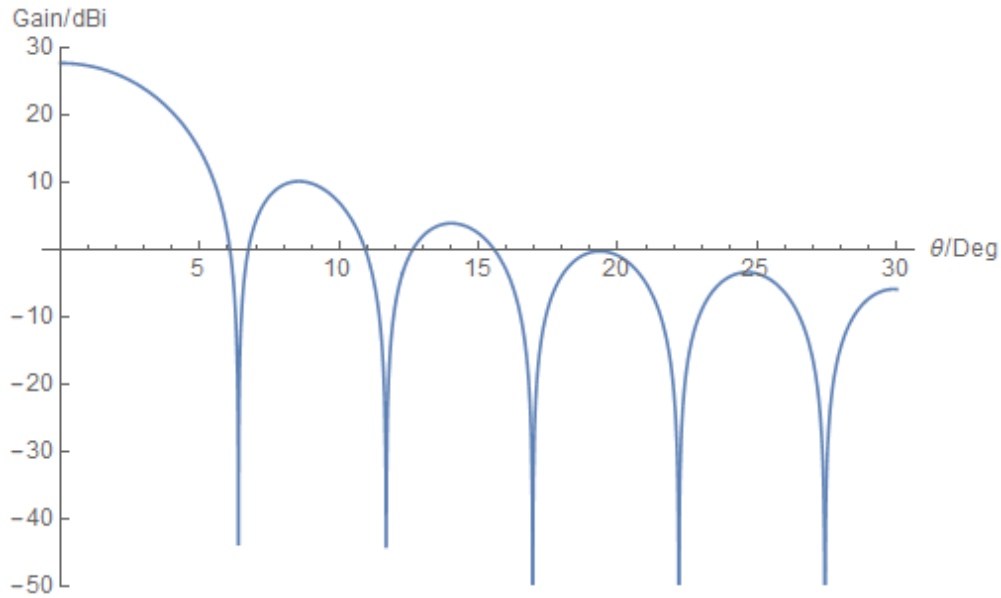


Figure 14: Theoretical antenna diagram in isotropic antenna gain (dBi) for a 2.3 meter dish at 1420 MHz

The theoretical antenna pattern for the SRT can be derived by equation (12) and (13). It is shown in isotropic antenna gain in Figure 14 for a working frequency of 1420 MHz. The first side lobe is 17 dB below the gain of the main beam. For an astronomical observation the first side lobe at 8.5° and second side lobe at 14° off the pointing axis will usually still point into the sky. For simplicity it can be assumed that the first side lobe which is potentially pointing towards the building is the third one at 20° with a gain of 0 dBi. The third side lobe would catch an EMI with the same gain as an isotropic antenna would do.

Under these conditions the critical field strength for seeing an EMI in the SRT is 27 dB above its sensitivity of 260 Kelvin. At higher levels an EMI can fall into the side lobes and can be seen on random sky positions. Using equation (1) to (3) the critical field strength at the site of the SRT can be calculated to -34.8 dBμV/m. This field strength is very low and can easily be reached by nearly any electronic device. As shown in chapter 4.3 most devices have higher emissions despite they are still far below the limits defined in EMC standards.

The only way to protect the SRT from seeing the EMI is to increase the distance to the EMI sources. By doubling the distance the field strength drops down by 6 dB. Figure 15 shows the critical field strength and EMI source power for different distances and antenna gains. The +27 dBi line has to be used when the main lobe of the beam is pointing directly to the EMI source. For a typical observation of the sky the EMI signal strength can increase up to the level of the 0 dBi line at which the EMI will begin to fall into the third side lobe.

Other EMI sources located inside the IfA building are at least 5 meter away from the SRT. For these devices an attenuation factor for the buildings walls has to be introduced. In radio telecommunication this is known as building penetration loss (BPL) or outdoor to indoor attenuation. The IfA is a historical building with very thick walls. By [13] the BPL of such an historic building was measured between a value of 22 dB and 27 dB.

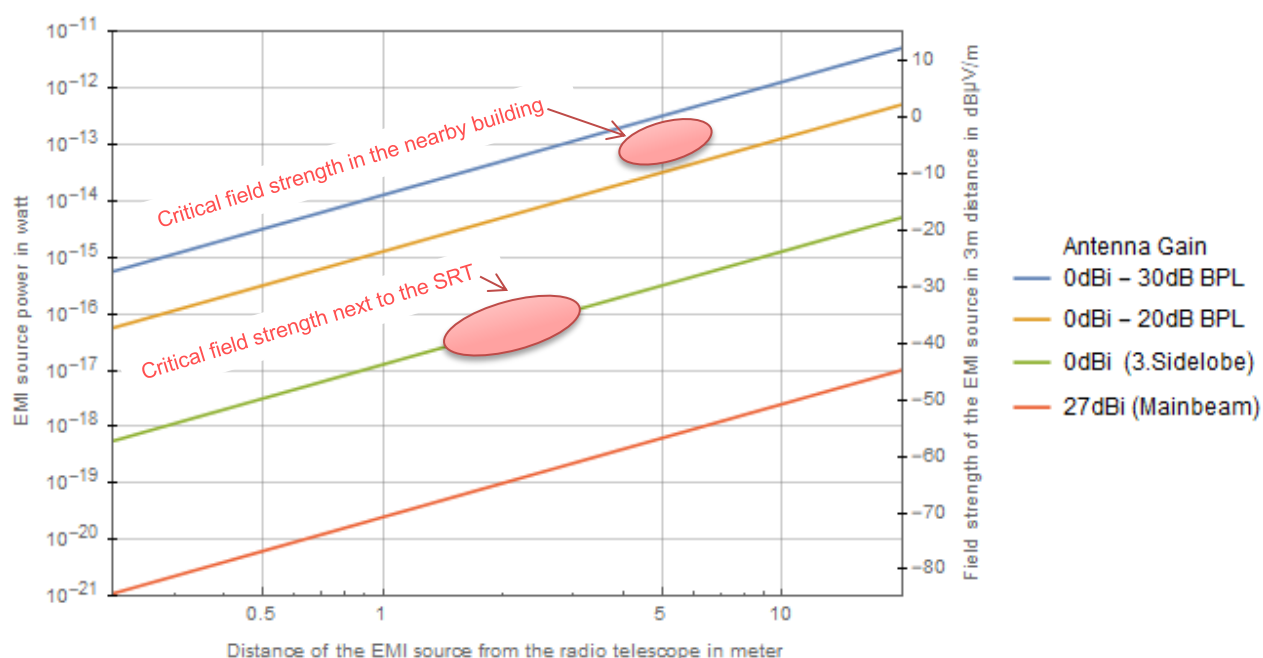


Figure 15: Critical distances in which the SRT sees an EMI source in the nearest part of the building and in the direct vicinity marked by the red circles. Plotted for EMI source power and electric field strength in 3 meter distance to the EMI source for different antenna gains and BPLs. A sensitivity of 260 Kelvin is assumed.

In Figure 15 the BPL is expressed by a negative antenna gain. For an EMI source inside the nearest parts of the building the critical field strength for falling into the third side lobe lies somewhere between the -20 dBi and -30 dBi antenna gain line. It can be seen that for a device inside the building in a distance of 5 meter the field strength in 3 meter distance of the device should not increase just about 0 dBμV/m as marked by the red circle. Compared to the EMC standard in Table 4 this is at least 70 dB below the allowed peak limits for MME. It can easily be reached by devices like a simple webcam as shown in Figure 75 or by the CHEOPS computing equipment shown in Figure 53.

2.3 Synthesized Antenna diagram of the SRT

A critical parameter in the design of radio telescopes is the tapering of the dish illumination caused by the antenna pattern of the feed. The feed picks up more intensity from the center of the main dish as from the edge. Due to the large wavelength it is not possible to achieve a constant dish illumination. A tradeoff between the best sensitivity in the main beam and the lowest side lobe pattern has to be made. A typical tapering of the illumination at the edge of the dish is -10 dB.

By using the technique of Fourier optics described in [12] the antenna diagram of the main dish can be synthesized out of the dish illumination pattern caused by the feed. Figure 16 shows a comparison between a theoretical rectangular illumination pattern and a more realistic triangular shaped illumination for a 2.3 meter dish at 21 cm wavelength. Where $D / \lambda = 10.95$ is the ratio of the aperture and the received wavelength. It can be seen that the rectangular illumination leads to a smaller main beam width, but also produces very high side lobes due to the sharp illumination transition at the edge of the dish. The side lobes can be reduced by tapering the illumination to zero at the edge of the dish for this example by a triangular illumination pattern. The 3 dB main beam width in this case is near to the Rayleigh diffraction limit $\arcsin(1.22 \lambda/D) = 6.4^\circ$ and the first null is at $1/D_\lambda = 5.2^\circ$ with is also close to the airy function.

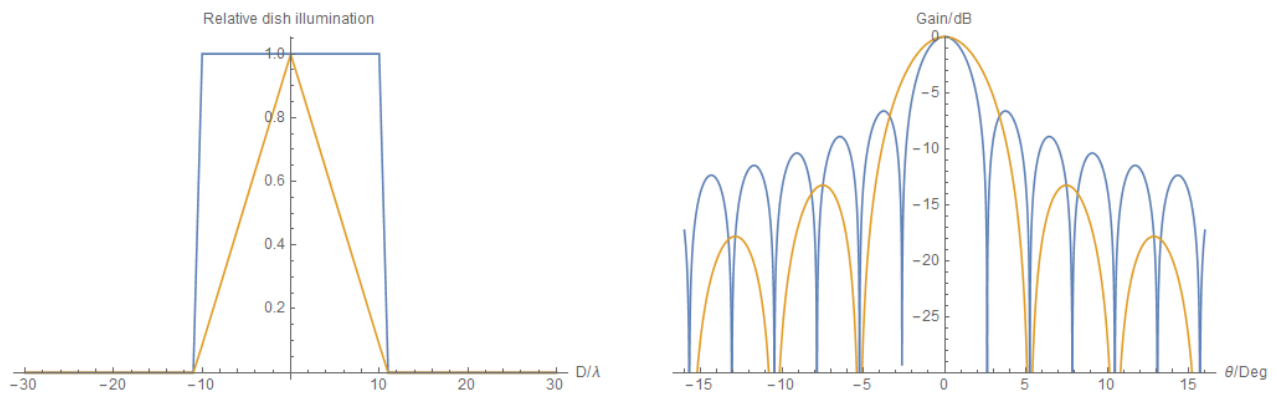


Figure 16: Theoretical antenna diagram (right) for a 2.3 meter dish at 1420 MHz for a rectangular (blue) and triangular (orange) dish illumination pattern (left)

To calculate a more realistic antenna diagram for the SRT the antenna diagram of the can antenna used as dish feed has been measured with the setup shown in Figure 17. A HM8135 signal generator set to 1420 MHz and a simple helical antenna are used as signal source. The power level of the received signal from the can antenna is measured with a MDO 3000 spectrum analyzer. By rotating the can antenna over the angle Θ the antenna diagram can be obtained.

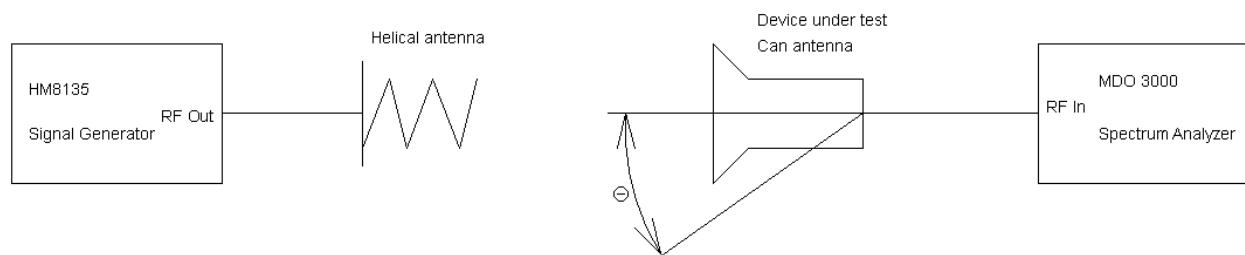


Figure 17: Setup used for measuring the antenna diagram of the can antenna

The results are shown in Figure 18 for the two cases with and without attached funnel to the can antenna. Values greater than 50° for the angle Θ could not be measured, because of the small signal and reflections on the surrounding. Therefore an airy function according to equation (13) has been fitted to the data points to extrapolate the antenna diagram to lower gain levels.

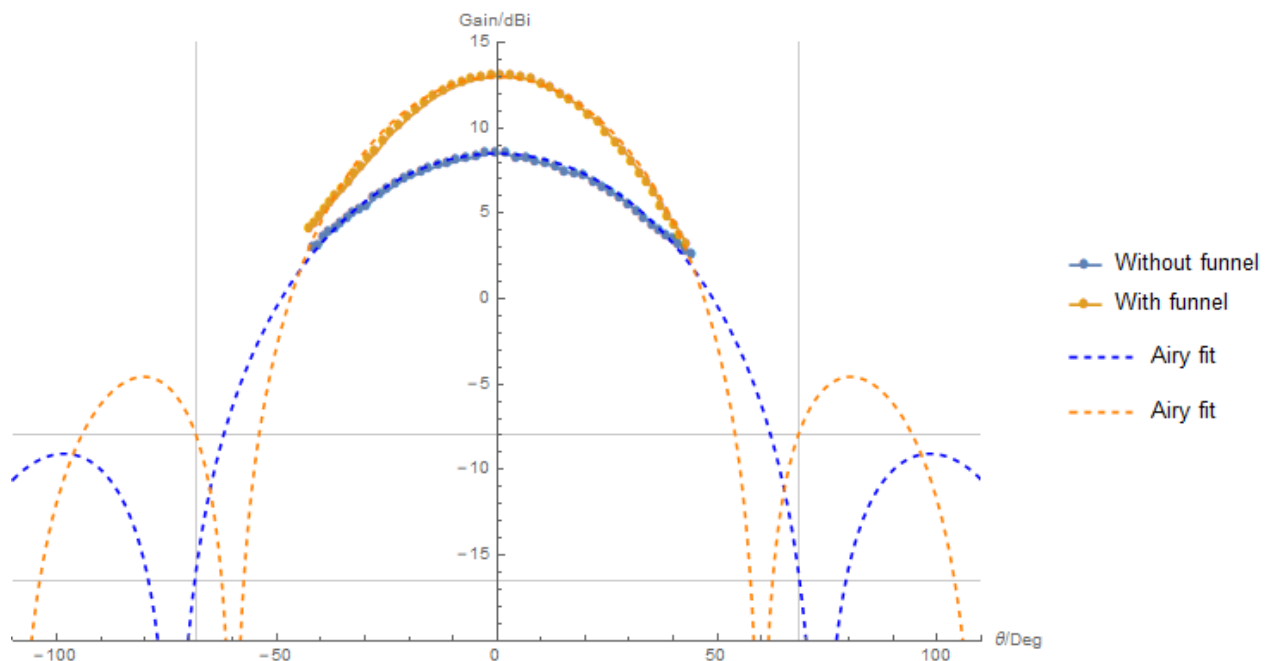


Figure 18: Measured antenna diagram for the can antenna used as dish feed for the SRT with attached funnel (orange) and without attached funnel (blue). Dashed lines are an airy pattern fit and the edge of the main dish at 68.5° is marked for both cases.

When looking at the geometry of the SRT in Figure 19 the can antenna is 0.87 meter away from the plane of the main dish which has a diameter of 2.29 meter and a couverture radius of 1.77 meter. Therefore a signal falling just right over the edge of the main dish will reach the can antenna at an angle of 68.5° .

The gain at the edge of the main dish is marked in Figure 18 by the grey lines for the can antenna with and without the funnel. It can be seen that the first zero of the airy pattern fit falls nearly at the edge of the dish when using the can antenna without funnel. This is a very high tapering of 25 dB at the edge of the dish. That cannot be reached with the funnel because of the narrower side lobe pattern the tapering is only 21 dB. The means the lowest side lobes are produced with the can antenna without the funnel.

To calculate the antenna diagram of the SRT the airy function fitted to the measured antenna diagram of the can antenna is used as dish illumination pattern between a $\pm 68.5^\circ$ opening angle. By Fourier transforming the illumination pattern the antenna diagram of the SRT in Figure 20 is derived.

It can be seen that a broader antenna diagram of the feed leads to a narrower main beam width. A narrower feed illuminates only a part of the main dish which leads to a broader main beam. By [12] this is called the similarity theorem.

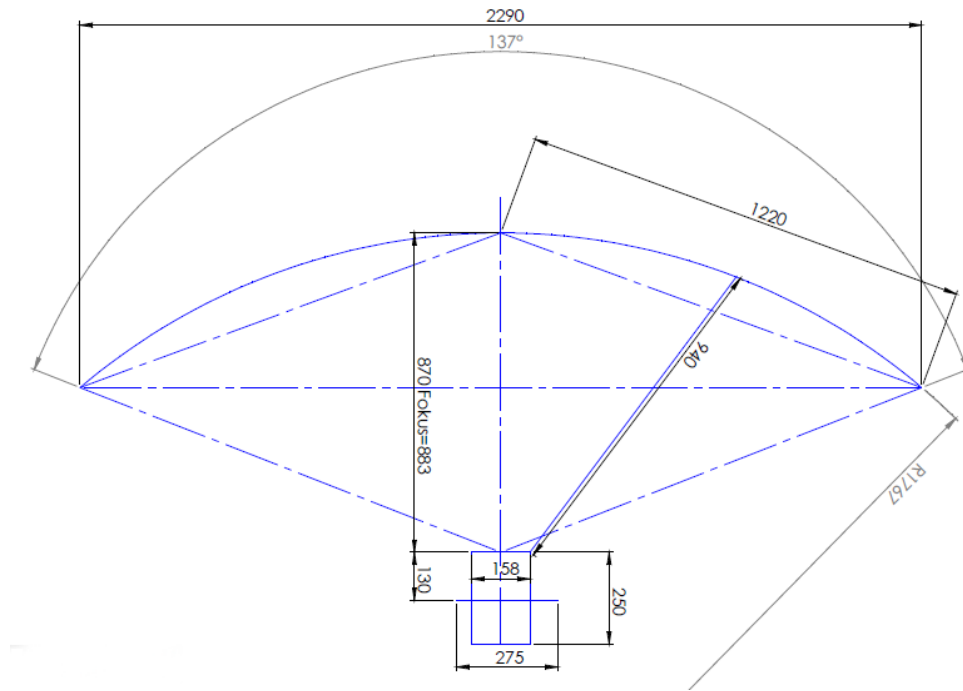


Figure 19: Dimensions given in millimeter for the SRT main dish and feed configuration

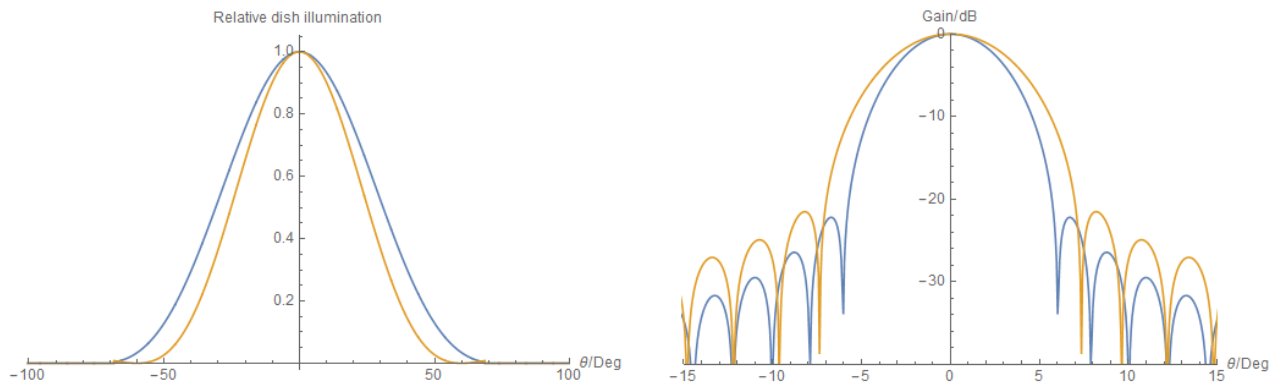


Figure 20: Synthesized antenna diagram (right) for the SRT using the measured dish illumination pattern (left) from the can antenna without funnel (blue) and with attached funnel (orange)

The illumination has also an influence on the aperture efficiency. A narrower illumination will decrease the aperture efficiency as the effective used area of the main dish decreases. Finally the funnel for the can antenna was not used as it increases the main beam with as well as the side lobe level. The results are summarized in Table 9.

Feed configuration	Can antenna without funnel	Can antenna with funnel
3 dB main beam width	5.4°	6.6°
1st side lobe position	6.7°	8.2°
1st side lobe level	- 22.3 dB	- 21.5 dB

Table 9: Calculated antenna characteristics of the SRT for different feed configurations

2.3.1 Comparing different dish Diameters for EMI immunity

Another approach for minimizing the side lobe sensitivity may be to increase the dish diameter. As discussed in the previous chapter a larger dish will automatically decrease the side lobes if the illumination pattern is kept the same. To get the benefit of the larger dish the tapering at the edge of the dish has to be the same for both cases.

Figure 21 shows the theoretical antenna pattern derived from equation (12) and (13) assuming an aperture efficiency of 50 %. This example compares a 2.3 meter dish with a 4.5 meter dish. The gain in the main beam increases from 27.7 dBi to 33.5 dBi. For the bigger dish all side lobes, even the first one, decrease in units of absolute isotropic antenna gain. But the integral over all side lobes only shows a decrease in the side lobe sensitivity of 3 dB. Therefore increasing the dish diameter does not have the same impact on the side lobes as on the main beam.

A bigger dish leads to a narrower main beam width. For this example the beam width decreases by the diffraction limit $\arcsin(1.22 \lambda/D)$ from 6.4° to 3.3° . That means for a point like astronomical source a smaller dilution factor is reached what leads to a higher input signal for that source. The SNR of the source signal is increased.

On the other hand the sensitivity against EMI falling into the side lobes is only reduced by 3 dB. The EMI would still be visible above the noise floor even when the wanted signal has increased dramatically. Therefore a bigger dish is not the best choice for increasing the EMI immunity.

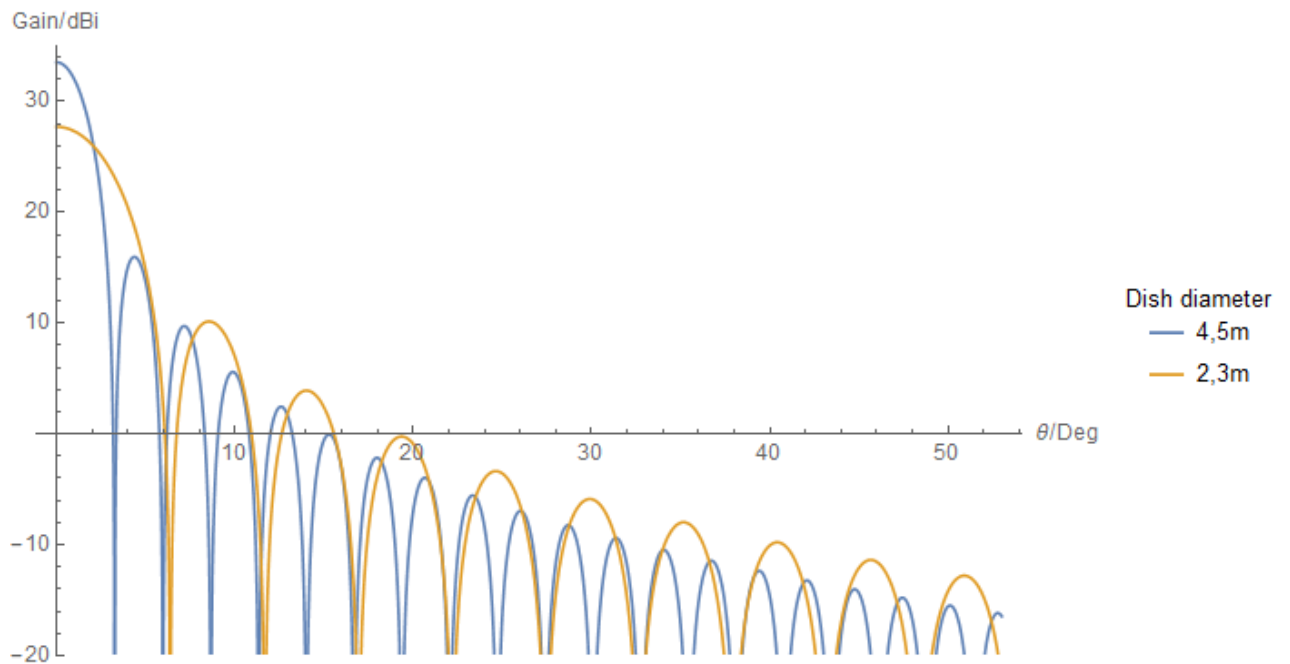


Figure 21: Theoretical antenna diagram derived by the airy function in equation (13) for a 2.3 meter dish (orange) and a 4.5 m dish (blue) working at 1420 MHz plotted in absolute isotropic antenna gain (dBi) obtained by equation (12)

3 EMI Monitoring Equipment

For measuring the EMI a receiver with large bandwidth and high sensitivity is required. But a broadband input in combination with a high gain in the first amplifier stage leads to vulnerability of creating unwanted intermodulation products by strong signals sources as described in appendix 6.2. This would cause false detections caused by sources emitting in other frequency bands than the monitored range. A special frontend amplifier equipped with bandpass filters has been designed for monitoring the two main radio astronomy frequency bands reserved for observing HI and OH maser emissions.

3.1 Frontend Amplifier

The frontend shown in Figure 22 is a combination of two bandpass filters and two low noise amplifiers. To avoid intermodulation in the first amplifier stage the bandpass filters are connected at the input of the first amplifier. The system is mounted in a waterproof housing that can be installed near the antenna to get the best SNR. It uses a bias tee to extract the supply voltage of 12V DC from the coaxial cable so it does not need an additional power supply cable. The input and output terminal are standard 50 Ω N-connectors.

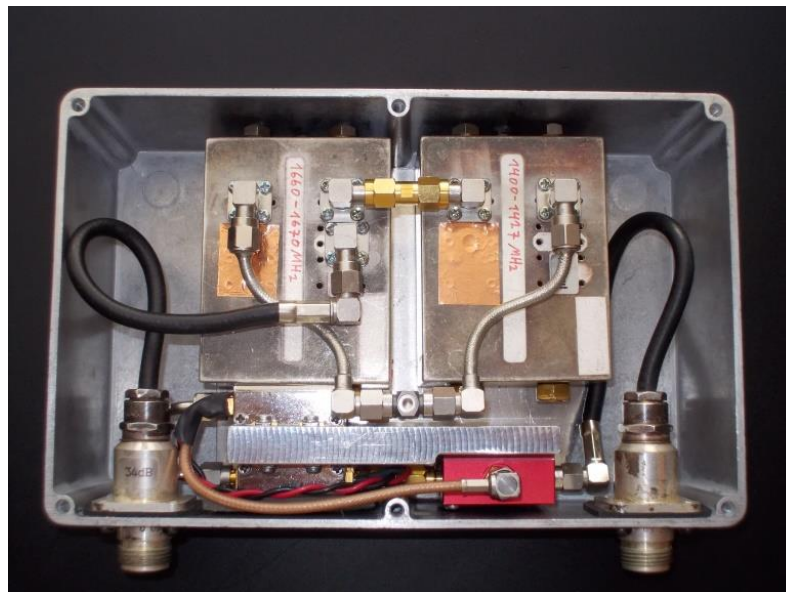


Figure 22: Dual band frontend amplifier used for EMI monitoring mounted in a waterproof housing

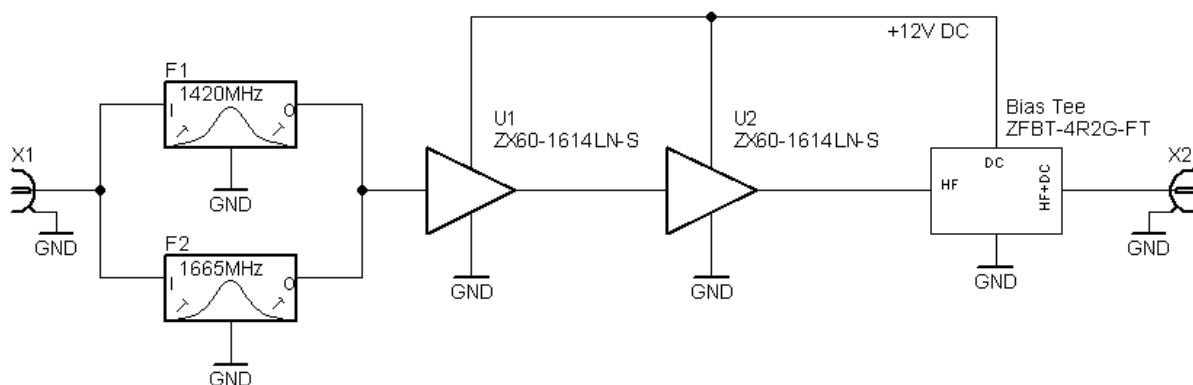


Figure 23: Circuit diagram of the dual band frontend amplifier used for EMI monitoring

The frontend uses two low noise amplifiers U1 and U2 of the type ZX60-1614LNS from Mini-Circuits⁷ in serial connection as shown in the circuit diagram Figure 23. Each amplifier provides a nominal gain of 14 dB in the frequency range from 1217 MHz to 1620 MHz. The OH maser frequency 1665 MHz is out of the specification of these amplifiers. To ensure the proper function of the amplifiers the input matching and the forward transmission of two amplifiers in series connection has been measured using the setup shown in Figure 26 and Figure 25.

The results are given in Figure 24 where the -40 dB division is the reference level for unity gain. As can be seen these amplifiers can easily be used at a frequency of 1665 MHz, where they still provide a gain of 11 dB per amplifier and an input matching of 10 dB.

Connecting two amplifiers in series can excite unwanted oscillations when the backward transmission of the amplifiers is exceeding the overall system gain. This measurement also proves that there are no instabilities when connecting two amplifiers in series.

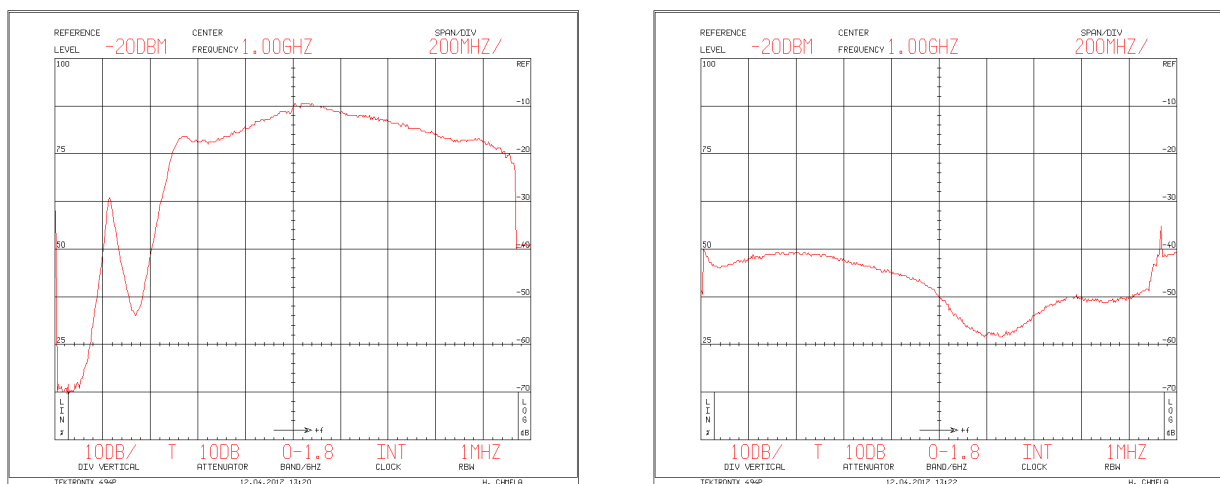


Figure 24: Forward transmission (left) and input matching (right) of two amplifiers ZX60-1614LNS in series connection

As shown in Figure 23 the design of the frontend uses two bandpass filters F1 and F2. These filters are of the same type as used at the SRT frontend described in chapter 2.1.2. The characteristics of such a filter are given in Table 8. Two filters are connected in parallel and directly to the 50 Ω SMA input connector X1 and to the first amplifier U1. This is necessary to suppress strong out of band signals from saturating the first amplifier U1 and to have the ability of simultaneously receiving two frequency bands.

But when connecting two 50 Ω ports in parallel the characteristic impedance drops down to 25 Ω , while the rest of the system still remains at 50 Ω . This would lead to return losses by back reflecting a part of the signal to the antenna. The input and output coupling of the filters have to be properly tuned to ensure a lossless transfer of the input power at X1 to the first amplifier U1. The setup shown in Figure 25 was used to measure the return loss at the input port under a 50 Ω test condition using a TEK494P spectrum analyzer in connection with a TR503 tracking generator and a 60NF50 VSWR bridge.

