Astronomy Lab

R) Radio Astronomy

Supervisor: Katharina Schreyer
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Astro internship experiment

Radio astronomy

Astrophysicalical Institute and University Observatory Jena, Schillergäßchen 2

Katharina Schreyer, Frank Perner, Reiner Bark

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This practical experiment is intended to provide an insight into the special features of radio astronomical measurements. One aim of this experiment is to measure the kinematics of the gas clouds in the galactic plane. The aim is to map the 21 cm HI line in the visible area of the sky. Furthermore, the angular resolution of the telescope must be determined, using the sun as a "point source". As an additional task, you can search for the radio radiation of suitable celestial objects.

1. Tasks

1.1 Determine the half width of the antenna lobe!
1.2 Map the sun and determine its size in comparison to the optically visible extent!
1.3 Map the HI line along the plane of the Milky Way and compare the spectra with the results of known surveys! Create a position-velocity map of the HI emission along the Milky Way plane!
1.4 (Additional task for those interested) Investigate the radio emissions of other objects of your choice!

2. Fundamentals

2.1 History

James Clerk Maxwell's 1870 predictions of electromagnetic waves and Heinrich Hertz's proof of their existence in 1888 led many scientists to speculate at the end of the previous century whether celestial bodies, like our sun and stars in general, also emit radio waves. Sir Oliver J. Lodge (1851-1940) began to think at the end of the 19th century that the sun does not only emit radiation in the optical wavelength range. He took the view that the solar spectrum should go further in the red and blue areas. With the help of galvanometric measuring methods, he made the first attempts to detect the radiation of the sun. However, at the time, the sensitivity of the devices was orders of magnitude too low. In addition, the sun was still at an activity minimum.

Years later, the US physicist and radio engineer Karl Guthe Jansky (born October 22, 1905 in Norman, Oklahoma) discovered cosmic radio emissions by chance. He worked at Bell Telephone Laboratories and was supposed to research interference signals in the shortwave band for improved transatlantic telephone contact. For this he built a directional antenna (Jansky's merry-go-round; Fig. 1), with which he identified three different sources of interference in 1932: nearby thunderstorms, the common radiation of distant thunderstorms and an obvious extraterrestrial source, the maximum of which is repeated every day, but each 4 minutes earlier than the previous day. This time shift led him to the realization that the cosmic source of the radio signal had to be outside the solar system! Furthermore, a little later he discovered that his devices displayed a maximum deflection when driving through the constellation "Sagittarius" (today we know that the center of our Milky Way lies in this direction). Jansky summarized his results and published them in the New York Times in 1933 (May 5, 1933). Karl Jansky was well aware of the importance of his discovery, but he did not have the financial means for further research. It was not until the communications engineer Grote Reber became interested in Jansky's discovery and he built his own radio telescope (Fig. 2), the first parabolic antenna, by 1937. With this telescope he scanned the observable sky at different frequencies (λ = 0.5m, 1.9m) in the radio range. By 1941 he was able to carry out a complete survey, and with a few additions, he finally published his data in 1943. James Stanley Hey, a British pioneer in radar research, specifically for radar countermeasures during World War II, discovered radio emissions from sunspots in 1942. In 1944 the two Dutch astronomers Jan Hendrik Oort and Hendrik van de Hulst considered that the 21cm line of atomic hydrogen was a potentially measurable radio spectral line, the actual proof of which six years later a new research era, spectroscopy in the mm and submm range, initiated. After the end of World War II in 1945, the Allies prohibited any kind of research in the field of radio measurement technology. After the withdrawal of all army troops from the occupied territories in Europe, many radar antennas of the "Würzburg giant" type remained. These have been converted into radio telescopes by many European countries, as the parabolic mirror was particularly suitable for such purposes. Regular research was resumed in Germany from 1950, e.g. at the Heinrich Hertz Institute in Berlin-Adlershof by Otto Hachenberg and at the University of Kiel by Albrecht Unsöld. Milestones of research in Germany in 1956 were the astropeiler, a

25m radio telescope near Bad Münstereifel and in 1972 the commissioning of the 100m radio telescope in Effelsberg of the Max Planck Institute for Radio Astronomy (1966) in Bonn, which is still involved in current research today.

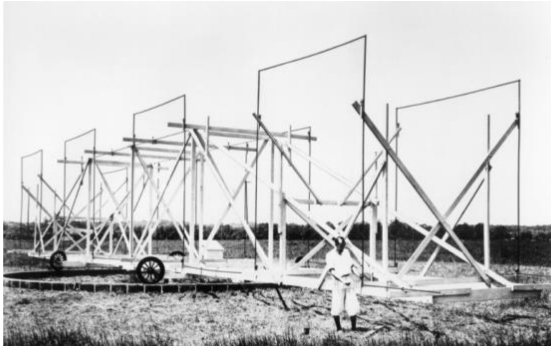


Fig. 1. Jansky's merry-go-round

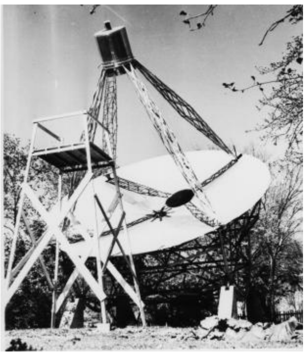


Fig. 2. Reber´s Radiotelescope

Fig. 3. *„Würzburger Riese“*
∅ 7.5m, Franse Douvres (Netherlands)

Fig. 4. ALMA: Interferometer made up of a total of 66 precision antennas, which can be up to 16 kilometers apart.

Compared to optical astronomy, radio astronomy had poor spatial resolution θ, as this is always a function of the wavelength λ ($\theta \approx \lambda/d$) divided by the "dish diameter" d of the parabolic antenna. Sir Martin Ryle (1918-1984) received the Nobel Prize in 1974 because he developed radio interferometry together with aperture synthesis at the University of Cambridge to significantly improve spatial resolution. In the meantime, high-resolution radio interferometers such as the Extended Very Large Array (EVLA) in New Mexico, the NOrthern Extended Millimeter Array (NOEMA) in the French Alps, the Low Frequency Array (LOFAR, with a station in Tautenburg close by Jena) or the Atacama Large Millimeter array (ALMA, Fig. 4) operate in the Chilean high Andes. These highly modern and complex hi-tech observation instruments have provided much more detailed knowledge about cosmic objects and their cycles in recent years. The future of radio interferometry lies not only with ever larger base lengths of the interferometer (diameter of the earth, basisline earth-moon) and ever shorter wavelengths, but also with the metrological development of very long-wave radiation ranges. The appearance of the universe at wavelengths longer than 100m is also almost unknown and may still hold interesting surprises. The exploration of the first "visible" minutes and hours of the very early universe (when it began to become transparent for electromagnetic radiation) will contain interesting details about the formation, since all information from this time is shifted in a straight red to the Radio area. But even the individual telescopes can now grow to ever larger dimensions with modern materials and construction techniques. It was not until 2016 that the world's largest single-dish radio telescope, the Fivehundredmeter Aperture Spherical radio Telescope (FAST, d = 500m), went into operation in China.

2.2 Radio astronomical basics

A more extensive treatment of the basics of radio astronomy can be found in Wilson, Rohls, Hüttenmeister "Tools of Radio Astronomy". Only the most important terms that are necessary to understand the experiment are to be briefly outlined here.

Radiation intensities

In honor of Karl G. Jansky, the unit „Jansky“ for the intensity of the flux radiation density was introduced in radio astronomy. The radiation intensities of many astronomical sources are so low that the unit W / m2 / Hz is too impractical, since very large exponents would have to be managed. So the unit for the spectral flux density became

$$\textbf{1 Jansky [Jy]} \quad = \quad \mathbf{10^{-26}\ W/m^2/Hz/sr}\ .$$

Typical values are e.g. at λ= 21cm ($\triangleq$ ν = 1.4 GHz):

500 000 Jy - Sun
2400 Jy - Cas A, Supernova- Remnant
1500 Jy - Cyg A, 3C405, Radio galaxy
810 Jy - Tau A, crab nebula
22 Jy - Radio galaxy 3C147
4 Jy - Jupiter

The unit Jy is used on the one hand for measuring broadband continuum radiation, but is also often used for interferometric line measurements.

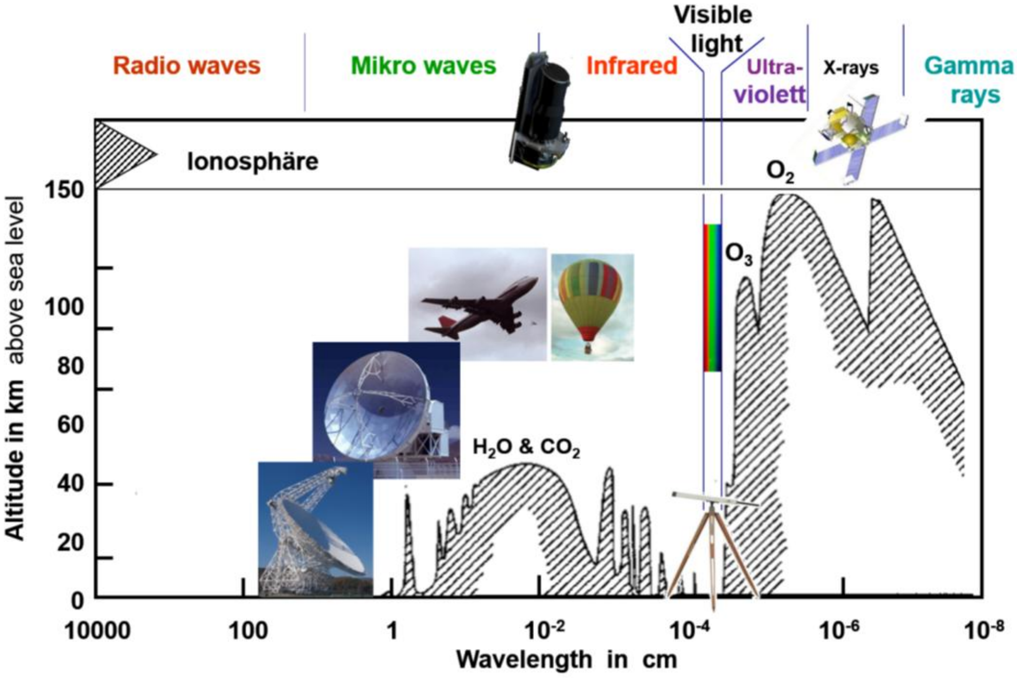


Fig. 5. A solid line shows how high a telescope has to stand on earth in order to detect half of the incident cosmic radiation.

The unit of temperature (in Kelvin) is also used to measure the intensity of spectral lines (especially with individual telescopes). This goes back to the definition of equating the power of antenna noise with the product of Boltzmann's constant with a real temperature $W = k \cdot T$, by defining a “fictitious” antenna temperature via $T_{\text{Antenne}} = W/k$. Here one should break away from the idea that this is a "warmth indication"! The antenna temperature is only a purely academically calculated variable, whereby it can be converted into a radiation flux density S_ν with S_ν [W Hz^{-1} m^{-2} (sr)] by means of the relationship $2 \cdot k \cdot T_{\text{Ant}}/A_{\text{eff}}$. Here A_{eff} is the effective antenna area. The factor 2 takes into account that the incoming radiation is non-polar. We only use one dipole as a receiver, which therefore only receives one polarization direction of the radiation.

