Experiment 36 – Extraterrestrial microwaves

Place :	**ML-laboratory, lab at the end of the flight-time tunnel**
Meeting place :	**Main entrance of the physics department (9.00 o'clock)**
Tutor :	**Mr. Hagn, Phys.-Dep. E 15, Tel.: 289-12518, Room-No. 2362**

1) Course of the experiment

The experiment provides an introduction to the measuring techniques of radio astronomy. The radio signals (at a wavelength of about 18 cm) of the Sun and the "milky way" are measured. From such measurements the flux and the radiation temperature of these sources are calculated. Calibration of the equipment (the amplifier characteristics – noise temperature – are determined) will be carried out with the hot-cold-measurement method. The radiated power of the weather satellite Meteosat is determined via a power comparison measurement.

2) Physical terms

Emission and absorption of electromagnetic waves in the range of microwaves, wave propagation, Planck's law, Rayleigh-Jeans's law, Nyquist theorem, generation mechanisms of electromagnetic waves in nature.

3) Equipment and measuring technique

Parabolic antenna 1.75m ∅, RF amplifier, frequency converter, demodulator, spectrum analyzer, impedance, attenuation are explained in detail during the course of the experiment.

4) Remarks concerning the course of the experiment

Before carrying out the experiment the height of the Sun above the horizon as well as azimuth and height of the weather satellite Meteosat have to be calculated. Some knowledge of electronics is of advantage, but not necessary.

5) Since the experiment takes place partially outside of the building, weatherproof clothing won't harm.

6) Please note that we have to start at 9:00 o'clock in order to finish the exercises in time.

Experiment 36

Extraterrestrial microwaves

1. Historical review, motivation, aims

The discovery of electromagnetic waves

As in most areas of physics theory was ahead of experiments: When in 1864 the Englishman James Clerk Maxwell described the laws of electrodynamics by the equations named after him, experimental physics was still far from being able to confirm these phenomena by measurements. Not until 1887 Heinrich Hertz succeeded in confirming Maxwell's thoughts by impressive experiments: The propagation of electromagnetic waves in empty space was proven. At this point in time the search for possibilities to transfer messages via the propagation of electromagnetic waves began.

The first transmissions with short waves

It was the Italian Guglielmo Marchese Marconi, who dared to do the decisive step on this search in 1901 and tried to transfer a message from Poldhu (Cornwall) to St. Johns (Newfoundland), although at that time the reach of electromagnetic waves was generally still believed to be limited to the range of sight. The attempt succeeded. The discovery of the potential for the world-wide transmittance of information, which lies in the propagation of electromagnetic waves, is due to his intuition concerning technical-physical possibilities. The transfer of a message over the Atlantic was the date of birth of short wave communication and this happened at a point in time, when the mechanism of this kind of wave propagation over the horizon was still unknown.

The discovery of the ionosphere

In 1902 the Englishman Oliver Heaviside and the American Arthur Kennelly, studying properties of wave propagation, independently came to the conclusion that there exists a reflecting layer in the Earth's atmosphere, which has later been named Kennelly-Heaviside-layer. This reflecting layer, the ionosphere, was experimentally confirmed in 1924 by the Englishman Edward Appleton when measuring the angle by which a radio wave is reflected. In this way one was able to conclude, that there is a reflecting layer in a height of about 170 km: the "sky wave" was experimentally proven. He detected further properties of the ionosphere: An electron concentration of 10^5 per cubic centimetre, an elliptic polarisation of the waves and a diminished wave propagation due to the superposition of sky and ground wave.
The ground wave propagation of electromagnetic waves takes place along the Earth's surface; it is largely determined by the dielectric properties of the Earth's surface and by the territory formation. In the following years Breit and Tuve have worked out their echo logging method, which allowed to explore fundamental properties of the ionosphere. Thus they found, that the ionosphere reflects radio

waves only up to an upper frequency limit depending upon time of the day and year, that fading appears also with pure sky wave propagation and that the electron density in the ionosphere varies more discontinuously than described by simple physical models.

Solar activity, number of sunspots and degree of ionisation

The analysis of the reflection performance of the ionosphere revealed its dependence upon time of the day and year; thus it was reasonable to assume that the reflection properties of the atmosphere are influenced by the solar activity. This conclusion was confirmed by studies of the reflection properties during a solar eclipse in 1927. Soon thereafter the following model for the reflection performance of the atmosphere emerged: The top layers of the Earth's atmosphere are partially ionized by the influence of the solar activity. Besides UV-radiation and X-rays also the particle radiation, the so-called solar wind, causes ionization. This ionized layer, respectively the ionized layers, reflect the electromagnetic waves.

However, the reflection properties of the ionosphere are not constant in time. Although it was obvious to suspect a variation of the solar activity with time, it took a fairly long time until the processes were better understood and a correlation between the solar activity and the number of sunspots was found. The observation of the Sun's surface led to intensive studies of the behaviour of the sunspots.