⁷ Mini-Circuits Inc., 13 Neptune Ave, Brooklyn, NY 11235, USA, www.minicircuits.com

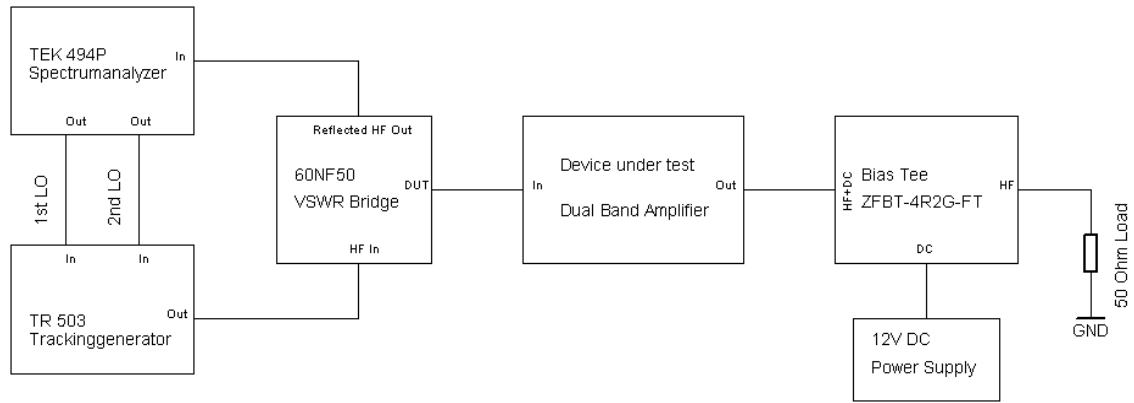


Figure 25: Setup for measuring the input matching

Figure 28 (right) shows the input matching at X1 using the -40 dB division as reference level. In both radio astronomy frequency bands the input matching is greater than 10 dB which means that less than 1/10 of the input signal is lost due to back reflection to the antenna. It is also important that at no other frequencies the input matching dips down to ensure that all unwanted frequencies are reflected back to the antenna and cannot reach the amplifier U1. At the positive gain point around 500 MHz no increased input matching can be found meaning that this frequency cannot reach the first amplifier.

The high gain of the amplifiers in combination with the low loss resonance circuits inside the bandpass filters can lead to the excitation of unwanted oscillations by the backward transmission of energy form the amplifiers into the resonant circuits of the filters. To ensure a proper function and to test the gain at 1665 MHz the forward transmission was measured using the setup shown in Figure 26.

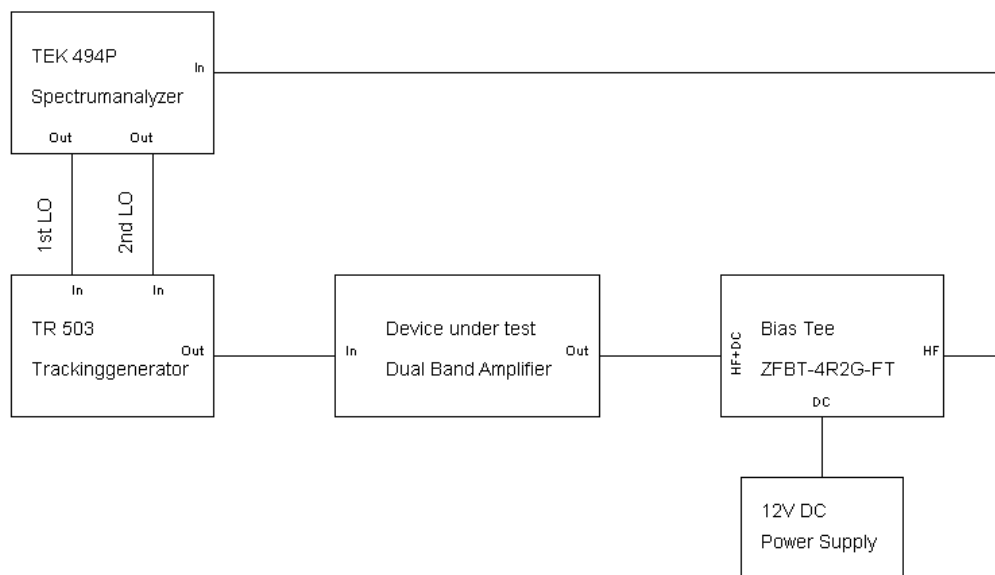


Figure 26: Setup for measuring the forward transmission

The result in Figure 27 and in detail in Figure 28 (left) uses the -40 dB division as a reference level for unity gain. The gain at 1420 MHz is 26 dB and the gain at 1665 MHz reaches at least 22 dB. There is a small positive gain around 500 MHz but besides that no other instabilities can be found in the system. All out of band signals are suppressed at least by 25 dB. In the higher frequency range from 1.7 GHz up to 5.5 GHz no further transmission peaks can be seen in Figure 27 (right) what is important to suppress WLAN and UMTS signals.

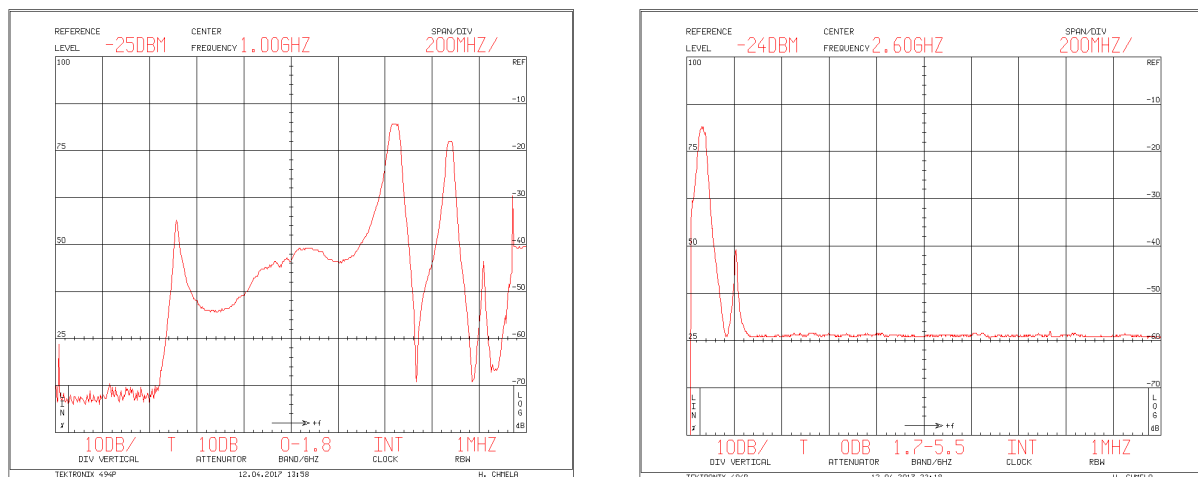


Figure 27: Forward transmission of the dual band frontend amplifier up to 1.8 GHz (left) and up to 5.5 GHz (right). The - 40 dB division is used as reference for unity gain.

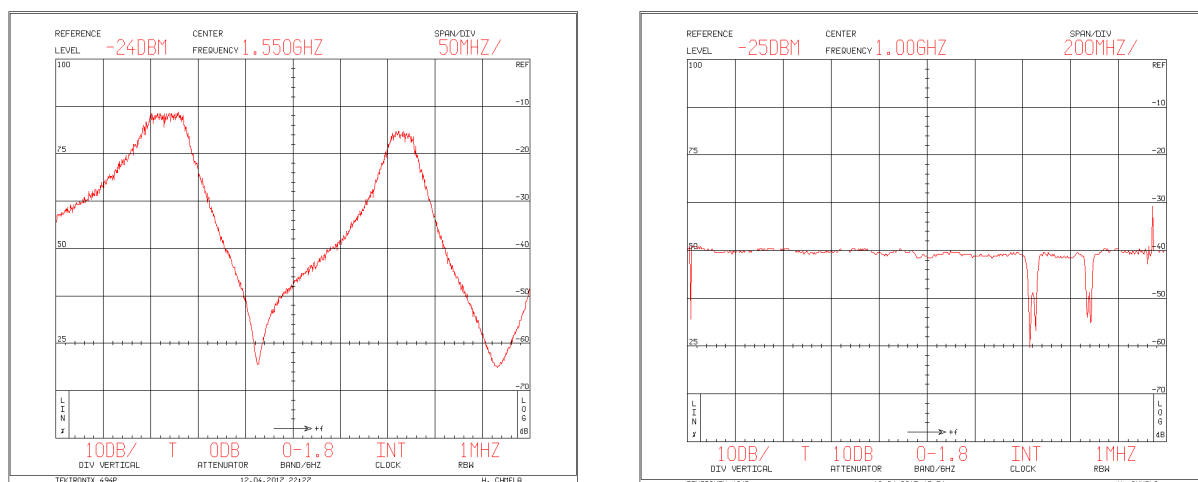


Figure 28: Detail of the forward transmission around 1.55 GHz (left) and input matching (right) of the dual band frontend amplifier. The - 40 dB division is used as reference for unity gain.

Gain at 1420 MHz	26 dB
Gain at 1665 MHz	22 dB
Input matching at 50 Ω	> 10 dB
Out of band suppression	> 30 dB
Supply voltage	12V DC over output port
Connectors	50 Ω N-connectos

Table 10: Performance data of the dual band frontend amplifier used for EMI monitoring

3.2 Receiver

The receiver is based on MIT Haystack Observatory Small Radio Telescope receiver⁸ mainly using Mini-Circuits⁹ components. Several modifications have been implemented to meet the special needs of broadband monitoring. The receiver is mounted inside a metal housing for better shielding as shown in Figure 29.

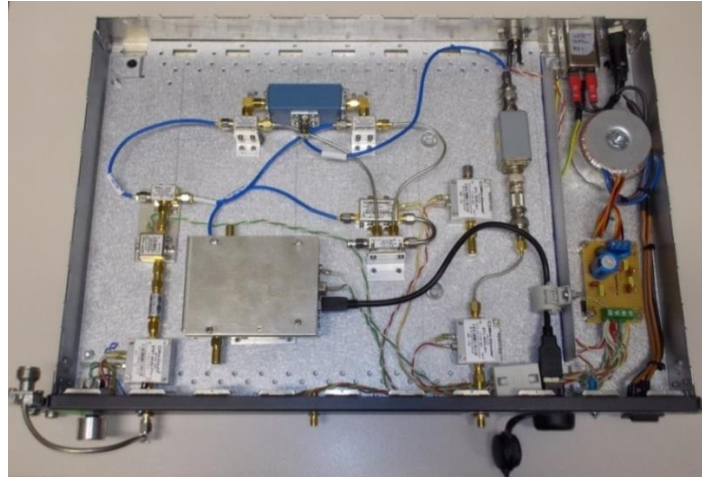


Figure 29: Inside view of the receiver used for EMI monitoring

The concept is based on an image rejection receiver to reduce the sideband noise, as shown in the circuit diagram Figure 30. The input signal passes through a wide band filter F1, is amplified by U1, divided in two equal phased parts by the splitter Z1 and then feed into the mixers M1 and M2. The signal from the local oscillator ADF4351 is amplified by U2 and divided in two 90° phase shifted parts by the splitter Z2. When adding the two IF signals coming from both mixers one sideband is suppressed in the combiner Z3. The not mirrored sideband is used for further easier processing.

The original intermediate frequency filters have been changed from two 10.7 MHz narrow band filters to one broadband 100 MHz low pass filter F2. Only one intermediate frequency amplifier U3 is used, as the attached software defined radio SDR14 has enough sensitivity.

In the original design a switch mode power supply was used. This produced a lot of spurious frequencies in the lower frequency range of the IF as shown in Figure 31. The intensity is given in dBFS related to the full scale of the connected software defined radio SDR14. A typical switching frequency of 100 kHz and harmonics up into the MHz range appeared in the spectrum. This could not be accepted for broadband monitoring which needs a clean 30 MHz bandwidth for the connected SDR14.

The situation could be improved by replacing the switch mode power supply with a linear regulated power supply as shown in the circuit diagram in Figure 30. With that modification there were still some spurious frequencies visible in the intermediate frequency as shown in Figure 31. This could be identified as noise produced by the digital synthesizer ADF4351 used as local oscillator. The complete circuit port is therefore mounted in a tin plated copper shielding case with HF seals. By switching the ADF4351 from low noise mode to low spur mode all of this noise could be eliminated, which leads to the clean spectrum shown in Figure 32.

⁸ [www.haystack.mit.edu/edu/undergrad/srt/pdf files/ElectricalSchematic.pdf](http://www.haystack.mit.edu/edu/undergrad/srt/pdf%20files/ElectricalSchematic.pdf)

⁹ Mini-Circuits Inc., 13 Neptune Ave, Brooklyn, NY 11235, USA, www.minicircuits.com

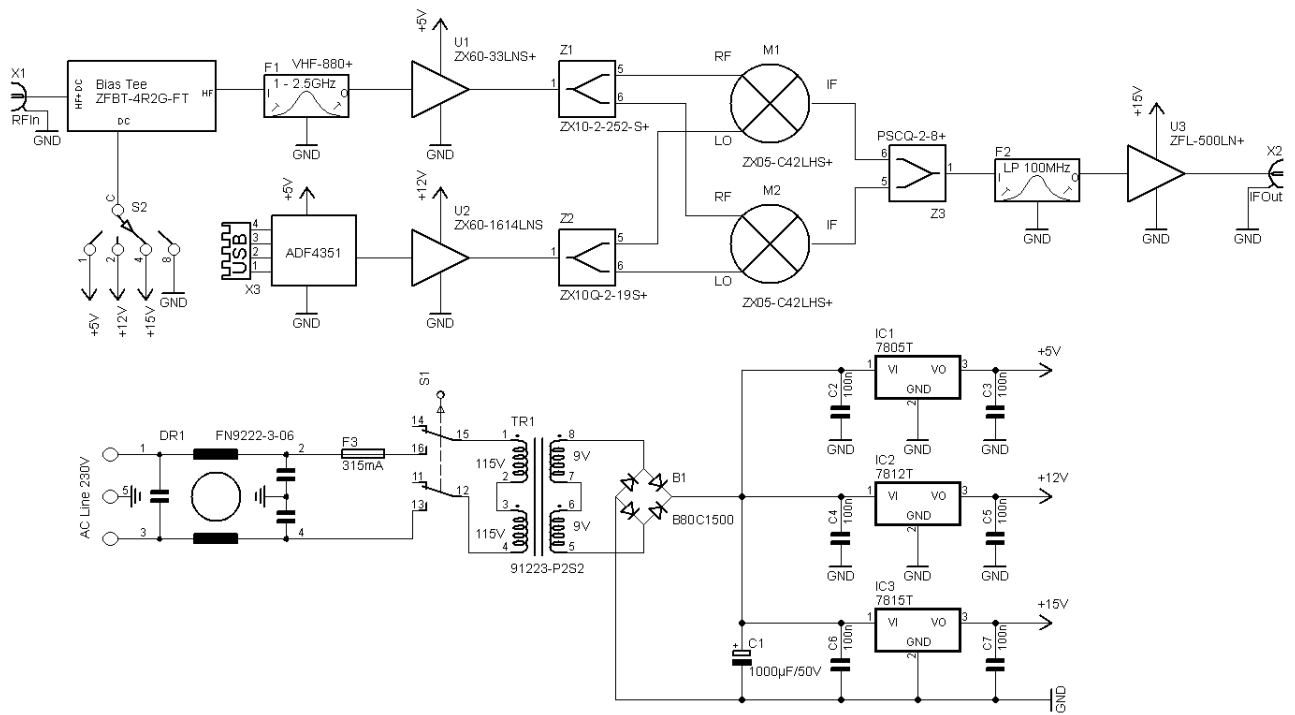


Figure 30: Circuit Diagram of the receiver used for EMI monitoring

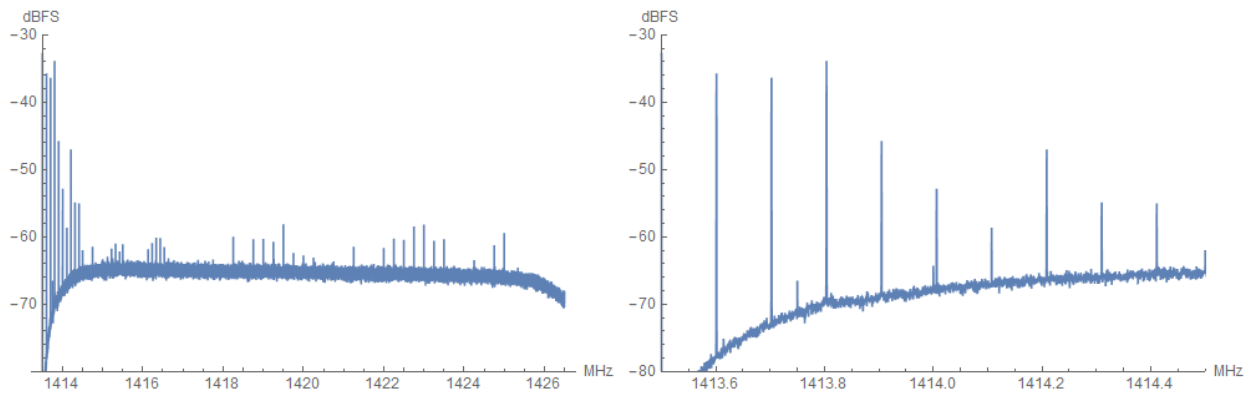


Figure 31: Dark noise of the receiver with switch mode power supply (left) and detail of the 100 kHz switching frequency (right)

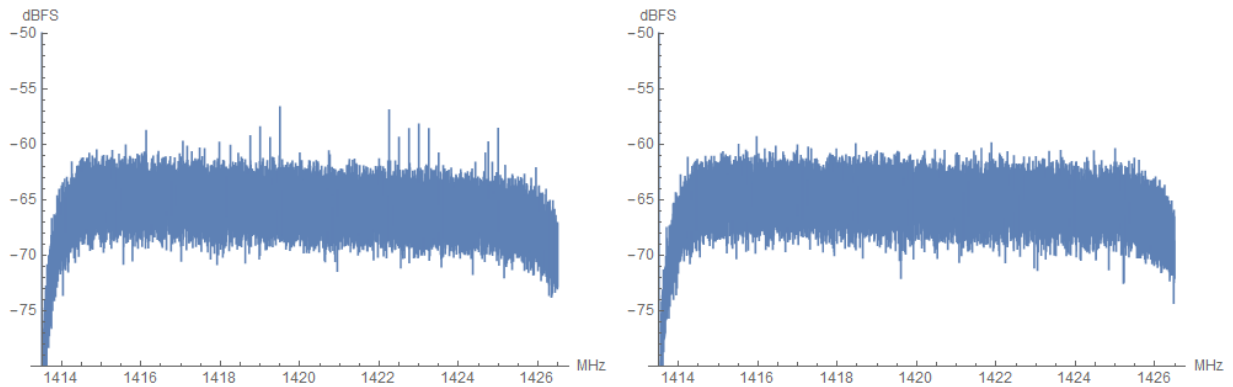


Figure 32: Dark noise of the receiver with linear regulated power supply running the ADF4351 in low noise mode (left) and low spur mode (right)

3.3 Recording Device

The broadband IF signal from 0 to 100 MHz is feed to RFSPACE's¹⁰ software defined radio SDR14. It is based on a 14 bit analog to digital converter (ADC) running at a sample rate of 66.67 MHz. The SDR14 has the capability of storing up to 262144 samples at a time and send them to a computer via a USB 1.1 link. It includes the digital downconverter AD6620 which reduces the output bandwidth to reach a lower noise by combining more time samples in the same spectral bandwidth. The down converted signal is given in complex I/Q data.

RFSPACE provides a spectrum monitoring software called SpectraVue. It allows the complete control of the SDR14 and offers different modes of output as binary raw data or spectral data in text form. Different modes for averaging over many spectra and automated timed recording with frequency switching are selectable.

3.4 Calibration

To calibrate the dB full scale (dBFS) reading of the SDR14 to the real input level in dBm of the frontend amplifier the setup shown in Figure 33 was used. The calibration source is the Hameg HM8135 digital HF synthesizer. The frequency generator feeds a signal of known level into the frontend amplifier. Due to the high gain of the system two additional coaxial attenuators were added to reduce the signal by 30 dB. A level of -70 dBm was set at the signal generator meaning -100 dBm are reaching the frontend. The frequency range for calibration is the complete radio astronomy band from 1400 MHz to 1427 MHz and from 1660 MHz to 1670 MHz. The signal generator is programmed to sweep over the whole frequency range with a step size of 0.5 MHz every 2.5 seconds.

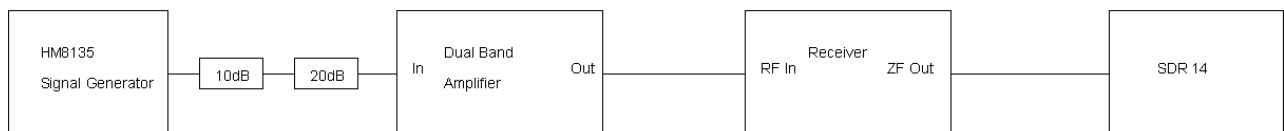


Figure 33: Setup for calibrating the receiving system to the known output level of the signal generator HM8135

One complete sweep was recorded by the SpectraVue software using the “Maxhold” feature. The complete frequency response of the system is shown in Figure 34. As suggested by [14] for measuring single spectral lines the FFT window setting “flat top” is the best choice to get the correct intensity for all spectral lines. For common measurements with unknown content the FFT window setting “Hanning” was used as it provides the best SNR and fair intensity accuracy.

After normalizing the spectral response to the known level of -100 dBm the calibrated spectrum in Figure 35 is obtained. As described in chapter 1.5 the input level can be converted to the electrical field strength in dB μ V/m by using the gain of the antenna and the distance to the object. In this way a calibration to the electric field strength at the point of the antenna can be achieved.

¹⁰ RFSPACE, Inc., P.O Box 191231, Atlanta, USA, www.rfspace.com

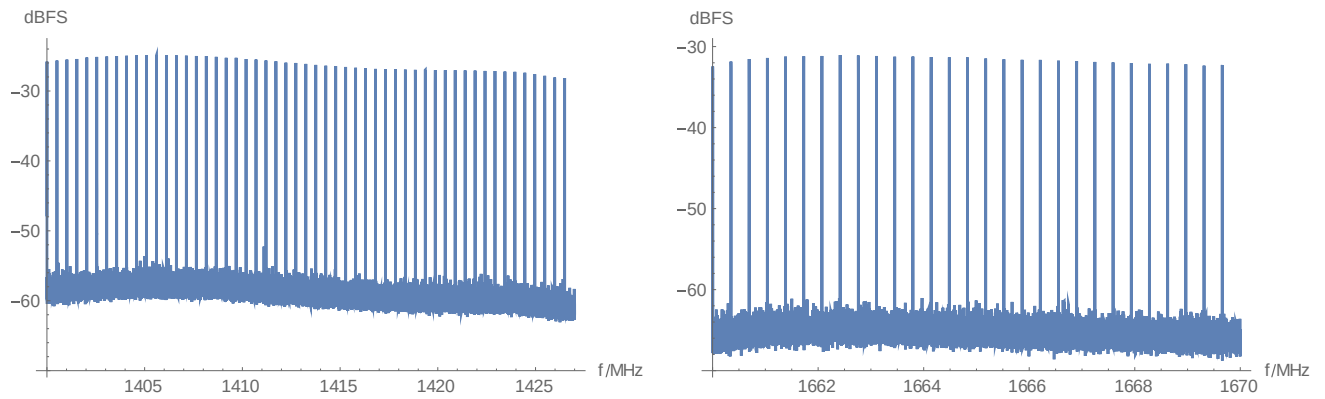


Figure 34: Frequency response of the dual band frontend amplifier at 1420 MHz (left) and 1665 MHz (right) for an input level of -100 dBm

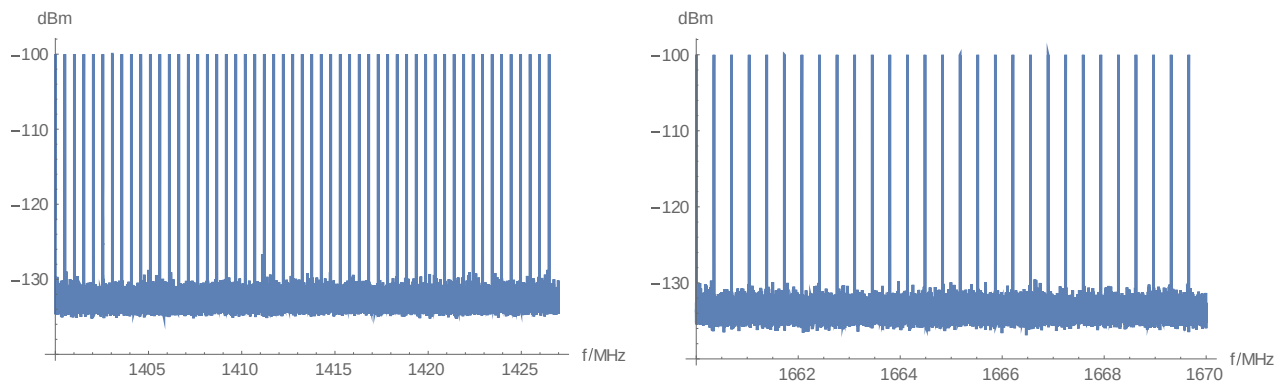


Figure 35: Calibrated frequency response for 1420 MHz (left) and 1665 MHz (right)

3.5 Receiver sensitivity

The best sensitivity is reached when the noise floor is the lowest. There are several settings which influence the noise floor. First of all the input attenuator of the SDR14 has to be set as low as possible but not to overdrive the ADC. The FFT size has to be as large as possible so that the bandwidth of one bin collects the smallest amount of noise. It depends on the maximum amount of time domain samples which can be captured continuously. For the SDR14 this is a maximum of 262144 samples. Also the FFT window type influences the noise floor as it reduces the amplitude of the time domain signal which increases the SNR. According to [14] the best choice for unknown signals is the “Hanning” FFT window as it provides a good compromise between spectral leakage and noise floor.

Using the digital downconverter AD6620 in the SDR14 also reduces the noise as more time domain samples are included in the same amount of spectral bins, which can be compared to averaging. Figure 36 shows the noise floor for different downconverter settings with the input of the frontend matched by a 50 Ω load at 20°C. The 30 MHz bandwidth is reached in the real ADC mode which does not use the AD6620 at all. The greatest drop in the dark noise is reached when using the AD6620 in the broadest possible bandwidth setting of 4 MHz. Compared to the real mode the noise is reduced by nearly 20 dB.

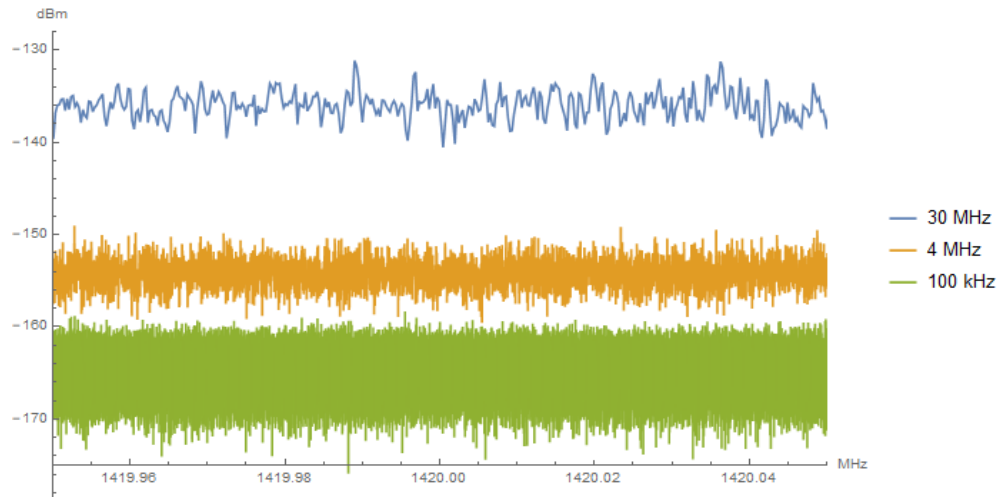


Figure 36: Receiver dark noise for different bandwidths settings of the digital downconverter AD6620

An even smaller bandwidth of 100 kHz only gains 10 dB in comparison to the 4 MHz mode. On the other hand a too small bandwidth requires a large observation time for the same frequency range. When expecting that EMI signals are static over a shorter period of time several spectra can be averaged too. The long time recording towards the Vienna city center, in chapter 4.6 needs a highest sensitivity to reach distant EMI sources and a time resolution in the range of minutes. A good compromise for that are the settings given in Table 11.

FFT size	262144
FFT average	60 spectra
FFT window type	Hanning
SDR14 RF attenuator	0dB
AD6620 downconverter bandwidth	4 MHz
AD6620 IF gain	24 dB

Table 11: SDR14 settings for long time recording and high sensitivity

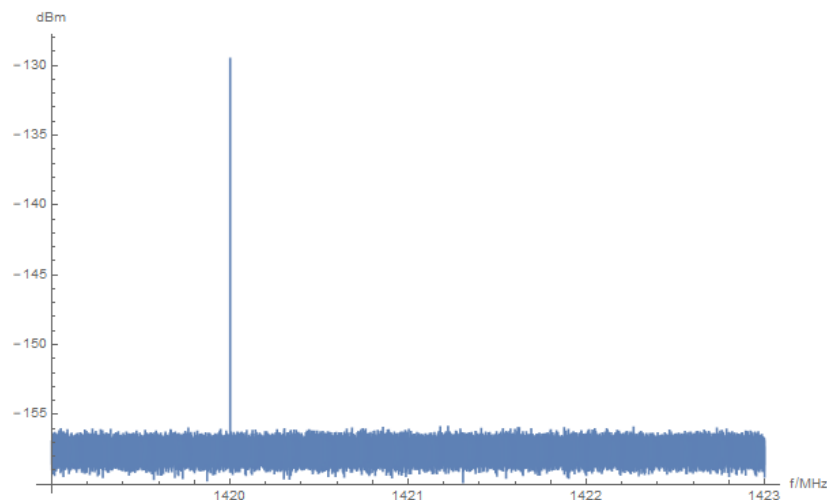


Figure 37: Noise floor of the dual band frontend amplifier and a -130 dBm signal at 1420 MHz

Using the equations in chapter 1.5 the minimal detectable electric field strength can be calculated. When using the directional antenna (see chapter 3.6.2) with 7.65 dBi gain the minimal detectable field strength at the location of the antenna is -22.4 dB μ V/m. For the omnidirectional antenna (chapter 3.6.1) with an expected gain of one the detection limit drops down to -15.7 dB μ V/m.

When measuring a known source the sensitivity can be improved by decreasing the distance to the source. This is helpful when calculating the field strength in 3 meter distance of a device according to the EMC standards. For example when measuring in 1 meter distance with the directional antenna the sensitivity for the 3 meter position increases to -31.9 dB μ V/m. As a general rule the field strength increases by 6 dB if the distance is reduced to the half.

Using the settings in Table 11 the noise floor reaches -155.8 dBm, as shown in Figure 37 in combination with a -130 dBm test signal at 1420 MHz. The standard deviation of the noise is 0.46 dB. Therefore a detection of an EMI source that is emitting in a single spectral line can be expected around -155 dBm input level at the front end amplifier.

3.6 Monitoring Antenna

Selecting an antenna with the proper directional characteristic is crucial since the antenna gain can increase the sensitivity of the monitoring system dramatically. When picking up more signal strength from the direction towards the EMI source the SNR of the whole receiving system is increased in comparison to an isotropic antenna.

The antenna gain is usually measured in dBi which is a logarithmic unit related to an isotropic antenna. The antenna gain describes how much signal a directional antenna receives from their line of sight in comparison to an isotropic antenna. Sometimes the antenna gain is also given in dBd which is a logarithmic unit related to a dipole antenna.

It can be expected that all the EMI signals are emitted from the ground unless one wants to measure the EMI coming from space crafts. But this project is all about earth based EMI, therefore observing the whole sky will not lead to any additional detection.

In this case ideally a vertical stacked dipole antenna array with many stages should be used. Such an antenna has its maximum sensitivity in a thin disk directed 360° around towards the horizon. It would not receive any signal from the zenith or from the ground underneath it. Such antennas with 32 or more vertical stacked stages are used for broadcasting purposes where one wants to have the transmitted power only at the ground. For monitoring EMI it has just to work the other way around.

But within the possibilities of this project no complex antenna structure could be built. Various types of antennas have been tested and finally two of them were selected for the monitoring. Simple isotropic antennas like $\frac{1}{4}$ wavelength open cables were only used for indoor monitoring without any calibration.



Figure 38: Omnidirectional antenna and dual band frontend amplifier mounted on the west side balcony of the IfA building



Figure 39: Directional antenna and frontend amplifier mounted at the roof of the IfA building

3.6.1 Omnidirectional Antenna

This Sigma SE-1500 Scan King antenna¹¹ is a broadband antenna originally used for a radio scanner receiver. It has a vertical polarization and a specified frequency range up to 1500 MHz. The performance data is given in Table 12. This antenna was used outside the IfA building at the west side balcony as shown in Figure 38. With this antenna signals emitted from any direction inside the IfA can be monitored.

Because of its limited frequency range the return loss at the antenna output port has been measured using a setup similar to that shown in Figure 25. The result in Figure 39 shows in general a very poor output matching. In the OH maser band at 1665 MHz this antenna can only be used with a strong reduction in the output matching to 4 dB. This means that a large part of the signal will be reflected back by the antenna and cannot be transferred to the connected cable.