On earth, cosmic rays cannot be received equally well from all wavelength ranges. Radiation with $\lambda > 30 \ldots 100$m on the ground cannot be detected at all. This radiation couples to the free electrons of the ionosphere of our athmoshere. All radiation that comes from "outside" is reflected back into space. Otherwise, e.g., amateur radio operators are happy to "send" long-wave signals around the earth due to the reflection properties of the upper atmosphere.

In the cm wavelength range, cosmic radiation can be detected very well. On the other hand, it gets worse in the mm and sub-mm range, towards shorter wavelengths, because here atmospheric water vapor, ozone, N2 and O2 molecule bands "cloud" the view into space. In the infrared, the view from the ground is completely blocked, only in the mid and near infrared do individual, narrow atmospheric windows open. In visible light we can see everything from the ground again. In the short-wave ultra-violet light, however, every atmospheric transparency closes again. An overview of how high a telescope has to be in order to detect 50% of the incident cosmic rays is shown in Fig. 5.

Cosmic radio emitters

Natural cosmic radiation sources / radiation mechanisms are (Fig. 6):

1) Thermal emission (from solids, $\lambda \leq 1$cm, Thermal radiation distributed over many wavelengths): These include all celestial bodies: stars, planets, moons, small planetary bodies and cosmic dust in extensive galactic clouds, as one of the most important radio sources.
2) Line radiation (from gas): Gas atoms and molecules emit narrow-band line radiation at fixed wavelengths due to quantum mechanical excitation and deexcitation transitions (Fig. 7).
2) Free Free radiation ($\lambda \geq 1$ cm, $T > 1000$ K, thermal emission of hot gas): electrons are deflected and slowed down by ions in the electric field = Bremsstrahlung.
3) Non-thermical radiation (synchrotron radiation, $\lambda \geq 1$cm): fast, free electrons that move on "spirelli" orbits around magnetic field lines.

Question about preparation: The SRT Jena measures at $\lambda = 21$ cm. What kind of radiation will we receive from e.g. the sun, the moon or molecular clouds? Do we expect an HI line in the solar spectrum?

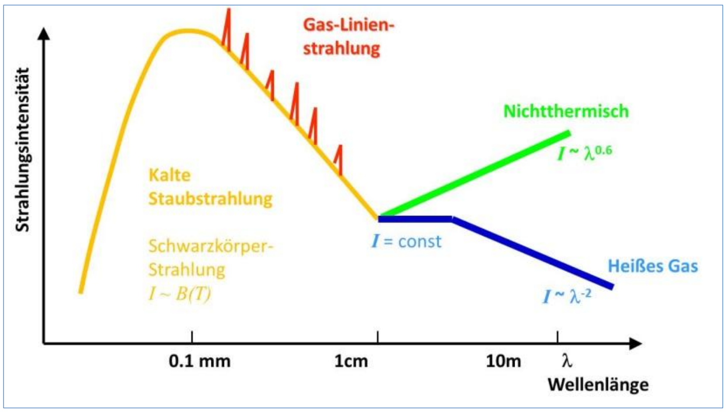


Fig. 6. Schematic representation of the radiation intensity distribution of various natural, cosmic radio emitters.

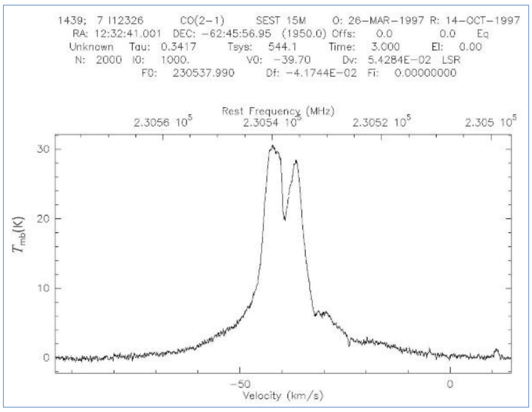
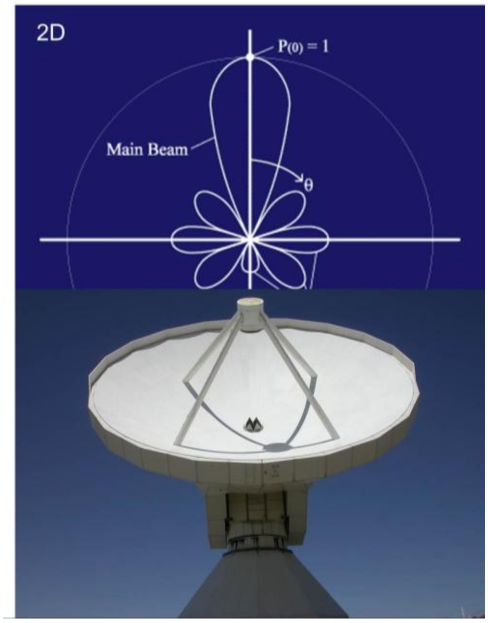


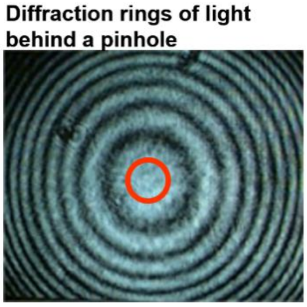
Fig. 7. Example of a typical CO $J = 2 \rightarrow 1$ line as a single spectrum with central absorption and broad line wings, measured in a molecular cloud (I12326).

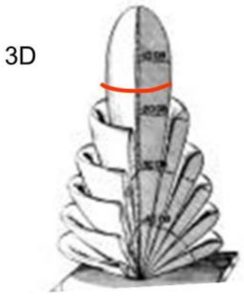
Antennendiagramm (Beam) und räumliche Auflösung

If we want to measure cosmic objects, it is important to know from which solid angle we can receive radiation and how good our spatial resolution is. To do this, we consider the antenna in the far field. As a first approximation, we can compare our "punctiform" antenna, if it were working in transmission mode, with light (see Fig. 8) that falls on a pinhole. If we represent the intensity distribution (transmission power P) over the (spatial) angle θ, we get the so-called directional characteristic or the antenna diagram. Following Huygens principle, constructive and destructive interference results in brightness rings behind the hole, which correspond to the respective diffraction orders. These diffraction orders can be detected in the same way with a parabolic antenna (at a sufficient distance, regardless of whether the rod antenna(s) or the horn act as the central receiver). The 0th order of diffraction is usually referred to as the **m**ain **b**eam in all antennas, the other orders of diffraction as side lobes. Cosmic sources are sufficiently far away and in our case (almost all) point-like. In this way we can measure our antenna characteristics with a strong point source (e.g. the sun). That will be one of the tasks of this internship experiment. The half-width θ_{mb} of our expected Gaussian main lobe results from $\theta_{mb} = ½\, P_{max}$. This size is therefore a good measure of the spatial resolution that can be achieved when mapping planar celestial objects (e.g. the Milky Way) and can theoretically be estimated at $\theta_{mb} = 1.22\lambda/d$ (d = reflector diameter). For example, the Effelsberg 100m radio telescope at λ = 7 mm has almost the same angular resolution as the 3m KOSMA telescope at λ = 0.35 mm.

To prepare: Calculate the expected angular resolution for the SRT Jena! How big would the SRT have to be to have a resolution comparable to that of the ESO Paranal single telescopes in the medium visual spectral range?







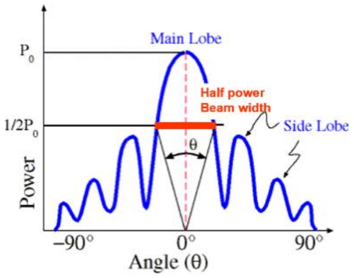


Fig. 8. Left: Two-dimensional schematic representation of the antenna main and side lobes of a radio telescope and comparison (middle) with the diffraction pattern of a pinhole in the optical wavelength range. The diagram shows the directional characteristic P over the angle θ. The angular extent of the main lobe (beam) is defined by $\theta_{mb} = ½\, P_{max}$ ($=P_o$). Right: 3D sketch of the antenna beam.

Mapping the Milky Way

We owe our knowledge of the nature and structure of the Milky Way, the large galaxy in which we live, to the extensive mapping of the entire sky in different gas lines in the radio wavelength range. It should be remembered that in the radio range we do not see any stars (apart from the closest star that offers a measurable intensity), but only the radiation from sufficiently extensive and high-intensity objects, such as interstellar gas and dust from the large galactic cloud complexes. In this experiment we will only be able to map a section of the entire Milky Way, since we never see the southern celestial sphere on our geographic coordinates. Fig. 9 shows a complete CO molecular line map of our galaxy for the rotation transition $J = 1 \rightarrow 0$ at a wavelength of 115 GHz, which was created with telescopes on different hemispheres on our earth. The largest part of interstellar gas and dust thus forms in a very thin (approx. 200 pc thick) galactic disk, similar to the main part of the stars. The gas clouds move in almost circular orbits around the galactic center. Since our Milky Way rotates differentially, the interstellar clouds in different viewing directions within the galactic disk also have different Doppler velocities. The advantage is that we can see through the optically opaque, dark clouds and identify the entire structure (e.g. the presence of spiral arms).