The sunspots were already known to the Chinese a few thousand years ago. Also Galileo Galilei had seen them with his telescope and described them very accurately: He believed them to arise constantly, to vanish with different velocities and to follow the rotation of the Sun with a circulation time of 27 days. After ideas about the nature of the sunspots, partially quite adventuresome, had been published in the 18th and 19th centuries, in 1908 Dr. George E. Hale, using a spectroheliograph, succeeded to prove that the sunspots were actually huge gas whirls.

A German hobby astronomer, the chemist Heinrich S. Schwabe from Dessau, discovered the sunspot cycle in the middle of the 19th century by regularly determining the number of sunspots for a long period of time (see Fig. 1). From 1849 to 1981 the "Zürich relative sunspot number" was daily determined and published by the Sun observatory of Zürich. The relative sunspot number was defined by Rudolph Wolf, then director of the observatory, via the following equation:

$$R = k\,(10\,g + f)$$

with:
- R = relative sunspot number
- g = number of sunspot groups
- f = number of sunspots
- k = correction factor for the measuring instruments used

Since 1st of January 1981 the SIDC, the sunspot-index data centre, in Belgium is responsible for this job. Around 1930 due to careful observations Dr. Edison Pettit of the Mount Wilson observatory was able to find the correlation between the UV-radiation (and the electron density in the ionosphere) and the relative sunspot number. In 1924 Pettit started measuring the intensity of the UV-radiation every day. From 1924 to 1928 he found the relative sunspot number to increase as continuously as the intensity of the UV-radiation; from 1928 on the decrease of the intensity was coupled to a decrease of the relative sunspot number. These and similar results allowed the conclusion, that the intensity of the UV-radiation emitted by the Sun was proportional to the relative number of sunspots.

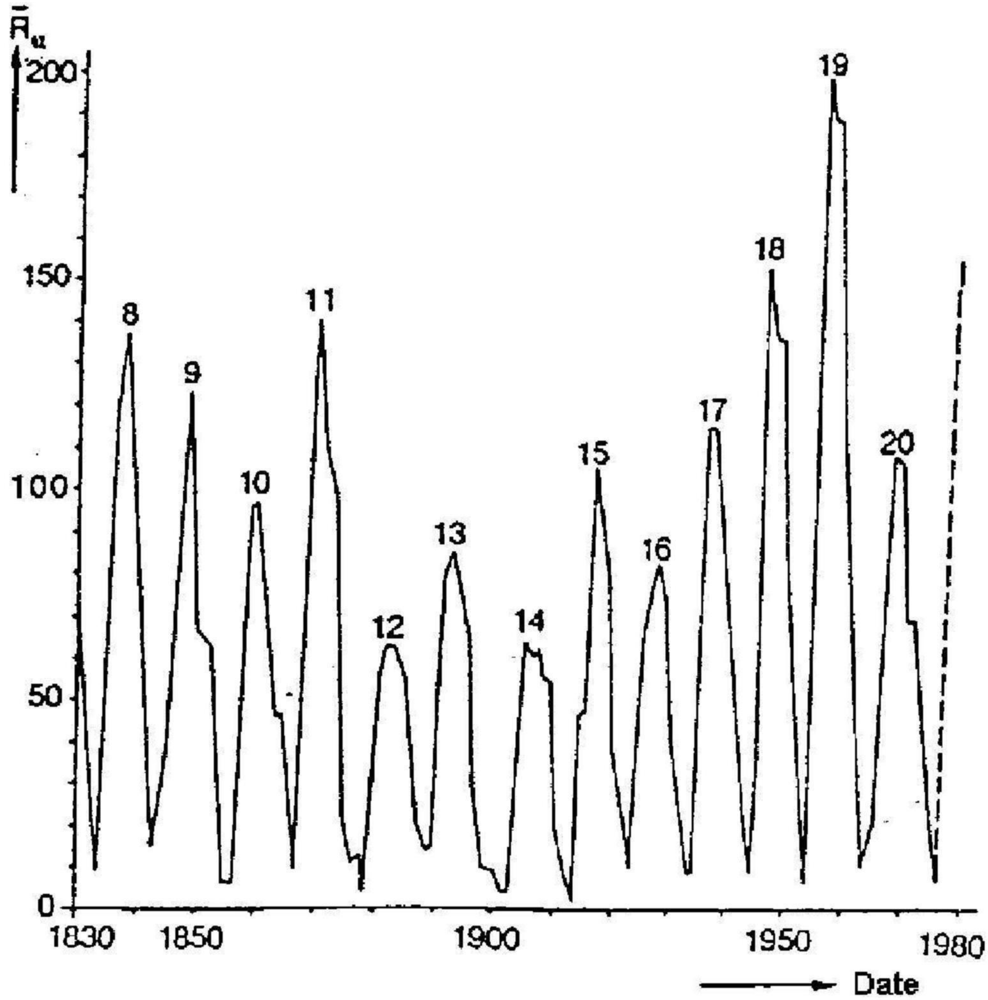


Fig. 1: Sunspot cycle since 1830 with cycle numbers indicated. As the daily number of sunspots exhibits very strong fluctuations, the monthly mean value is calculated; the harmonized twelve-month-value R12 is the mean value of 12 months.