Frequency range	500 kHz to 1500 MHz
Length	1.10 m
Radials	4 x 150 mm
Output matching at 1420 MHz	7 dB
Output matching at 1665 MHz	4 dB
Output connector	50 Ω N-connector

Table 12: Specifications of the Sigma SE-1500 omnidirectional antenna

¹¹ Sigma Euro-Comm Ltd, Birmingham, United Kingdom, sigmaeurocomm.co.uk

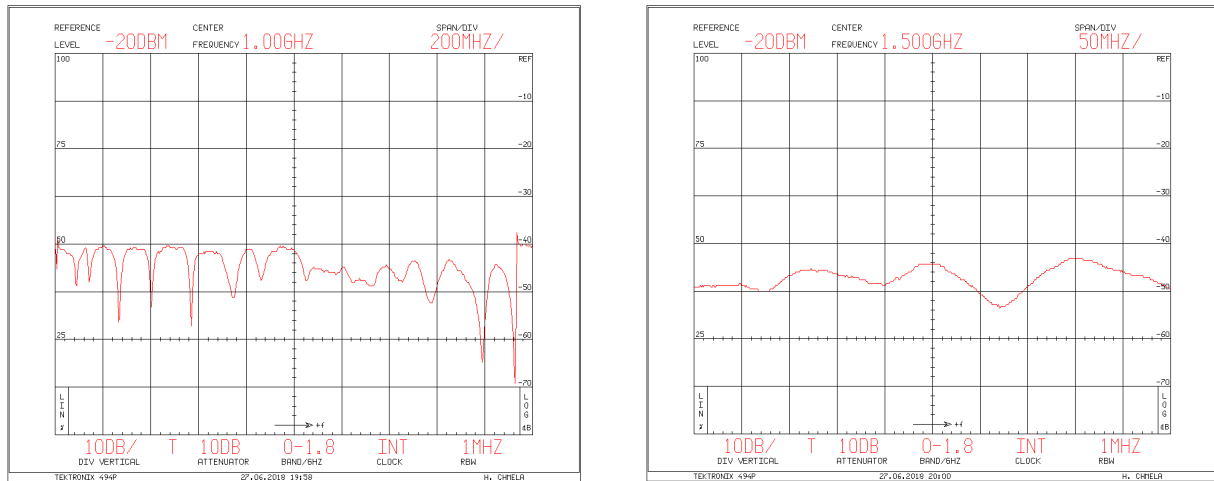


Figure 40: Output matching of the Sigma SE-1500 omnidirectional antenna up to 1.8 GHz (left) and detail around 1.5 GHz (right) using the - 40 dB division as 0 dB reference

3.6.2 Directional Antenna

The LHCP Helix Dish Feed¹² shown in Figure 39 is a left hand circular polarized helical antenna originally designed for the use as a dish feed for radio telescopes. A circular polarization is the best choice when receiving signals with unknown polarization direction. It can be expected that the EMI are polarized, since their artificial origin but the polarization direction is randomly distributed. So this antenna will receive two signals with the same intensity but with different polarization direction at the same level.

The antenna is protected by a waterproof tube and a bracket for mounting is provided. The main characteristics are given in Table 13. The gain in dBd is referring to a dipole antenna. To get the usually used gain in comparison to an isotropic antenna a factor of 2.15 dB has to be added to reach dBi.

With a setup similar to Figure 25 the return loss at the antenna port shown in Figure 40 was measured. At 1420 MHz it reaches 15 dB and at 1665 MHz 14 dB output matching. It shows a slight dependence on the position of the metal mounting clamp. The best matching is reached when the mounting clamp is at the back end of the antenna.

Frequency range	1400 MHz to 1800 MHz
Gain referred to a dipole antenna	5 dBd to 6 dBd
3 dB opening angle	69°
10 dB opening angle	109°
Output matching at 1420 MHz	15 dB
Output matching at 1665 MHz	14 dB
Output connector	50 Ω N-connector

Table 13: Specifications of the of L-band LHCP dish feed helical antenna

¹² RF Hamdesign, Leeuwarden, Netherlands, www.rfhamdesign.com

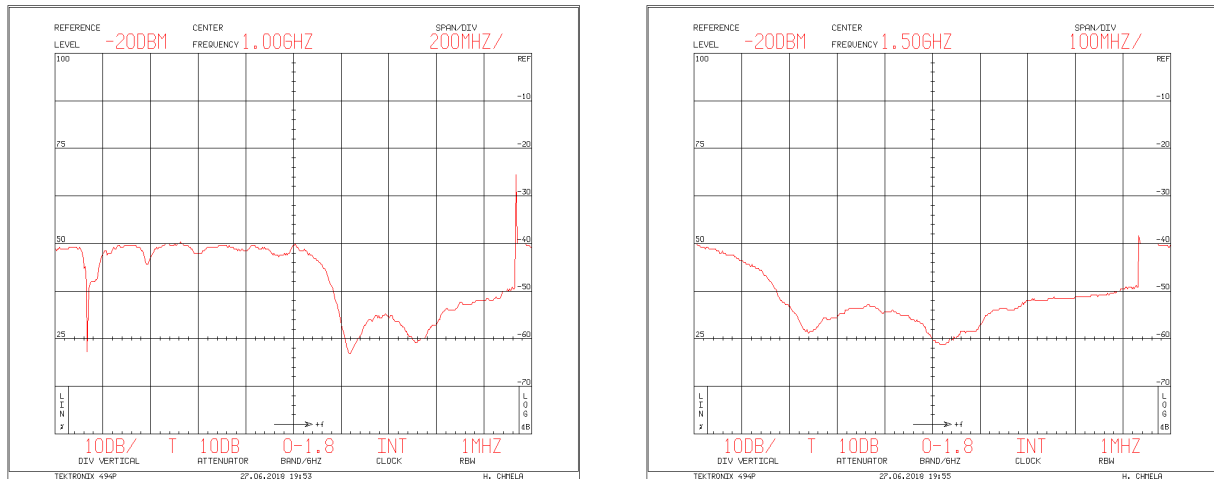


Figure 41: Output matching of the L-band LHCP dish feed helical antenna up to 1.8 GHz (left) and detail around 1.5 GHz (right) using the - 40 dB division as 0 dB reference.

As this is a directional antenna the antenna diagram has been measured at 1420 MHz by using the setup shown in Figure 17. A HM8135 digital HF synthesizer and a simple helical antenna are used as signal source. The output power at the port of the antenna has been measured using a MDO 3000 spectrum analyzer. By turning the antenna in small steps over the angle Θ the diagram in Figure 42 has been achieved.

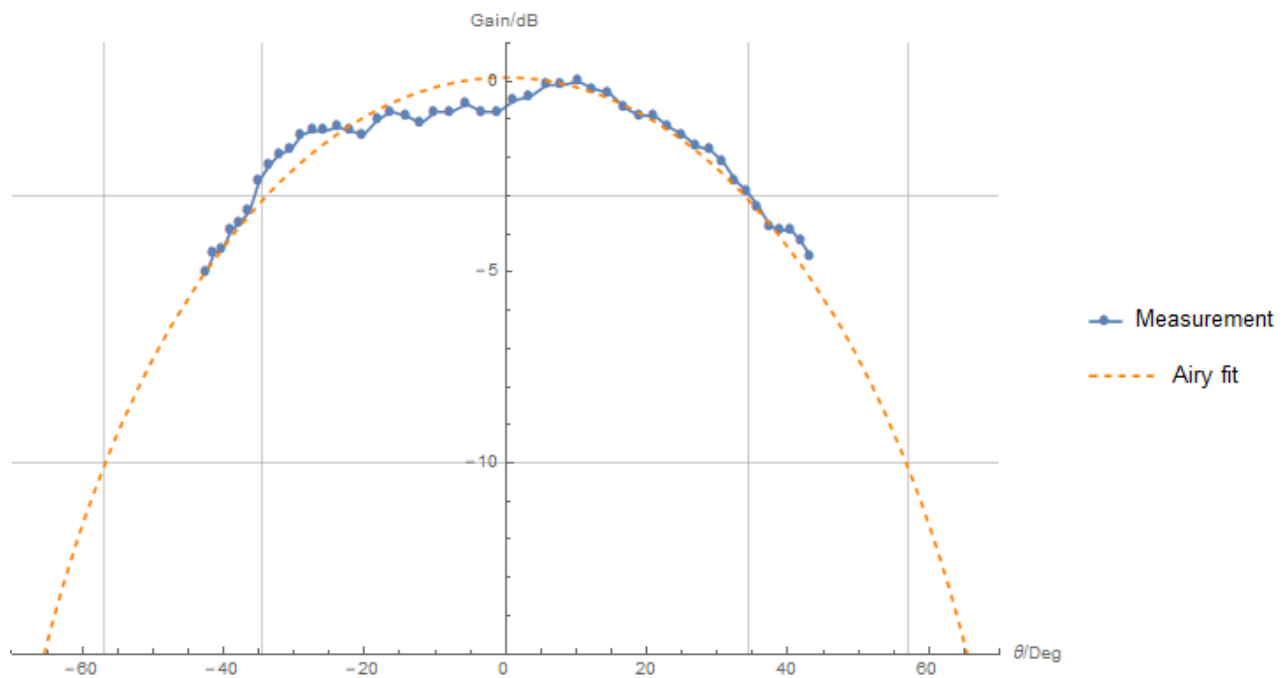


Figure 42: Measured antenna diagram and airy pattern fit for the L-band LHCP dish feed helical antenna at 1420 MHz. The 3 dB and 10 dB opening angle is marked by the grey lines.

It shows light fluctuations in the gain which are caused by a grounding problem as the antenna does not have a metal case. This leads to a slight change in the signal level when the cable connections are moved. Nevertheless the airy pattern fit shows a good agreement with the 3 dB and 10 dB opening angle given in the specification in Table 13 and marked in Figure 42 by the grey lines.

4 Recorded Data

4.1 Frequency usage at the SRT site

To get an overview of the frequency usage at the SRT site, a broadband spectrum from 100 MHz up to 3000 MHz has been recorded with the receiver described in chapter 3.2 and the omnidirectional broadband antenna (chapter 3.6.1). The preamplifier was not used as it would limit the frequency range to a very narrow bandwidth.

The receiver uses an internal bandpass filter with a bandwidth from 1 GHz to 2.5 GHz as shown in Figure 23. Out of that range the received level will not be correct. The levels for the lower frequency range cannot be compared to the high frequency range. Therefore only relative readings in dBFS are given in Figure 43.

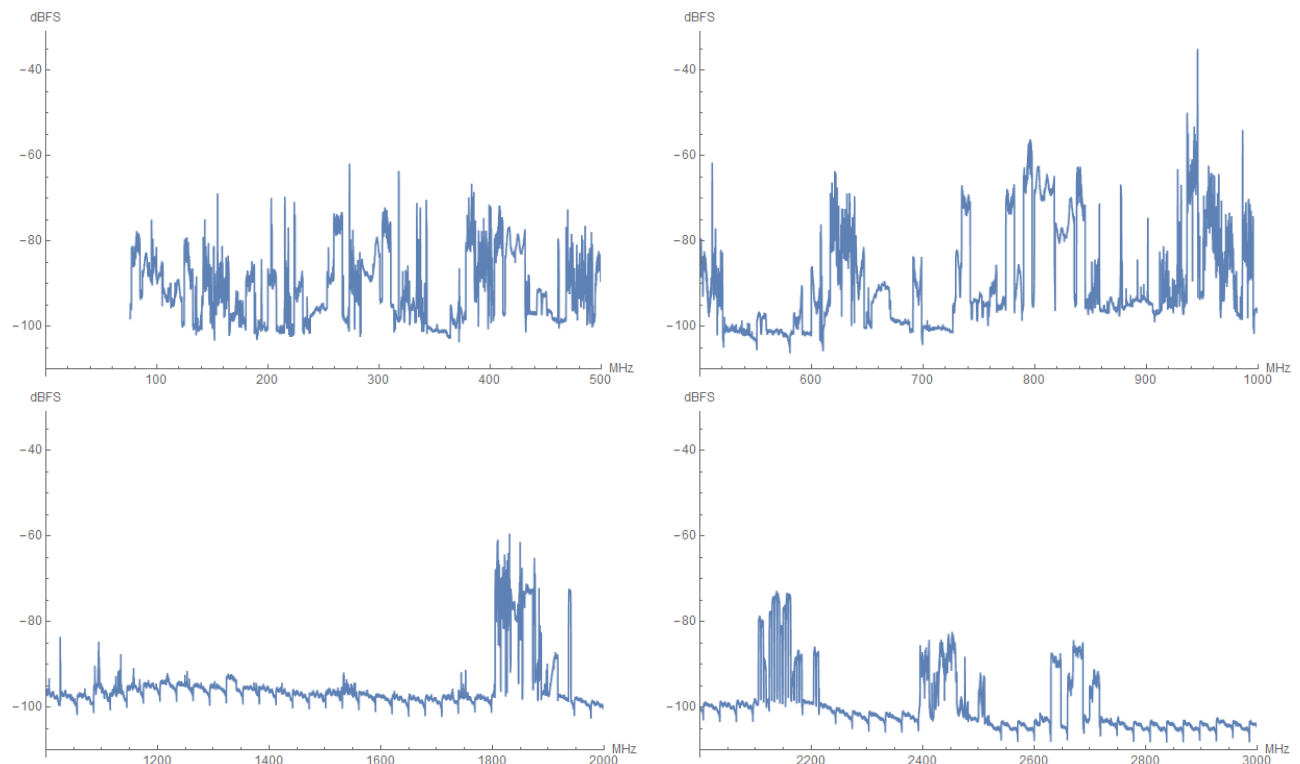


Figure 43: Frequency usage at the site of the SRT recorded with an omnidirectional antenna

The spectrum is starting at 100 MHz where the UKW radio stations are located. Actually the UKW stations produced the strongest signals but this cannot be measured correctly due to the internal bandpass filter of the receiver.

Followed at 128 MHz by the aeronautic band, around 200 MHz two digital radio (DAB) transmissions are visible. At a frequency around 400 MHz a lot of TETRA base stations appear which is a mobile communication network used in Austria by authorities and security services. Starting from 450 MHz to 800 MHz some digital television transmitters (DVBT) are operated. At 800 MHz the LTE 800 block is visible.

The strongest signals are in the 900 MHz GSM band. These signals produced intermodulation in the frontend amplifier of the original SRT design. Therefore the frontend has been modified and equipped with a bandpass filter and a narrow band feed as described in chapter 2.1.

The 1800 MHz GSM band is the nearest occupied frequency to the 1420 MHz radio astronomy band. It has also high signal levels but is at least 20 dB below the 900 MHz GSM band and therefore less critical.

In the highest frequency range the UMTS blocks appear at 2100 MHz and the WLAN signals are at 2400 MHz. At 2700 MHz mobile communication signals from the third generation is visible. The levels in the high frequency regime are also copied at a too low level due to the bandpass filter in the receiver.

For a better understanding of the nearest EMI sources which are emitting into the radio astronomy frequency bands at 1420 MHz and 1665 MHz a monitoring was done with the narrow bandwidth dual band preamplifier described in chapter 3.1 and with the directional antenna (chapter 3.6.2) pointing towards the SRT receiver from a distance of 3 meter.

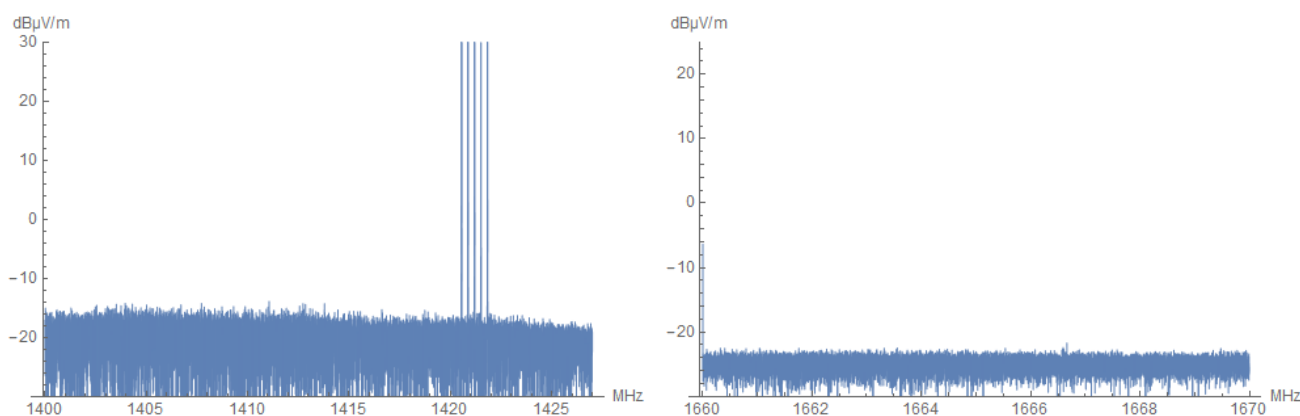


Figure 44: Electrical field strength in 3 meter distance to the SRT receiver

Figure 44 shows a clear spectrum beside the emission at 1421 MHz. This very strong signal is coming from the SRT receiver itself. The SRT uses an intermediate frequency of 800 kHz. The local oscillator (LO) appears around 1421 MHz in 5 steps. When recording broader spectra the LO of the SRT switches continually in 320 kHz steps, which appear simultaneously in the averaged data.

Besides that the SRT receiver does not produce any noticeable EMI. It is impossible that a super heterodyne receiver can be disturbed by its own LO. Care has to be taken not to disturb the EMI monitoring project, because the emission is with 30 dBμV/m the strongest that have been measured during this whole project, see Table 15.

As it showed up during this project the SRT LO is visible even at the roof top of the IfA building in a distance of nearly 100 meter. In cases where it was possible the SRT was tuned to a frequency where the LO is out of the monitored frequency range. But as the SRT is used for education purposes an interference with the monitoring project could not always be avoided. For example the long time recording with the omnidirectional antenna near the SRT was disturbed by the LO at a frequency of 1421.2 MHz as can be seen in Figure 89.

4.2 EMI Measurements with the SRT

The high antenna gain of 27 dBi and the high sensitivity of 260 Kelvin make the SRT ideal for the search of EMI sources inside the IfA. The location of the SRT on the west side balcony (see Figure 51) provides a perfect view of a large portion of the higher parts of the building.

The whole 360° azimuthal range was scanned in 2° steps for elevations up to 45° also in 2° steps. For each position a complete spectrum from 1400 MHz to 1427 MHz with a RBW of 7.81 kHz was recorded. Figure 45 shows a map of the continuum calculated from the whole spectral range. The continuum radiation from the hot buildings wall shows a good correlation with the actual horizon line of the building shown in Figure 6.

The hot buildings walls are emitting thermal noise at a temperature around 300 Kelvin. The sky shows up in dark blue at temperatures below 50 Kelvin. The radio dark sky is not measured with only the 3 Kelvin background radiation because of the spillover from the hot buildings wall. The building is emitting thermal noise in the side lobes of the main beam and over the edge of the dish directly into the feed which is always pointing towards a wall or the ground when observing the sky.

Beside that a few hotspots can be located with temperatures above 300 Kelvin. Especially at an azimuth of 330° a bright hotspot shows up. This is an indication for an EMI sources within the building, as it is impossible that the temperature of the buildings wall is above 350 Kelvin on only one concentrated point. Actually the SRT server and the SQM server computers are located at this position.

But in a continuum map further EMI sources that are only emitting in a view single spectral lines could be hidden because they are suppressed when averaging over a large amount of spectral bins. A better method for identifying single line EMI emissions has to be developed and is now introduced in the following chapter 4.2.1.

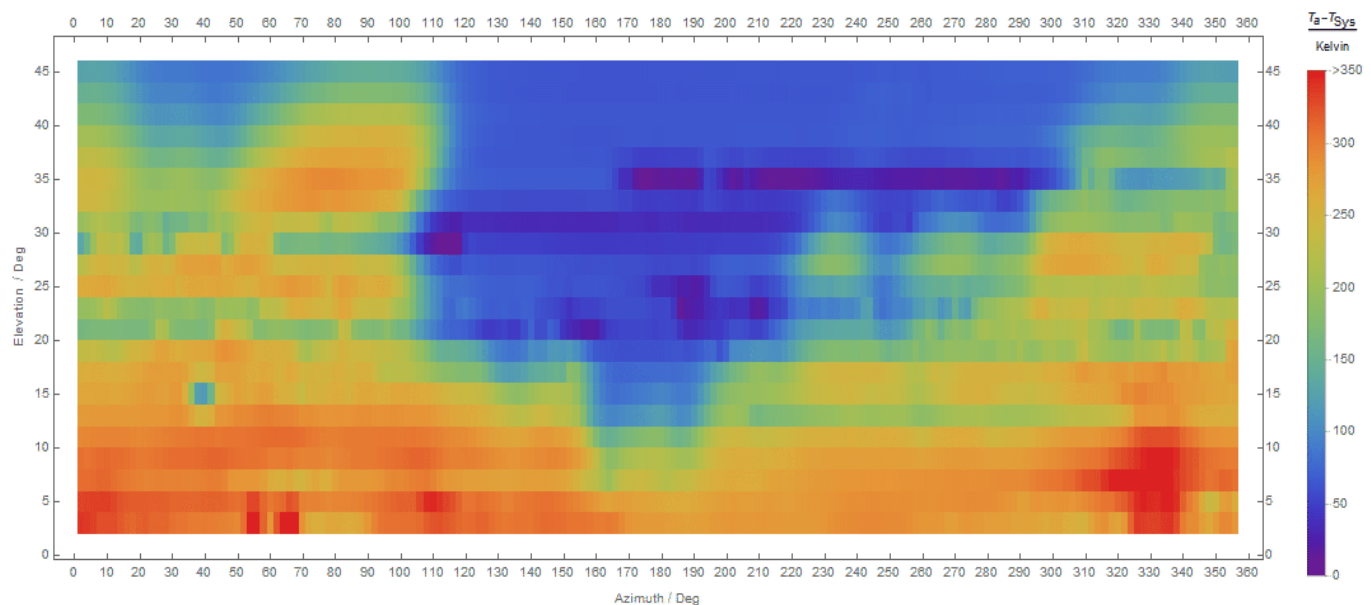


Figure 45: Continuum map between 1400 MHz and 1427 MHz of the surrounding at the SRT site

4.2.1 Method for identifying single spectral line emissions

Figure 46 left shows the raw spectrum of one data point in the continuum map Figure 45. The level is in uncalibrated ADUs and the baseline is not flat. A view EMI lines can be seen at very high levels. A unique feature of artificial produced lines is the extreme narrow bandwidth of usually only one spectral bin which makes them nearly invisible in a continuum map.

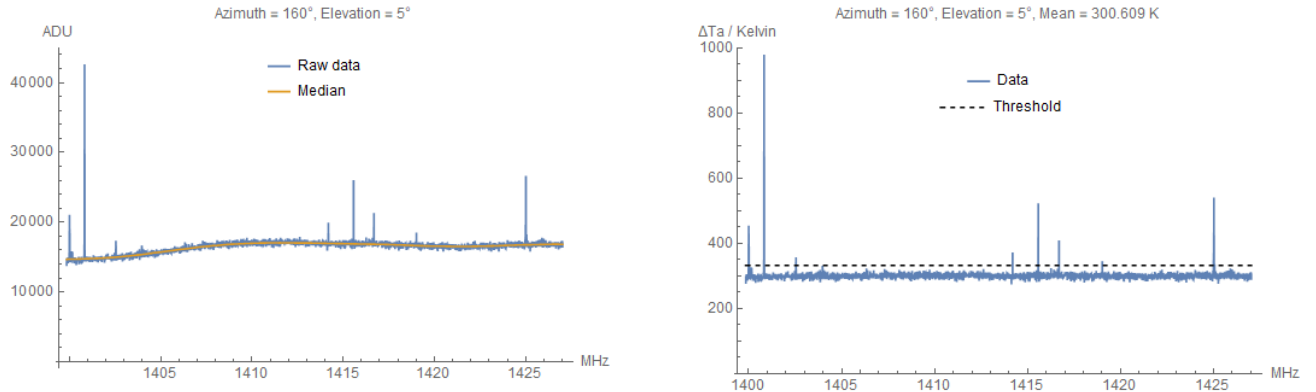


Figure 46: Data reduction process for EMI line counting, raw data left and calibrated data right

The first step in the data reduction process is to calculate a median filter of the data this is indicated by the orange graph in Figure 46. By subtracted the median from the data the baseline is flattened as showed in Figure 46 on the right side. The system temperature is subtracted and the level is calibrated to the 300 Kelvin temperature of the buildings wall. Then a threshold of 320 Kelvin is introduced showed by the dashed line in Figure 46 right. Finally all single lines above this threshold are counted. In Table 14 the highest counts of single EMI lines are listed. Figure 47 shows a map plot of the counted EMI lines.

Azimuth [Deg]	Elevation [Deg]	Number of counted EMI lines	Peak Intensity [Kelvin]	Continuum [Kelvin]
332	3	396	1522.5	394.6
334	5	343	1517.3	410.5
334	9	323	1469.3	432.6
326	7	312	1490.3	453.5
328	11	244	1516.6	373.4
80	23	128	1429.6	305.7
80	25	122	1369.1	262.7
80	27	105	1341.2	304.9
82	21	99	1425.1	245.1
80	19	86	1173.5	280.7

Table 14: The highest numbers of counted EMI lines in the two hotspots at azimuth 80° und 330°

The hotspot at azimuth 330° is the SRT server room by itself and was already seen in the temperature map Figure 45. But an additional hotspot appears now at an azimuth position of 80° in 25° elevation which could not be seen in the temperature map. This is an indication for two different types of EMI structures.

The SRT server produces a raised continuum emission and single lines emission, while the other source only produces single line emissions without raising the continuum. Figure 48 and Figure 49 show the difference in the emission between the two hotspots. The difference in the spectral structure also indicates that these are two different devices and not a reflection of one and the same emission on the wall.

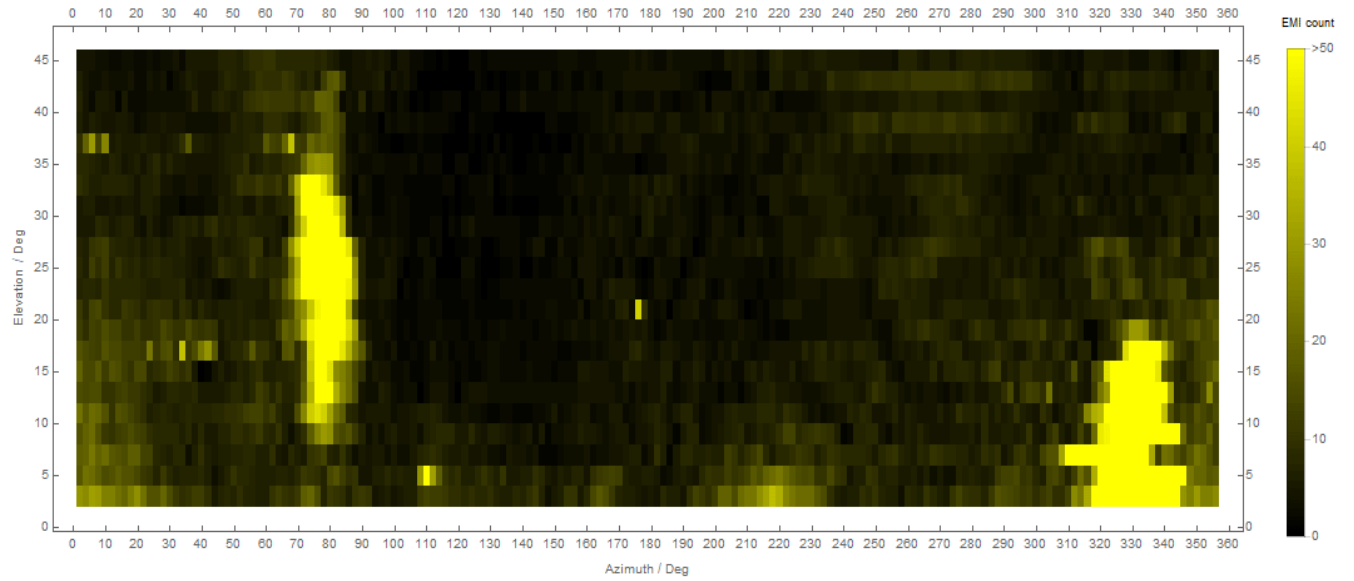


Figure 47: Number of detected EMI lines between 1400 MHz and 1427 MHz in the surrounding of the SRT

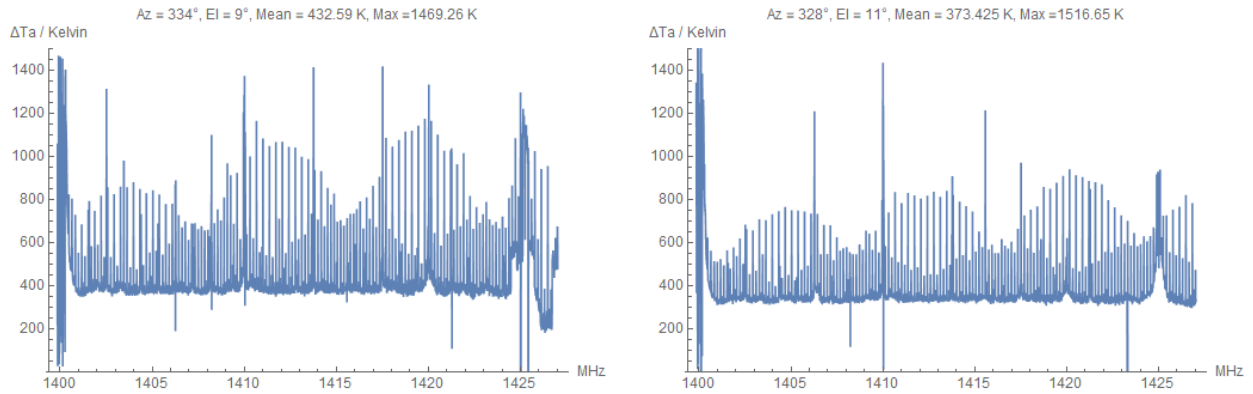


Figure 48: Selected spectra from the hotspot at azimuth position 330°

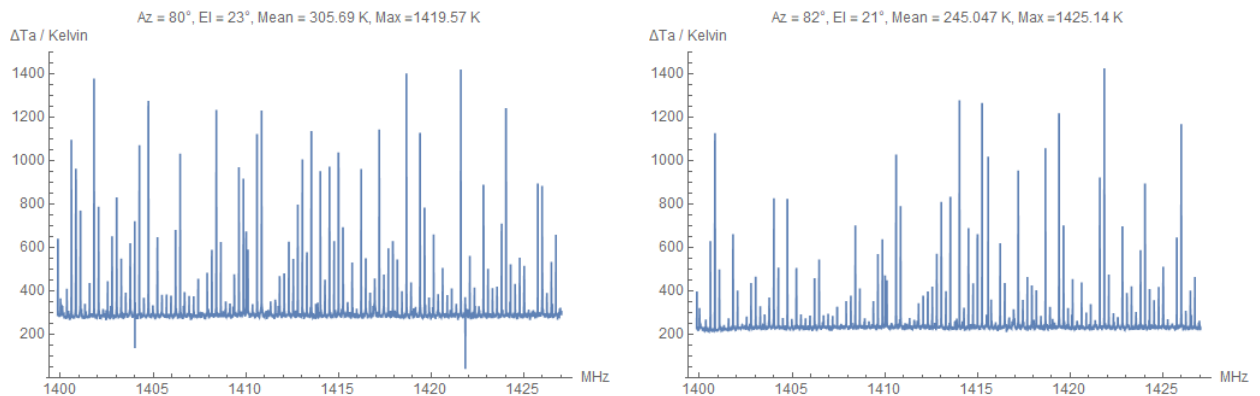


Figure 49: Selected spectra from the hotspot at azimuth position 80°

4.2.2 Localizing a EMI source with the SRT

Figure 50 shows two typical observations with the SRT of the HI gas in the Milky Way galaxy at two different galactic longitudes (GLON). Two hydrogen lines with different VLSR are visible around 1420.4 MHz and 1420.6 MHz.

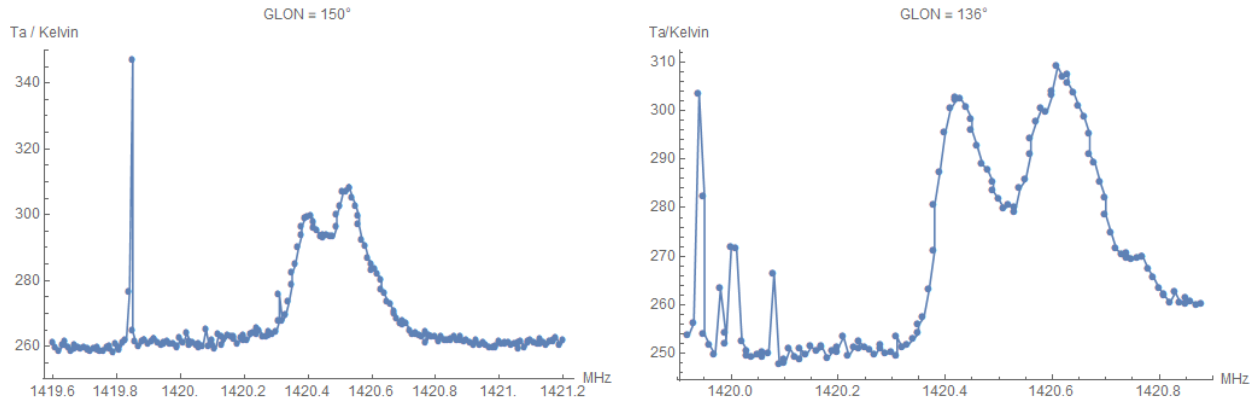


Figure 50: EMI occurring during two HI observation with the SRT of the Milky Way galaxy

These observations are disturbed by EMI signals around 1420 MHz. The best indication for an artificial produced spectral line is its very narrow bandwidth of typical only one or two spectral bins. This makes it easy to distinguish EMI signals from natural occurring spectral lines which are usually very broad band signals due to the different Doppler shifts along the line of sight.

When moving the SRT the EMI occurred on random sky positions with different strength. This is an indication that it was falling into one of the side lobes pointing towards the building. Since the location of the source is unknown it is not possible to find the optimal pointing of the SRT to reduce the EMI.

Figure 51 shows the position of the SRT at the west side of the IfA building. It is expected to find most of the EMI sources inside the building between azimuthal angles from 270° to 135°. It is more usual to find the source in the nearest rooms with the numbers 122 to 128.