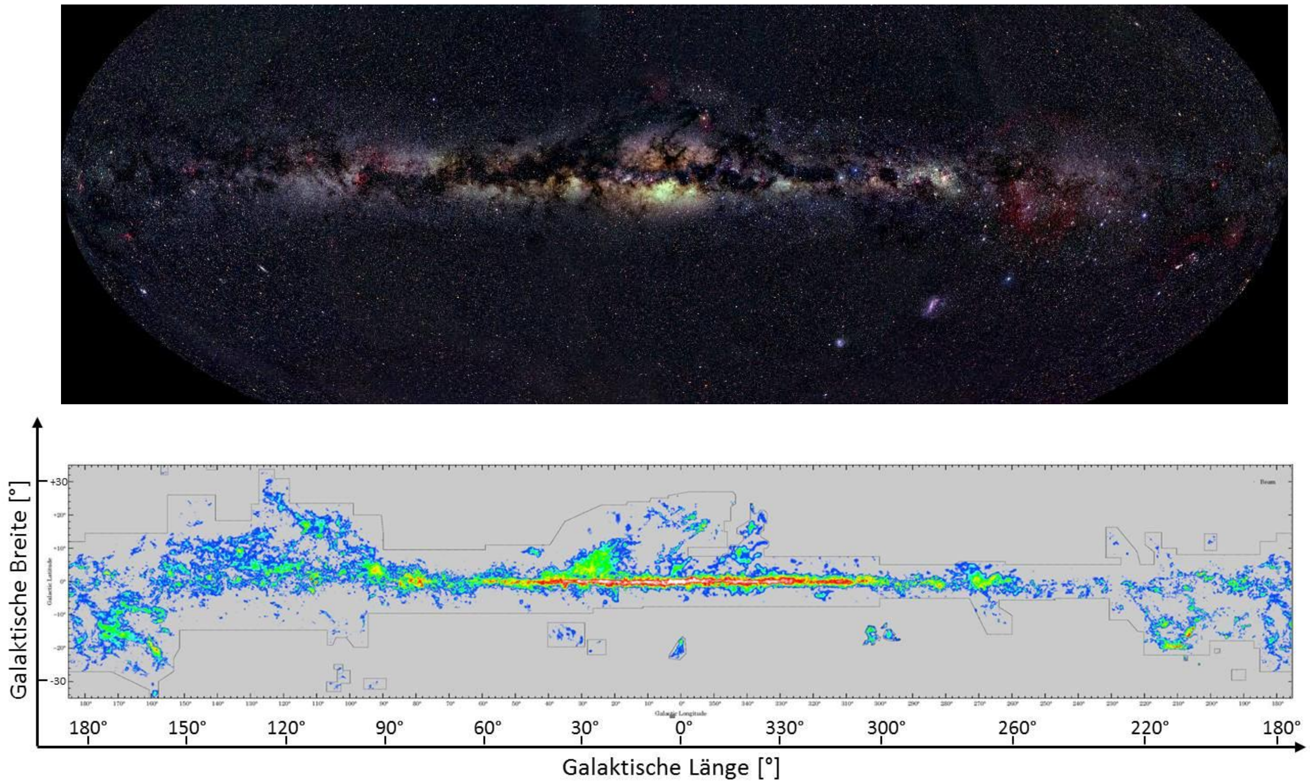


Fig. 9: Comparison (above) Milky Way in the optical spectral range (Axel Mellinger) and (below) mapping in CO $J = 1\rightarrow0$ (Dame, Hartmann & Thaddeus 2001). (Galaktische Länge = galactical longitude, Galaktische Breite = galactical latitude)

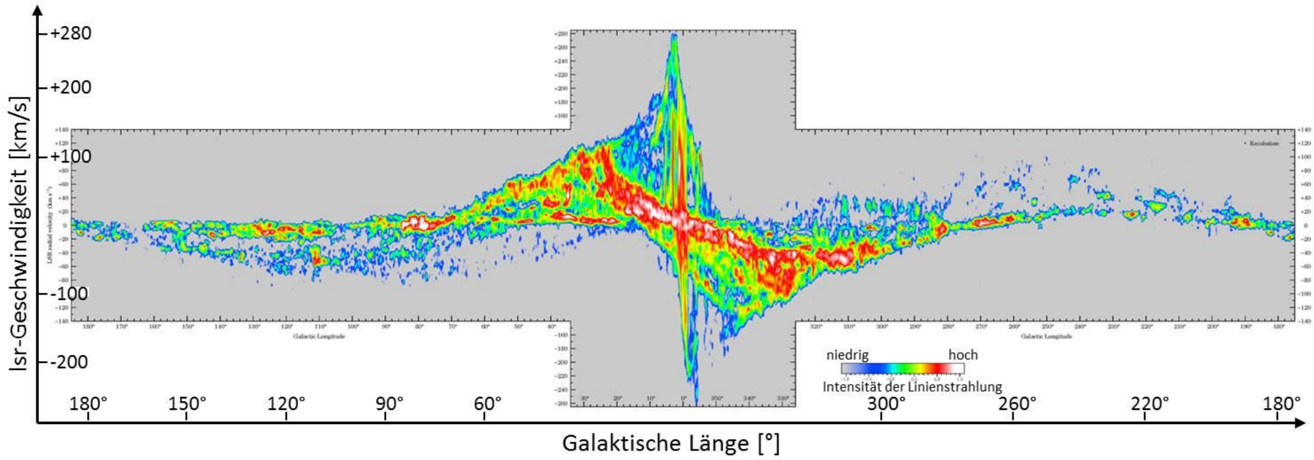


Fig. 10: Position-velocity diagram: Representation of the Doppler shift of the spectral line CO $J = 1\rightarrow0$ along the galactic plane (galactic latitude = 0 °). In the central area (galactic longitude 350 ° to 10 °) the gas shows very high speeds with which it moves around the central black hole of the Milky Way. The broad “red bar” shows the inner galactic gas ring. To the right and left of it, the various spiral arms appear as different "arcs".

In this experiment, the hyperfine structure transition $F = 1\rightarrow0$ bei $\lambda = 21.1$cm bzw. $\nu = 1420$ MHz of atomic hydrogen can be mapped. Historically, this measurement was already carried out in the 1950s, since at 21cm no receiver cooling is necessary, as is the case with frequencies higher than 80 GHz. The result is similar to the CO mapping, only with a not so good spatial resolution, since our antenna beam is much larger.

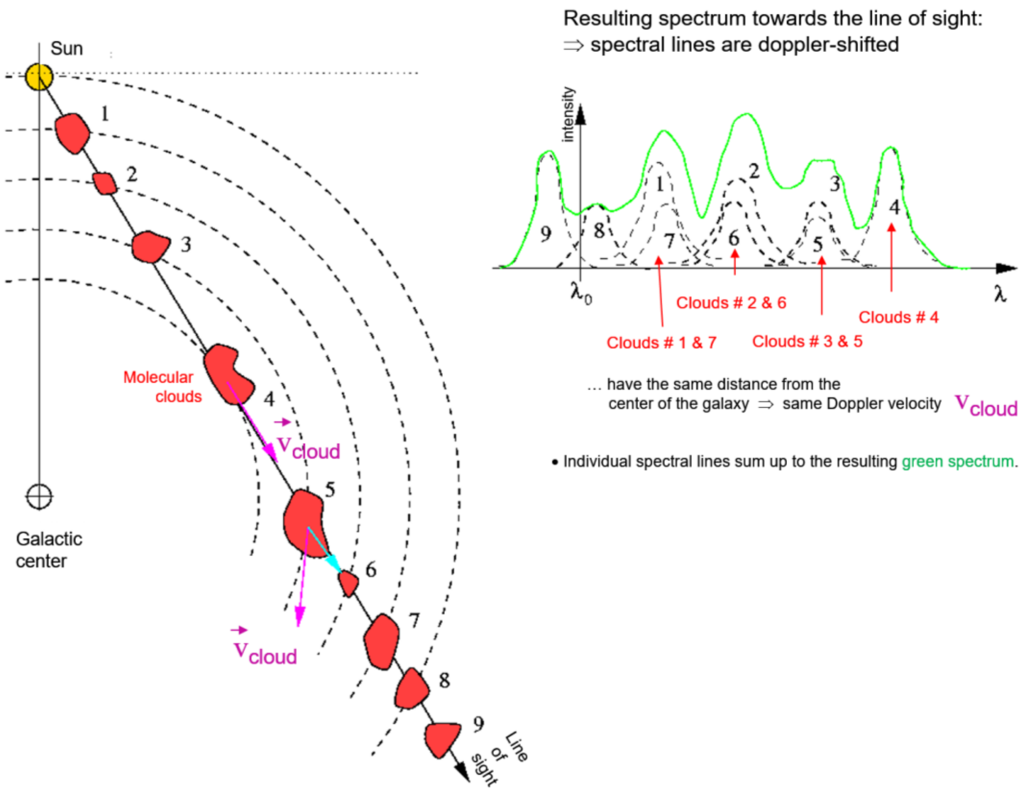


Fig. 11. Development of the HI line profile. Left: If several HI gas clouds (1-9, red areas) lie one behind the other in the line of sight (long, black arrow), these gas clouds transmit at different wavelengths λ due to their galactic movement (purple arrows) around the center of the Milky Way. In our line of sight, however, we always only measure a radial speed component (lying in the line of sight), the lateral component (proper movement on the sky surface) is practically undetectable within a person's life. In the spectrum, a HI line profile is created from several superimposed, individual (Gaussian) HI lines of the individual clouds 1-9. The wavelength can be converted into a speed so that the speed profiles per galactic position, as in Fig. 10, can be created.
(http://www.astro.uni-bonn.de/~deboer/galstruc/galstr.html)

The system of speeds concerning the local standard of rest (lsr)

In order to determine the movement of cosmic celestial bodies in three dimensions, the proper movement of the object (on the apparent celestial surface) is measured and the radial velocity component in our line of sight is determined using the Doppler shift of (atomic and / or molecular) spectral lines. With the SRT Jena we want to investigate the movement of the atomic HI cloud complexes within the Milky Way at $\lambda = 21$cm. These have a sufficiently large planar extent in the sky that they do not represent point sources for the SRT main lobe beam. The gas clouds have a hardly measurable movement due to their size and distance in the Milky Way, but they have a well measurable speed in our line of sight, which we can determine with the Doppler shift of the 21 cm line compared to the laboratory rest wavelength. The measurement is so precise that we also have to correct for the movement of the earth (rotation + movement around the sun). In addition, the sun moves in a so-called “local rest system” (= local standard of rest = lsr). This rest system is defined by the averaging of all spatial directional movements of stars with the spectral type A and K III of our immediate cosmic environment and is set as the standard. All movements within the Milky Way are given for this system. The typical representation of the spectra in the radio range does not take place via the wavelength or the frequency, but these are converted into the respective lsr speed of the object.

Note: The calculation is not simple, because the celestial coordinates of the line of sight within our galaxy are included, the earth's rotation, as well as the position and speed of the earth around the sun in the year with regard to the special galactic line of sight.

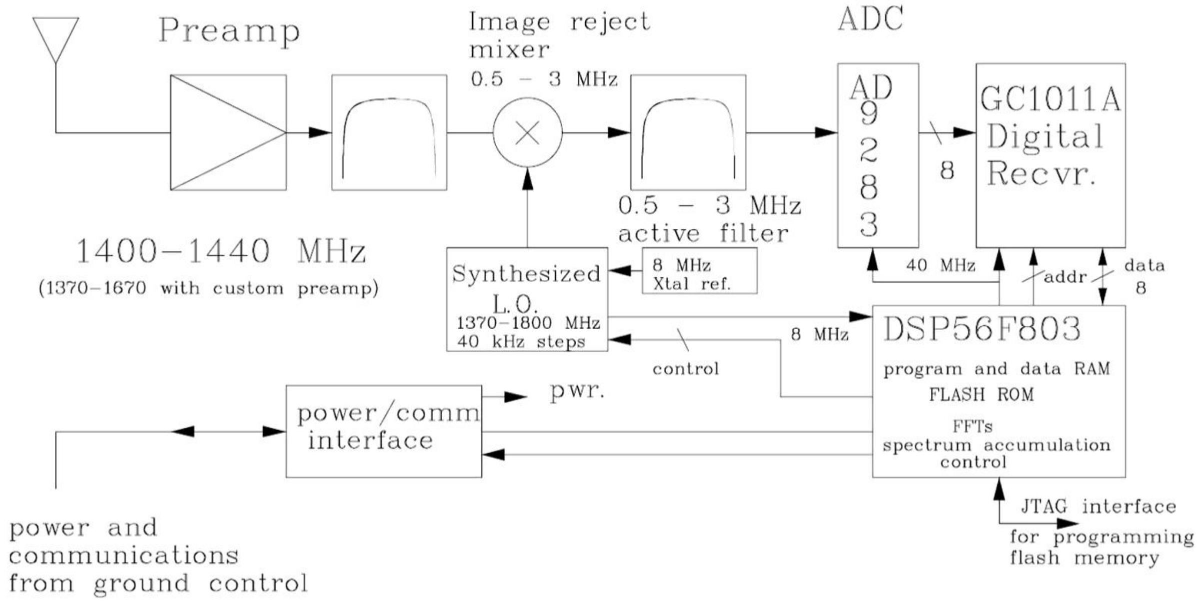


Fig. 12. Block diagram for the signal flow diagram of the SRT.