The beginning of intensive short wave communication

Around 1930, the properties of short wave propagation were sufficiently investigated to use it as a technical communication medium. That's why in this time a boom in the development of devices for long distance communication and also an intensive exploration of related phenomena took place.

In 1932, on the occasion of such investigations at the US-Bell-Laboratories, K. G. Jansky discovered electromagnetic radiation from the centre of our galaxy (in the range of 15 MHz).

However, G. Reber's measurements concerning the distribution of the radio signals at λ = 1.8m in the sky, which he performed with a big parabolic reflector (10m) during the years 1939 – 1944, were the first to convince astronomers of the existence of this phenomenon. From 1939 on, with the development of radar the search for radio sources in the range of dm and cm became possible. The radiometer developed by R. H. Dicke in 1946 presented a further, essential contribution to the observation of radio signals. The discovery of the spectral line of hydrogen and of the nitrogen radical was a stimulant to enlarge the measurements to the range of mm and below.

2. Basics

2. 1 Astronomical coordinate systems

As we observe the objects in the sky from the Earth rotating around its own axis it is necessary to introduce appropriate coordinate systems.
Hint: Look at fig. 2, in particular, and try to qualitatively make clear to yourself the situation at the sky.

- The horizon system

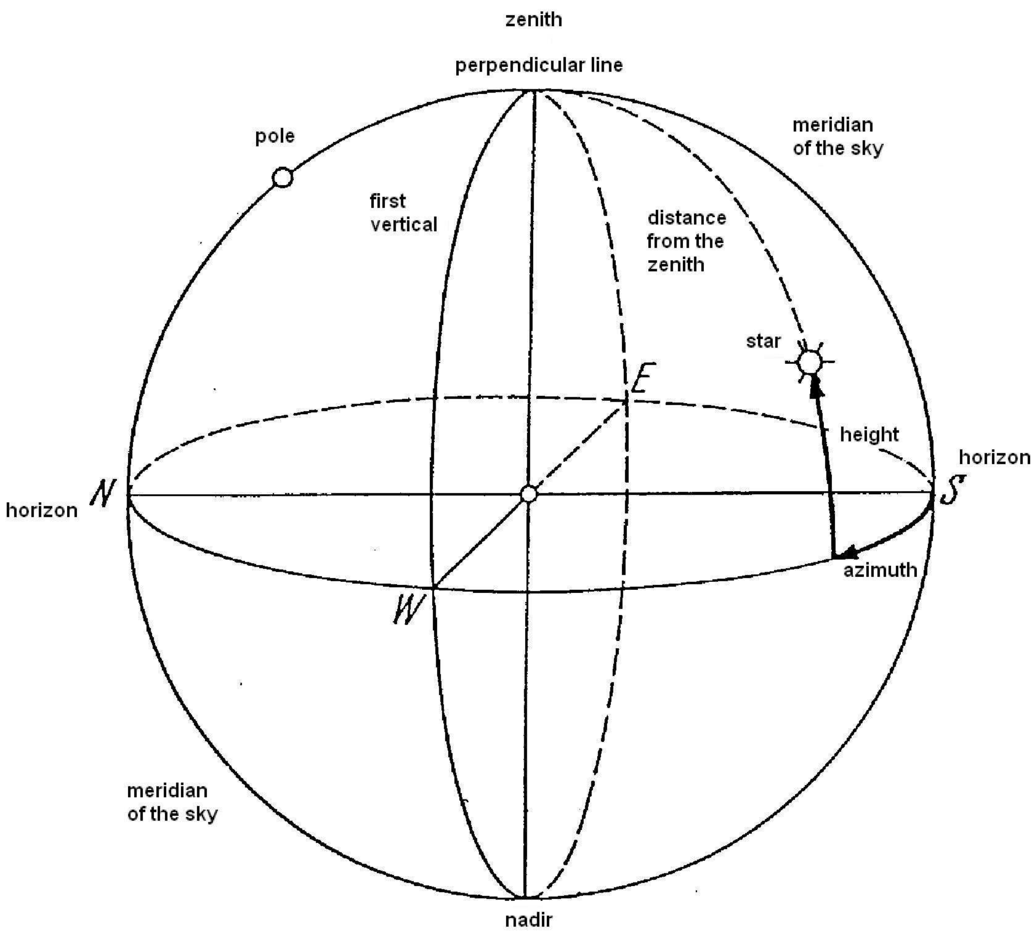


Fig. 2: The horizon system: The celestial globe, the horizon with north, east, south and west points. The (sky) meridian passes through north point, pole, zenith, south point and nadir. – Coordinates: height and azimuth.

Keep in mind that we observe the sky from a certain point on the Earth given by its longitude and latitude (Garching lo = 11.6°, la = 48.2°). For thi s point on Earth the so-called horizon system can be used. In doing so the direction in which an object in the sky appears is given by the two angles azimuth and height. The ground plane of this system is the horizon plane of the observer. The zenith is perpendicular above the observer. The direction south-north is defined by a great circle through the (sky) pole (direction of the rotation axis of the Earth) and the zenith. This great circle is called local meridian. In order to determine the coordinates azimuth and height of an object (star) in the sky the great circle passing through the zenith and the object is essential. Then the height is the angle between the horizon plane and the object (star). The azimuth indicates the angle between the southward direction and the great circle, which includes the object in the sky, along the horizon plane (see fig. 2).