To locate the EMI source around 1420 MHz the SRT was used for a complete 360° azimuthal scan in 10° steps. The highest EMI level appeared at azimuthal positions around 10°. Therefore a detailed scan was done between 1° and 35° in 1° steps at an elevation of 5°. The peak antenna temperature for each position is plotted in Figure 52.

A clear peak can be found at the azimuthal position of 8° where the telescope is pointing towards the rooms 124, 126 and 127. At this position an elevation scan was done between 3° and 30° as shown in Figure 52. The peak can be found at an elevation of 13° pointing somewhere to the ceiling of room 126 or 124. For a further localization of the EMI source the directional antenna described in chapter 3.6.2 was used inside the building.

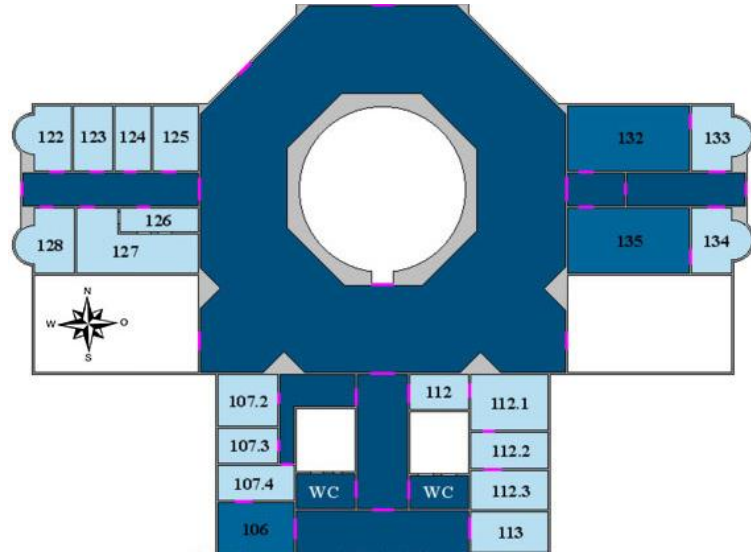


Figure 51: Part of the IfA building with the compass dial showing the location of the SRT

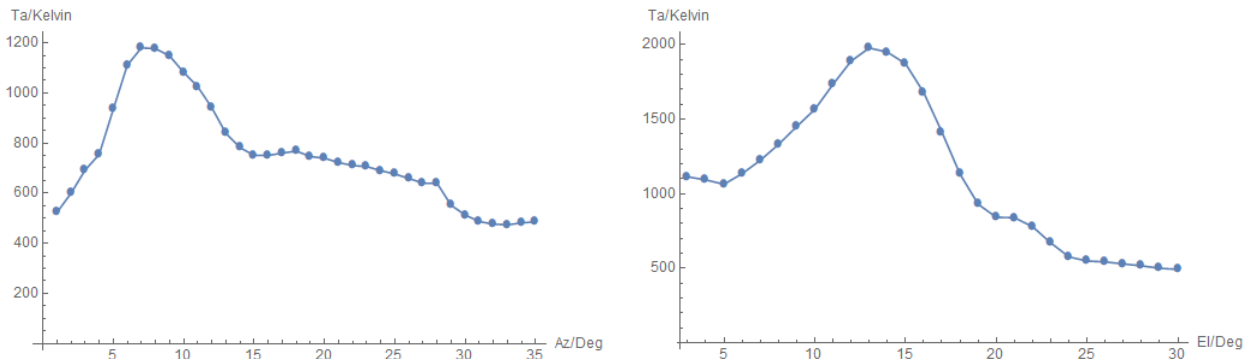


Figure 52: Azimuthal scan (left) and elevation scan (right) for the EMI source at 1420 MHz

The source could be identified in room number 124 where the software development for CHEOPS, a space mission project for characterizing exoplanets, is located. In front of the rack containing the computing equipment a large field strength in several narrow lines at 1404, 1410, 1416 and 1420 MHz could be measured. As shown in Figure 53 the peak intensity of 28 dB μ V/m is at 1416 MHz. This is still lower than the 70 dB μ V/m limit for multimedia equipment. Nevertheless this leads to a visibility in the SRT at nearly every sky position, which means that this signal is strong enough to overcome the SRT antenna gain of 27 dBi.

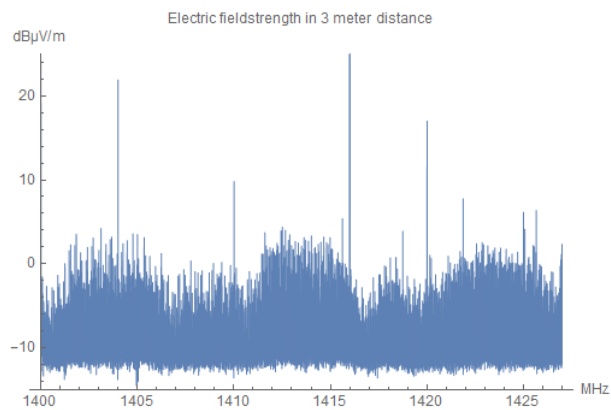


Figure 53: Electric field strength of the CHEOPS computing equipment

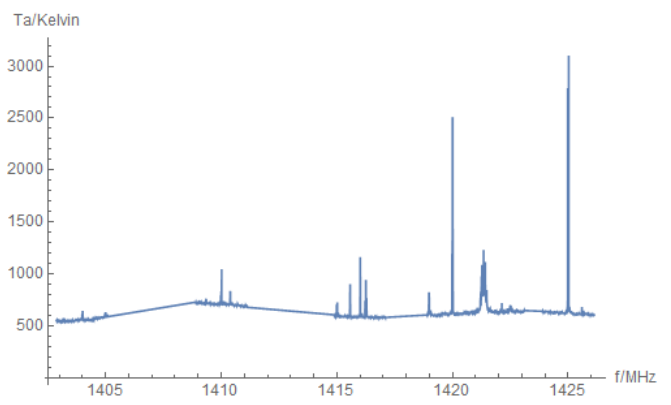


Figure 54: EMI of the CHEOPS computing equipment received by the SRT

Finally every strong spectral line of the CHEOPS computing equipment could be found in the spectrum received by the SRT when pointing towards room number 124. Figure 54 shows the large antenna temperature around 2000 Kelvin which is even higher than the signal from the strongest radio source, the sun, which reaches around 700 Kelvin.

To identify the device which produces the strongest emission several parts of the CHEOPS computing equipment were switched off and differential spectra were calculated. Figure 66, Figure 67, Figure 68 and Figure 69 show that the main contribution to the emission comes from the GR712 SparcV8 processor evaluation board. Figure 55 shows this evaluation board where the front cover has been removed for easier connection of the cables. This breaks the shielding capability of the metal case and a very strong emission at 1403 MHz with nearly 20 dB μ V/m in 3 meter distance could escape.

The strong spectral line at 1420,0 MHz, which is very disturbing for HI observations is emitted by the two CHEOPS computers with a field strength of 18 dB μ V/m in 3 meter distance even if they look to be shielded correctly.

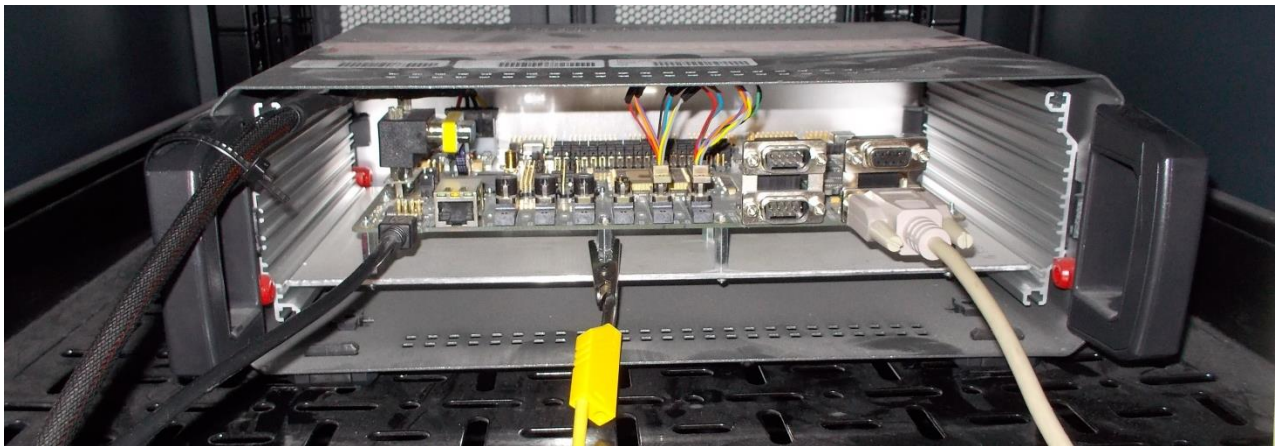


Figure 55: The GR712 SparcV8 processor evaluation board with removed front cover

To find other EMI sources inside the building a complete 360° azimuthal scan with the whole HI frequency band was conducted. As shown in Figure 56 a new EMI source could be found at an azimuth position of 330° where the SRT is pointing towards the SRT server room number 128.

The source could be identified as the webcam which is used to watch the SRT during observations. By switching it off the EMI reduced but did not completely disappear as Figure 57 shows. There is still a lot of EMI present which is emitted from the computers in the SRT control room. As the webcam is needed during remote observations with the SRT it has been shielded as described in chapter 4.4.

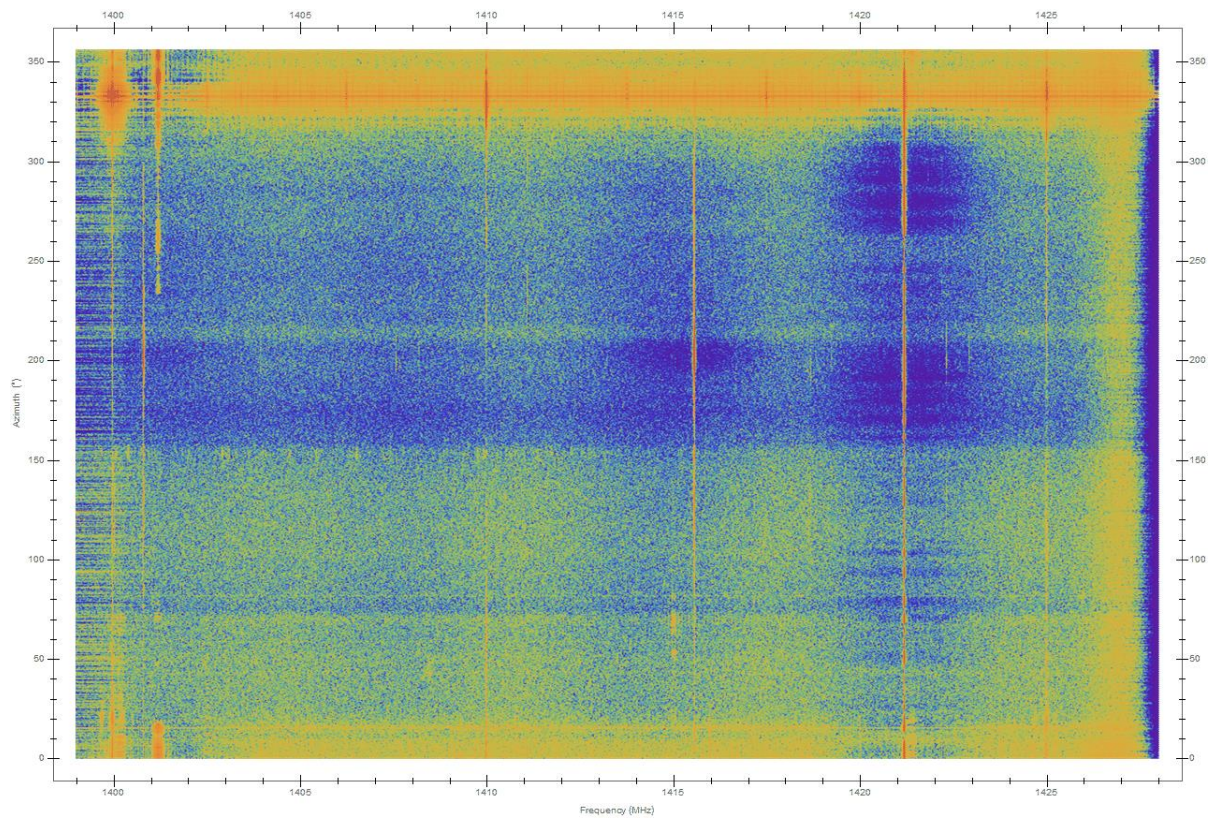


Figure 56: 360° azimuthal scan with the SRT, AXIS 211 webcam on

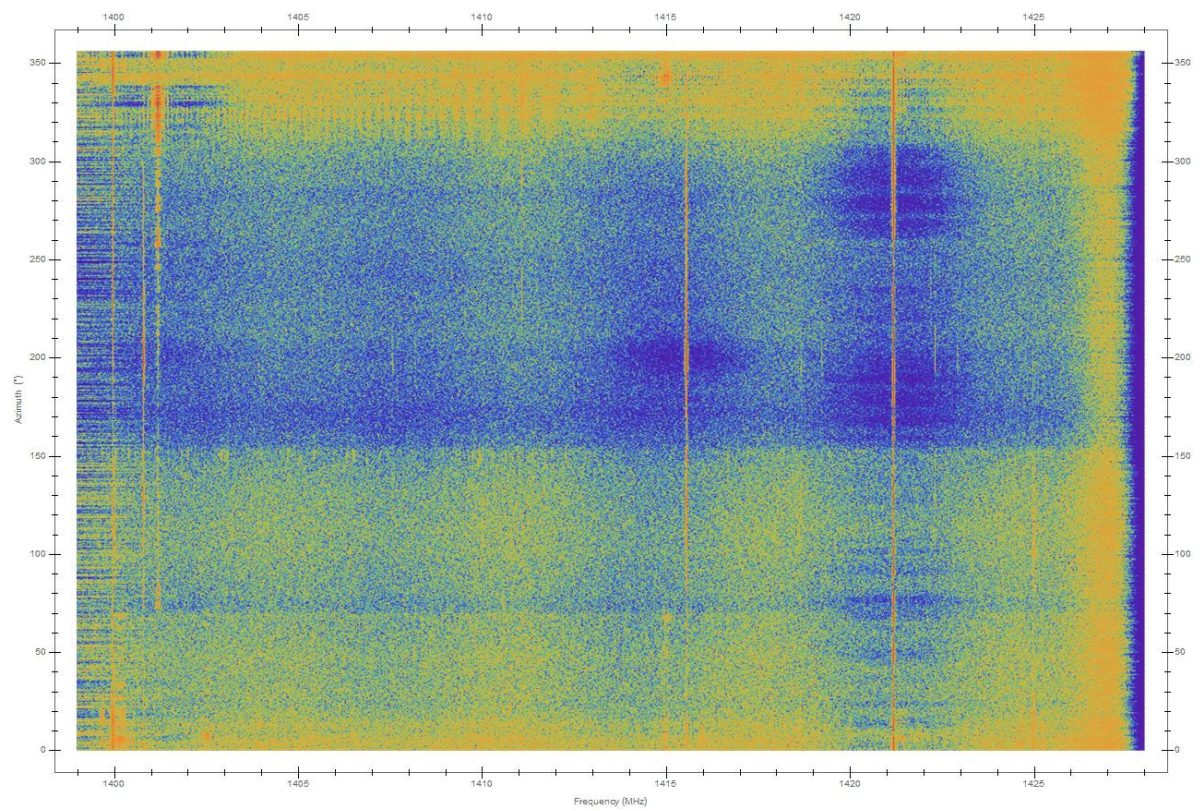


Figure 57: 360° azimuthal scan with the SRT, AXIS 211 webcam off

4.3 EMI Spectra of electronic Devices

To get an overview of the spectral structure and maximum field strength of the expected EMI several electronic devices which are used in the vicinity of the SRT were measured. Such EMV measurements are usually conducted in an anechoic chamber with walls that absorb all electromagnetic radiation. The device is placed on a rotating table and the electrical field strength is measured in a distance of three meters from the device in different heights. The maximal value that can be found is the emitted field strength of the device.

According to [9] the measurement can also be done in a distance of one meter. This distance makes it easier to point the antenna to the device and was used for all measurements. But for a comparison with the EMC standard the field strength in three meter distance has to be calculated. By the definition of the logarithmic unit for the field strength in equation (3) it drops down by 9,5 dB when increasing the distance from one to three meter.

For this project no anechoic chamber could be used. This leads to disturbances of the measurement with signals from other nearby devices. Also standing waves due to reflections on the surrounding are produced. Thereby the detected intensity becomes a function of the distance and position of the antenna and the device. By carefully adjusting the setup the maximum intensity can still be found but the intensity might be incorrect. This method can only give an overview and not a precise emission value.

The setup used the directional antenna described in chapter 3.6.2, the dual band amplifier (chapter 3.1) and the receiver (chapter 3.2). The two frequency bands 1420 MHz and 1665 MHz were measured with the 30 MHz bandwidth setting, which is the maximum for the SDR14 and without using the digital downconverter. The resolution bandwidth (RBW) of the SDR14 is 114 Hz per spectral bin. This is different to the EMC standard where usually a RBW of 1 MHz is prescribed to catch as much as possible from continuum emissions. But with such a large RBW no single lines could be seen in the small observed frequency range. Also the continuums emissions are less problematic for the SRT than single line emissions.

A light and a dark spectrum was recorded and subtracted to flatten the baseline and to suppress signals from the surrounding. When subtracting readings given in dB the subtraction has to be done in linear units according to equation (14) for every spectral bin. To preserve the absolute signal level the mean value of the dark spectrum has to be added again. The mean value of logarithmic units has also to be calculated in linear units using equation (15). The resulting spectrum is calibrated as described in chapter 3.4 and the received power is converted to electric field strength in a distance of 3 meter using the equations given in chapter 1.5.

$$DarkSubtracted_{[dBm]} = 10 \log \left(10^{\frac{Light_{[dBm]}}{10}} - 10^{\frac{Dark_{[dBm]}}{10}} + 10^{\frac{DarkMean_{[dBm]}}{10}} \right) \quad (14)$$

$$DarkMean_{[dBm]} = 10 \log \left(\frac{1}{N} \sum_{i=1}^N 10^{\frac{Dark_i}{10}} \right) \quad (15)$$

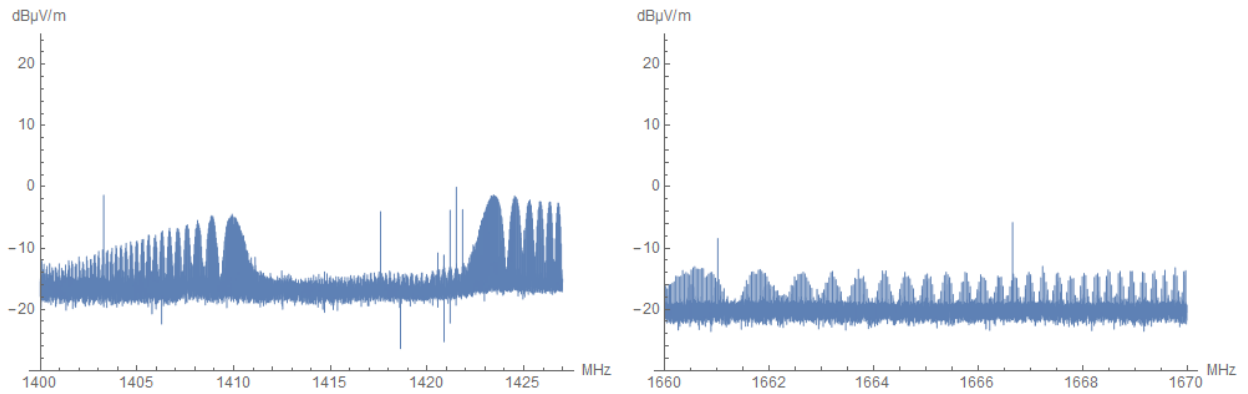


Figure 58: Electrical field strength in 3 meter distance of a Dell U2715H flat screen monitor

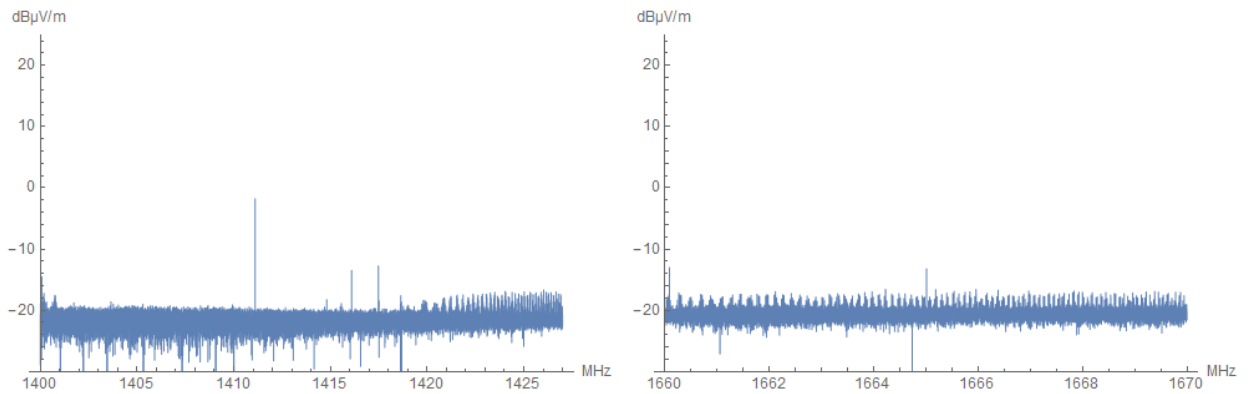


Figure 59: Electric field strength in 3 meter distance of Samsung S23A300B flat screen monitor

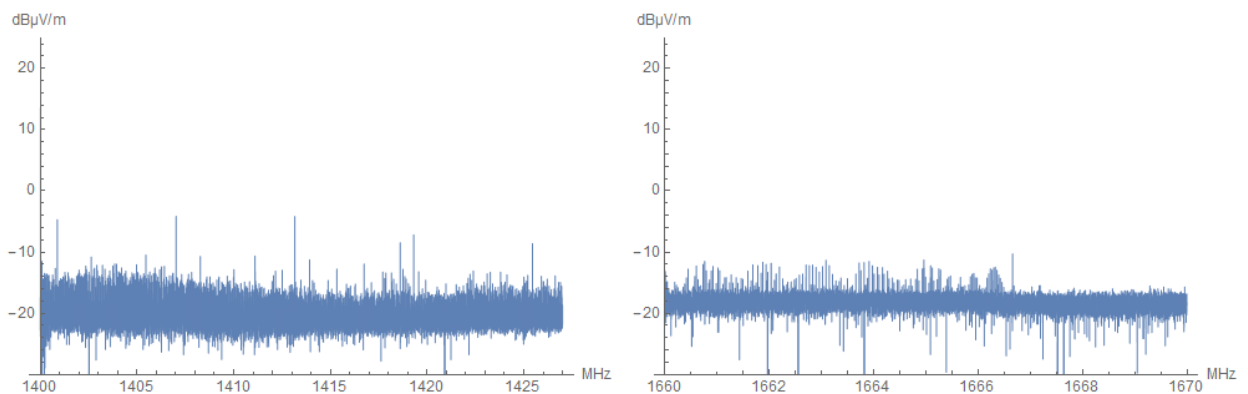


Figure 60: Electric field strength in 3 meter distance of Antec computer

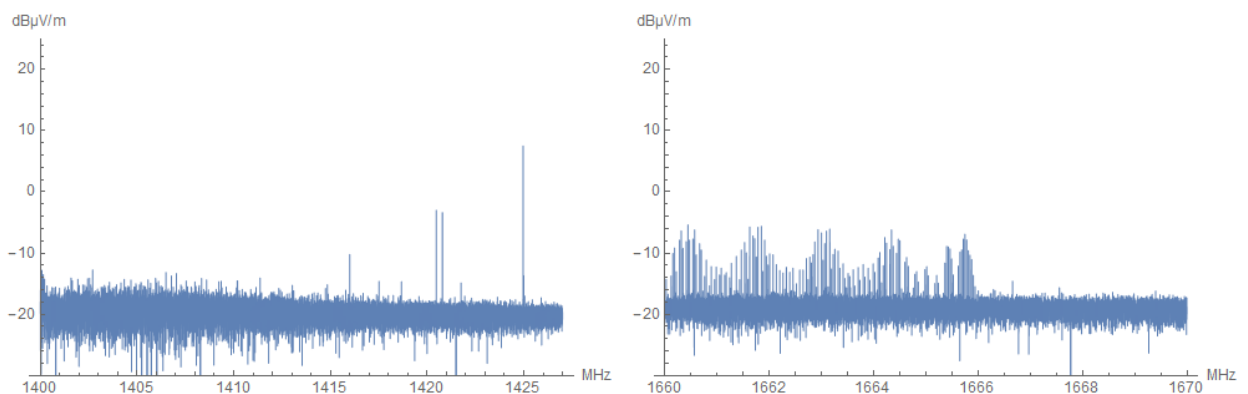


Figure 61: Electric field strength in 3 meter distance of HP2760 laptop

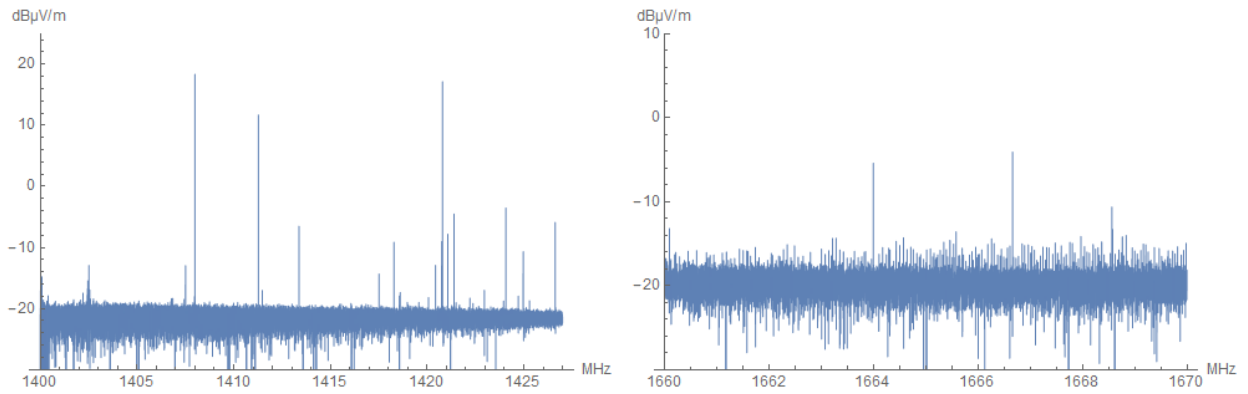


Figure 62: Electric field strength in 3 meter distance of AR3000A radio receiver

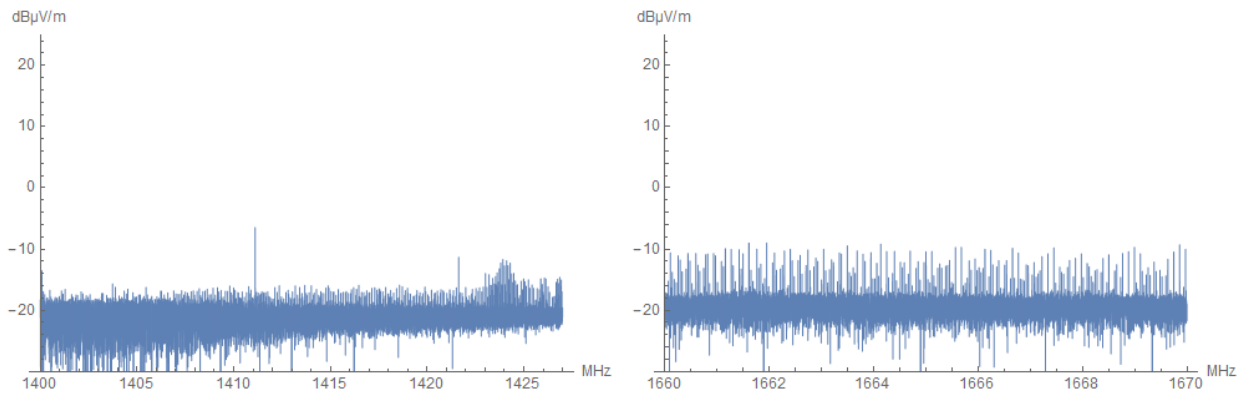


Figure 63: Electric field strength in 3 meter distance of FP222W flat screen monitor

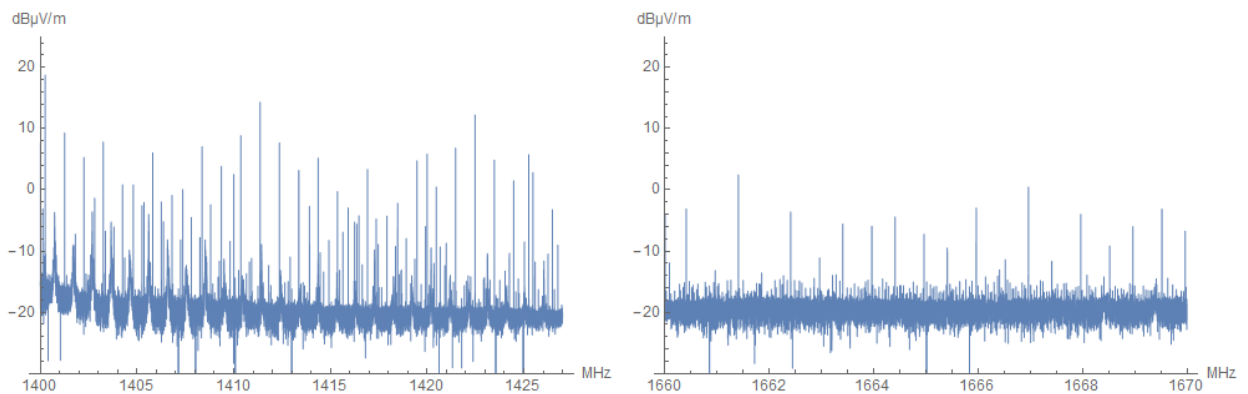


Figure 64: Electric field strength in 3 meter distance of DG4162 signal generator

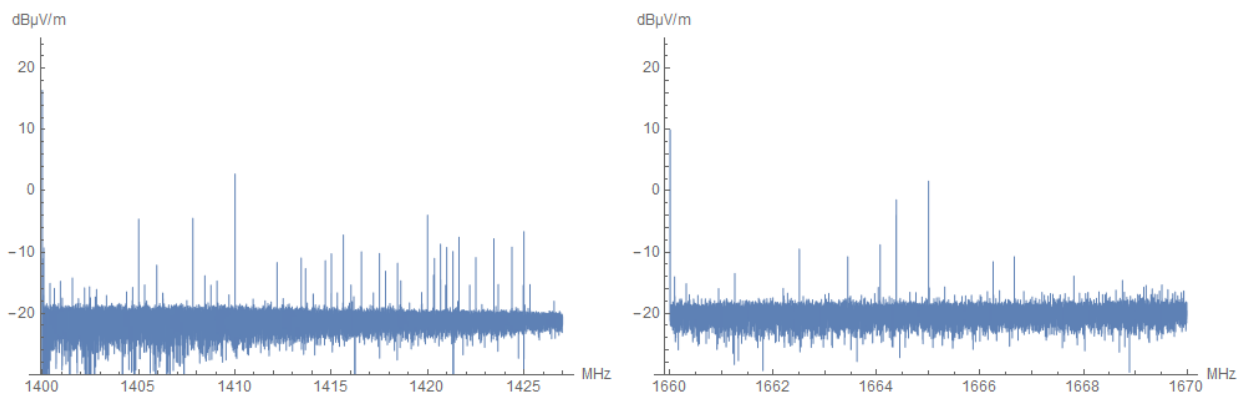


Figure 65: Electric field strength in 3 meter distance of HM8135 signal generator

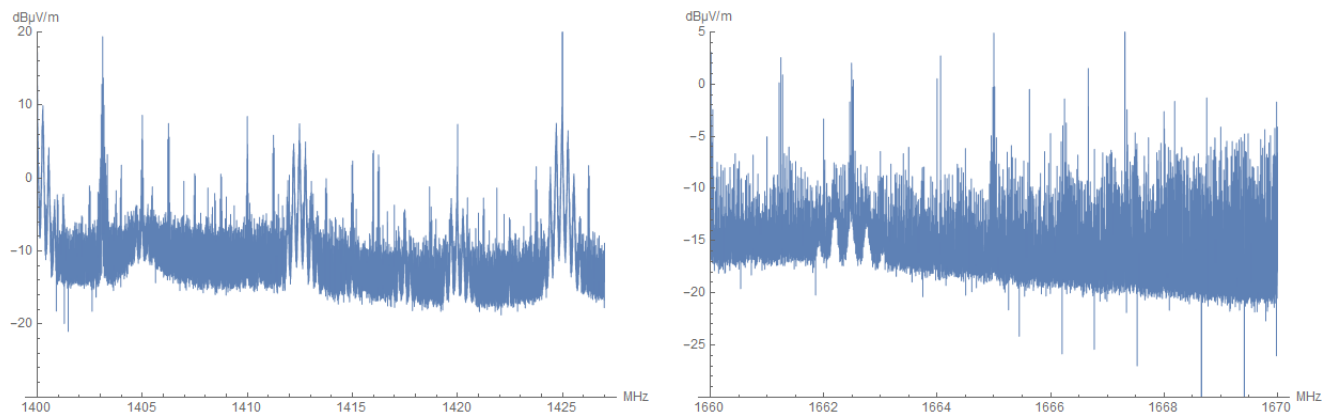


Figure 66: Electric field strength in 3 meter distance when complete CHEOPS computing equipment is running