2.3 Metrological basics

The radio telescope is an original satellite television reception system for reception at 4.2 GHz, which was produced by Cassi Coorp. (USA, Prof. Dr. Michael Cobb, formerly Haystack Observatory of MIT) has been converted for astronomical radio measurements. A parabolic grid wire reflector with a diameter of 2.3 m is used for reception, which directs the astronomical radiation onto an additional built-in dipole in the reflector focus. The signal is pre-amplified (Fig. 12) and its bandwidth is limited with a bandpass filter in the range 1.40–1.44 GHz. Usually, these frequencies cannot be further amplified directly (uncooled). For this reason, the signal from a local oscillator is superimposed in a mixer and mixed down to a lower intermediate frequency of 800 kHz. After a further limitation of 0.5–3 MHz, the signal is digitized with a 40 MHz sampling rate and converted into a spectrum with the help of a Fourier transformation, which can be displayed using the telescope control software. A very detailed and extensive representation of the signal path can be found in the Vienna astropractical course with the almost identical instrument which is available at the test site. For a simple calibration of the signal intensity, an additional noise source is installed in the center of the reflector, which emits a defined noise signal. A temperature can be assigned to this noise equivalent via S[W/m^2/Hz] = $k{\cdot}T$[K] (k = Boltzmann const.), so that the inherent noise of the entire "radio telescope" system can be characterized by a system temperature T_{sys}.

For strong sources, we need relatively short integration times to see our desired signal. For weaker sources, we have to integrate longer at one position, i.e. record many individual spectra and then add them up. The intensity of the noise can thus be reduced over a longer period of time so that, for example, spectral lines with a weaker intensity can be detected. The sensitivity in which integration time which $1\sigma_{\text{rms}}$ noise level can be achieved for the bandwidth $\Delta\nu$ can be estimated for a point source in the following way:

$$1\sigma_{\text{rms}} = \frac{2k\;\eta_{\text{spec}}\;T_{\text{sys}}}{\eta_{\text{atm}}\;\eta_{\text{forw}}\;A_{\text{eff}}\sqrt{\Delta\nu\cdot t_{\text{int}}}}\;.$$

Unfortunately, not all efficiencies (efficiency of the spectrometer η_{spec}, radiation loss component at the telescope - forward efficency η_{forw}, atmospheric damping η_{atm}) are exactly known and would have to be estimated at 1 in a first approximation. The integration time tint required can be estimated from this. Note that usually 50-100% overhead for calibration, telescope movement, etc. must be planned for the entire observation time at the telescope.

3. Execution of the Tasks

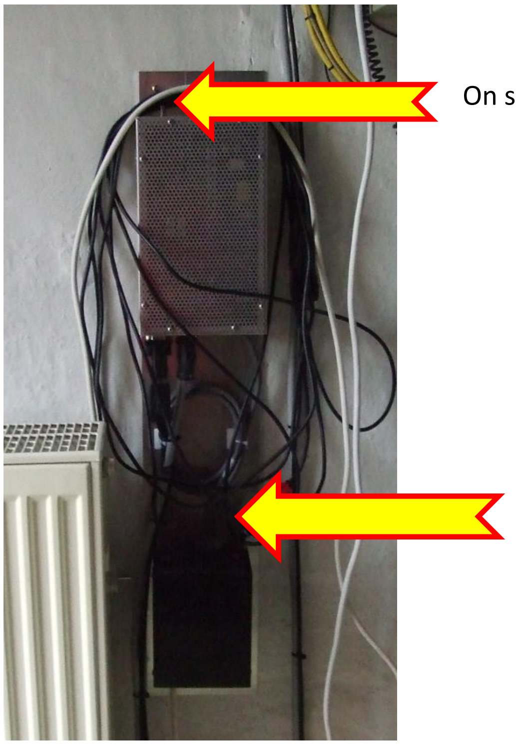
The telescope is on the roof of the observatory in Schillergäßchen 2 and is controlled by a notebook located in the east stairwell, on the same floor level as the top floor. It makes sense to work with the door to the roof terrace open to ensure constant visual contact with the telescope. Please, enter all measurements, but also special features, anomalies, file names and paths in the **observation logbook** at the measuring station! Add a copy (e.g. picture with cell phone) to your finished protocol. It is recommended to take the data home with you on a USB stick (private).

Attention: The SRT should never be operated unsupervised, as the cables can be torn off and tangled.

3.1 Start of the observing session

The following steps have to be taken (do not switch on the computer first! For the sequence of switching on and for the devices see Fig. 13.):

1. Switch on the power strip
2. Switch on the controller power supply
3. Switch on the controller
4. Plug the USB cable from the controller into the PC
5. only now switch on the notebook >> SRT-pc01 <<
6. Log in as "SRT" (without password)



On switch for controller [to 3.]

Power supply for controller [to 2.]

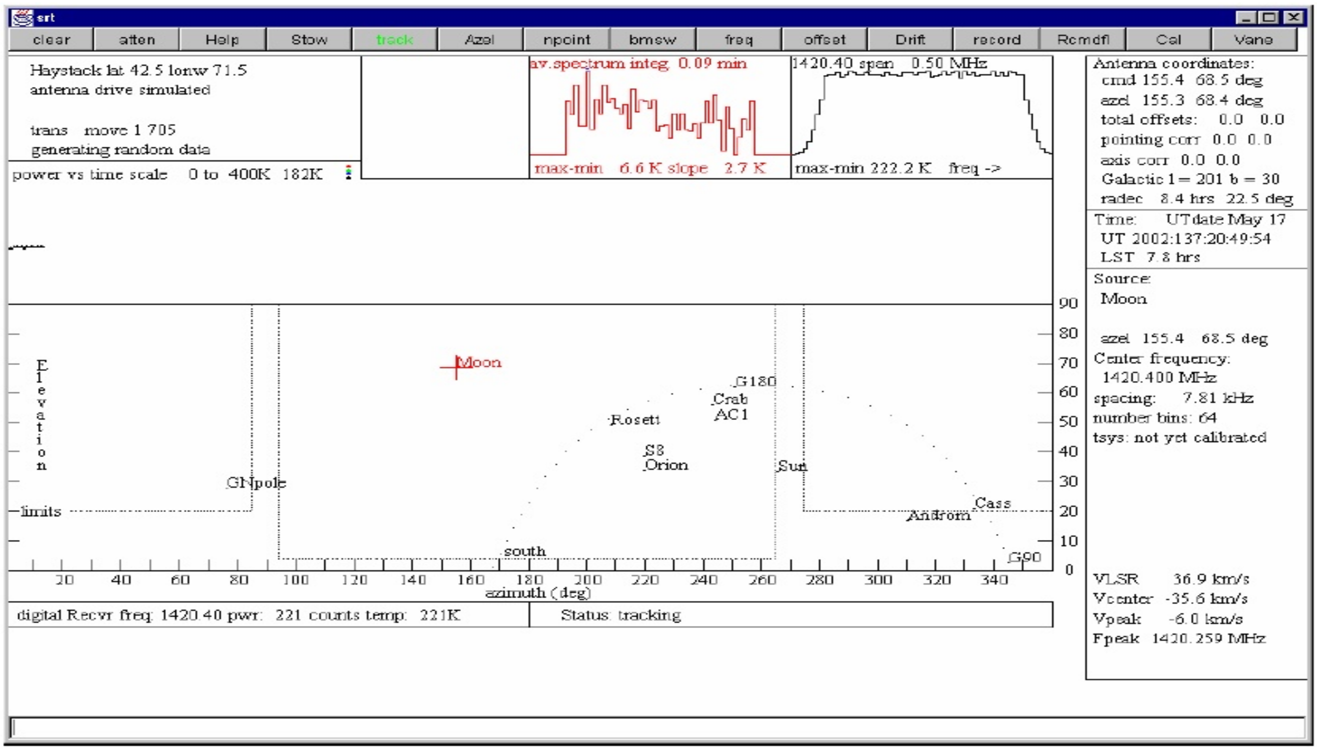
Fig 13. Control units at the SRT Jena.

3.2 SRT - Control software

The SRT software "srt.exe" is started via the link on the desktop. All necessary files are contained in the main directory "D: \ SRT" of the PC. When the software is started, the start file "srt.cat" is automatically loaded, in which the basic settings for the measurement software are specified. If necessary, this file can be changed with the text editor (but please be careful!). The file can be seen in full in the attachment.

After each start of the SRT program, the satellite antenna is always directed to position El = 0.0/Az = 0.0. That means azimuth = 0 ° ≙ direction north (geographical) and elevation = 0 ° ≙ horizontal orientation of the recipient. This is necessary so that the starting position of the antenna is right calibrated.

Fig. 14 shows an overview of the user interface of the SRT program. The most important commands can be initiated at the top of the screen. Active functions always appear in green. Below there are various display windows for map results as well as the currently measured spectrum (red) and the summed up spectrum (black). Below these, the radiation intensity (po who) is shown continuously over time. The largest overview shows the current sky with different radio sources and points of the galactic plane (e.g. G150 G180 G220, each of which corresponds to the galactic coordinates ℓ = 150 °, ℓ = 180 °, ℓ = 220 ° at ℓ = 0 °). Below is a message window that provides information about the current activity of the telescope and also provides brief assistance. The input window for command lines is located at the bottom of the screen. In the right display window, information about the target coordinates (cmd) and the current actual coordinates (azel) as well as other telescope parameters are given.



```
Haystack lat 42.5 lonw 71.5
antenna drive simulated

trans   move 1 705
generating random data
```

```
power vs time scale   0 to  400K  182K
```

```
av.spectrum integ  0.09 min
max-min   6.6 K slope   2.7 K
```

```
1420.40 span   0.50 MHz
max-min 222.2 K
```

```
Antenna coordinates:
 cmd 155.4  68.5 deg
 azel  155.3  68.4 deg
 total offsets:   0.0   0.0
 pointing corr  0.0  0.0
 axis corr  0.0  0.0
 Galactic 1 = 201 b = 30
 radec   8.4 hrs  22.5 deg
Time:    UTdate May 17
 UT 2002:137:20:49:54
 LST  7.8 hrs
Source:
 Moon

 azel  155.4   68.5 deg
Center frequency:
 1420.400 MHz
spacing:     7.81 kHz
number bins: 64
tsys: not yet calibrated

VLSR      36.9 km/s
Vcenter  -35.6 km/s
Vpeak     -6.0 km/s
Fpeak  1420.259 MHz
```

```
digital Recvr freq: 1420 40 pwr:  221 counts temp:  221K
```

```
Status: tracking
```

Fig. 14. The user interface of the SRT program. The currently active function is green.