This coordinate system is easy to use and of interest for radio telescopes, as, due to their dimension and weight, they are mounted in a way that azimuth and height can be adjusted directly (rotation around a vertical and a horizontal axis). Our antenna is mounted in that way, too.

- The equatorial system

In order to easily compensate the rotation of the Earth around its own axis the equatorial system is normally used for astronomical observations and for tabulating positions of objects in the sky (fig. 3). In this system, the equator of the sky is the ground plane (extension of the equator of the Earth to the fictitious celestial sphere). The northern resp. southern pole of the sky are perpendicular above resp. below this ground plane. In this coordinate system the position of an object (star) in the sky is determined by the two angles, right ascension (RA) and declination (δ). The right ascension is measured along the equator of the sky, considering the great circle including the object and the poles of the sky (hour circle of the star, fig. 3). The zero-point of the right ascension angle is the position of the Sun, when, in spring, it changes from the South to the North side of the equator of the sky on its fictitious path among the fixed stars generated by the revolution of the Earth around the Sun (point of intersection: ecliptic (= fictitious path) – equator of the sky). This point is called vernal equinox or Aries point (it used to be in this zodiac sign). The declination (δ) indicates the angle of the object below or above the equator ($-90° < \delta < 90°$).

After the zero-point of this system has been defined, all fixed stars can be tabulated with distinct coordinates in this coordinate system (RA, δ) (in order to take into account the remaining changes due to the precession of the axis of the Earth and possible peculiar (eigen) motions of the “fixed” stars, the catalogues are regenerated every 50 years).

In order to establish a relation to the point of observation and to its horizon system, which is also plotted in fig. 3, the term “local sidereal time” is needed. This is the current angle between the local meridian and the vernal equinox. It is given in hours, minutes, …, and is equal to 0^h, if the vernal equinox is exactly in the South of the point of observation. As our (civic) time is connected to the Sun, which moves ahead of the fixed stars by about 4 minutes per day, the momentary local sidereal time has to be evaluated by calculation, with the help of tables or by using a suitably set sidereal time clock; the longitude of the point of observation has to be known.

If one desires to locate an object in the sky at a certain time, one needs its hour angle indicating how far one has to go along the equator of the sky in a westward direction in order to cross the hour circle of the star. In fig. 3 the following relation can be seen:

Hour angle = sidereal time – right ascension RA

Annotation: sidereal time = hour angle of the vernal equinox.