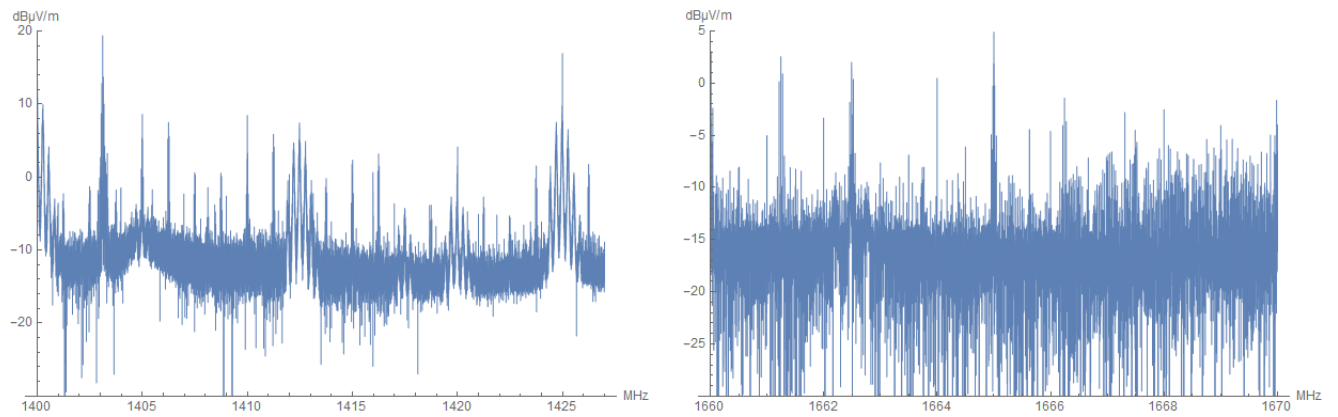


Figure 67: Electric field strength in 3 meter distance of GR712 evaluation board only

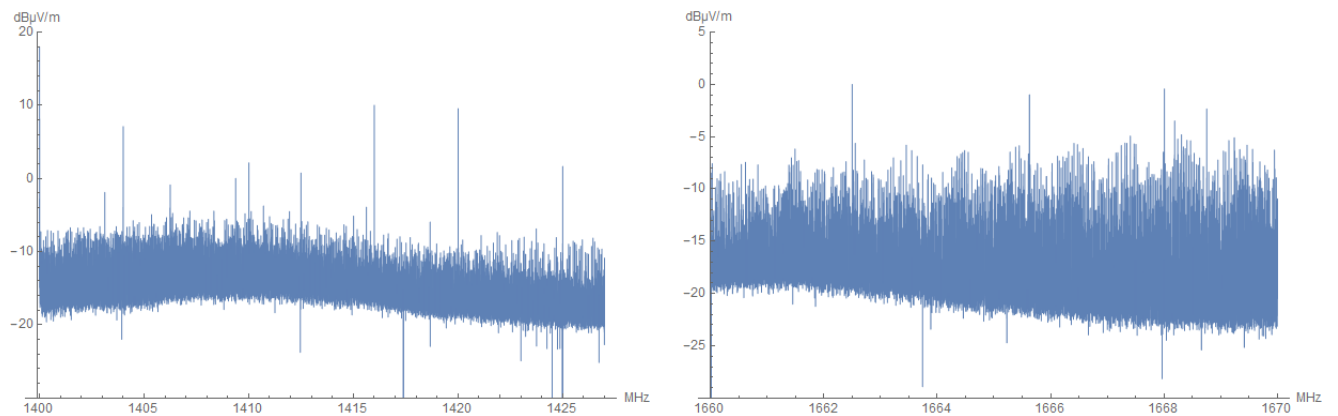


Figure 68: Electric field strength in 3 meter distance when both CHEOPS computers are running

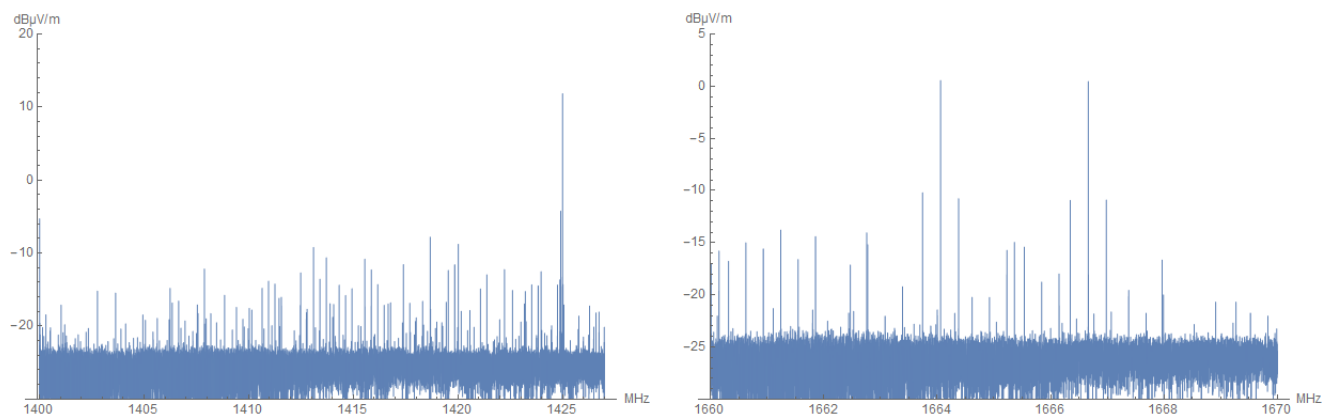


Figure 69: Electric field strength in 3 meter distance when both CHEOPS computers are switched off

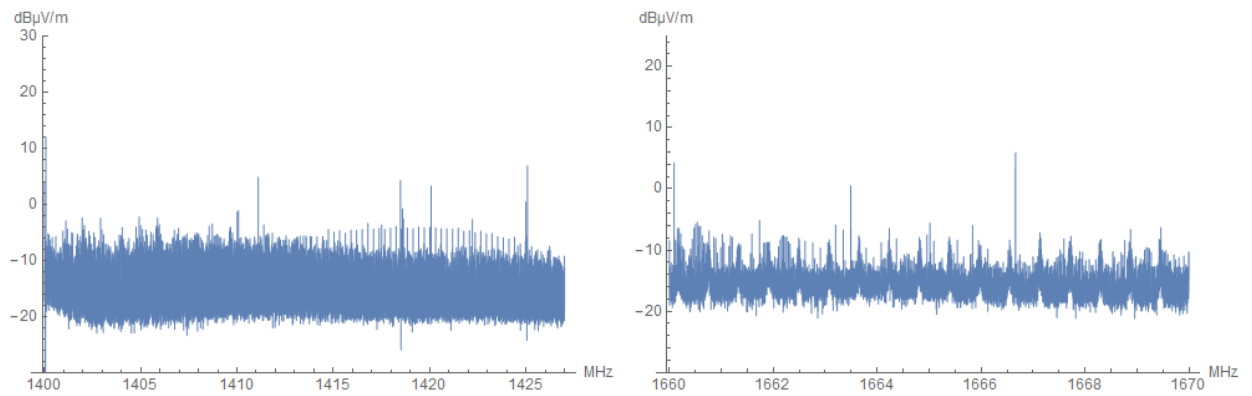


Figure 70: Electric field strength in 3 meter distance of the SRT server computer

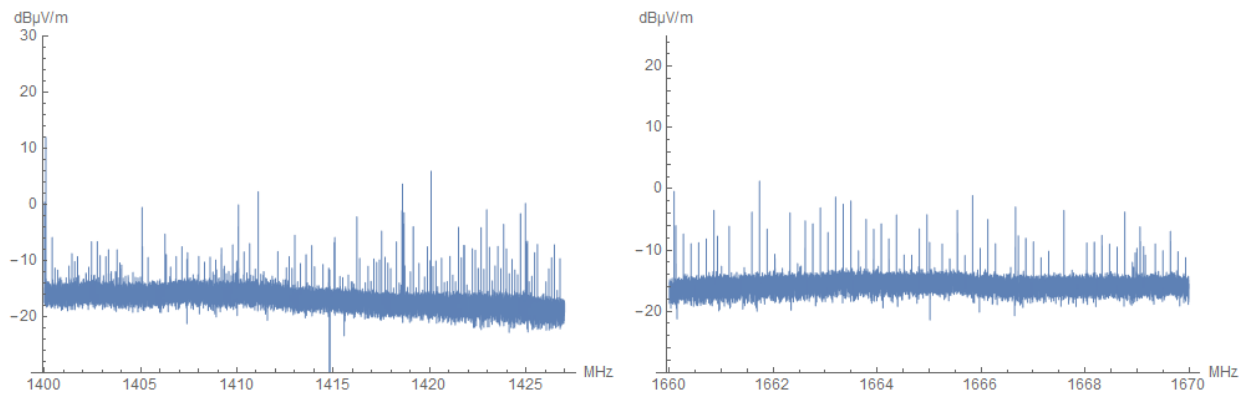


Figure 71: Electric field strength in 3 meter distance of the SQM server computer

Device	Peak in 1420 MHz band		Peak in 1665 MHz band	
	[MHz]	[dBμV/m]	[MHz]	[dBμV/m]
Dell U2715H flat screen	1421.51	-0.04	1666.66	-5.81
Samsung S23A300B flat screen	1411.10	-1.76	1660.09	-12.99
CHEOPS computing equipment	1425.00	22.29	1667.31	6.44
GR712 evaluation board	1403.11	19.38	1665.00	4.9
CHEOPS computer	1400.00	18.02	1662.50	0.01
AXIS 211 Webcam	1410.01	20.99	1665.01	30.4
Antec computer	1400.01	13.63	1666.66	-10.2
HP2760 laptop	1424.96	7.51	1660.44	-5.38
AR3000A radio receiver	1407.99	18.3	1666.66	-4.08
FP222W flat screen	1411.10	-6.47	1661.95	-9.0
DG4162 signal generator	1400.25	18.77	1661.41	2.45
HM8135 signal generator	1400.00	16.43	1660.00	9.97
Sky quality meter one	1415.56	16.86	1666.24	0.91
Sky quality meter two	1403.99	2.09	1663.99	-6.08
SRT receiver	1420.87	31.05	1660.00	-6.34
SRT server computer	1400.07	11.91	1666.67	5.94
SQM server computer	1400.07	11.94	1661.74	1.28
Avg:		17.41	Avg:	9.41

Table 15: Peak electric field strength in 3 meter distance for both frequency bands and all measured devices

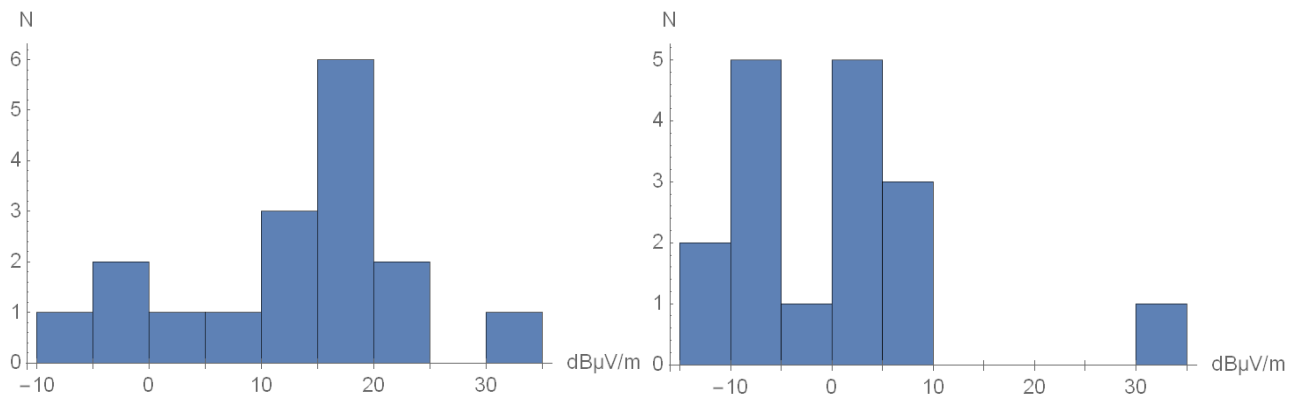


Figure 72: Distribution of peak electric field strength in 1420 MHz band (left) and 1665 MHz band (right) for all measured devices

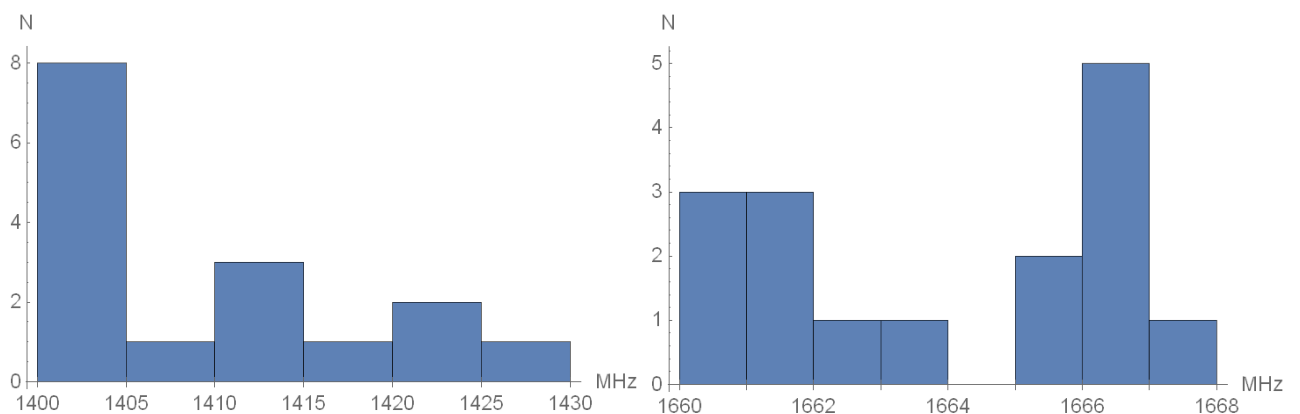


Figure 73: Distribution of the frequencies with maximum field strength in 1420 MHz band (left) and 1665 MHz band (right) for all measured devices

It could be found that devices with active transmitting functions like mobile phones usually emit very low electric fields into the radio astronomy frequency bands. The reason for this is that the standards for transmitting devices are stricter than that for MME. Therefore electronic devices like digital cameras, flat screens or webcams produce higher emissions than devices like mobile phones or WLAN routers except the actual transmitting frequency of course.

Devices which are enclosed in a plastic casing have higher emissions than such with a metal casing. Especially to mention are flat screen monitors. Du to their translucent design it is not possible to electrically shield the active part of the display. The pixels on the display are controlled with high speed signals what means sharp transition edges in the electric signals and therefor a lot of harmonic frequencies. The unshielded line length is very large and the generated EMI can radiate freely through the plastic front of the display.

When computers are measured without any connected cables except the power supply than the emission is usually very low. When cables are connected to a device the emission is increased depending on the shielding quality of the cable. Very strong sources of emissions are cable connections which are carrying high speed digital signals. Especially connections to flat screen monitors like DVI or HDMI cables tend to emit very strong signals as these connections use a very high data rate. This means electrical signals with very sharp transition edges on the cable. This results in harmonic frequencies reaching up into the radio astronomy frequency bands.

Even when computers are working with clock frequencies that reach up into the radio astronomy bands nearly no emission could be detected at the clock frequency. The reason therefore is that the high clock frequency is produced by frequency multiplication directly on the silicon chip and is only used there. The chip is shielded very well by its small design. The emissions that can be found outside the chip are of much lower frequency and related to the memory bus clock. The bus connection to the memory modules has large unshielded structures on the circuit board. Especially to mention is the 1666 MHz bus frequency which lies directly in the 1665 MHz OH maser band. Such an emission can be seen in Figure 99 which disturbed the whole measurement. This is also a favored frequency as can be seen in the distribution for all measured devices in Figure 50.

In contrast to computer chip clock frequencies the highest emissions are produced when a HF device is using a frequency which lays directly in one of the radio astronomy frequency bands. A good example for that is the LO of the SRT itself as shown in Figure 44, which produced the highest emission of the whole measuring project. Inside the receiver the LO frequency is generated by a digital synthesizer and then distributed over the circuit board to the mixers. This leads to long unshielded conductors which can radiate the frequency. In case of a receiver the LO frequency can also reach the antenna and be radiated from there.

The same is true for any frequency generator when it is set to a frequency within the radio astronomy frequency bands. Even when a dummy load is connected directly to the output of the frequency generator the emission is very strong. For example when setting the HM 8135 signal generator to 1420 MHz and maximum power level of 13 dBm with a 50 Ω dummy load directly connected to the output connector it can be seen from the SRT in a distance of several meters within the building.

The typical field strength in 3 meter distance for all the measured devices is around 17 dB μ V/m in the 1420 MHz band and 10 dB μ V/m in the 1665 MHz band as can be seen in Table 15. Compared to the EMC standards these values are very low and at least 50 dB below the maximum allowed peak limits defined in the EMC standard given in Table 4. Usually the emissions are higher in the lower frequency regime up to 10 MHz. A very common emission is the switching frequency of switch mode power supplies around 100 kHz with harmonics up into the MHz range. In the GHz regime where the HI and OH maser emission are located the emissions are usually very low.

That protects radio astronomy in some way but it also means that potentially every new device may have much higher emissions in total compliance with the EMC standards. A device which would emit the maximum allowed power according to the EMC standards in a single spectral line could be seen in a distance of several kilometers.

4.4 EMI shielding Measures

The nearest electronic devices to the SRT are two sky quality meters (SQM) which are measuring the light pollution of Vienna in the optical range. They are mounted on the handrail of the west side balcony in only 2 meter distance to the SRT. The extreme proximity to the SRT is problematic as the influence increases with the inverse square of the distance as it was shown in Figure 15. Also they are not located behind a wall of the building, which would provide a good attenuation for the EMI. Both SQMs have been shielded by wrapping an adhesive copper foil around the casing as shown in Figure 74.

Another very strong EMI source is the AXIS 211 webcam used to watch the SRT during observations. It is mounted at a window with direct sight to the SRT. Their spectrum shown in Figure 75 has a very strong emission at 1665 MHz of 30 dB μ V/m in 3 meter distance. To suppress the influence of the webcam it has been shielded by wrapping an adhesive copper foil around the casing as shown in Figure 74. This reduced the emission in the 1420 MHz band by 8,5 dB and in the 1665 MHz band by 25 dB as can be seen in Figure 76 and Table 15.

The emitted spectrum of all devices has been measured before the shielding by the method described in chapter 4.3. After shielding a second measurement under the same conditions has been done to document the reduction of the emission.



Figure 74: Shielded webcam next to the SRT (left) and shielded sky quality meters (right). SQM 1 in the foreground and SQM 2 in the background.

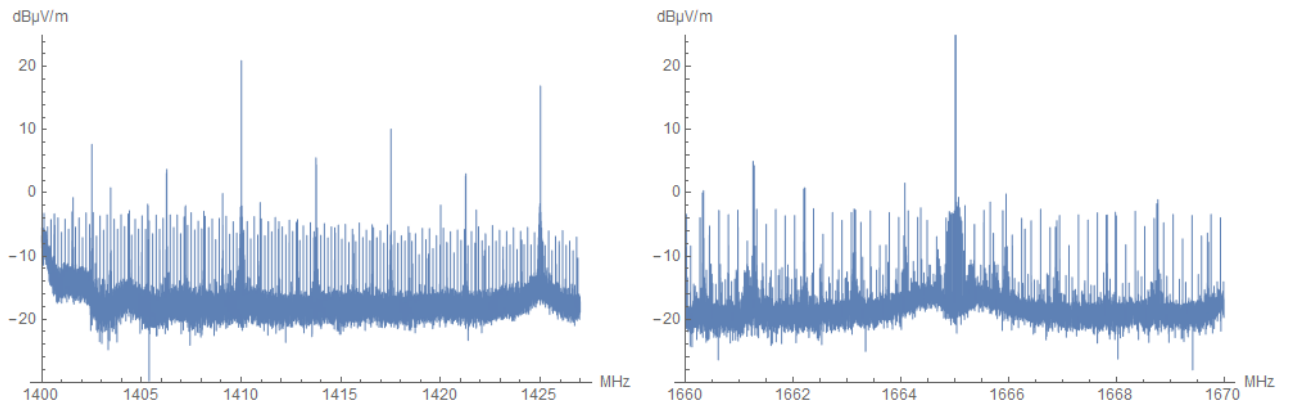


Figure 75: Electric field strength in 3 meter distance of AXIS 211 webcam

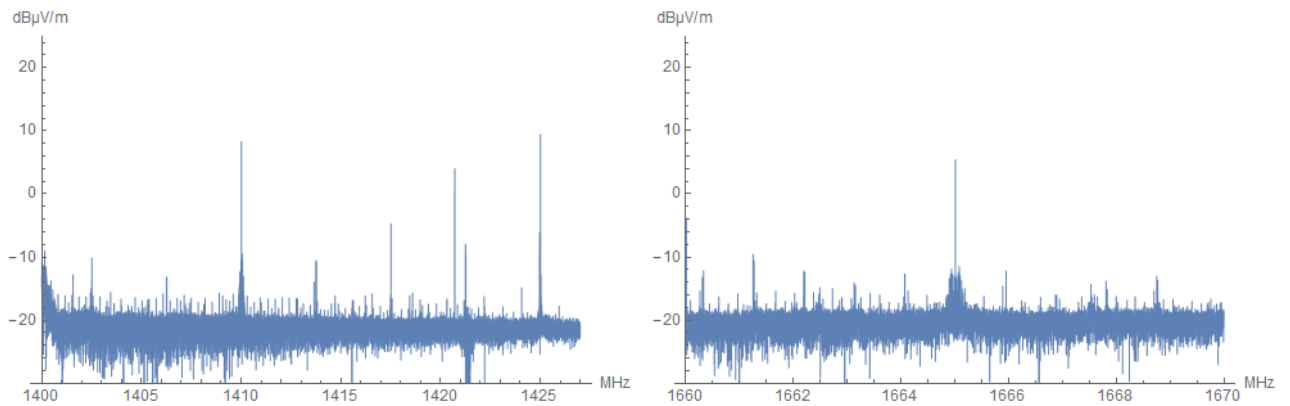


Figure 76: Electric field strength in 3 meter distance of AXIS 211 webcam after shielding

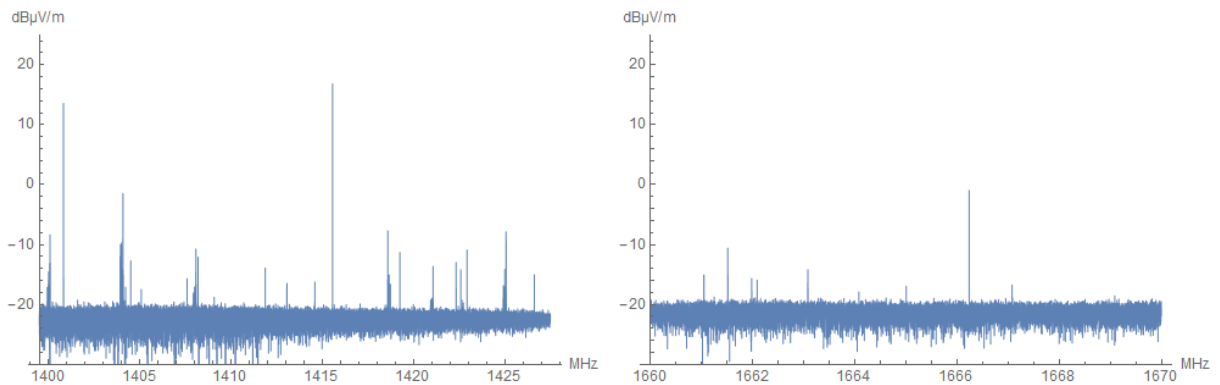


Figure 77: Electric field strength in 3 meter distance of sky quality meter one

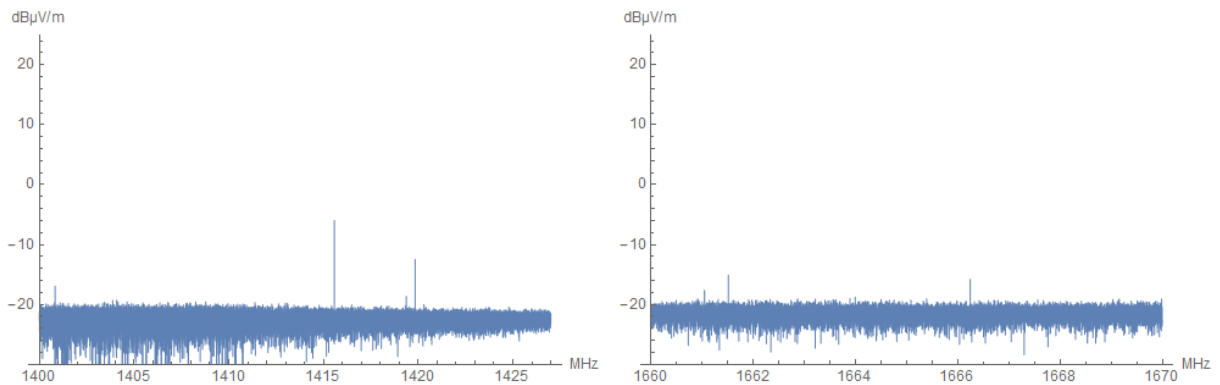


Figure 78: Electric field strength in 3 meter distance of sky quality meter one after shielding

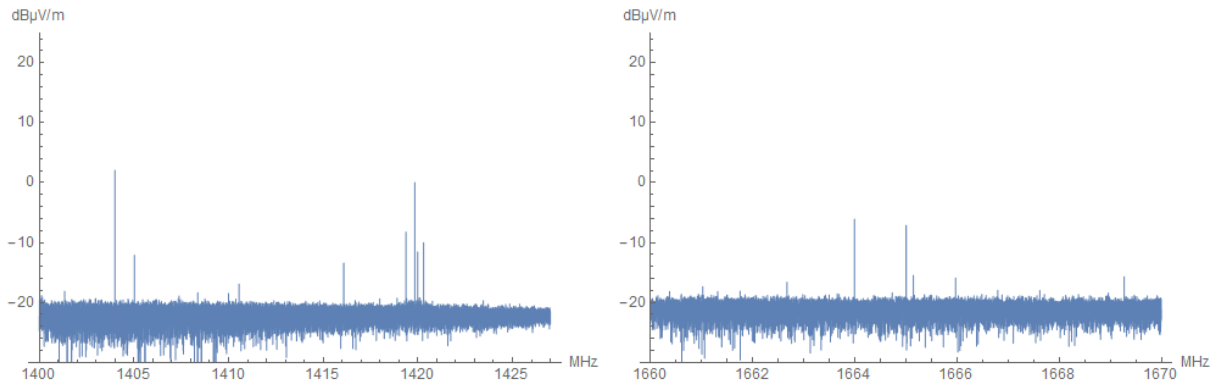


Figure 79: Electric field strength in 3 meter distance of sky quality meter two

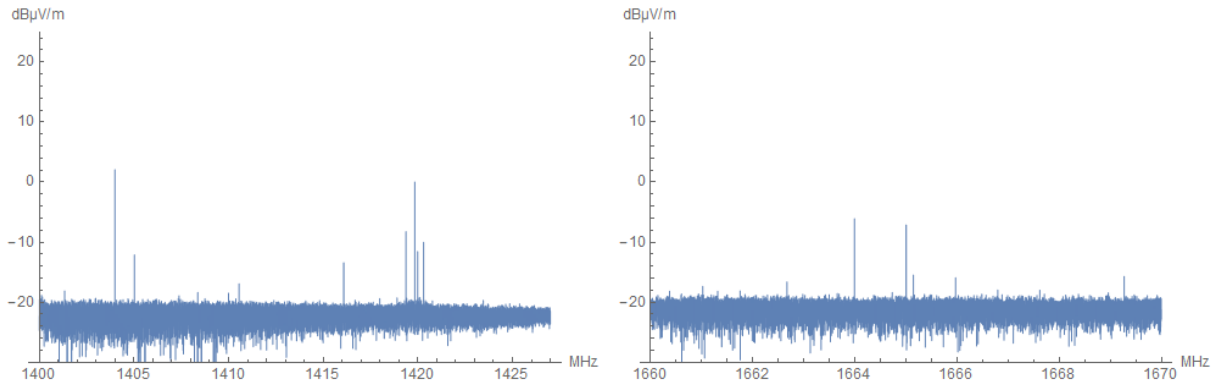


Figure 80: Electric field strength in 3 meter distance of sky quality meter two after shielding

Using a simple EMI shielding technique like adhesive copper foil can reduce the EMI in most cases. The EMI spectrum of SQM1 is shown in Figure 77 before shielding and in Figure 78 after shielding and for SQM2 in Figure 79 and Figure 80. In case of the SQM2 there was nearly no reduction of the emissions in the 1665 MHz band. This could be due to the unshielded and ungrounded cable from the power supply.

It could also be caused by the WLAN connection which is used by the SQM2 to transmit its data. The WLAN module is placed within the shielded case but a connection to the access point is still possible. The WLAN probably has increased its transmitting power to overcome the damping of the shielding. For a typical wireless system the receiver margins are 30 dB to 40 dB. The attenuation of the copper foil around 18 dB can be easily overcome by increasing the transmitting power. This also shows the limited shielding effect of this copper foil.

Device	Peak emission in 1420 MHz band				Peak emission in 1665 MHz band			
	MHz	Before dBμV/m	After dBμV/m	Gain dB	MHz	Before dBμV/m	After dBμV/m	Gain dB
AXIS 211 Webcam	1410.01	20.99	12.42	8.57	1666.24	30.4	5.44	24.96
Sky quality meter one	1415.56	16.86	-5.99	22.85	1666.24	0.91	-15.09	16.0
Sky quality meter two	1403.99	2.09	-10.88	12.97	1663.99	-6.08	-6.73	0.65
			Avg:	16.91			Avg:	18.45

Table 16: Reduction of the peak electric field strength for all shielded devices

Table 16 shows the reduction in the electric field strength for all shielded devices. On average the electric field strength could be reduced through the self-adhesive copper foil by 17 dB in the 1420 MHz band and by 18 dB in the 1665 MHz band. But it has to be expected that also nearly no reduction can be possible as in case of the SQM2 at 1665 MHz.

For a better shielding effect the used material has to have a very high conductivity. That means a metal case with thick walls built from highly conductive material like silver or at least silver plated materials should be used. Copper has always be preferred instead of aluminum. All gaps should stay in good contact with the opposite site over the whole length. Usually HF seals in combination with an screw spacing underneath $\frac{1}{4}$ wavelength are used to achieve this.

All cable connection leading into the shielding case should be shielded as well and the screen of the cable must be connected to the case and to the earth on both sides. All connections to the earth must be as short as possible and they must have a low inductivity. This means very thick and highly conductive cable connections.

Every conductor inside the shielded cable should go via a feed through capacitor into the shielding case. Also a separate ground connection from the circuit to the power supply should be led into the shielded cable. The EMI falling on to the shielding case are travelling to the earth causing a voltage drop on any conductor in their path. This causes the EMI to couple into the ground connection if it is not laid and shielded separately.

It also has to be mentioned that shieling can only reduce the emission but never prevent it completely. This is caused by the finite conductivity of the shielding material. An electromagnetic wave which is hitting the shieling case will always induce an electric current inside the material. This current will cause a voltage drop on the surface of a case with finite conductivity. This voltage will automatically lead to a secondary emission of electromagnetic waves from the surface of the shielding case itself. This could only be avoided by using a superconducting shielding case.

The best way to avoid EMI from a device is to shut it down. If that is not possible at least the distance to the radio telescope should be increased. Also changing the operation mode of the device could help. For example changing the clock frequency of a device can shift the EMI out of the critical frequency range.

4.5 Analysis of the spectral Structure of the EMI

Very common features in the recorded EMI spectra are repeating groups of narrow single lines with a constant spacing in between. A good example for that are the spectra in Figure 75. Sometimes the amplitude distribution of the groups shows a repeating pattern too, as the spectra in Figure 58. This behavior is interesting as the line spacing is different for each device. This can provide the possibility to distinguish between different EMI sources.

To examine the data for their line spacing it is necessary to detect each single spectral line above a threshold level. As a first step in the analysis process the spectrum is normalized to get a flat baseline. This is done by subtracting a median filtered spectrum from the original data. Figure 81 shows the results after normalizing the spectra of the AXIS 211 webcam in Figure 75.

By applying a peak detection algorithm above a threshold level of 4 dB above the noise floor and by skipping direct neighbors a total number of 342 single spectral lines in the 1420 MHz band and 300 lines in the 1665 MHz band could be identified. The distribution of the frequency differences between neighboring peaks is plotted in the histograms in Figure 82 for both frequency bands.

There is a clear preference of short line distances of 20 kHz and large distances of 180 kHz. This can be considered as some kind of spectral fingerprint which is characteristic for the webcam. Even in the 1665 MHz band the same structure for small distances appears, whereas the clear peak at 180 kHz disappears completely.