Short explanation:

Clear … The displays are cleared and the measurements are integrated again. Recommendation: Perform before each new measurement.

ATTEN … without function

STOW … Approaching the parking position (with azimuth 0 and elevation 0)

TRACK … Activates / deactivates the tracking function

AZEL … Moves the antenna to a certain position (azimuth XXX degrees, elevation YY degrees), either enter the object in the command line, e.g .: „**: sun**“. But this must be defined in the srt.cat or click the object directly in the sky preview, or enter the command completely in the command line: “**: azel XXX YY**“ (the space after the colon is mandatory).

NPOINT … Starts a 5 x 5 point grid map for a preset object

BMSW … Starts a measurement in beam switching mode for a preset object (actually a position switch, a difference measurement is made between the celestial object and a position a few degrees away, "next to the source").

FREQ … Changes the center frequency of the receiver, input: Center frequency bandwidth, e.g .:

„: **1420.4 4**"

explanation: frequency=1420.4 MHz in mode 4. The following entries are possible:

mode 1 = 7.81 kHz x 64 channels = 500 kHz Bandbreite,
mode 2 = 3.91 kHz x 64 channels = 250 kHz Bandbreite,
mode 3 = 1.95 kHz x 64 channels = 125 kHz Bandbreite,
mode 4 = 7.81 kHz x 156 channels (3 x 500 kHz overlapping) = 1.22 MHz Bandwidth,
Channel 78 corresponds to the center frequency (12 sek ca. 4 scans)

Center frequency can be selected in the range 1370 to 1800 MHz

OFFSET … Adds the entered values as an offset to all coordinates, but keeps the original source position

DRIFT … Starts a drift measurement, i.e. the telescope steers half a beam width in the direction of increasing right ascension parallel to the celestial equator to a point that the selected object traverses shortly afterwards and deactivates the tracking function, whereby the rotation of the earth guides the object through the antenna beam.

RECORD … Saves all measurements until the button is pressed again.
If no file name is given, a file with the format name yydddhhmm.rad is created (see Chap. 3.3).

RCMDFL … Starts an automated measurement from a command file (Batch program), E.g. entry in command line command:"**: +sonnenkreuz.cmd**", If you only press **Rcmdfl**, the **srt.cmd** file in the directory D:\SRT is called up.

CAL … Starts a calibration measurement and calculates Tsys - duration approx. 15 seconds

VANE … without function

Further information on operation can be found in the SRT-Manual.pdf of Wien University.
Attention: Aborting a cmd procedure: press the >green< buttom RCMDFL again ⇒ blackening of the bottom!

3.3 Data storage

The measured values recorded with the SRT program can be saved. Either manually using the "record" button or automatically if the command is defined in a batch program (see below).
All of these measured value files have the file extension "**.rad**". Because of the clarity of the data, it is recommended to save in a certain directory (e.g. "**D:\SRT\+messwerte** ") and to use meaningful file names.
These files are simple text files and can be viewed (and changed) with an editor. These contains all values, such as the date of recording, frequency informations and the intensity values per channel in units of a temperature. These values can be copied out and processed in any other software for the data reduction/analysis.

Structure of the rad-Datei:

```
* STATION LAT=  50,90 DEG LONGW= -11,60
* +sonnenkreuz.cmd: line 23 : record d:\SRT\+messwerte\sonnenkreuz.rad
2017:146:08:22:34  116,3  45,8   ,0   ,0  1419,75  ,00781250   1  64   9,0  11,0  19,0  37,0  68,0 126,0 201,0 267,0  … 193,0 123,0  73,0  37,0  19,0  11,0
2017:146:08:22:37  116,3  45,8   ,0   ,0  1419,75  ,00781250   1  64   8,0  10,0  17,0  36,0  68,0 120,0 187,0 261,0  … 188,0 120,0  67,0  35,0  18,0  11,0
```

1.line: geographical coordinates
2.line: Command instructions or calibration values
3. to … line: observing time, in the format yyyy:ddd:hh:mm:ss (2017:146:08:22:34), azimuth und elevation of observation (116,3 45,8), offsets in azimuth and elevation (,0 ,0), frequenzy (MHz) of the first channel (1419,75), the width of a channel (bins) in MHz (,00781250 = frequency resolution), the number of channels: channel 1 to channel last number (1 64), followed by the spectrum intensities for each channel: channel 1 (9,0), channel 2 (11,0), channel 3 (19,0), channel 4 (37,0), channel 5 (68,0), channel 6 (126,0), …, channel 63 (19,0), channel 64 (11,0).

Each single observing scan (á 10 seconds) is always writen on one line. If you want to get a temporally integrated spectrum, you have to write out several scans individually (by increasing the integration time) and then average them appropriately.

3.4 DataViewer-SRT - Software

It is also possible to use the LabView program „**+DataViewer-SRT.exe**“ It can be started via the link on the desktop. After selecting your *xxxx*.rad-file, the temperature - frequency spectrum is automatically displayed (Fig. 15). The value assignments can also be corrected manually if display errors occur in automatic mode.

Certain evaluation options are included in this software. A renewed saving in a new „**.txt**“ file with only the xy measured values and saving of images of the spectrum can be used.

HP Color LaserJet 1600
15.03.2017 15:39:23

3 aktuelle Zeile
Zeile auswählen 3
Center Frequenz[MHz] 1420,399
Mode 4
1,211 Bandbreite [MHz]

01	2016	1419,79	0,00781	4	156	14548,8	14780,9	16731	21739,2	32047,3	48013,4	71713,6	24133,7	52792,9	56777	60290,2	61787,3	61602,3	57835,6	52489,2	20
21	52953,1	55161,8	55032,3	52920,7	54712,2	51619,9	49184,6	50419,5	48967	51223,5	47409,1	52986,7	52053,3	50781,7	48364,5	46730,2	46552,2	45882	43376,6	47393,5	40
61	42181.1	49284.4	51460.1	50677.1	47000.2	38947.3	39824.5	43296.7	39737.4	46489.8	41271	39291	39260.8	36124.4	32519.4	32600.6	33140.1	36011.2	32864.9	34749.9	80
151	26884,9	22407,8	18735,2	36796,3	6743,4	42075,6	19203,7	3859,8	0	0	0	0	0	0	0	0	0	0	0	0	170
Datei Wert																					Datei Wert

Dez.stelle/Trennz.=Komma
Zeile/Trennz.=Leerzeichen
Suche Lower Frequenz bis Datei-Wert 20
Datei-Wert Lower Frequenz [MHz] 02 1419,790
Datei-Wert Step Width [MHz] 03 0,007812
Datei-Wert Samples Anzahl 05 156
erster Datei-Wert Spektrum 06 14548,800
letzter Datei-Wert Spektrum 160 0,000

5000 Ymax
60682
10227
1419.7 Xmin
+ Cursor 1420,368 50909,091
Xmax 1421.1
srt
D:\srt.txt
D:\srt.bmp
64x
0

Abb. 15. Die Bedienoberfläche des DataViewer-SRT Programms.

3.5 Batch processing program „ .cmd“ - files

A batch processing program can be started from the SRT program in order to be able to run certain commands automatically. These files have the file extension „**.cmd**“. These files can also be written or modified and saved with a text editor. Please use meaningful file names for application-specific .cmd-files! These files must also be stored in the main directory „**D:\SRT**“. An example file can be found in the appendix.

3.6 Manual telescope control

After commissioning the SRTs, the telescope can be controlled manually, with the commands being entered directly in the command line. Lines that begin with an asterisk "*****" **are comment lines**. Lines that begin with a colon "**:**" are command lines. The colon must also be written and this must be **followed by a space**, except for time specifications in which the telescope, for example, should integrate a spectrum or wait for a new command.

Examples:

Task: Point the telescope at the sun:

Enter the object name in the command line (this must be defined in the srt.cat file) or click on the sky map, the red cursor appears when the object has been accepted

```
: sun
```

If the telescope continuesly follow the sun, the button >**track**< appears green in the upper command bar, if not, click on it. The spectrum is measured and integrated, but without data recording.

Task: Drive a cross scan over the sun

(= Do a pointing), start the recording beforehand and perform a calibration:

```
: record  D:\SRT\+messwerte\Sonnenkreuz.rad
: azel 130 45       *Align the antenna to the position Az = 130°, El = 45°
: freq 1415.0       *center frequency with mode 1, 500MHz bw (default)
: noisecal          *A calibration is carried out with the noise diode.
: Sun               *align with the sun
: offset -30 0      *horizontal scan -30 to +30 degrees
: offset -25 0
: offset -20 0
 ...
: offset -06 0
: offset -04 0
: offset -02 0
: offset  00 0
: offset  02 0
 ...
: offset  25 0
: offset  30 0
: offset 0 30       *vertical scan (if sun Elevation is <60 degrees! Keep attension in summer!)
: offset 0 25
...
: offset 0 -25
: offset 0 -30
: roff              * End the data recording and close the file
```

This task can also be processed using a batch processing program with the following commands:

```
: +sonnenkreuz.cmd
```

(don't press Enter!)

and click on the button **RCMDFL** in the top command bar.

Task: Create a 5x5 point map

e.g. from the sun. Click on the desired celestial object or enter the celestial coordinates and enter the name of the recording file:

```
D:\SRT\+messwerte\Sunmap.rad
```

(don't press Enter!)

and click on the button **RECORD** .

Starting the 5x5 point measurement: click on the button **NPOINT**

The recording file is closed with a second click on **RECORD** .

Task: Map the HI clouds in the visible sky of the Milky Way. We recommend using a stacking program: D:\SRT\+rotation.cmd. Please specify the optimal area of the galactic plane for an observation elevation of> 30° in the sky map: e.g. G80 to G250. This area depends on the time of day and time of year. Please take a look first, if necessary adapt the observation area to the current observation sky and define the output file. Program start using

+rotation.cmd **(don't press Enter!)**
and click on the button **RCMDFL**.

For advanced and interested people who have some time:

Task: Attempt to measure the HI spectrum of the Andromeda Galaxy (vlsr = -300km / s). Start the recording beforehand and carry out a calibration (see last page in the orange folder). Necessary preliminary considerations: Compare the line intensity to be expected with the lines of the gal. Plane! Estimate the integration time! Create a cmd program with the following content in the directory D:\SRT

```
: record  D:\SRT\+messwerte\Andromeda.rad
: gal 130   -30        *Align the antenna to the galactical position l = 130°, b= -30° (a point next to Andromeda)
: freq 1419.0  1       *center frequency mit mode 1, 500MHz bw (default)
: noisecal             *calibration with the noise diode
: Androm               *Align to Andromeda (l = 121.1743°, b = -21.5733°)
: freq 1420.4   4      *first center frequeny (1. part of the spectrum, = galactic emission)
:900                   *900 Seconds integrates the telescope on Andromeda
: freq 1421.4   4      *second center frequeny (2. part of the spectrum, = red-shifted HI-Emission Androm.)
:900                   *900 Seconds integrates the telescope on Andromeda
: freq 1422.4   4      *3.Mittenfrequenz (3. part of the spectrum, = blue-shifted HI-Emission Androm.)
:900                   *900 Seconds integrates the telescope on Andromeda
: roff                 *End the data recording and close the file
```

3.7 Ending measurements with the SRT

Click on **STOW** and wait until the telescope has reached its final parking position (**STOW** is green on the display), only then do you close the program (Exit)! Switch off all devices in the reverse order in which they were switched on! Shut down the computer properly, do not close it!