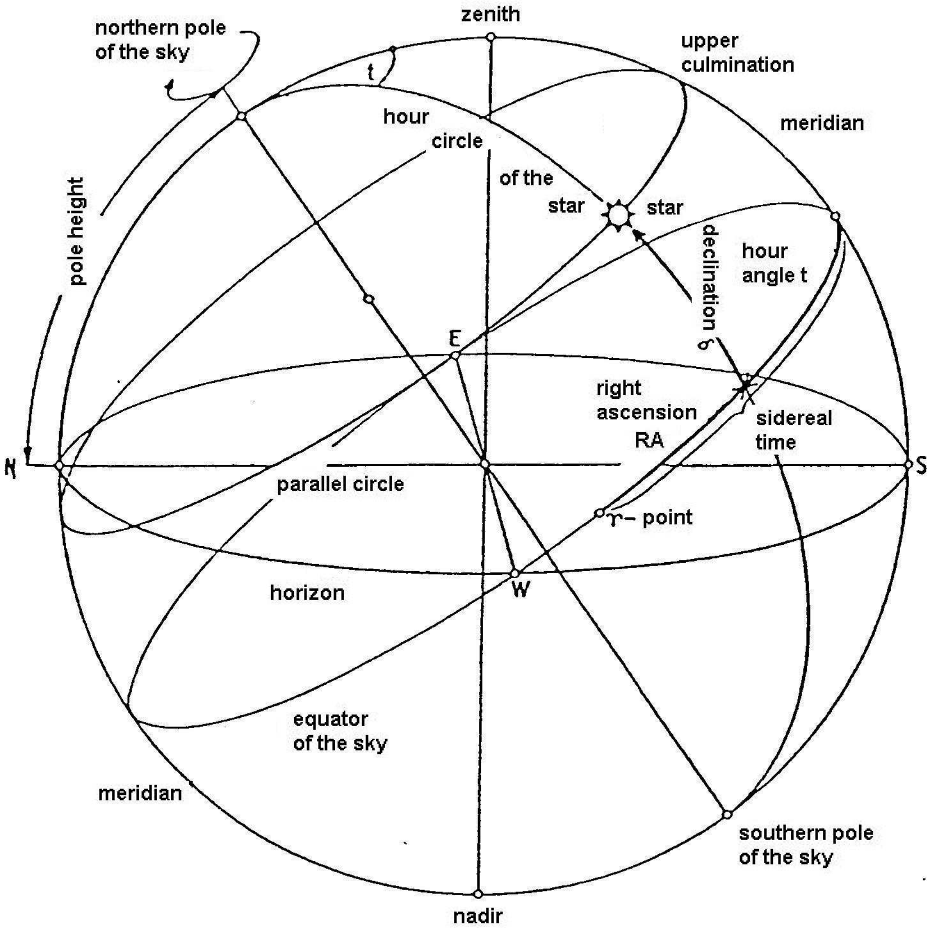


Fig. 3: Equatorial system with the coordinates: right ascension RA (distance Aries point (γ)-hour circle of the star on the equator of the sky) and declination δ. Hour angle t = sidereal time minus right ascension RA. Pole height = latitude.

Most optical astronomic telescopes are mounted in a way that one axis of rotation is parallel to the rotation axis of the Earth (parallactic mounting). The hour angle can be adjusted by rotating the telescope around this axis. The second axis is mounted perpendicular to it and directly permits the adjustment of the telescope to the declination of the object.

- example: object at RA = 3h, 30min, δ = 40°, local sidereal time 6h

  This results in an hour angle of the object of t = 2h 30min.

Using a parallactically mounted telescope it has to be set, starting from the southern direction, to an angle corresponding to 2h 30min, which means 37.5° to the west, and then, by rotation around the axis of declination, to 40° above the equator of th e sky.

- Objects in the solar system

In the coordinate systems never more than two angles appear because the finite extension of the Earth can be neglected for the distant objects in the sky. This is true for the fixed stars and still for the planets and the Sun (not for Meteosat!). Also for the fixed stars the annual motion of the Earth around the Sun plays no role for practical observations (RA and δ virtually fixed, hence the name). For practical observations, in order to handle the complicated fictitious paths of planets, comets etc. in front of the fixed stars arising from the combination of their eigen motion and the revolution of the Earth around the Sun, RA and δ of these objects are tabulated in compendia for each year (ephemeris).

- Conversion: Horizon – equatorial system (according to F. Becker, Einführung in die Astronomie, page 26ff).

As our radio antenna, as mentioned before, is only adjustable in azimuth and height, we finally need the formulas to be able to adjust an object tabulated in RA and δ (-> t). Frequently used relations between the equatorial and horizontal coordinates can be deduced from the spheric triangle, named astronomical or nautical triangle, with the corners: pole of the sky, zenith, star. With α meaning right ascension, ϑ sidereal time, t hour angle (given by $t = \vartheta - \alpha$), further δ the declination of the star, A its azimuth, z its distance from the zenith and φ the height above the pole, the application of the basic formulas of spheric trigonometry on the triangle mentioned above leads to two groups of formulas for the transformation between the two coordinate systems

$$\sin z \sin A = \cos \delta \sin t$$
$$\cos z = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos t$$
$$- \sin z \cos A = \cos \varphi \sin \delta - \sin \varphi \cos \delta \cos t$$

and

$$\cos \delta \sin t = \sin z \sin A$$
$$\sin \delta = \sin \varphi \cos z - \cos \varphi \sin z \cos A$$
$$\cos \delta \cos t = \cos z \cos \varphi + \sin z \sin \varphi \cos A.$$

2.2 Extraterrestrial sources of radiation

Microwaves are in a frequency range from 1 GHz up to 300 GHz, according to a wavelength range from 30 cm to 1 mm. The range of interest to us is restricted to the so-called radio window (fig. 4), in which the absorption of the electromagnetic waves by the atmosphere of the Earth is negligible. Extraterrestrial sources of radiation may have a continuous spectrum (synchrotron radiation, thermic radiation) or a discrete spectrum (e.g. the 21 cm H line). The thermic radiation can be described by Planck’s law of radiation in the approximation $\nu \ll kT/h$ (Rayleigh-Jeans).