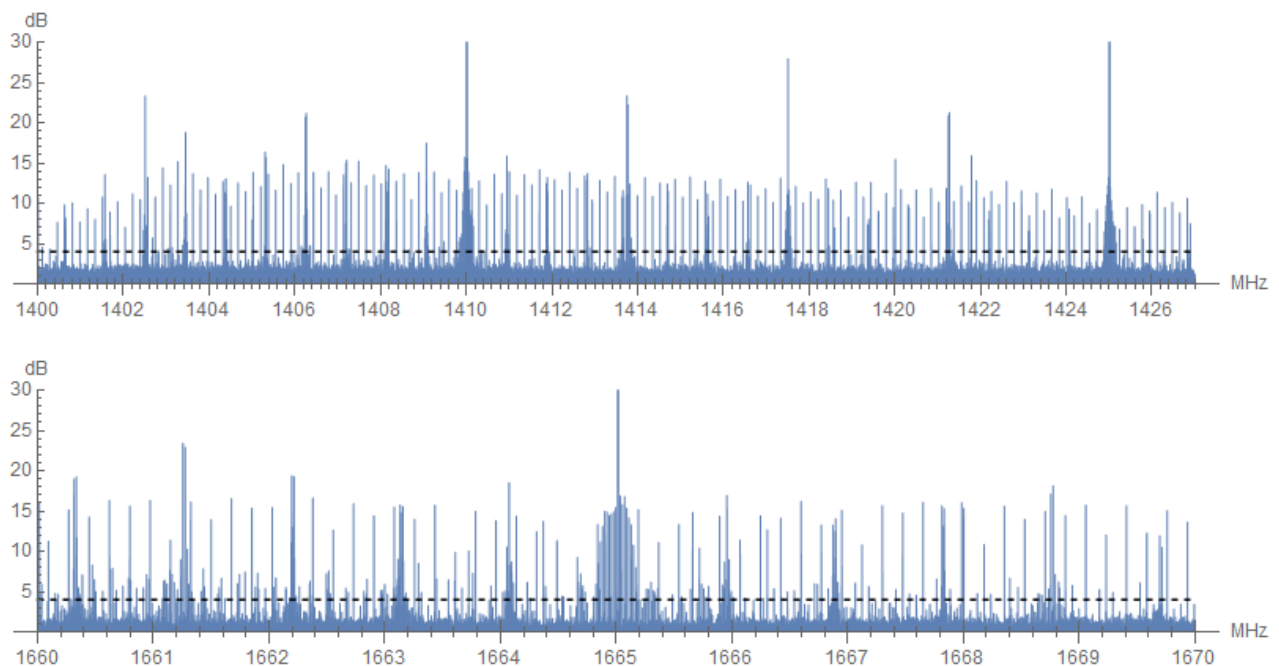


Figure 81: Normalized and flattened spectrum in the 1420 MHz band (top) and 1665 MHz (bottom) of the AXIS 211 webcam extracted from Figure 75 with a 4 dB threshold level (dashed line) for the peak detection

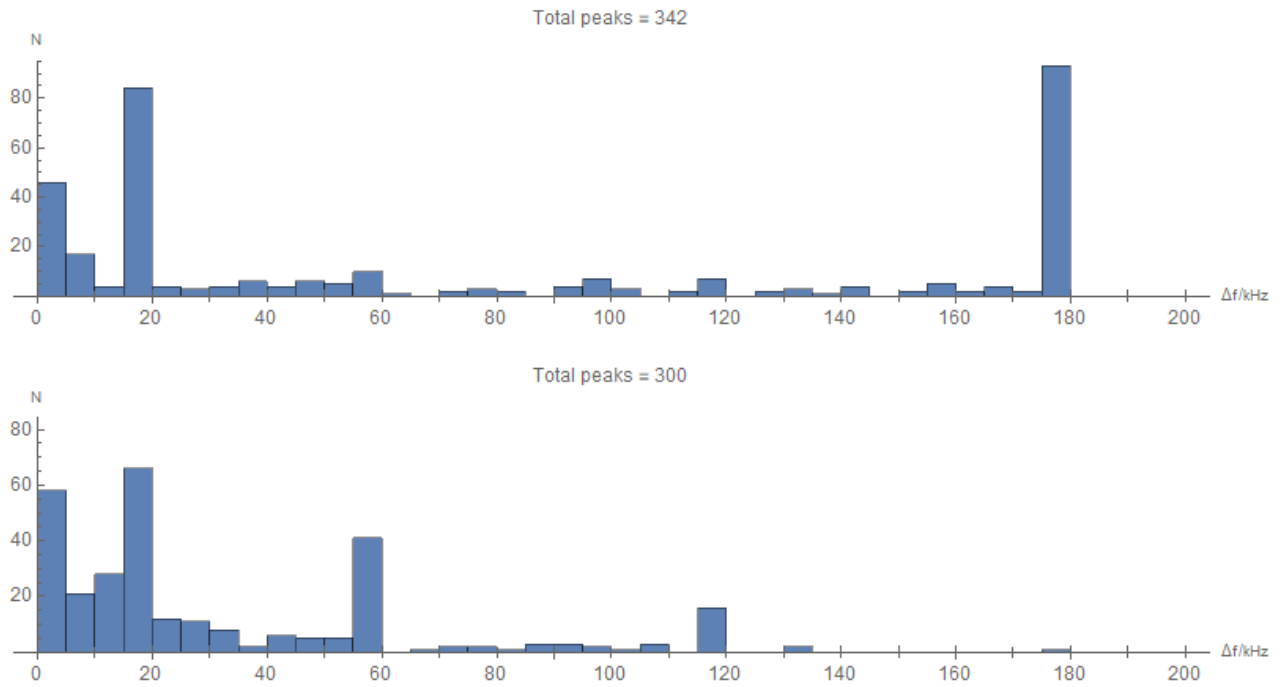


Figure 82: Distribution of the line spacing between neighboring detected peaks in the 1420 MHz band (top) and 1665 MHz band (bottom) in the spectrum of the AXIS 211 webcam Figure 81

The same analyzing method has been deployed to the EMI spectra of the Dell flat screen monitor. The normalized spectra are plotted in Figure 83 and the line spacing distributions are plotted in Figure 84. A clear variation in the line spacing between the two devices can be identified. The webcam has 20 kHz line spacing whereas the flat screen monitor has 35 kHz. This is a method to distinguish between different EMI sources.

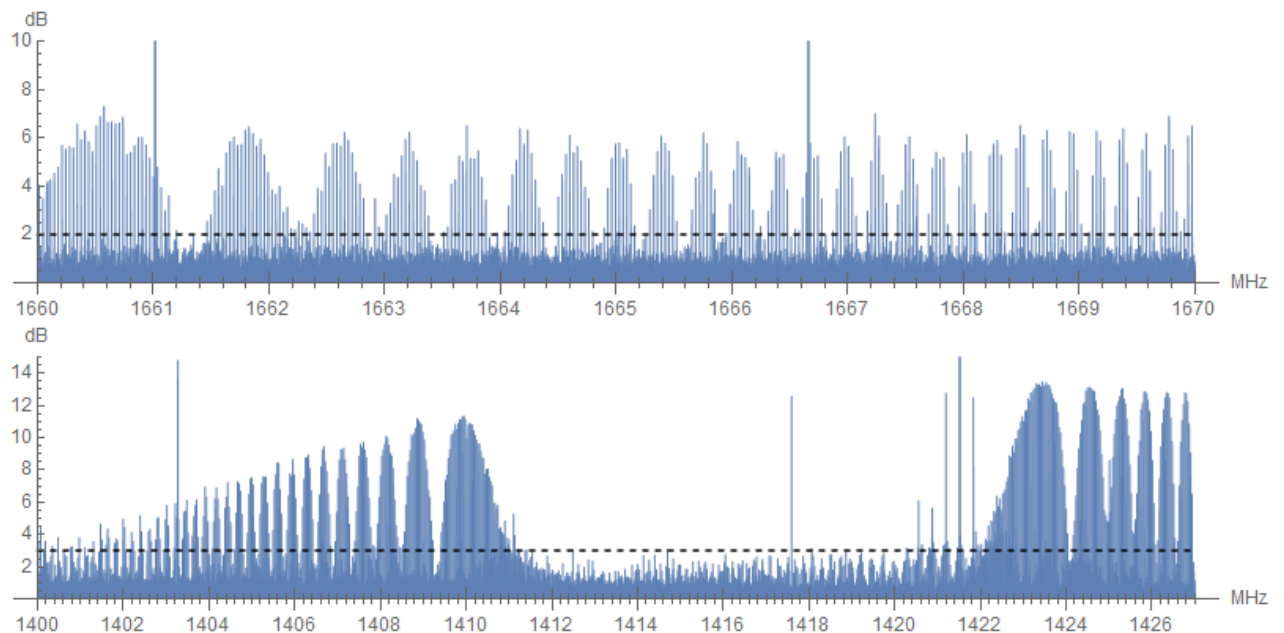


Figure 83: Normalized and flattened spectrum in the 1420 MHz band (top) and 1665 MHz (bottom) of the Dell U2715H flat screen monitor extracted from Figure 58 with a threshold level (dashed line) for peak detection

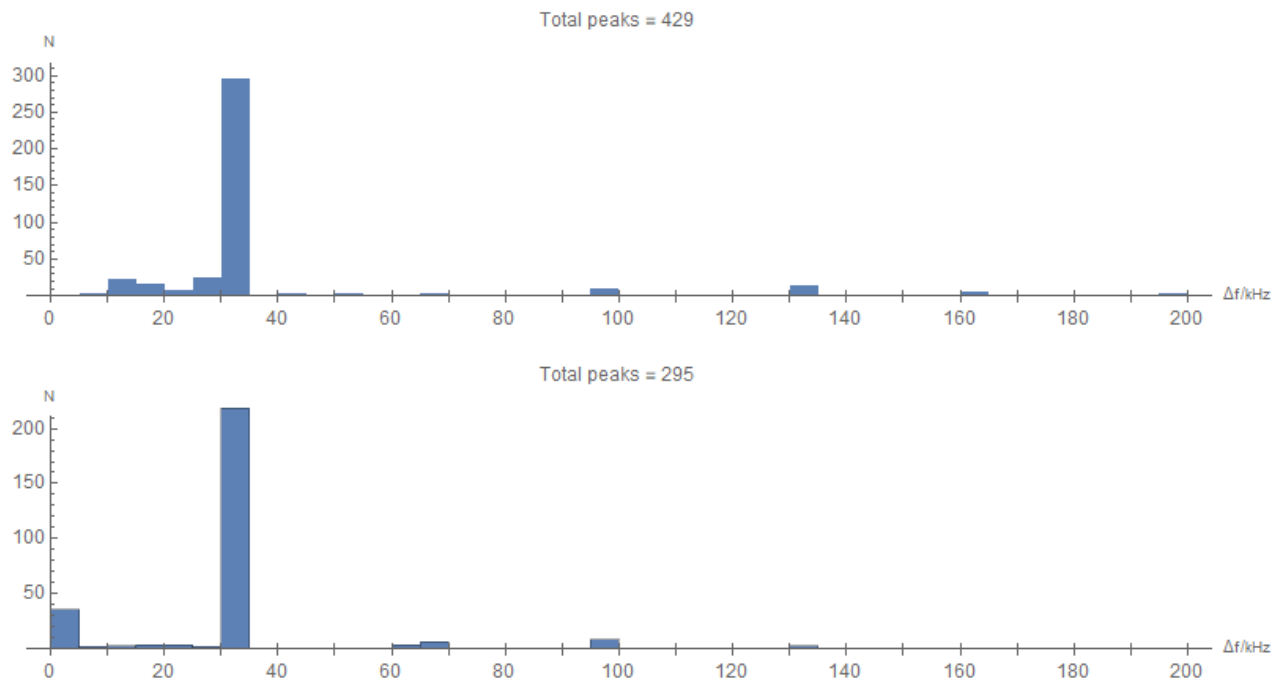


Figure 84: Distribution of the line spacing between neighboring detected peaks in the 1420 MHz band (top) and 1665 MHz band (bottom) in the spectrum of the Dell U2715H flat screen monitor Figure 83

The method of analyzing the differences between neighboring lines in an EMI spectrum can provide the opportunity to identify a single EMI source by its prominent spectral line spacing. Even when a large amount of EMI spectra are overlaid the spectral fingerprint of one single device could still be revealed by analyzing the distribution of the differences between neighboring spectral lines.

This method can also provide an alternative way of presenting the recorded data than the normally used spectral view. It can make it much easier to identify the activity of different EMI sources in a large amount of data.

The usefulness of this method has been demonstrated by reducing the complex spectral structure in Figure 89 obtained during a long time recording to the very easy to read diagram in Figure 92. This analyzing method revealed that most of the EMI are produced by only one single device.

Even at the transition from Monday April 3, 2017 to Tuesday April 4, 2017 where the spectral structure clearly changes, the line spacing remains still the same, revealing that these emissions are coming from the same device.

4.5.1 Generic Model for producing digital Noise

The spectral structure of the EMI can give us some information about their origin and their formation process. The question to be answered is how the very often observed spectral feature of repeating lines with a constant spacing between neighboring lines can be reproduced.

The typical EMI source is an electronic device which is using some kind of digital signal processing technique. Such devices use electric signals with very sharp transition edges in the time domain. This produces a large number of harmonics in the frequency domain.

The processed information is coded in the different pulse length of the ones and zeros in the digital signal. As this data is not known it can be assumed to be white noise in a first approach because it has the greatest information density.

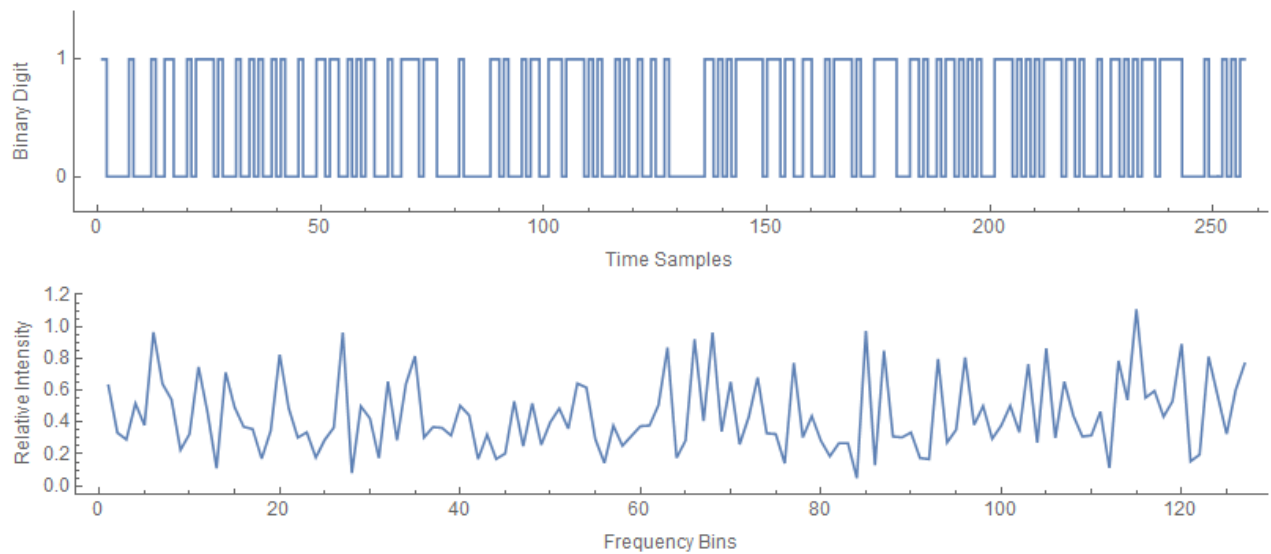


Figure 85: Digital white noise in the time domain (top) and frequency domain (bottom)

Figure 85 shows 265 bits of digital white noise in the time and frequency domain. It can be seen that such a completely random signal produces a white noise in the frequency spectrum as well which does not match the observed spectra.

But for a typical computing system the processed data is always used in repetitive loops and calculation processes always use the same structure to generate the next result. That means there is always some redundancy in the data and the information density is lower than in pure white noise. Therefore a more realistic digital signal is a sequence of blocks containing the same amount of random data.

Figure 86 shows a repetitive sequence of four identical blocks with 64 bits of digital white noise in the time and frequency domain. The repetitive arrangement of four identical data blocks in the time domain signal leads to a broader line spacing of four frequency bins in the spectrum.

The amplitude distribution of these lines remains still random but the line spacing is constant over the whole spectrum and lines appear only on every 4th spectral bin. This behavior looks very similar to the observed EMI spectra of many devices. Therefore repeating groups of identical random data is a good method for simulating EMI spectra.

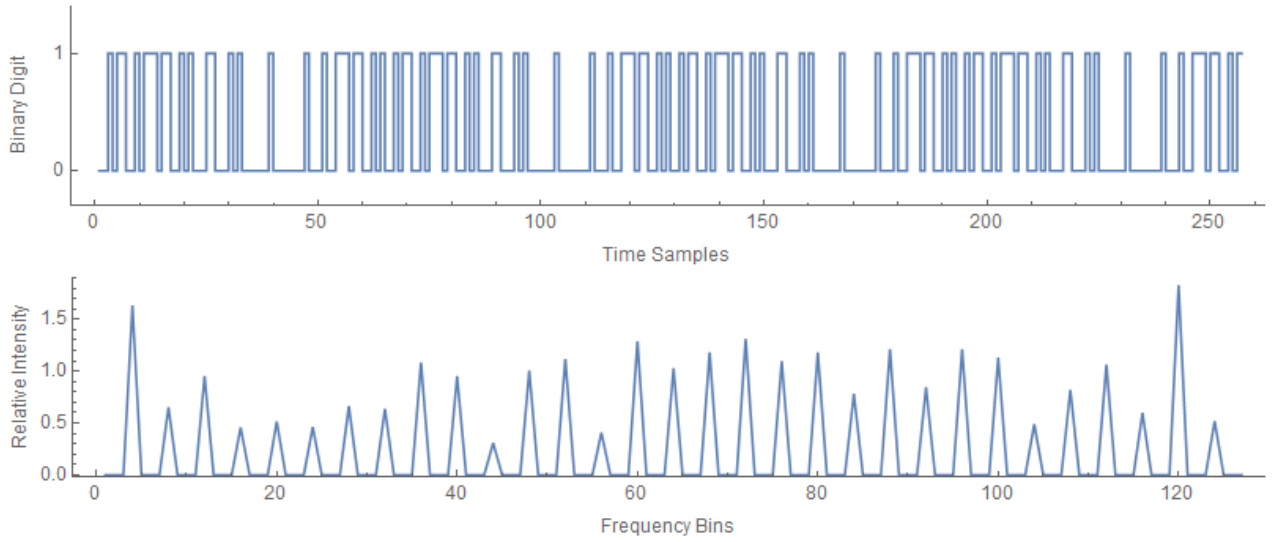


Figure 86: Sequence of four identical blocks containing 64 bits of digital white noise in the time domain (top) and in frequency domain (bottom)

For a more realistic simulation of EMI spectra the linear congruential pseudorandom generator based on the equation (16) was used to produce a larger amount of data. This recursion creates a period length of 256 bytes with only one occurrence of each number on a random position. The data stream was repeated 5 times obtaining a total length of 1280 bytes. This data was converted into a binary stream of 10240 bits and then Fourier transformed.

The resulting spectrum in Figure 87 is a good example for a typical EMI spectrum with the characteristic repetitive and symmetric pattern. The line spacing in the detail (bottom) shows the distance of 5 spectral bins caused by the 5 repetitions of the random numbers. By changing the parameters of the congruential generator (16) different frequency patterns can be produced.

$$y_i = (9 \cdot y_{i-1} + 1) \bmod 256$$

(16)

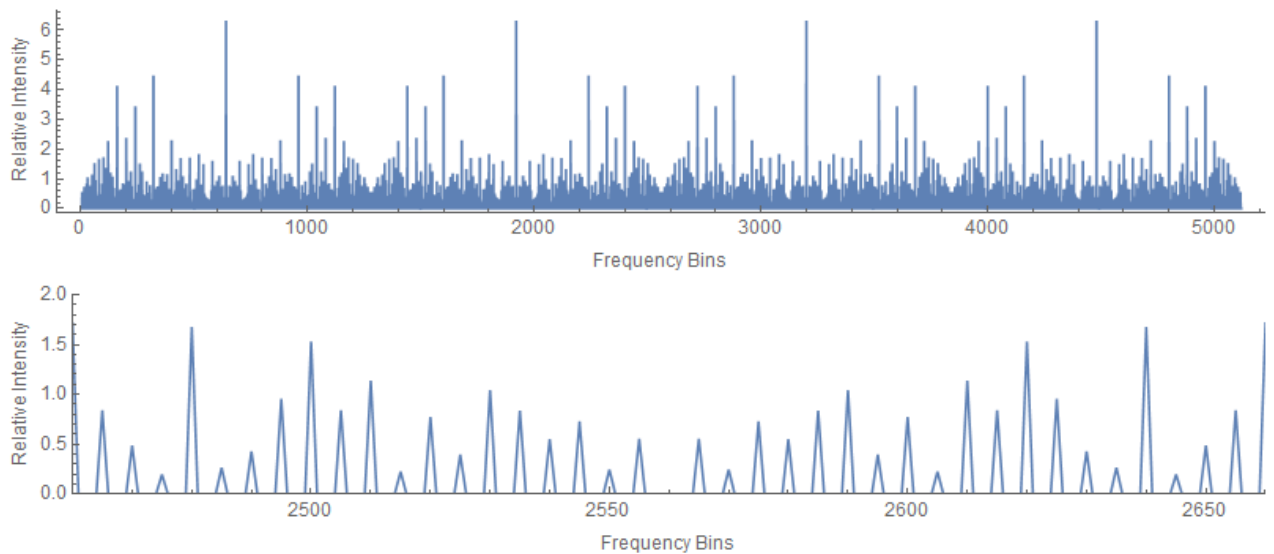


Figure 87: Frequency spectrum of the linear congruency random generator (16) with 5 cycles of 256 bytes period length (top) and detail around the center frequency at bin 2560 (bottom)

When using a random number generator with the recursion equation given in (17) the sequence of the random numbers changes. The period length of 265 bytes stays still the same as the same module 256 is used. When repeating this sequence for 5 times the frequency spectrum shown in Figure 88 is obtained. It shows again a line spacing of 5 spectral bins caused by the 5 repetitions of the random sequence. In comparison with the spectrum in Figure 87 only the amplitude pattern has changed.

$$y_i = (25 \cdot y_{i-1} + 13) \bmod 256$$

(17)

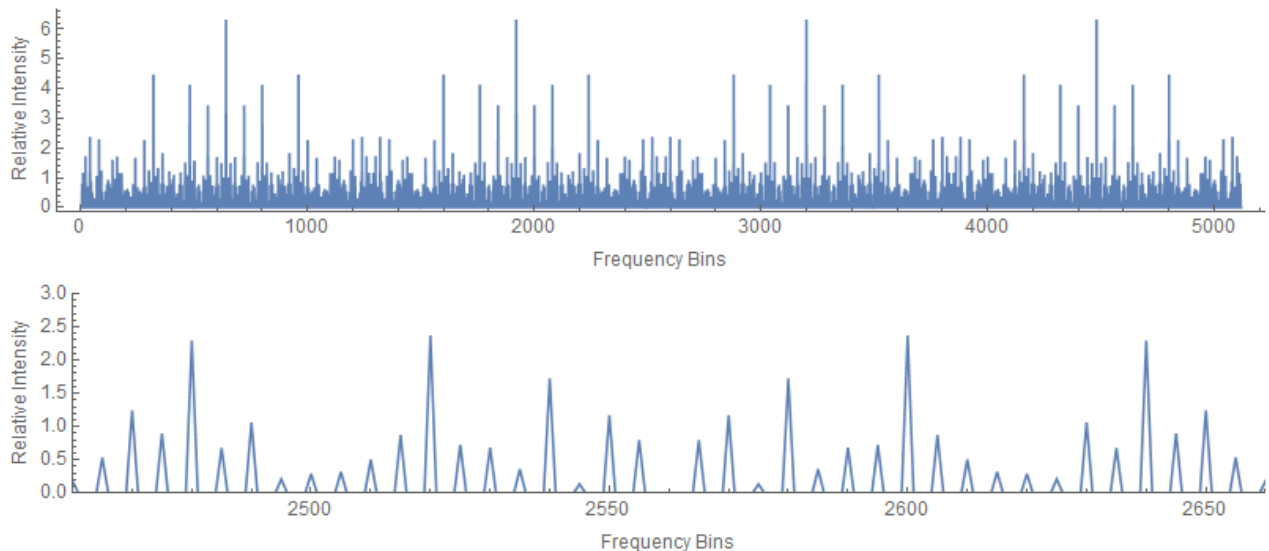


Figure 88: Frequency spectrum of the linear congruency random generator (17) with 5 cycles of 256 bytes period length (top) and detail around the center frequency at bin 2560 (bottom)

This can give us some insight into the formation process of the EMI spectra. The characteristic constant line spacing observed by many devices as shown in Figure 82 and Figure 84 is caused by a cycle with constant period length equal to the line spacing. The variation of the processed data only changes the amplitude distribution of the lines but not their spacing. This can provide a method for identifying one and the same device even when it is processing a different set of data. A comparable behavior has been observed during the long time EMI monitoring at the IfA shown in Figure 89 and Figure 92 where the spectral structure of an EMI with constant line spacing changes over the duration of several days.

A good example for such a repeating cycle can be the refreshing of a dynamic memory module inside a computing system. The content of the memory nearly is the same between each refreshing but the refreshing cycle time stays the same all the time. When these signals with sharp transition edges are transferred over the memory bus electromagnetic radiation can emit from the long connection lines between the central processor and the memory module. This would produce an EMI emission with a spectral line spacing equal to the refreshing time of the memory.

4.6 Analysis of the Time Structure of the EMI

A typical observation of the whole galactic plane with the SRT will last for several hours on at least two different days. Therefore of greater interest are EMI signals on a larger time scale, as short time EMI will be canceled out by the large integration time or can be skipped in the recorded data. Under these requirements averaging of the EMI spectra can be used to archive a better SNR.

To get an overview of the time structure of the EMI a recording over several weeks is needed. It can be expected that artificial signals are correlated with typical working hours and working days at the IfA and do not change at short timescales.

4.6.1 Measurements at the IfA

For this measurement the omnidirectional antenna described in chapter 3.6.1 was used to receive signals from all over the IfA building. The antenna was mounted on the west side balcony outside of the IfA near to the site of the SRT as shown in Figure 38.

To get the highest sensitivity the settings given in Table 11 was used for the SDR14 recording device, meaning the received spectral data was averaged over the period of one minute. That still leads to a very large dataset of 1440 spectra per day with 262144 frequency bins for each spectra. A dataset for one day occupies 6 GB of memory. This is a very huge amount of data that cannot be displayed in a single picture on one page. Therefore a large binning of 200 spectral bins has been used to only select the strongest spectral line out of 200 frequency bins. This increases the noise floor of the resulting spectrum but it is the only way to reduce the huge data.

Figure 89 shows a spectral waterfall diagram of the 1420 MHz band from March 23, 2017 to April 12, 2017. Red color indicates strong signals, yellow and light blue are for medium signals and dark blue is the noise floor of the receiving system.

First of all there are many very strong lines which are static over the complete recording period. The strongest signal at 1421 MHz is the LO from the SRT itself. Other strong signals are produced by the nearest computers in the SRT server room which are running 24 hours a day. Besides that it can be seen that an EMI with many correlated spectral lines starts at Monday April 4, 2017 bevor midday and ends at Friday April 7, 2017 at midday. This can be considered as a typical working time in one of the offices at the IfA near to the SRT. Several shorter timed EMI also with many correlated spectral lines occur on some days. This can be interpreted in that way that many students are bringing their own devices for the duration of one lecture and leaving afterwards.

Most EMI appear as series of dense spectral lines with correlated distances. A complete different spectral structure can be seen at 1419.9 MHz between Friday March 31, 2017 and Monday April 3, 2017. It appears as completely uncorrelated frequencies of short duration and is a unique feature in the whole recording period. It also shows a correlation to the weekend.

Groups of dense spectral lines with correlated distances can also be found in the 1665 MHz band as shown in Figure 90. But the time correlation to typical working hours is less distinct as in the 1420 MHz band. The dominant feature at June 5, 2017 even starts at night time. Other shorter features only occur on midday.

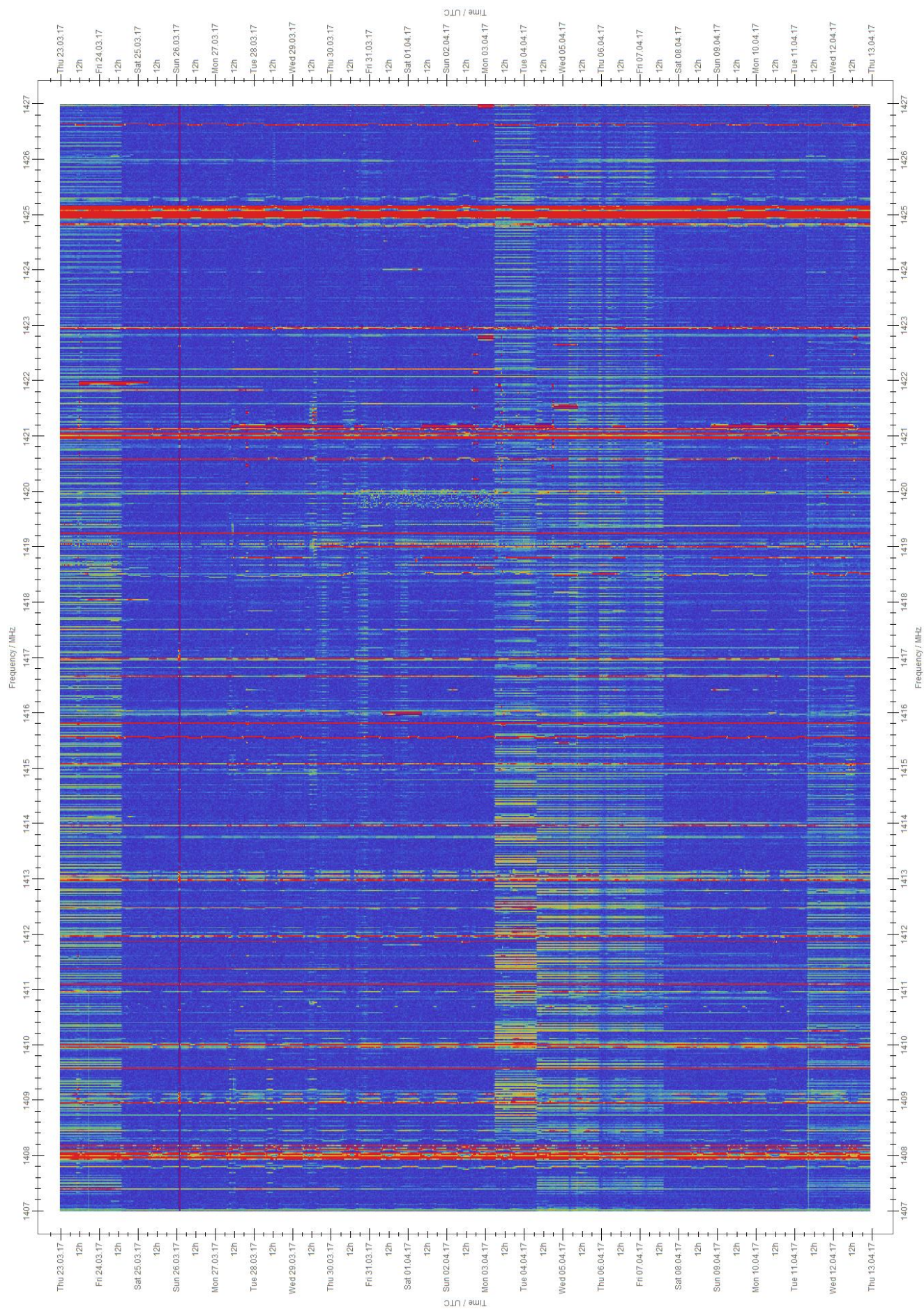


Figure 89: Recorded EMI spectra at the IfA in the 1420 MHz band between March 23, 2017 and April 12, 2017

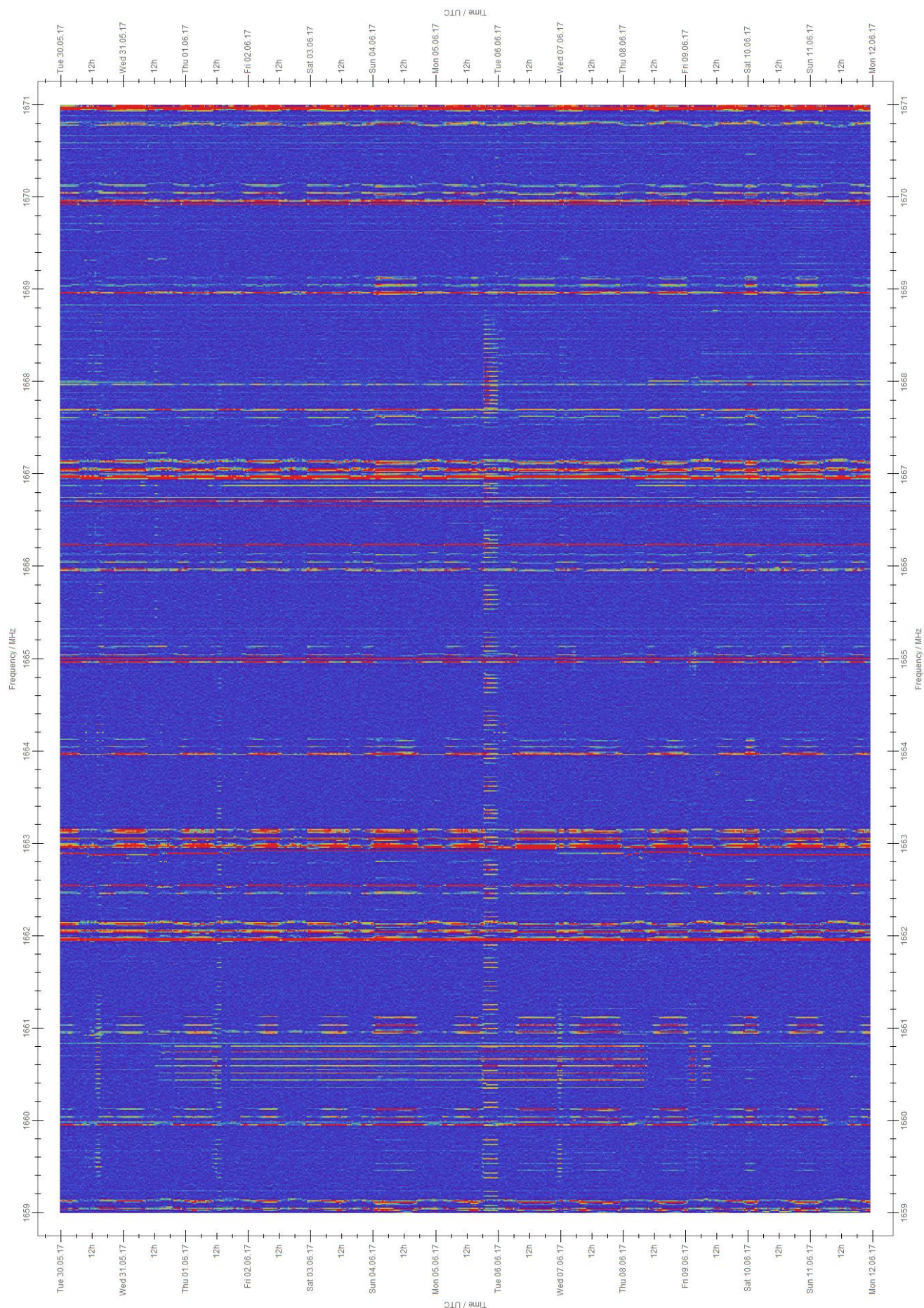


Figure 90: Recorded EMI spectra at the IfA in the 1665 MHz band between May 30, 2017 and June 12, 2017

Figure 89 shows a great amount of different spectral EMI structures. It is hard to say how many different sources are involved. To distinguish between different devices the method described in chapter 4.5 for analyzing the line spacing has been applied to this data set.