4. Notes for the Data analysis

4.1 Analysis of the continuum measurements (e.g. cross over the sun)

A spectrum with 64 channels (bins) was recorded for each point in the sky. It is advisable to omit the first ten and the last ten channels and to average the remaining intensities to a value so that we get a single (broadband) continuum value for each point in the sky. The broadband continuum values for the sun cross can then be plotted over the offset coordinate (separated into azimuth and elevation, -30 ° to + 30 °). Fit a Gaussian curve to the data and determine the beam size in azimuth and elevation separately! Please note: The half-width σ of the Gaussian curve is not the beam width θ_{mb} (!), But both are linked via $\theta_{mb} = 2\,\sigma\,\sqrt{2ln2}$.

Since the intensity values are calibrated, determine the measured spectral flux and compare it with measurements of the Weather Prediction Center des US National Weather Space Service

(http://www.swpc.noaa.gov/ →*F10.7cm Radio Emissions*,

in solar radioflux units (sfu): 1 sfu = 10^4 Jy = 10^{-22} W m^{-2} Hz^{-1}) for the corresponding day! The spectrum of the calm sun can be converted approximately from one to the other wavelength in the range 1-10 GHz with a power law: $S_2 = S_1(\nu_2/\nu_1)^{0.8}$ für $\nu_2 > \nu_1$.

For broadband continuum measurements of other celestial objects (e.g. moon, Cas A, pulsar, ...), which were only measured on one celestial point, determine the spectral flux value in a manner comparable to that for each celestial point in the sun cross. Compare the determined flow value with the literature.

4.2 Analysis of HI Line measurements

For the Galaxy:
a) Several spectra were recorded at each position in the sky. These must first be averaged, as no HI line can be seen in a simple scan (lasting a few seconds)! Limit the number of channels yourself by cutting off the first ten and the last ten channels! The HI spectrum per celestial position, averaged over a longer period of time, generally shows an overlay of several Gaussian line profiles with different half-widths that originate from different galactic HI clouds in our galaxy. Compare the measured spectra in the sky with the All Sky Leiden-Argentine-Bonn-HI-Survey (LAB) https://www.astro.uni-bonn.de/hisurvey/AllSky_profiles/ (or at least with the spectra in the Appendix) by displaying both spectra side by side!

b) Determine the channel positions of - up to three, four - maxima of the HI lines in each spectrum. Represent (for the sake of simplicity) these channel positions over galactic longitude and compare the result with Figure 10 (it makes sense to use the same x-axis scale and orientation!). Remember that you have only measured part of the position-velocity diagram of the Milky Way! Show Fig. 10 and your results together in one diagram on a suitable scale. For advanced users: Convert the channels (or Doppler frequencies) into Doppler velocities v [km/s] concerning the laboratory frequency ν_o of HI $(\Delta\nu-\nu_o)/c = v/\nu_o$ and than create the plot!

For Andromeda (Messier 31): Since this galaxy is completely contained in the beam, we expect a very broad double (?) line HI profile, as one side of the large gas ring in this galaxy comes towards us, the other side moves away from us (see information in Attachment). This galaxy has a v_{lsr} = -300 km/s. Find out beforehand how broad the presumed spectrum will be, whether you are expecting emissions from our galaxy at this position at the same time, and by which frequency shifts you have to move the bandpass in order to be able to put the entire spectrum together using individual measurements. The spectrum does not fit in a frequency setup!
Determine the maximum rotation speed of the gas here! For a good spectrum you should have integrated in this position as long as possible in each frequency segment.

If you would like to measure other cosmic line objects, then you should inform yourself beforehand about the vlsr speeds and the line widths to be expected so that you can position the bandpass correctly.

Literature:

Dame, Hartmann & Thaddeus, 2001, ApJ 547, 792
Wilson, Rohlfs, Huettemeister, 2014: Tools of Radio Astronomy. ISBN 978-3-642-39950-3, e-book
Schlosser, 1990, Fenster zum All : Instrumente und Beobachtungsmethoden in der Astronomie. ISBN 3534021525

Appendix

Content of the srt.cat - file:

```
* ++++++++++ srt.cat file ++++++++++
* ----------------------------------------
* This file is executed each time the SRT program is started.
* ----------------------------------------
* ! Command lines with a preceding * are not executed!
* ------------ HINWEIS ------------
* if receiver not conneted than
* SIMULATE RECEIVER without *
* otherwise no start
* ----------------------------------------
*SIMULATE RECEIVER
* ----------------------------------------
*SIMULATE ANTENNA 100
*SIMULATE ANTENNA

* ------- befehle für die konfiguration ---------------
DIGITAL           /* needed for digital receiver - SRT*/
```

```
STATION 50.9 -11.6 Jena
UTHOURS -1.0

AZLIMITS 0.0 359.0
ELLIMITS 0.0 90.0  // sg2100 -VSRT

CASSIMOUNT
COMM 16             /* COM 1 */
CALCONS 1.0         /* gain correction constant to put power in units of K */
BEAMWIDTH 7.0       /* 3 dB antenna beamwidth in degrees  - used to set offsets for scans - SRT*/
MANCAL 1            /* 0 or absence indicates automated cal vane  - SRT*/
NOISECAL 200.0      /* initial value for noise diode calibration - SRT*/
TOLERANCE 1         /* optional max error in counts */

* ----------------------------
*DEBUG
*VSRT 3 1000 400 10 150 250 480 490 570          // for 3 stations = 3 baselines
*VSRT_CDIFF 3 1000 400             // for 3 stations = 3 baselines
*VSRT 2 1000 400 250 270
*VSRT_USB1 2 1000 400
*VSRT 2 1000 400    //For VSRT
*ISOCHRONOUS // not yet supported
*HH90MOUNT 10.0 4.0 Sun
*SG2100MOUNT    //For VSRT
*POLARMOUNT Sun
*AZFEEDOFFSET 11  //For VSRT
*AXISTILT 5 180 5
* first word is key word
* STATION: latitude longitude west in degrees
* SAT: satellite ID then longitude west
* ------- from here preprogrammed observation objects ------
* SOU: source ra, dec, name, epoch
* source coords epoch 1950 unless specified
SOU 05 31 30  21 58 00 Crab
SOU 05 32 48  -5 27 00 Orion
SOU 05 42 00  -1 00 00 S8
SOU 23 21 12  58 44 00 Cass
SOU 00 00 00  00 00 00 Sun
SOU 17 42 54 -28 50 00 SgrA
SOU 06 29 12  04 57 00 Rosett
SOU 18 17 30 -16 18 00 M17
SOU 20 27 00  41 00 00 CygEMN
SOU 00 00 00  00 00 00 Moon
SOU 21 12 00  48 00 00 G90
SOU 05 40 00  29 00 00 G180
SOU 12 48 00  28 00 00 GNpole
SOU 00 39 00  40 30 00 Androm
SOU 05 14 12  18 44 00 AC1
SOU 03 29 00  54 00 00 PULSAR
SOU 17 45 37 -28 56 10 G0
SOU 18 27 32 -11 29 19 G20
SOU 19 04 23  06 17 13 G40
SOU 19 43 54  23 53 25 G60
SOU 20 35 53  40 39 49 G80
SOU 22 00 01  55 02 59 G100
SOU 00 25 48  62 43 32 G120
SOU 03 07 15  58 17 51 G140
SOU 04 46 58  45 14 46 G160
SOU 06 27 32  11 29 19 G200
SOU 07 04 23 -06 17 14 G220
SOU 07 43 54 -23 53 25 G240
SOU 08 35 53 -40 39 49 G260
SOU 10 00 00 -55 03 00 G280
SOU 12 25 48 -62 43 33 G300
SOU 15 07 15 -58 17 52 G320
SOU 16 46 59 -45 14 47 G340
* ----------------------------
SSAT 10 10
SSAT 20 20
SSAT 30 30
SSAT 40 40
SSAT 50 50
SSAT 60 60
SSAT 70 70
SSAT 80 80
SSAT 90 90
SSAT A0 100
SSAT B0 110
```

```
SSAT C0 120
SSAT D0 130
SSAT E0 140
SSAT F0 150
SSAT DBS 102
GALACTIC 10 1 RC_CLOUD
* ----------------------------
*AZEL 269 28 vane
*AZEL 264 28 vane
*AZLIMITS 92.0 265.0 /* mid az range is south * - H180 Mount*/
*ELLIMITS 5.0 175.0  /*  elevation limit south - north  - H180 mount*/
*ELLIMITS 10.0 175.0
*ELLIMITS 5.0 89.0  /*  elevation limit south - north  - CASSI mount*/
*AZLIMITS 115.0 270.0 // sh2100 - VSRT
*AZLIMITS 280 80 // sg2100 for southern hemisphere
*ALFASPID 1.0 1.0
*CASSIMOUNT 14.25 16.5 2.0 110.0 30.0
* COUNTPERSTEP 50     /* optional stepped antenna motion - SRT */
* RECORDFORM TAB VLSR /* optional tabs between fields and VLSR in output - SRT*/
* ELBACKLASH 3.0      /* optional correction for elevation backlash - SRT*/
* ------------- SCRIPT ENDE --------------
```

Example file for a „ .cmd “ - Batch processing program:

```
* ++++++++++ sonnenkreuz.cmd file ++++++++++
* ------------ SCRIPT begin -------------
* Horizontal (Azimuth) und danach Vertical (Elevation) scans
: record d:\SRT\+messwerte\sonnenkreuz.rad
: azel 130 45           *antenne aligns in the direction of 130 45
: 1415.0                *center frequency with mode 1, 500MHz bw (default)
: noisecal              *calibration
: Sun                   *align to the sun
* Azimuth Scan
: offset -30 0          *horizontal scan -30 to +30 degrees
: offset -25 0
: offset -20 0
: offset -18 0
: offset -16 0
: offset -14 0
: offset -12 0
: offset -10 0
: offset -08 0
: offset -06 0
: offset -04 0
: offset -02 0
: offset  00 0
: offset  02 0
: offset  04 0
: offset  06 0
: offset  08 0
: offset  10 0
: offset  12 0
: offset  14 0
: offset  16 0
: offset  18 0
: offset  20 0
: offset  25 0
: offset  30 0
* Elevation Scan
: offset 0 30           *vertical scan (if sun Elevation is <60 degrees!)
: offset 0 25
: offset 0 20
: offset 0 18
: offset 0 16
: offset 0 14
: offset 0 12
: offset 0 10
: offset 0 08
: offset 0 06
: offset 0 04
: offset 0 02
: offset 0 00
: offset 0 -02
: offset 0 -04
```