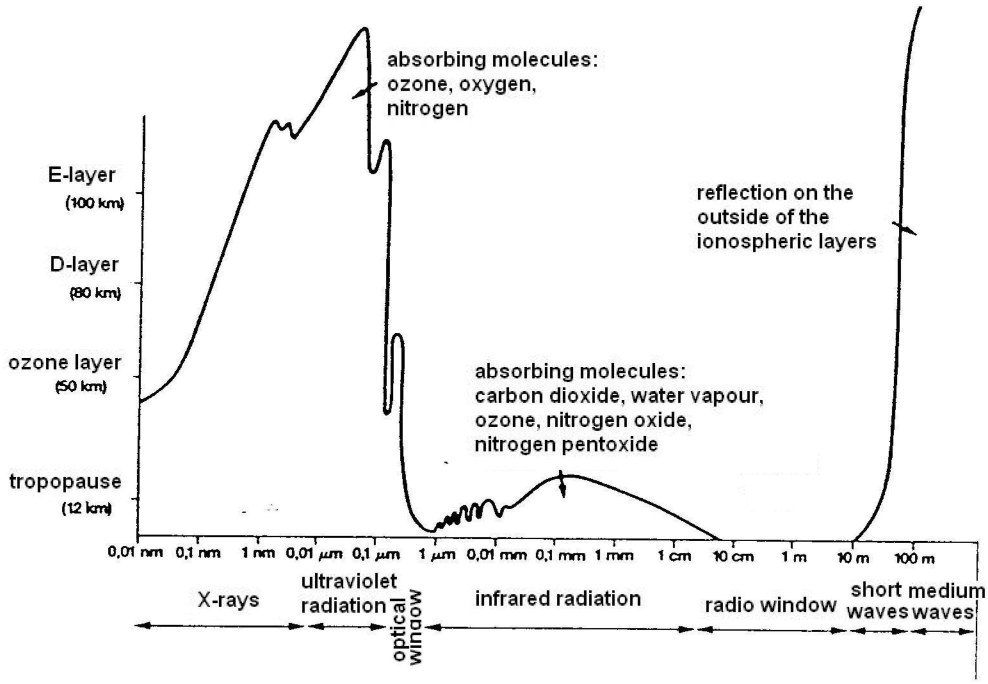


Fig. 4: Absorption of electromagnetic waves in the atmosphere

This radio window allows the observation of extended and point radio sources in the sky. The well-known 3 K background radiation fills out the hole sky isotropically. In the following we want to deal with sources standing well out of the 3 K background and amongst them we restrict ourselves to the strongest radio sources. If you're further interested in the methods and results of the vast field of modern radio astronomy, you'll find additional literature in the library of the physics department. Using the equipment of the lab some objects quoted in fig. 5 can be observed. Fig. 5 shows spectra of these objects: the radio flux (in Jansky) reaching the Earth is plotted against the frequency (resp. wavelength at the top edge of the picture). Apart from these single objects we can observe the band of our milky way in the radio range, too. The unit Jansky represents 10^{-26} W/(m²Hz). In table 1 further radio sources are listed together with their flux at λ = 20cm. The radio flux indicates the power (W) per unit area (m^2) perpendicular to the direction of incidence and per unit frequency interval (Hz) reaching Earth. The choice of the unit "Jansky" already tells you that very low radiation power has to be measured correctly in the experiment.