A threshold level of 3 dB above the noise floor has been used for the peak detection algorithm. Figure 91 shows the total number of detected EMI lines over the whole recording period. A slight tendency to more EMI between Monday and Friday is also visible here.

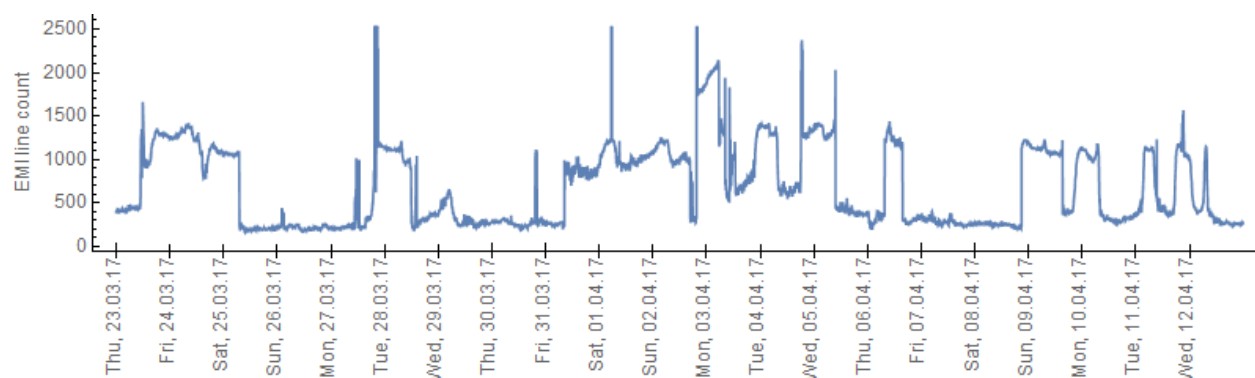


Figure 91: Number of detected single EMI lines in the longtime recording at the IfA shown in Figure 89

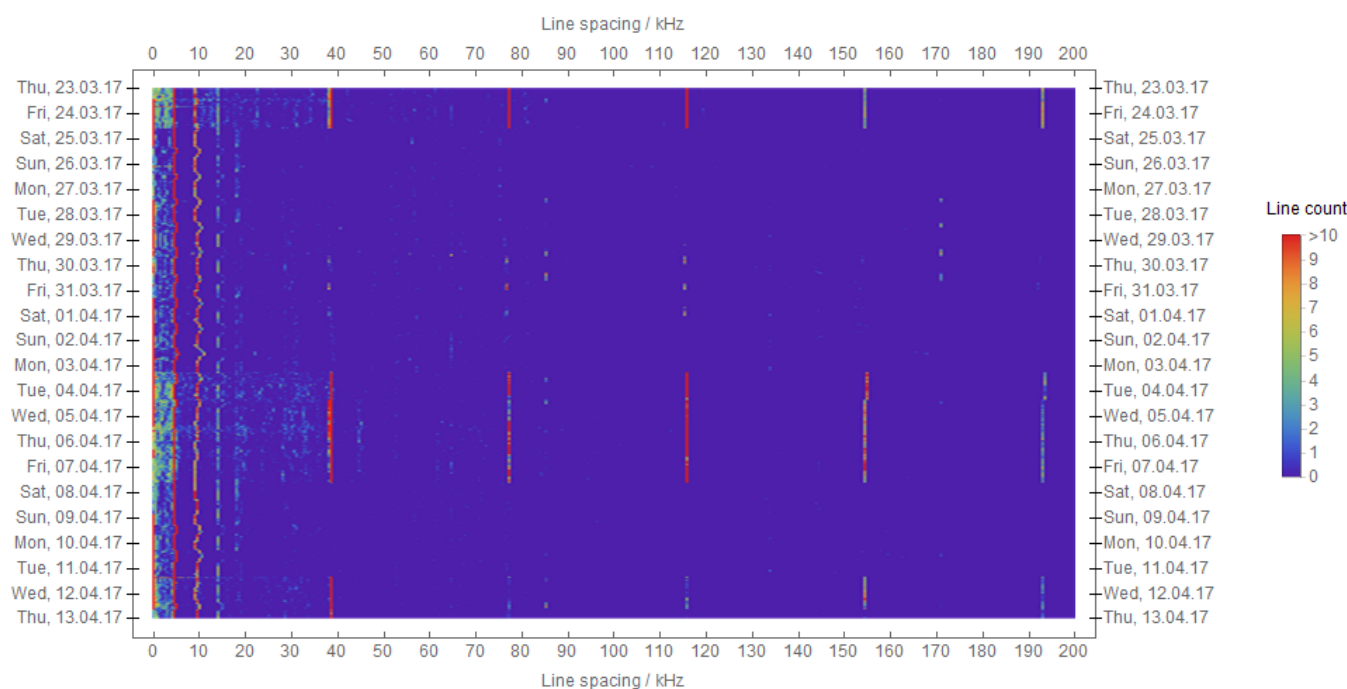


Figure 92: Distribution of the EMI line spacing in the long time recording at the IfA Figure 89

The distribution of the line spacing in Figure 92 shows that the dominant EMI between Monday April 3, 2017 and Friday April 7, 2017 is caused by a single device which has a constant line spacing of 38 kHz. It is easy to see that the EMI in the beginning and in the end of the recording is caused by the same device. This demonstrates that the method of analyzing the line spacing distribution is a very efficient way to reduce a complex EMI spectrum to an easy to read diagram, which shows the activity of different EMI sources.

5 Proposal for a EMI monitoring Project

The examined devices in chapter 4.3 cannot give a general overview of the spectral and time structure of EMI emissions into the radio astronomy frequency bands. It would be necessary to investigate a larger sample of more different devices. A huge amount of electronic devices is operated in the city of Vienna. The location of the IfA makes this site ideal for measuring the emission coming from the nearby city of Vienna.

The geographic location of the IfA is $48^{\circ} 13' 54.4''$ N, $16^{\circ} 20' 2.3''$ E. This site has an elevation of 233 m and provides a free view towards the Vienna city center. Figure 93 shows the elevation profile from the IfA located at 0 km to the Vienna city center at $48^{\circ} 12' 29.8''$ N, $16^{\circ} 22' 22.8''$ O, 172 m in a distance of 4 km and then further on to 8 km distance. The elevation from the IfA to the city center drops constantly by 61 m providing a free path propagation for electromagnetic radiation. The elevated site also reduces the mutually shading of the buildings, as it can be expected that most of the EMI are emitted from inside the buildings.

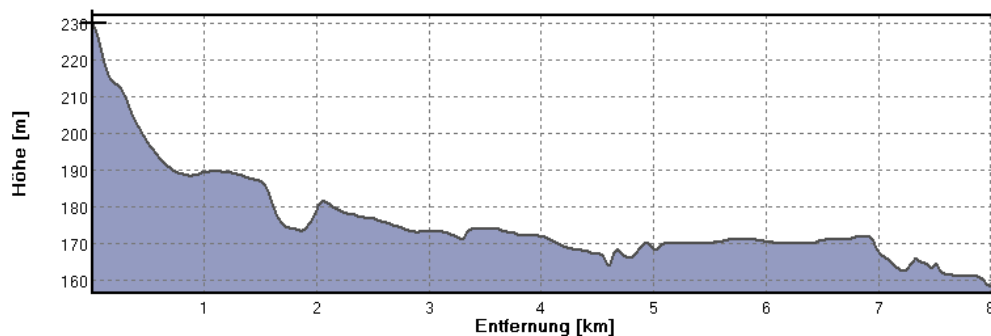


Figure 93: Elevation profile from the IfA towards the city center of Vienna in 4 km distance

To test the feasibility of a large area EMI monitoring project the low gain antenna described in chapter 3.6.2 was mounted at the roof top of the IfA as shown in Figure 39. It was pointed towards the Vienna city center in southeast direction to get a direct view of the densest populated part of the city. As shown in Figure 94 only some trees on the left side block the free sight. The pointing of the antenna is marked in Figure 95 by the 0° line and the 3 dB opening angel of the antenna is marked by the $\pm 35^{\circ}$ lines.

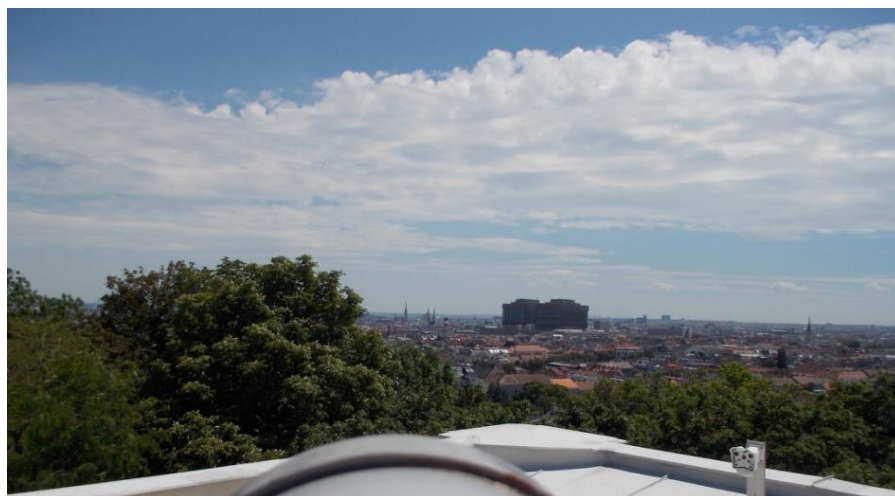


Figure 94: View of the monitoring antenna over the city of Vienna

5.1 Range of the EMI monitoring Project

The sensitivity of the monitoring system is dominated by its dark noise. The noise floor of the receiver has been measured as described in chapter 3.5. Its sensitivity for a single EMI line reaches a power level of -155 dBm at the input of the frontend amplifier. It can be converted to a minimum detectable electrical field strength at the site of the antenna by using the its gain and the equations given in chapter 1.5.

To express the receiver sensitivity in terms of distance in which an EMI source can be seen the maximal distance in which an EMI source is detectable can be calculated following the Friis transmission equation (6).

This assumes a complete free space propagation which is not realistic when the EMI sources are located inside buildings. Some sources may reach this distance when they are emitting near a window or when they are located at the outside.

For a more realistic calculation a building penetration loss (BPL) for radio waves at 1420 MHz and 1665 MHz has to be introduced. This depends on the structure and used building materials and can vary on a large scale. Measurements of BPL are widely done for mobile phone network planning. According to [13] the BPL for a comparable frequency range can vary between 6 dB and 27 dB.

Also reflections on the buildings have to be considered. They lead to multiple path propagation which can cause a cancelation of the signal at the site of the monitoring antenna. To avoid this, diversity antenna should be used but this technique is too complex to be realized within this project.

Table 17 shows the dramatic decrease of distance when a BPL of 20 dB and 30 dB is introduced. Nevertheless the maximal allowed source power for EMI emissions by MME can be seen in a distance of several kilometers. This should be enough to reach a large part of the city of Vienna.

Figure 95 shows the maximum distances for the different EMC standards which can be reached on the map of Vienna. It assumes a 30 dB BPL factor and an emission of the maximum allowed source power in a single spectral line. This looks very promising in the first place and therefore a long time monitoring project was started.

EMC standard	Source power	Free path	20 dB BPL	30 dB BPL
Class B, average	30 nW	12 km	1,2 km	400 m
Class A, average	120 nW	25 km	2,5 km	800 m
Class B, peak	3 μ W	124 km	12,5 km	4 km
Class A, peak	12 μ W	249 km	25 km	8 km

Table 17: Distances in which an EMI source can be detected when it is emitting the maximal allowed power in a single spectral line according to the EMC standards. Assuming a receiver sensitivity of -155 dBm. Distances calculated for free path propagation, 20 dB and 30 dB building penetration losses.

5.2 Measurements of the EMI arising from Vienna

The EMI monitoring project was running for a few weeks in 2017 alternately covering both radio astronomy frequency bands 1420 MHz and 1665 MHz. To reach a good sensitivity and a fair time resolution the settings given in Table 11 was used. A noise floor of -156 dBm could be reached as shown in Figure 37. The SDR14 bandwidth was 4 MHz therefore five junks between 1407 MHz and 1427 MHz have been recorded. The time resolution for one complete spectrum is five minutes. In the 1665 MHz band four junks with 3 MHz bandwidth was recorded, leading to a time resolution of four minutes.

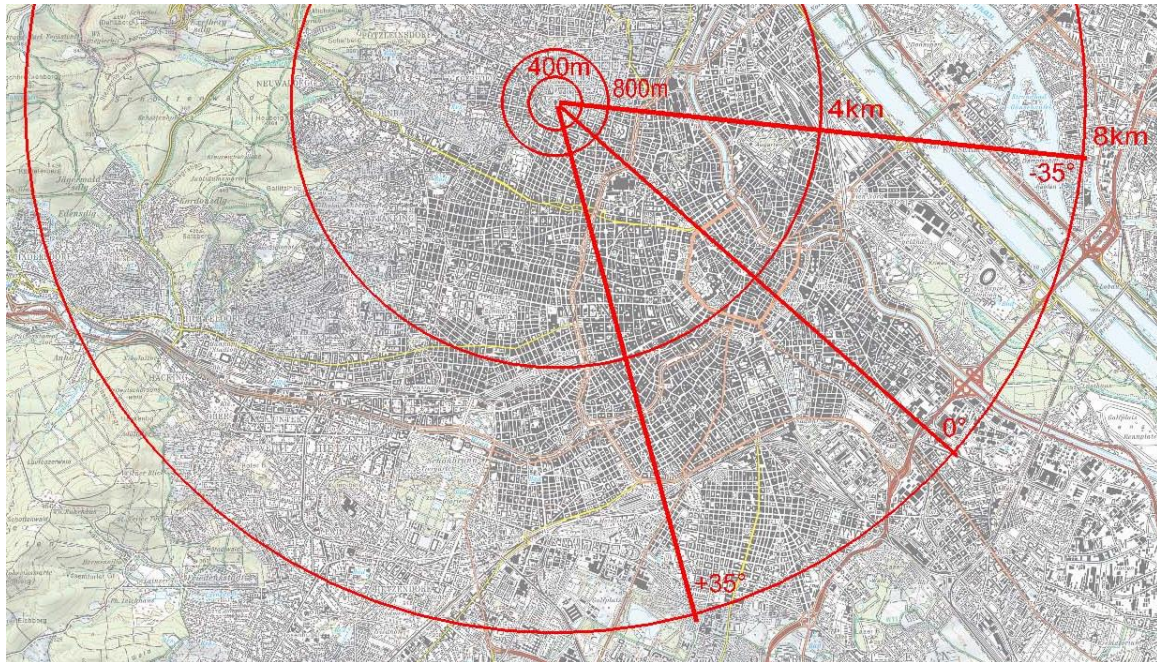


Figure 95: Direction of the EMI monitoring towards the Vienna city center. Distances are marked in which an EMI source can be detected when it is emitting the maximal allowed power according to the EMC standards in a single spectral line.

The receiving equipment was placed at the site of the MOST satellite uplink station located at the attic of the IfA building. By [15] the MOST uplink frequency is 2055 MHz and the electrical output power of the transmitter is 50 watt. The signal is broadcasted by a group of four yagi antennas with a gain of 25 dBi. The bandpass filter in the dual band frontend amplifier (see chapter 3.1) should in principal suppress this frequency. But due to the extreme proximity of the transmitter interference could not be avoided, as can be seen in Figure 96. The first amplifier gets saturated by the narrow band uplink signal which leads to an increased noise by the principle described in appendix 6.2, showing up as a broadband noise in the 1665 MHz band. The uplink transmissions appear as horizontal lines eight times a day.

IFA_GS-To-MOST_27843					
Access	Start Time (UTCG)		Stop Time (UTCG)		Duration (sec)
1	28 Jun 2017	03:02:05.173	28 Jun 2017	03:09:27.658	442.486
2	28 Jun 2017	04:39:56.863	28 Jun 2017	04:54:57.952	901.090
3	28 Jun 2017	06:20:12.496	28 Jun 2017	06:35:00.900	888.404
4	28 Jun 2017	08:01:27.734	28 Jun 2017	08:11:09.772	582.038
5	28 Jun 2017	12:55:11.549	28 Jun 2017	12:58:03.916	172.367
6	28 Jun 2017	14:28:12.761	28 Jun 2017	14:40:53.389	760.627
7	28 Jun 2017	16:06:14.266	28 Jun 2017	16:21:39.395	925.129
8	28 Jun 2017	17:48:19.168	28 Jun 2017	18:01:15.544	776.375

Table 18: Transmission log file from the MOST satellite uplink station located at the IfA on 28, June 2017

The time of the interference could be correlated with the transmission log file of the uplink station in Table 18. Besides that a lot of steady frequencies appear around 1665 MHz. These emissions are coming from the computing equipment used at the MOST uplink station. It is related to a memory bus clock frequency of one of the computers used in the MOST satellite uplink station equipment.

These interferences make that site very unfavorable for EMI monitoring in the 1665 MHz band. In the 1420 MHz band the suppression of the bandpass filter in the front end amplifier is high enough to avoid any saturation of the front end amplifier.

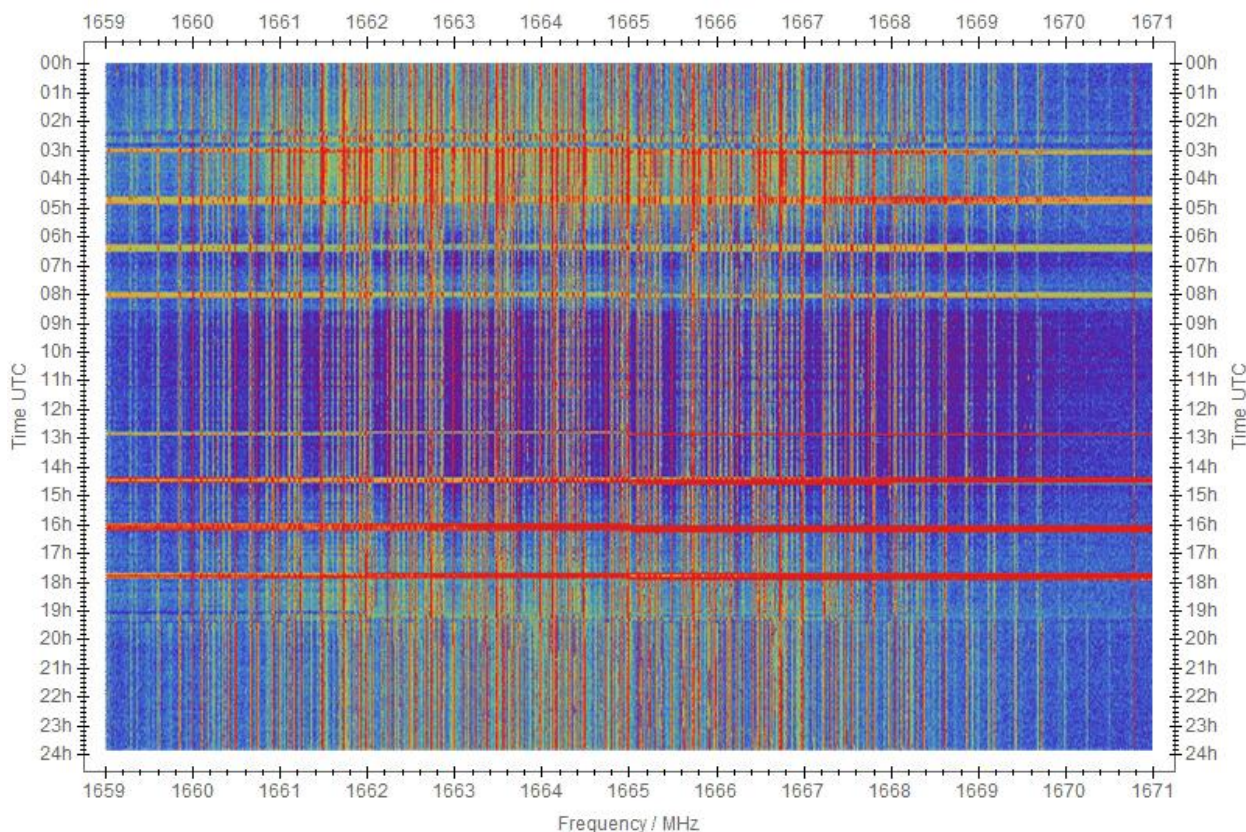


Figure 96: Recorded EMI spectrum of Vienna in the 1665 MHz band on 28, June 2017 with eight interferences from the MOST satellite uplink station appearing as horizontal lines.

As a result of the locally produced EMI by the computing equipment of the MOST satellite uplink station the longtime recorded spectrum in the 1665 MHz frequency band shown in Figure 99 is nearly useless to see any EMI coming from the city of Vienna. A more radio quiet site at the IfA building, where no electronic equipment is running, should be used for measuring the emissions coming from Vienna.

The situation is better for the recorded data in the 1420 MHz band shown in Figure 98. Also some strong spectral lines in red color which are steady over the whole recording period can be seen. These lines are also emitted by the nearby MOST uplink station equipment, which is running 24 hours a day.

Besides that the expected EMI of hundreds of sources located in the city of Vienna cannot be seen. Following the results of the IfA long time monitoring in Figure 89 it can be expected to see many different spectral structures with a correlation to the daytime. Only very few lines show this correlation and besides that some uncorrelated specs appear.

The main reason to see nearly nothing is that a typical electronic device does not reach the maximum allowed power defined in the EMC standards where the range calculation in chapter 5.1 was based on.

It was shown in chapter 4.3 that the typical electric field strength for MME is at least 50 dB below the allowed limits defined in the EMC standards. This makes it difficult to receive signals from distant sources located in the city of Vienna.

Figure 97 shows the situation for the actual reached receiver sensitivity of -155 dBm. It would be easy to see a device emitting at the maximal allowed power for MME in a single spectral line, marked by dashed and dotted lines, in a distance of several kilometers even when introducing a 30 dB BPL. But when applying a 50 dB attenuation to the source power as it was observed during the measurements of electronic devices described in chapter 4.3 the distance shrinks down to 100 meter which is not enough to see anything outside the IfA itself.

Increasing the receiver sensitivity by lowering the noise floor in the system would increase the distance in which an EMI source can be seen. As shown in Figure 36 decreasing the bandwidth of the SDR14 can lower the noise too. But this means that the time resolution is also decreased because more spectra have to be recorded to cover the same frequency range.

As the dark noise of the receiving system is dominated by the noise of the first amplifier improvements can be made by using an amplifier with a better noise figure. Also cooling of the first amplifier can decrease the noise.

These measures may increase the sensitivity by several dB but the only way to archive the amount of 40 dB is to use an antenna with very high gain. Thus a high gain is hard to reach with helical or yagi antennas. The best choice would be a parabolic mirror.

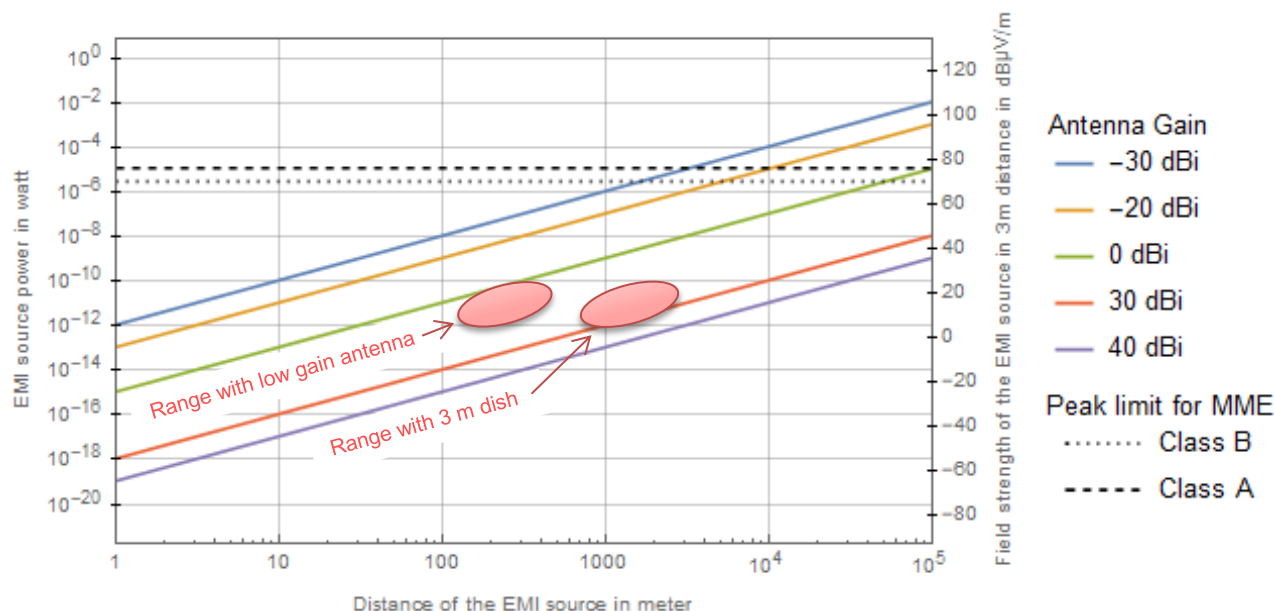


Figure 97: Distance in which an EMI source can be seen for a receiver sensitivity of -155 dBm and different antenna types marked by the red circles. The peak limits of the electric field strength according to the EMC standard for MME class A and B are marked by the dashed and dotted line.

There is already a parabolic mirror with 3 meter diameter mounted at the roof of the IfA used as a receiving antenna for the MOST satellite station. This antenna would produce a gain of 33 dBi at 1420 MHz and 34 dBi at 1665 MHz.

It would be easy to share the usage time of the 3 meter dish with the MOST downlink station and an EMI monitoring project. The MOST satellite is only visible for eight very short time slots each day. In the remaining time the 3 meter dish could observe the horizon towards the city of Vienna to record the EMI arising from the city.

As can be read out of Figure 97 at the 30 dBi antenna gain line it would be possible to detect sources which are emitting 50 dB below the EMC limits in a distance of several kilometers. Even when introducing a BPL of 20 dB indicated by the negative antenna gain line still a lot of devices should be seen in the range of several kilometers.

As an additional benefit of the directional antenna also a bearing towards the sources would be provided. With that additional information a rough situation map of the EMI sources located inside the city of Vienna could be plotted.

To realize such an EMI monitoring project all artificial emission in the 1420 MHz and 1665 MHz band have to be eliminated and a very radio quiet site at the IfA for the receiving equipment has to be found.

Receiver sensitivity	-155 dBm	-155 dBm
Antenna gain	33 dBi	33 dBi
Building penetration loss	20 dB	30 dB
Detectable field strength in 1 km	22 dB μ V/m	32 dB μ V/m
Detectable field strength in 2 km	28 dB μ V/m	38 dB μ V/m

Table 19: Detectable field strength for distant EMI monitoring with a 3 meter dish for 20 dB and 30 dB BPL

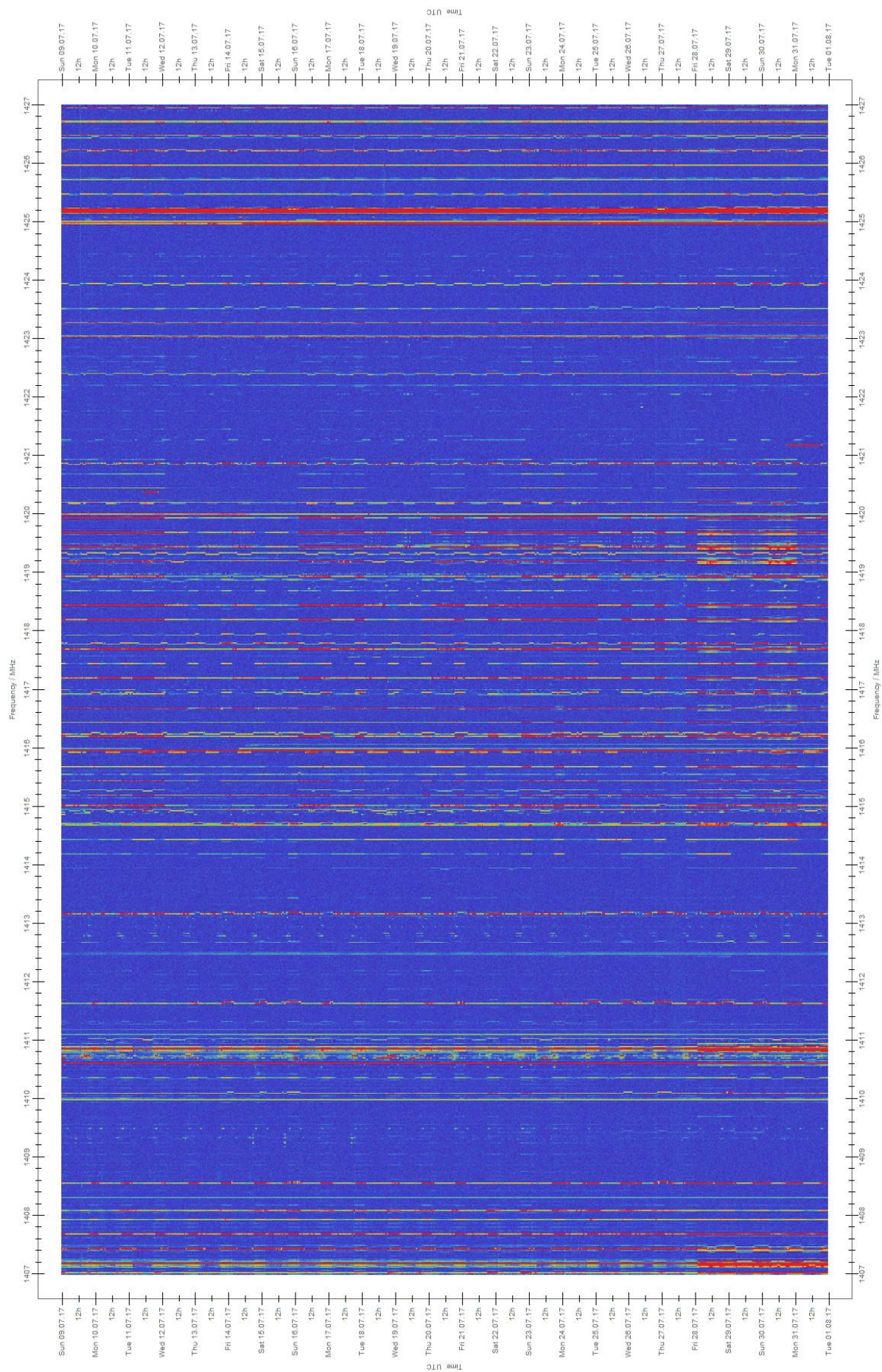


Figure 98: Recorded EMI spectrum emitted from the city of Vienna in the 1420 MHz band between July 9, 2017 and August 1, 2017

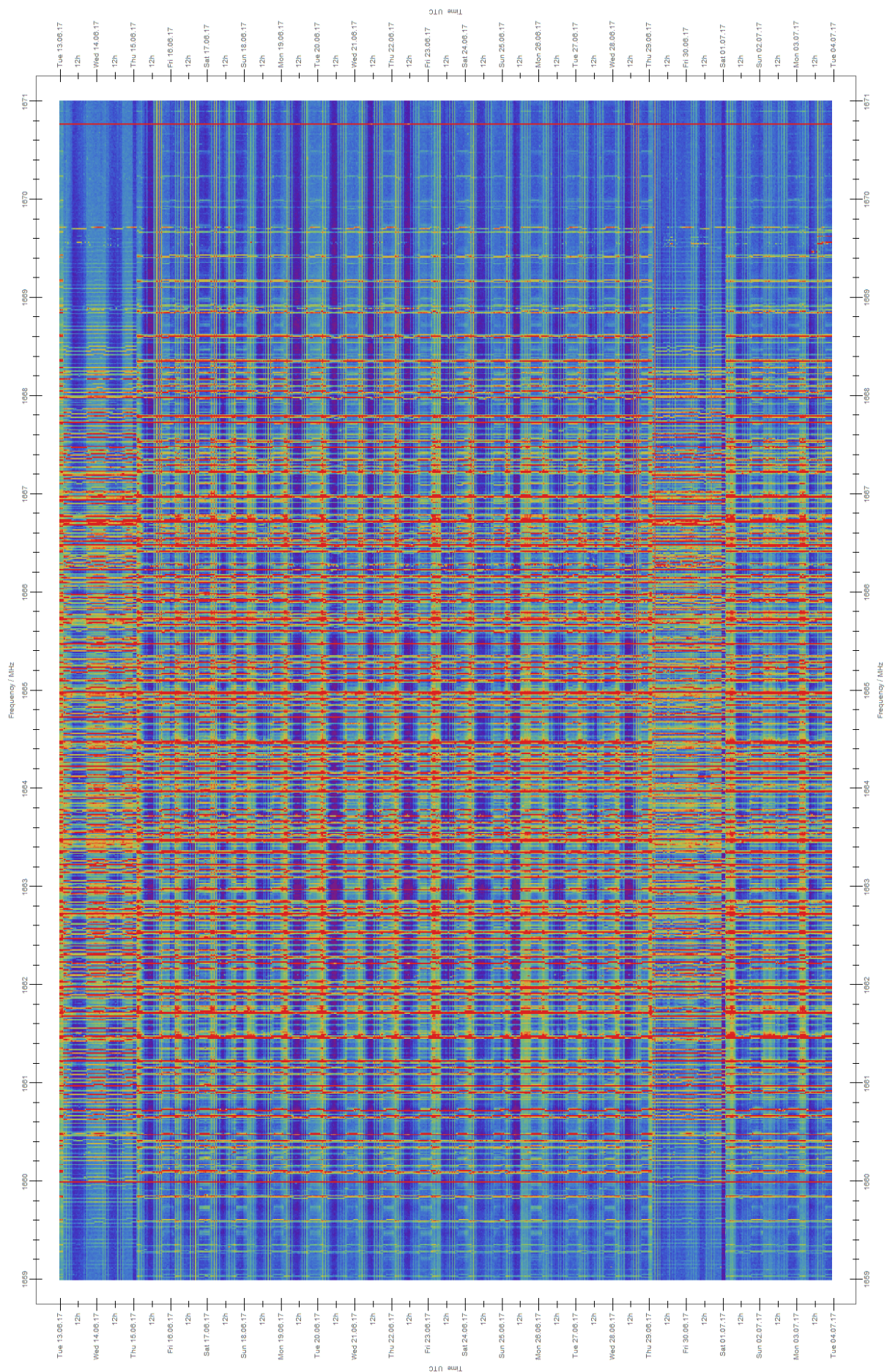


Figure 99: Recorded EMI spectrum emitted from the city of Vienna in the 1665 MHz band between June 13, 2017 and July 4, 2017

6 Appendix

6.1 Conclusion

The ongoing operation of the radio telescope at the Institute for Astrophysics showed constantly increasing electromagnetic interferences over the last years. A long time monitoring of the electromagnetic interference showed a clear correlation with typical working hours at the institute when most electronic devices are operated. The interference situation is better at night time and at the weekends.