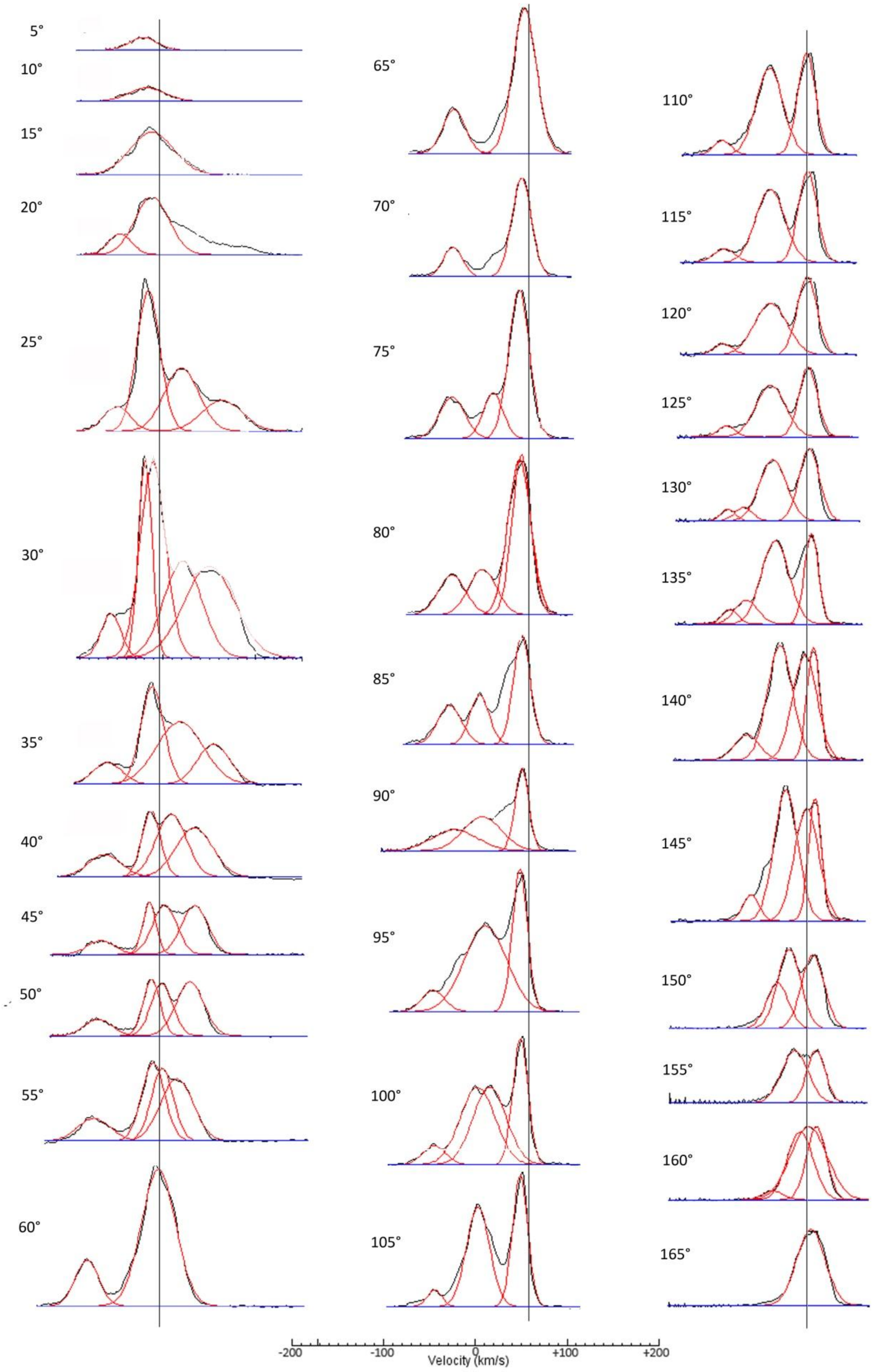
```
: offset 0 -06
: offset 0 -08
: offset 0 -10
: offset 0 -12
: offset 0 -14
: offset 0 -16
: offset 0 -18
: offset 0 -20
: offset 0 -25
: offset 0 -30
: roff                    *End recording
* ------------- SCRIPT ENDE --------------
```

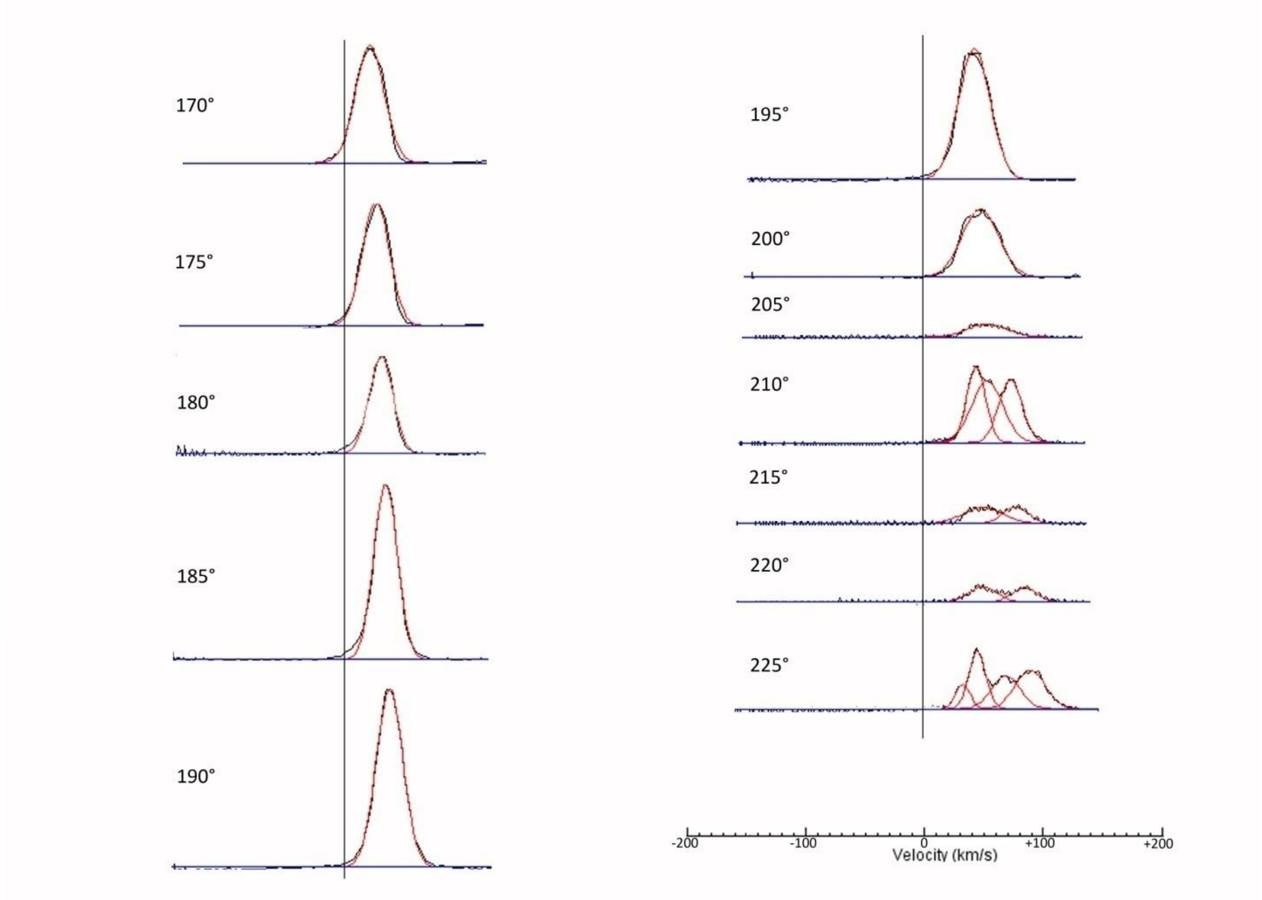
Calculation of velocity resolution Δv: $\Delta v\,[\mathrm{km/s}] = \Delta\nu\,[\mathrm{s}^{-1}] \cdot c\,[\mathrm{km/s}] / \nu\,[\mathrm{s}^{-1}]$.

Calculation of the Doppler frequency shift $\Delta\nu/\nu = v/c$,

whereby is ν = the frequency, c the light speed, and v = the velocity of the HI cloud.

Small catalog of the expected HI spectra on the various galactic positions:




170°
175°
180°
185°
190°
195°
200°
205°
210°
215°
220°
225°
-200
-100
0
+100
+200
Velocity (km/s)

Additional images - for information:

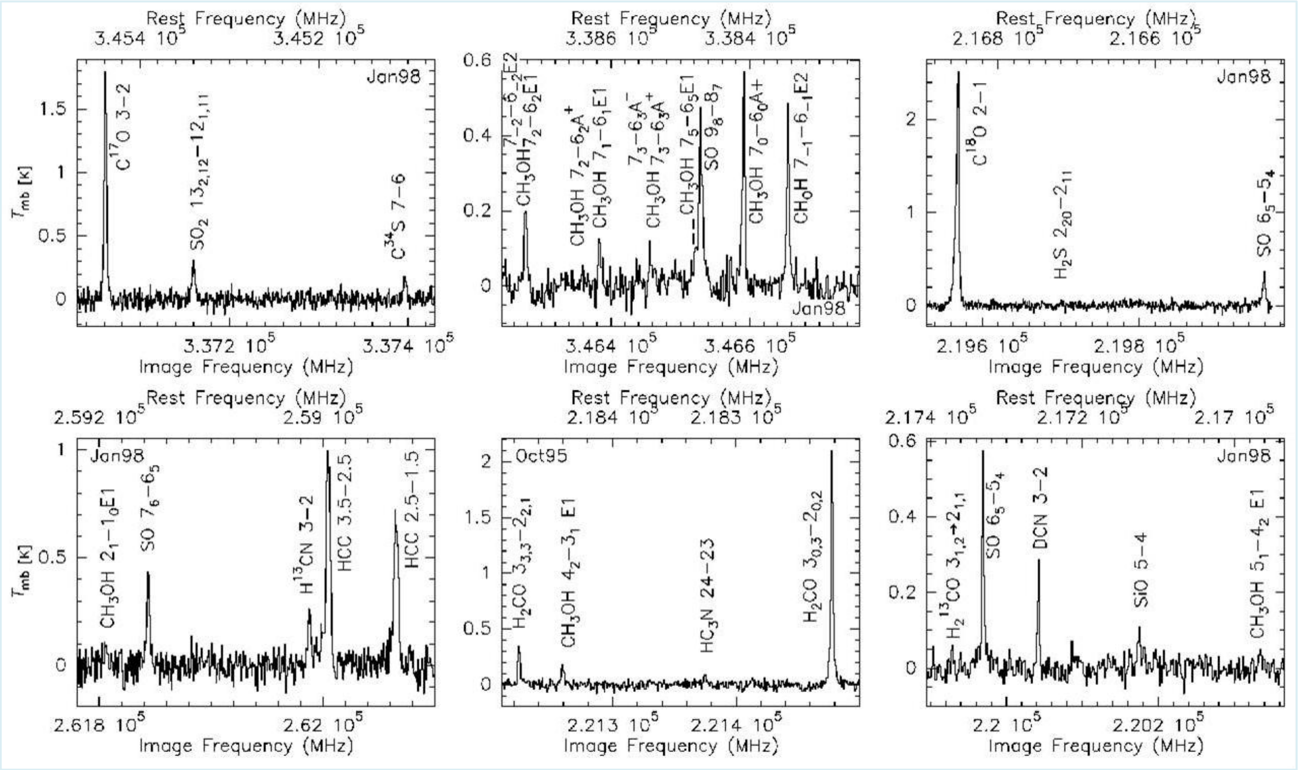


Fig.A1. Spectral lines in the radio range (molecular rotation transitions) recorded with the James Cerk Maxwell Telescope in Hawaii in a gas cloud with star formation. Many molecular lines are stimulated here. Tmb is the calibrated antenna temperature (on the main beam).