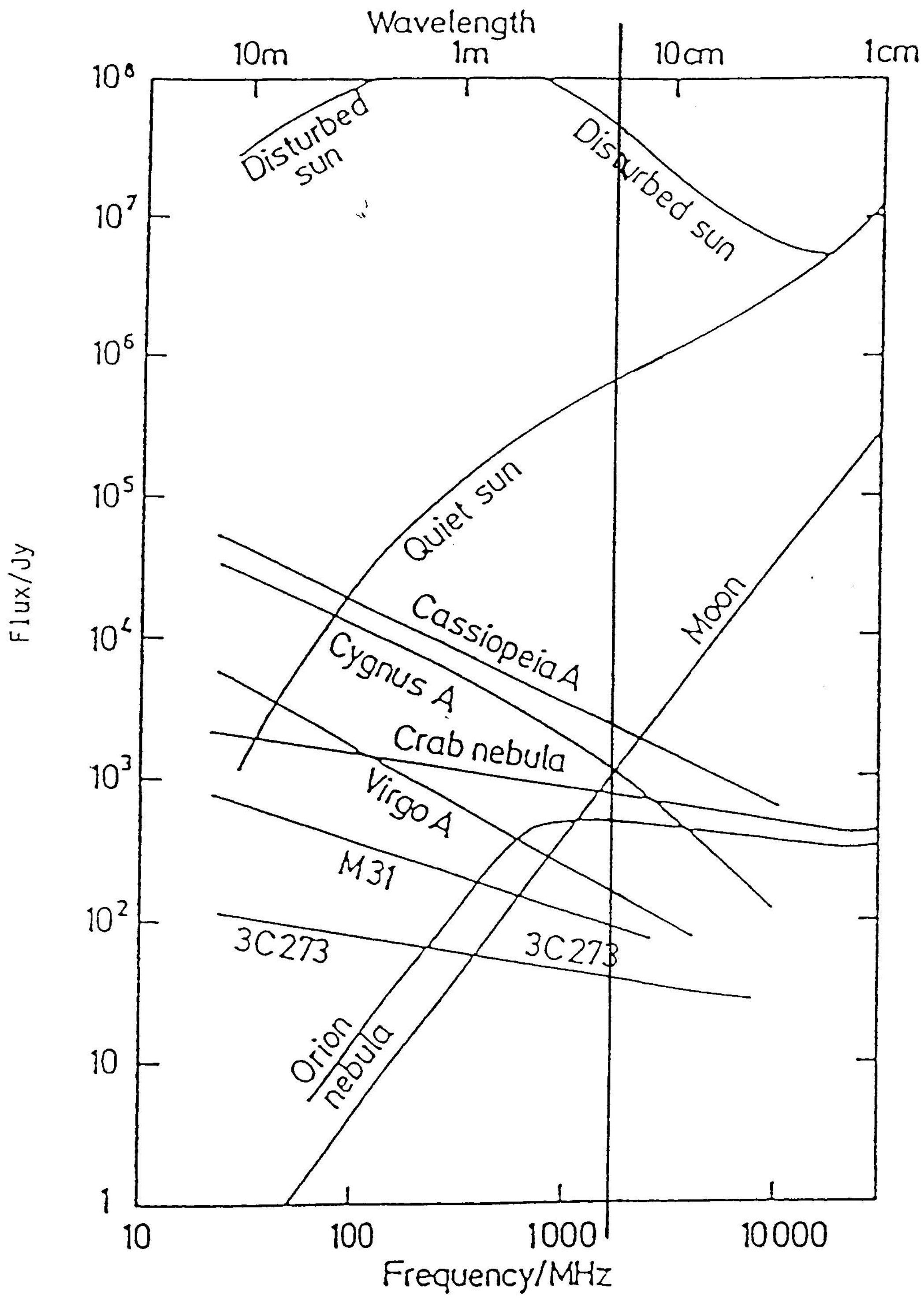


Fig. 5: The flux of the most intensive sources as a function of frequency. The vertical line at 1.7 GHz corresponds to our frequency of observation.

2.3 About the devices

- The parabolic antenna of the radio telescope

As long as d >> λ (d is the diameter of the antenna), the resolution of the reflector, i. e. the angular distance between the primary maximum and the first diffraction minimum, is given by

$$P_0 = 1.22 * d \text{ (rad)} \cong 70 * \lambda/d \text{ (°)}.$$

In radio astronomy, often the beam width, i. e. the distance between two opposing points at which the measured power has fallen to half of its maximum value, is given instead of the resolution of the reflector. The beam width is

$$2 * p_{1/2} = 1.03 * d \text{ (rad)} \cong 59 * \lambda/d \text{ (°)}.$$

Fig. 6: Comparative characteristics of parabolic reflectors for some idealized illuminations.*

Illumination	Half-Power Beam Width	Peak Side Lobe Level, dB Down	Relative Gain	First Null Position
A. Rectangular Aperture of Length L				
$G(x) = \cos^m(\pi x/L)$ for $\lvert x \rvert < L/2$				
m = 0 (uniform)	50.4° λ/L	13.2	1.00	57.3° λ/L
m = 1	68.7° λ/L	23	0.81	85.9° λ/L
m = 2	83.1° λ/L	32	0.667	114.6° λ/L
m = 3	95.1° λ/L	40	0.575	143.2° λ/L
B. Circular Aperture of Diameter D				
$G(\rho) = \left\{1 - (2\rho/D)^2\right\}^m$				
m = 0 (uniform)	58.4° λ/D	17.6	1.00	69.9° λ/D
m = 1	72.8° λ/D	24.6	0.75	92.2° λ/D
m = 2	84.2° λ/D	30.7	0.55	116.3° λ/D
m = 3	94.5° λ/D	36.1	0.45	138.7° λ/D