The radio telescope has been equipped with a matched feed horn and a bandpass filter to protect the frontend amplifier of creating unwanted intermodulation products by strong out of band signals. It has been proven that with these modifications it is possible to operate a radio telescope even in an environment with strong nearby signal sources like mobile phones. The side lobe pattern of the radio telescope has been analyzed for different feed configuration against the sensitivity to electromagnetic interferences and the best configuration has been realized.

Beside intermodulation products a lot of interfering signals are emitted from electronic devices directly into the radio astronomy frequency bands which makes the bandpass filter useless. The two frequency bands 1420 MHz for neutral hydrogen observations and 1665 MHz for hydroxyl maser emissions have been monitored in the vicinity of the radio telescope. Therefore a receiver and a front end amplifier with large signal immunity for these two frequency bands have been developed.

It has been shown that the electromagnetic emissions of electronic devices which are in total compliance with the standards for electromagnetic compatibility are very strong sources of interference for the radio telescope which sensitivity to the interferences is $-34.8 \text{ dB}\mu\text{V/m}$. Several devices have been tested and their emission is on average with an electric field strength of $18 \text{ dB}\mu\text{V/m}$ in 3 meter distance 50 dB below the allowed limits in the EMC standards. Critical devices in the immediate vicinity of the radio telescope have been shielded by simple measures like wrapping it with self-adhesive copper foil what decreased the emission on average by 17 dB.

The spectral structure of many devices was analyzed and as a common feature the constant spacing between neighboring spectral lines could be identified. Based on this insight a method for analyzing the distribution of the line spacing has been introduced. The usefulness of this method for identifying and localizing a single source of interference in a complex spectrum has been demonstrated. A generic model was given which can produce similar spectra and which can provide an explanation for the origin of the observed spectral structure.

A large area monitoring project has been proposed to access a huge amount of electronic devices located in the city of Vienna. This would give a general overview of the frequency and time structure of the emissions into the radio astronomy frequency bands. The range and the feasibility of such a project have been analyzed and it was shown that with existing equipment it would be possible to reach a monitoring range of several kilometers even when applying the observed 50 dB reduction to the maximal allowed field strength defined in the standards for electromagnetic compatibility. First measurements with a low gain antenna are presented which showed the need of a more radio quiet site in the institute for such a monitoring project.

6.2 Intermodulation Products

Intermodulation is a kind of distortion which occurs between two or more different signals in active systems like amplifiers whenever the system becomes nonlinear. For example an amplifier with gain g will have the theoretical transfer function $f(x) = g * x$. This function is linear for all frequencies and amplitudes for the signal in x .

In reality an amplifier has always some limitation to the maximal possible output amplitude. This is mainly caused by the finite supply voltage, as the output signal can never exceed the supply voltage. When the gain and the input signal is high enough saturation of the amplifier occurs, which is leading to a signal distortion of the output signal. In this case the transfer function is more complex, it becomes nonlinear.

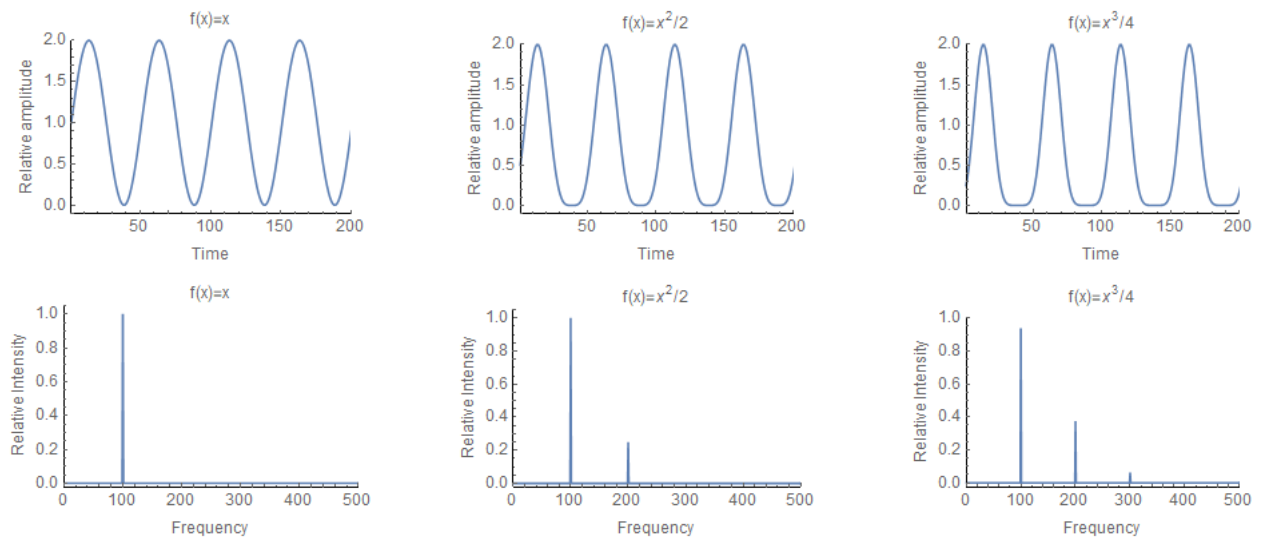


Figure 100: A sinusoidal signal in the time domain (top row) and in the frequency domain (bottom row) plotted for a linear transfer function (left), a quadratic transfer function (middle) and a cubic transfer function (right)

As long as the amplifier is working with a single sinusoidal signal a nonlinear transfer function only leads to the creation of harmonics, as the distorted signal can be decomposed into its harmonics by the Fourier series. This kind of distortion is not called intermodulation.

Figure 100 shows a simulation of the distortion of one sinusoidal signal. The signal at 100 arbitrary frequency units (left) is distorted by a quadratic transfer function (middle) and cubic transfer function (right). This can be compared to an amplifier which bias setting is too low so that it gets saturated in the small signal amplitudes. As can be seen in the spectra this leads only to the creation of harmonics in this case integer multiples of the 100 frequency units. In a real system this would not be a big problem as long as the frequency is sufficiently high so that the harmonics will fall out of the maximum frequency of the system.

The situation becomes more complex when two or more sinusoidal signals are superimposed. This is the case for nearly any artificial signal which is carrying some kind of information. Figure 101 shows two superimposed sinusoidal signals at the same amplitude level with 100 and 120 arbitrary frequency units. As the quadratic transfer function (middle) is applied an amplitude modulation pattern occurs in the frequency spectrum. This leads to additional frequency components at 20, 200, 220 and 240 frequency units at lower intensity than the main signals. The difference frequency between the two main signals appears around any harmonic signal with the two sidebands of an amplitude modulation. Therefore this behavior is called intermodulation.

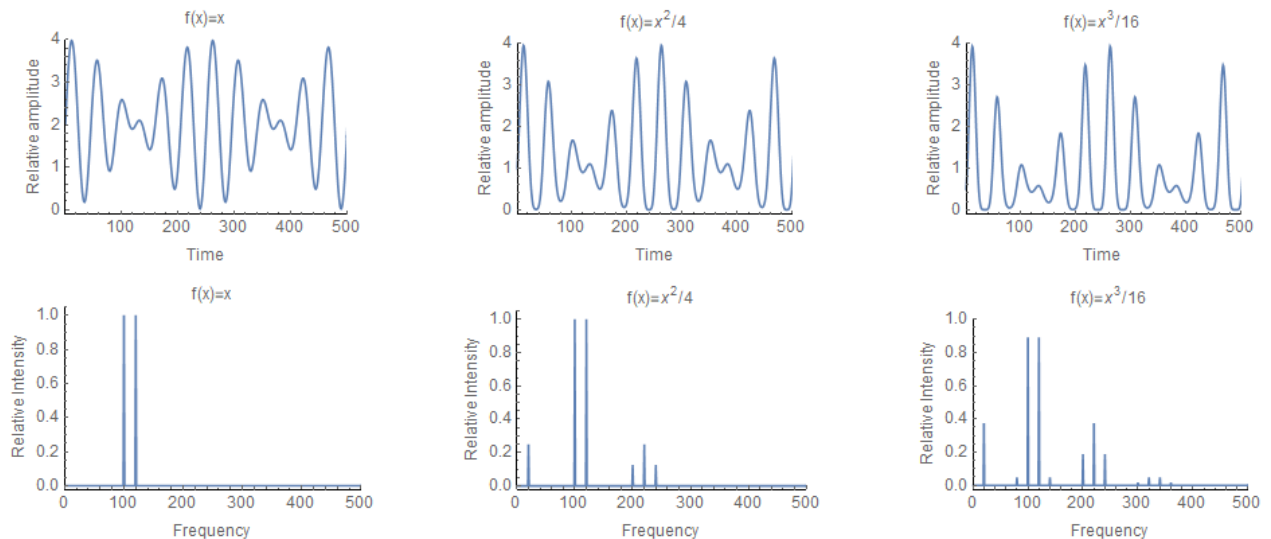


Figure 101: Two superimposed sinusoidal signals in the time domain (top row) and in the frequency domain (bottom row) plotted for a linear transfer function (left), a quadratic transfer function (middle) and a cubic transfer function (right)

When the active semiconductor components in a real amplifier get saturated the transfer function can become very complex involving highest order of distortion. Additionally an amplifier usually has to deal with more than two strong signals, where the situation gets even worse.

In Figure 102 five signals between 100 and 200 frequency units are distorted by a second, third and fifth order transfer function. With higher orders more and more intermodulation products occur in the spectrum. In a system with many superimposed signals and a highly distorted signal this leads to intermodulation products at nearly any frequency making the amplifier useless for identifying a single signal occurring at the input.

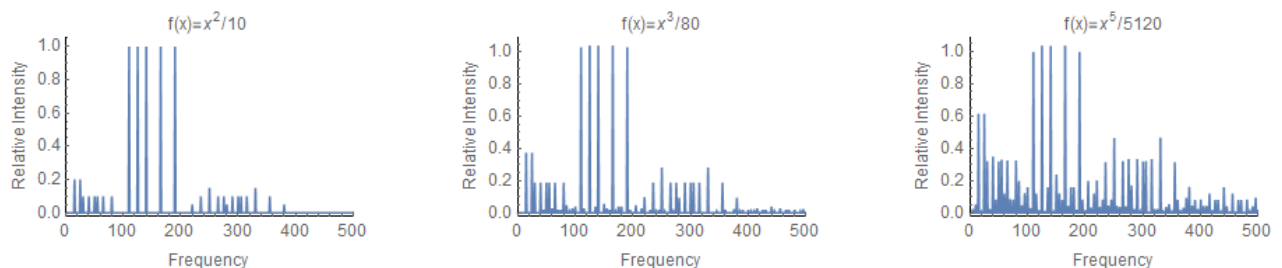


Figure 102: Five sinusoidal signals between 100 and 200 frequency units distorted by transfer function of second order (left), third order (middle) and fifth order (right)

To avoid intermodulation the amplifier has to be protected from strong signals. This can be done by limiting the frequency range to a narrow bandwidth which is sufficient low that only the wanted signal can pass through. This can be achieved by connection a bandpass filter at the input of the amplifier. A filter with a low insertion loss has to be used, as the attenuation in the filter increases the signal to noise ratio of the amplifier.

6.3 Power matching and reflected Power

In high frequency systems power matching is a very important concept to achieve a lossless signal transfer. Figure 103 left shows the principle of power matching in a simple direct current (DC) circuit. The greatest amount of power is transferred from the source V1 to the load RL when the inside resistance RI of the source is equal to the load resistance RL.

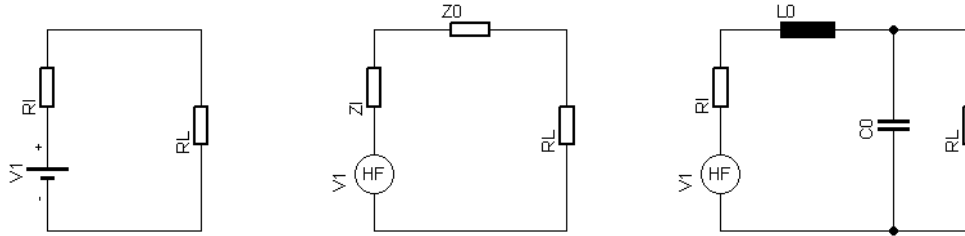


Figure 103: Power matching for a DC circuit (left), a HF circuit (middle) and in an equivalent circuit diagram for the transmission line (right)

In an high frequency circuit shown in Figure 103 (middle) the inside resistance RI is replaced by the complex impedance ZI and the characteristic impedance Z_0 of the transmission line has also to be taken into account. Z_0 can be calculated following equation (18), where C_0 is the capacitance of the transmission line in open circuit and L_0 is the inductance of the transmission line in short circuit like it is shown in the equivalent circuit diagram for a transmission line in Figure 103 right. Z_0 is therefore independent of the frequency and mainly caused by the geometrics to the transmission line. It is usually standardized to 50 Ω .

$$Z_0 = \sqrt{\frac{L_0}{C_0}}$$

(18)

Power matching in the HF circuit means that all impedances have to be the same. The greatest amount of power from the source V1 is transported to the load RL if $Z_I = Z_0 = R_L$. If this is not the case a part of the power will be temporary stored in the reactive components L_0 and C_0 of the transmission line and transported back to the source V1 this is called reflected power P_R .

The quality of the load matching is described by the return loss R defined in equation (19) by the logarithmic unit dB where P_F if the forward power drawn out of the source and P_R is the power which is reflected back to the source.

$$R_{[dB]} = 10 \text{ Log } \frac{P_F}{P_R}$$

(19)

For example in a system with a return loss R of 10 dB there is 1/10 of the forward power P_F reflected back to the source. This power is lost as it cannot reach the load. A typical return loss in a well matched circuit should be better than 10 dB.

6.4 Summary

This master thesis is about the influence of electromagnetic interference on radio telescopes. A small radio telescope with 2.3 meter dish diameter was modified with a bandpass filter and a narrow band feed so that it remains functional in an environment with strong interfering signals. The sensitivity of the radio telescope to electromagnetic interference was analyzed.

A broadband receiver with large signal immunity was developed for monitoring the electromagnetic interference in the two radio astronomical frequency bands 1420 MHz and 1665 MHz. Emissions from electronic equipment operating near the radio telescope has been measured and compared to then electromagnetic compatibility standards. Measures to shield these devices were taken and the improvement documented.

A project for large area monitoring of the electromagnetic emissions emanating from the city of Vienna into the radio astronomical frequency bands is proposed. Long term measurements were carried out to assess the feasibility and range of such a monitoring.

6.5 Kurzfassung

Diese Masterarbeit befasst sich mit dem Einfluss von elektromagnetischen Störungen auf Radioteleskope. Ein kleines Radioteleskop mit 2.3 Meter Spiegeldurchmesser wurde durch einen Bandpassfilter und ein schmalband Feed so modifiziert dass es in einer Umgebung mit starken Störsignalen weiter funktionsfähig bleibt. Die Empfindlichkeit des Radioteleskops gegenüber von Störsignalen wurde analysiert.

Es wurden ein breitbandiger Empfänger und ein großsignalfester Vorverstärker für die Überwachung von elektromagnetischen Störungen in den zwei radioastronomischen Frequenzbändern 1420 MHz und 1665 MHz entwickelt. Die Störaussendungen von elektronischen Geräten, die in der Nähe des Radioteleskops in Betrieb sind wurde gemessen und mit den Normen für die elektromagnetische Verträglichkeit verglichen. Maßnahmen zur Abschirmung dieser Geräte wurden ergriffen und die Verbesserung dokumentiert.

Es wurde ein Projekt zur großflächigen Überwachung der von Wien ausgehenden elektromagnetischen Störungen in den radioastronomischen Frequenzbändern vorgeschlagen. Erste Langzeitmessungen wurden durchgeführt und die Reichweite einer solchen Überwachung wurde abgeschätzt.

6.6 List of Figures

Figure 1: Two HI observations of the Milky Way galaxy disturbed by EMI of different strength	3
Figure 2: Alignment of the magnetic moments of the proton and the electron in the hydrogen atom	4
Figure 3: Frequency usage by telecommunication in Austria 2018.....	8
Figure 4: Block assignment in the LTE 1500 MHz band (reprinted [7]).....	8
Figure 5: The small radio telescope operated by the institute for astrophysics at the Vienna university	14
Figure 6: Sky map at the SRT site with the horizon line in pink and the clear field of view in white.	14
Figure 7: Circuit diagram of the modified frontend assembly of the SRT.....	15
Figure 8: Modified frontend assembly of the SRT with WLA15-3525A low noise amplifier	16
Figure 9: Primary focus assembly with original amplifier mounted at the SRT	17
Figure 10: Dimensions of the can antenna used as a dish feed for the SRT	17
Figure 11: Circuit diagram and inside view of the two cavity bandpass filter for 1420 MHz	18
Figure 12: Forward transmission (left) and input matching (right) of the two cavity bandpass filter	19
Figure 13: Detail of the forward transmission (left) and input matching (right) of the two cavity bandpass filter ...	19
Figure 14: Theoretical antenna diagram in isotropic antenna gain (dBi) for a 2.3 meter dish at 1420 MHz	21
Figure 15: Critical distances in which the SRT sees an EMI source in the nearest part of the building	22
Figure 16: Theoretical antenna diagram (right) for a 2.3 meter dish at 1420 MHz.....	23
Figure 17: Setup used for measuring the antenna diagram of the can antenna	23
Figure 18: Measured antenna diagram for the can antenna used as dish feed for the SRT	24
Figure 19: Dimensions given in millimeter for the SRT main dish and feed configuration	25
Figure 20: Synthesized antenna diagram (right) for the SRT.....	25
Figure 21: Theoretical antenna diagram derived by the airy function	26
Figure 22: Dual band frontend amplifier used for EMI monitoring mounted in a waterproof housing	27
Figure 23: Circuit diagram of the dual band frontend amplifier used for EMI monitoring	27
Figure 24: Forward transmission (left) and input matching (right) of two amplifiers ZX60-1614LNS	28
Figure 25: Setup for measuring the input matching	29
Figure 26: Setup for measuring the forward transmission	29
Figure 27: Forward transmission of the dual band frontend amplifier	30
Figure 28: Detail of the forward transmission around 1.55 GHz (left) and input matching (right)	30
Figure 29: Inside view of the receiver used for EMI monitoring	31
Figure 30: Circuit Diagram of the receiver used for EMI monitoring.....	32
Figure 31: Dark noise of the receiver with switch mode power supply	32
Figure 32: Dark noise of the receiver with linear regulated power supply	32
Figure 33: Setup for calibrating the receiving system to the known output level of the signal generator	33
Figure 34: Frequency response of the dual band frontend amplifier	34
Figure 35: Calibrated frequency response for 1420 MHz (left) and 1665 MHz (right)	34
Figure 36: Receiver dark noise for different bandwidths settings of the digital downconverter AD6620	35
Figure 37: Noise floor of the dual band frontend amplifier and a -130 dBm signal at 1420 MHz	35
Figure 38: Omnidirectional antenna and dual band frontend amplifier	37
Figure 39: Directional antenna and frontend amplifier mounted at the roof of the IfA building	37
Figure 40: Output matching of the Sigma SE-1500 omnidirectional antenna	38
Figure 41: Output matching of the L-band LHCP dish feed helical antenna	39
Figure 42: Measured antenna diagram and airy pattern fit for the L-band LHCP dish feed helical antenna	39
Figure 43: Frequency usage at the site of the SRT recorded with an omnidirectional antenna	40
Figure 44: Electrical field strength in 3 meter distance to the SRT receiver	41
Figure 45: Continuum map between 1400 MHz and 1427 MHz of the surrounding at the SRT site	42
Figure 46: Data reduction process for EMI line counting, raw data left and calibrated data right	43
Figure 47: Number of detected EMI lines between 1400 MHz and 1427 MHz in the surrounding of the SRT	44
Figure 48: Selected spectra from the hotspot at azimuth position 330°	44
Figure 49: Selected spectra from the hotspot at azimuth position 80°	44

Figure 50: EMI occurring during two HI observation with the SRT of the Milky Way galaxy	45
Figure 51: Part of the IfA building with the compass dial showing the location of the SRT	46
Figure 52: Azimuthal scan (left) and elevation scan (right) for the EMI source at 1420 MHz	46
Figure 53: Electric field strength of the CHEOPS computing equipment	46
Figure 54: EMI of the CHEOPS computing equipment received by the SRT.....	46
Figure 55: The GR712 SparcV8 processor evaluation board with removed front cover	47
Figure 56: 360° azimuthal scan with the SRT, AXIS 211 webcam on	48
Figure 57: 360° azimuthal scan with the SRT, AXIS 211 webcam off.....	48
Figure 58: Electrical field strength in 3 meter distance of a Dell U2715H flat screen monitor	50
Figure 59: Electric field strength in 3 meter distance of Samsung S23A300B flat screen monitor	50
Figure 60: Electric field strength in 3 meter distance of Antec computer	50
Figure 61: Electric field strength in 3 meter distance of HP2760 laptop	50
Figure 62: Electric field strength in 3 meter distance of AR3000A radio receiver	51
Figure 63: Electric field strength in 3 meter distance of FP222W flat screen monitor.....	51
Figure 64: Electric field strength in 3 meter distance of DG4162 signal generator.....	51
Figure 65: Electric field strength in 3 meter distance of HM8135 signal generator.....	51
Figure 66: Electric field strength in 3 meter distance when complete CHEOPS computing equipment is running ..	52
Figure 67: Electric field strength in 3 meter distance of GR712 evaluation board only.....	52
Figure 68: Electric field strength in 3 meter distance when both CHEOPS computers are running	52
Figure 69: Electric field strength in 3 meter distance when both CHEOPS computers are switched off	52
Figure 70: Electric field strength in 3 meter distance of the SRT server computer	53
Figure 71: Electric field strength in 3 meter distance of the SQM server computer	53
Figure 72: Distribution of peak electric field strength in 1420 MHz band (left) and 1665 MHz band (right)	54
Figure 73: Distribution of the frequencies with maximum field strength	54
Figure 74: Shielded webcam next to the SRT (left) and shielded sky quality meters (right).....	56
Figure 75: Electric field strength in 3 meter distance of AXIS 211 webcam.....	57
Figure 76: Electric field strength in 3 meter distance of AXIS 211 webcam after shielding	57
Figure 77: Electric field strength in 3 meter distance of sky quality meter one	57
Figure 78: Electric field strength in 3 meter distance of sky quality meter one after shielding	57
Figure 79: Electric field strength in 3 meter distance of sky quality meter two	58
Figure 80: Electric field strength in 3 meter distance of sky quality meter two after shielding	58
Figure 81: Normalized and flattened spectrum in the 1420 MHz band (top) and 1665 MHz (bottom).....	60
Figure 82: Distribution of the line spacing between neighboring detected peaks	61
Figure 83: Normalized and flattened spectrum in the 1420 MHz band (top) and 1665 MHz (bottom).....	61
Figure 84: Distribution of the line spacing between neighboring detected peaks	62
Figure 85: Digital white noise in the time domain (top) and frequency domain (bottom).....	63
Figure 86: Sequence of four identical blocks containing 64 bits of digital white noise	64
Figure 87: Frequency spectrum of the linear congruency random generator	64
Figure 88: Frequency spectrum of the linear congruency random generator	65
Figure 89: Recorded EMI spectra at the IfA in the 1420 MHz band.....	67
Figure 90: Recorded EMI spectra at the IfA in the 1665 MHz band.....	68
Figure 91: Number of detected single EMI lines in the longtime recording at the IfA shown in Figure 89	69
Figure 92: Distribution of the EMI line spacing in the long time recording at the IfA Figure 89	69
Figure 93: Elevation profile from the IfA towards the city center of Vienna in 4 km distance	70
Figure 94: View of the monitoring antenna over the city of Vienna	70
Figure 95: Direction of the EMI monitoring towards the Vienna city center.....	72
Figure 96: Recorded EMI spectrum of Vienna in the 1665 MHz band	73
Figure 97: Distance in which an EMI source can be seen for a receiver sensitivity of -155 dBm	74
Figure 98: Recorded EMI spectrum emitted from the city of Vienna in the 1420 MHz band	76
Figure 99: Recorded EMI spectrum emitted from the city of Vienna in the 1665 MHz band	77
Figure 100: A sinusoidal signal in the time domain (top row) and in the frequency domain (bottom row)	79
Figure 101: Two superimposed sinusoidal signals in the time domain (top row) and in the frequency domain	80

Figure 102: Five sinusoidal signals between 100 and 200 frequency units distorted by transfer function.....	80
Figure 103: Power matching for a DC circuit (left), a HF circuit (middle) and in an equivalent circuit diagram	81

6.7 List of Tables

Table 1: Maser emission frequencies in the ground state and first excited state of the OH molecule from [1]	5
Table 2: Important spectral lines in radio astronomy and reserved bandwidth between 1 GHz and 2 GHz	7
Table 3: A selection from [5] of frequency ranges reserved for passive use by radio astronomy	9
Table 4: Limits for the electric field strength in a distance of 3 m for the frequency range 1 GHz to 3 GHz	10
Table 5: Maximum allowed electric field strength in 3 meter distance to the device	12
Table 6: Performance characteristics of the WLA15-3525A low noise amplifier	15
Table 7: Performance characteristics of the SRT after modification	16
Table 8: Performance characteristics of the SRT frontend bandpass filter	19
Table 9: Calculated antenna characteristics of the SRT for different feed configurations	25
Table 10: Performance data of the dual band frontend amplifier used for EMI monitoring	30
Table 11: SDR14 settings for long time recording and high sensitivity	35
Table 12: Specifications of the Sigma SE-1500 omnidirectional antenna	37
Table 13: Specifications of the of L-band LHCP dish feed helical antenna	38
Table 14: The highest numbers of counted EMI lines in the two hotspots at azimuth 80° und 330°	43
Table 15: Peak electric field strength in 3 meter distance for both frequency bands and all measured devices	53
Table 16: Reduction of the peak electric field strength for all shielded devices	58
Table 17: Distances in which an EMI source can be detected	71
Table 18: Transmission log file from the MOST satellite uplink station located at the IfA on 28, June 2017	72
Table 19: Detectable field strength for distant EMI monitoring with a 3 meter dish	75

6.8 Abbreviations

ADC	Analog to Digital Converter
ADU	Analog to Digital Unit
BNC	Bayonet Neill Concelman connector
BPL	Building Penetration Loss
BRITE	BRight Target Explorer satellite
CEPT	European Conference of Postal and Telecommunications Administrations
CHEOPS	CHAracterising ExOPlanet Satellite
DC	Direct Current
dBd	Decibel related to a dipole antenna
dBFS	Decibel related to Full Scale
dB _i	Decibel related to an isotropic antenna
dBm	Decibel related to a power of 1 mW
dB μ V	Decibel related to a voltage of 1 μ V
dB μ V/m	Decibel related to a field strength of 1 μ V/m
dBW	Decibel related to a power of 1 W
DVI	Digital Visual Interface
ECC	Electronic Communications Committee
EMC	Electro Magnetic Compatibility
EMI	Electro Magnetic Interferences
ETS	European Test Services
FFT	Fast Fourier Transformation
GLON	Galactic Longitude
GSM	Global System for Mobile communications
HDMI	High Definition Multimedia Interface
HI	Neutral Hydrogen
HII	Ionized Hydrogen
HF	High Frequency
IAU	International Astronomical Union
IfA	Institute for Astrophysics
LOFAR	Low Frequency Array, network of radio telescopes
LTE	Long Term Evolution, high speed wireless standard
MASER	Microwave Amplification by Stimulated Emission of Radiation
MME	Multimedia Equipment
MOST	Microvariability and Oscillations of STars satellite
LO	Local Oszillator
OH	Hydroxyl radical molecule
RF	Radio Frequency
RBW	Resolution Bandwidth
RTR	Austrian Regulatory Authority for Broadcasting and Telecommunication
SDR	Software Defined Radio
SMA	Sub Miniatur type A connector
SNR	Signal to Noise Ratio
SQM	Sky Quality Meter
SRT	Small Radio Telescope
TETRA	Terrestrial Trunked Radio
UKW	Ultra Short Wave
UMTS	Universal Mobile Telecommunication System
VLSR	Velocity relative to the Local Standard of Rest
VSWR	Voltage Standing Wave Ratio
WLAN	Wireless Local Area Network

6.9 References

- [1] R. Cesaroni, C.M. Walmsley, OH maser models revisited, Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-5300 Bonn, July 6, 1990.
- [2] F. S. B.F. Burke, An Introduction to Radioastronomy, Cambridge University Press, 1997.
- [3] J. D. Kraus, Radio Astronomy, Cygnus-Quasar Books, 1986.
- [4] National Research Council, Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses, Washington, DC: The National Academies Press.
- [5] BGBl. II Nr.63/2014, Verordnung der Bundesministerin für Verkehr, Innovation und Technologie betreffend die Frequenznutzung (Frequenznutzungsverordnung 2013 - FNV 2013), Vienna, 2014.
- [6] Electronic Communications Committee (ECC), Report from CEPT to the European Commission in response to the Mandate "To develop harmonised technical conditions in the 1452-1492 MHz frequencyband for wireless broadband electronic communications services in the EU", November 2014.
- [7] Austrian Regulatory Authority for Broadcasting and Telecommunications (RTR), The harmonised use of the frequency bands 1427-1452 MHz and 1492-1518MHz for Mobile/Fixed Communications Networks Supplemental Downlink, Mariahilfer Straße 77-79, 1060 Vienna, Austria, November 2017.
- [8] European harmonized standard, EN 55032 CISPR 32, Electromagnetic compatibility of multimedia equipment - Emission requirements.
- [9] M. Japp, M. Christos, R.J. Baptiste, M. Christos, CHEOPS Units EMC Test at ETS/ESTEC, Noordwijk, Netherlands: ESTEC test center, July 2016.
- [10] H. Vogel, Gerthsen Physik, Berlin: Springer, 1995.
- [11] J. A. Shaw, Radiometry and the Friis transmission equation, Montana State University, Bozeman, Montana 59717, July 2011.
- [12] U. Klein, Radio astronomy, tools applications and impacts, Bonn: Argelander Institut for Radioastronomy, January 2006.
- [13] D. Micheli, A. Delfini, M. Marchetti, P. Gianola, G. Bertin, R. Diana, Measurements of the Outdoor-To-Indoor Attenuation of Mobile Phone Signal, Roma Italy, December 2014.
- [14] S. Scholl, Exact Signal Measurements using FFT Analysis, Microelectronic Systems Design Research Group, TU Kaiserslautern, Germany.
- [15] W. Keim, A. L. Scholtz, PERFORMANCE AND RELIABILITY EVALUATION OF THE S-BAND VIENNA SATELLITE GROUND STATION, Vienna: University of Technology, 2006.