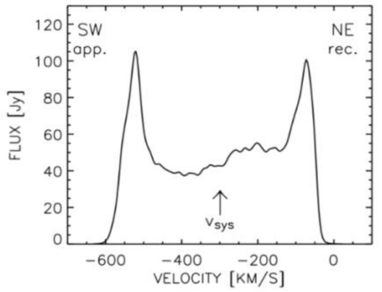


FIG. 3.— HI integrated profile of Messier 31. v_{sys} refers here to as the integrated weighted mean systemic velocity derived from the profile.

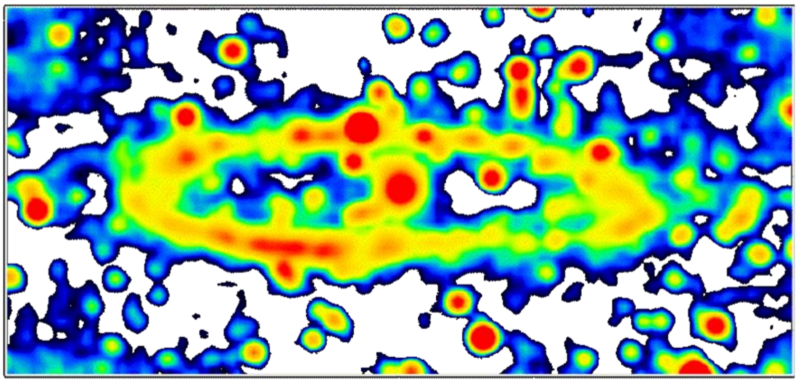
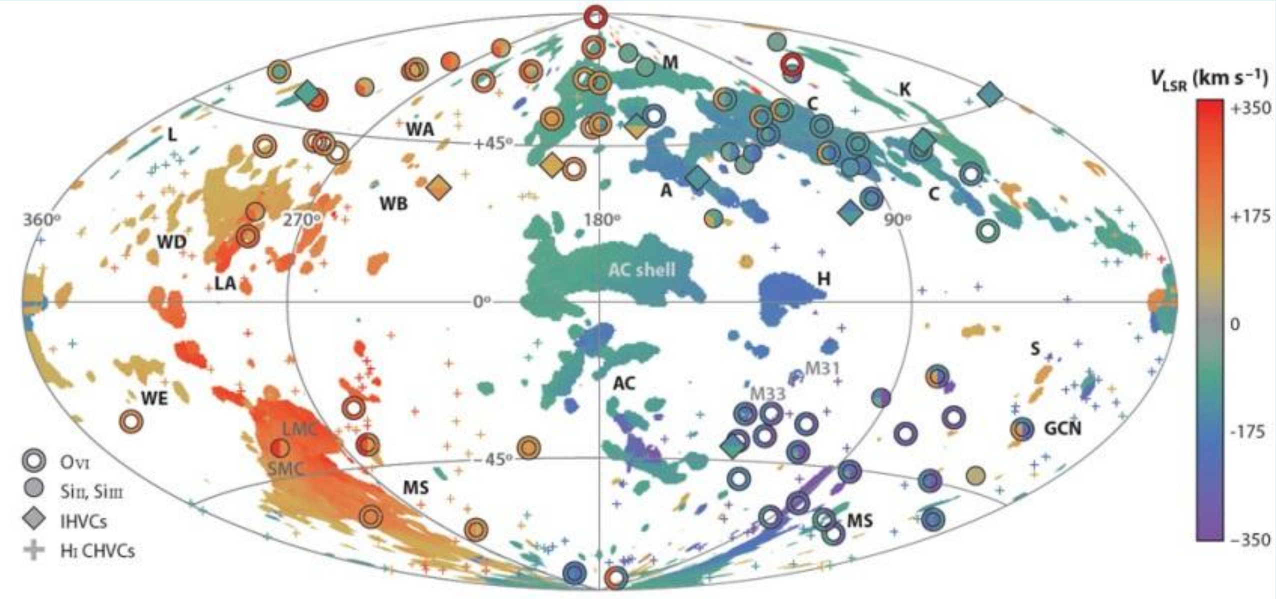


Abb. A2. HI-Line of M31
(Chemin, Carignan and Foster, 2009).

Fig. A3. The andromeda galaxy M31 recorded in the broadband continuum at 6 cm with the 100 m telescope in Effelsberg. Intensities: red = high intensity, blue = low intensity. The picture shows a gas ring in the galaxy that may have been initiated as a shock wave when a smaller, wider galaxy flew through this system.



Putman, M.E. et al. 2012.
Annu. Rev. Astron. Astrophys. 50:491–529.

Fig.A4. “High speed HI clouds” in / around our galaxy.

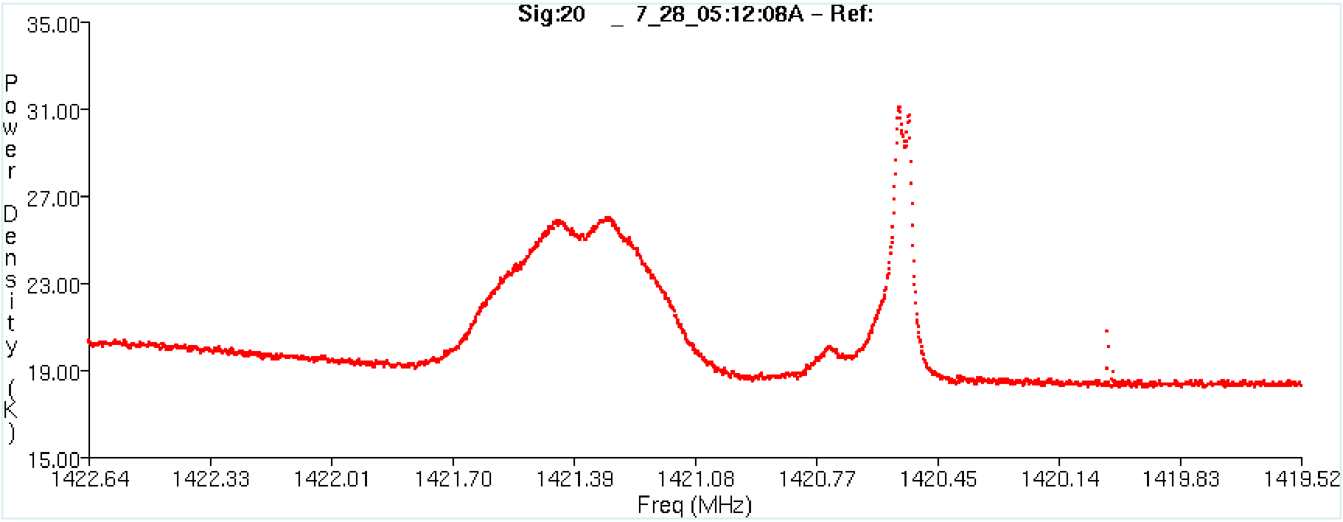


Fig. A5. The image shows a calibrated observation of Messier 33 with the GBT. The X axis shows the channel number of a 32767 channel spectrum covering the frequency range 1425 to 1375 MHz. The Y axis is intensity (Kelvins). The spectrum is the average of the X and Y polarization signals. (The narrow line @ 1420.4 MHz indicates the galactic HI emission, whereas the broad double line show the M33 HI emission).

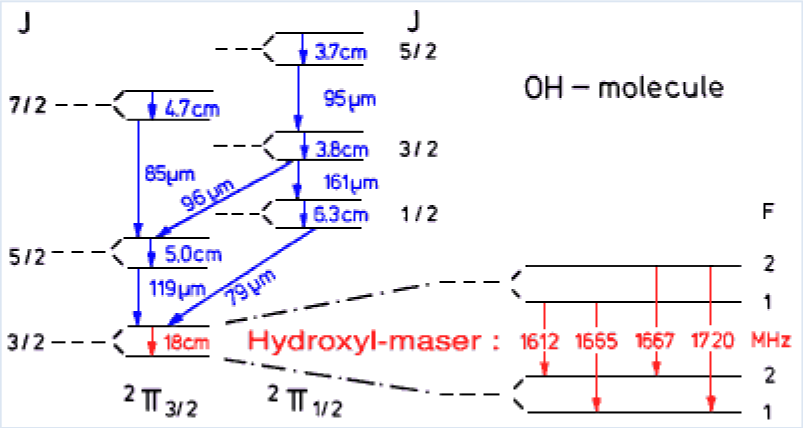


Fig.A6. A measurable OH maser transition is at 1665 MHz. A potential target is W75N.

Command overview - Quickstart of the telescope

1. Switch on the power strip
2. Switch on the controller power supply
3. Switch on the Controller
4. Plug the USB connection from the controller into the PC
5. only now switch on the notebook >>SRT-pc01<<
6. Login as „Student“ (without password)

7. Start of the Software: Double click on the desktop icon >>Verknüpfung mit srt<<

8. Click on the object on the sky map - e.g. GNpol oder SUN
or manual entry Azimuth and Elevation in command line:
90 45
and click on button **AZEL**

9. Make a continuum cross over the sun (Pointing):
Type in the command line:
+sonnenkreuz.cmd (no >Enter<)
and click on the button **RCMDFL**

10. Mini-map: 5 x 5 Measurement points that provide a sky intensity map:
Click on the sky object - e.g. SUN
and than on **NPOINT**

11. Take H I - Spectra:
At several points in the sky (marked with Gxxx) there is a four-minute spectra recording
Type in the command line:
+rotation.cmd (no Enter)
and than click on **RCMDFL**

12. Data recording
Type in the command line:
D:\SRT\+messwerte\testdatei.rad (no Enter)
and than click on **RECORD**
(then carry out the desired measurement) ⇒ RECORD appears green on the display
A second click on **RECORD** ends the data recording + closing the file.

End the measurement:

Click on **STOW** and wait until the telescope has reached its final parking position!
(then STOW turns green on the display)
Only then: close the program! Switch everything off in reverse order!
Shut down the computer properly, don't just close it!