* Source: M. I. Skolnik

- The electronic setup

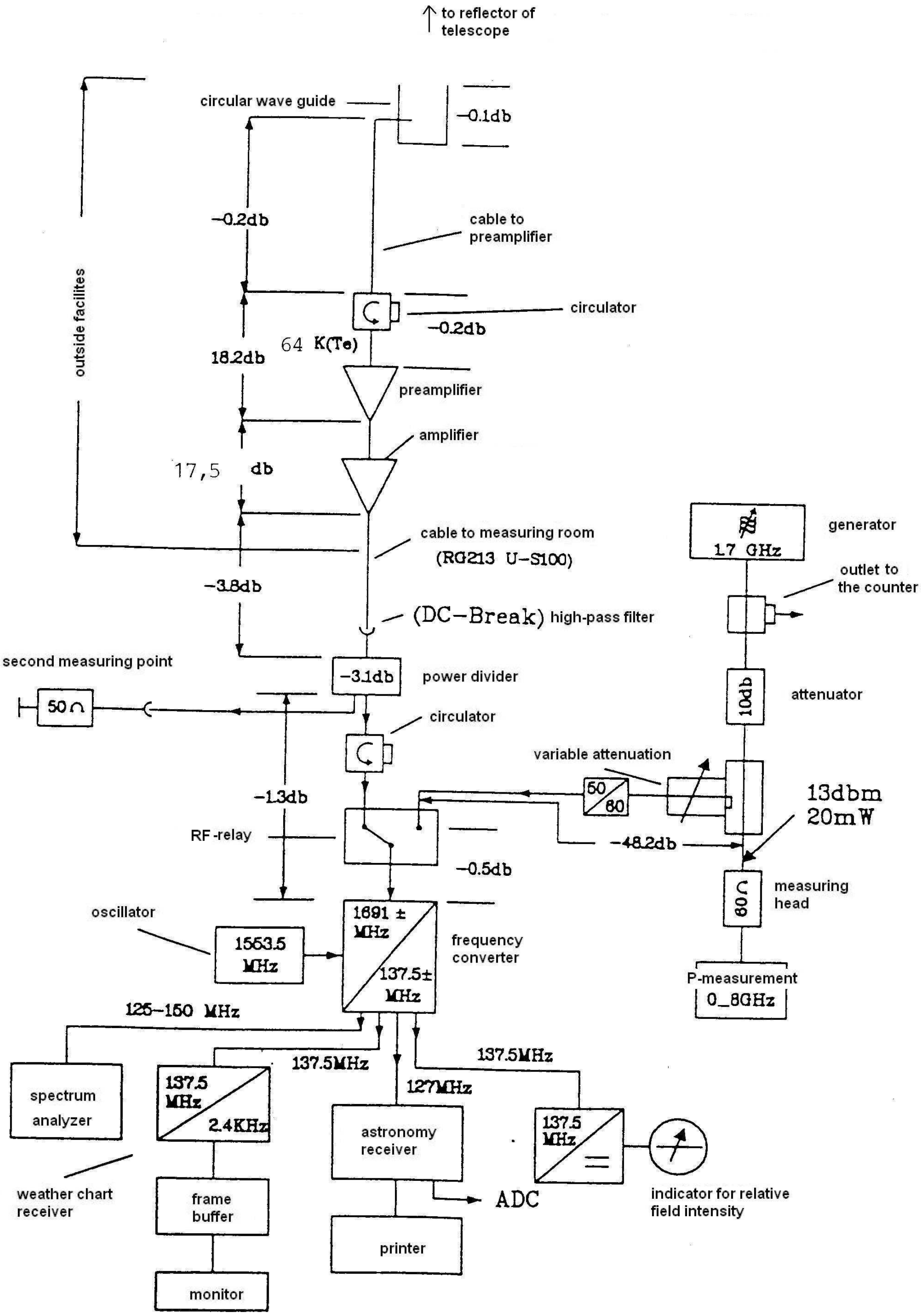
From the parabolic reflector (1.75 m diameter) the radio signal goes via a circular wave guide, a cable of 1 m length with low attenuation (Fa. Andrews) and a circulator to a low-noise GaAs-FET preamplifier. Then a further amplifier follows, from which the signal is brought into the measuring room. Having passed through a high-pass filter and a power divider the signal is given to a frequency converter via an RF-relay. This frequency converter “converts” the input frequency range 1675 – 1700 MHz to the range 121.5 – 146.5 MHz. In the so-called “Meteosat branch” the frequency 137.5 MHz (band width 30 kHz) is filtered out. The “astronomy branch” works at about 127 MHz (band width 1.5 MHz). Further explanations will be given when the experiment is performed.

Table 1 Radioastronomical sources at 20 cm

Name	Right ascension [h]	[m]	Declination [°]	[']	Flux * [Jy]	Identification - Remarks
(a) HII-Regions/Emission nebula						
W 3	02	22,7	61	51	170	IC 1795
Ori A	05	32,8	− 05	27	520	NGC 1976, 3C145
Ori B	05	38,4	− 01	54	95	NGC 2024, 3C147.1
W 28	17	58,2	− 23	22	360	M 20
W 29	18	01,0	− 24	22	260	M 8, NGC 6523
W 33	18	10,4	− 18	00	190	IC 4701
W 37	18	16,3	− 13	45	260	M 16, NGC 6611
W 38	18	17,8	− 16	09	1060	M 17, NGC 6618
W 49 A/B	19	08,2	+ 09	02	75	NRAO 598 + 3C398
W 51	19	20,8	+ 14	08	710	3C400
(b) Supernova Remnants (SNR)						
3C10	00	22,6	+ 63	52	44	Tychos SNR von 1572
3C58	02	01,9	+ 64	35	34	
Tau A	05	31,5	+ 21	59	875	M 1, Crabnebula, SNR from 1054
3C157	06	14,3	+ 22	36	190	IC 443
3C358	17	27,7	− 21	27	15	Kepler´s SNR from 1604
W 41	18	31,6	− 08	57	75	
3C391	18	46,8	− 00	59	20	NRAO 583
W 44	18	53,6	+ 01	15	171	3C392
W 78	20	48,2	+ 29	30	90	Zirrusnebula, Cygnus Loop
Cas A	23	21,1	+ 58	33	2480	3C461, SNR from about 1700
(c) Radio galaxies						
3C84	03	16,5	+ 41	20	14	NGC 1275, Seyfert Galaxy
3C123	04	33,9	+ 29	34	47	
3C218	09	15,7	− 11	53	43	D Galaxy
3C270	12	16,8	+ 06	06	18	E Galaxy
Vir A	12	28,3	+ 12	40	198	M 87, E Galaxy
3C295	14	09,6	+ 52	26	23	D Galaxy
Her A	16	48,7	+ 05	05	45	3C348, D Galaxy
3C353	17	17,9	− 00	56	57	D Galaxy
3C390.3	18	45,9	+ 79	43	12	N Galaxy
Cyg A	19	57,7	+ 40	36	1495	3C405, D Galaxy
(d) Quasars						
3C48	01	34,8	+ 32	54	16	
3C138	05	18,3	+ 16	35	10	
3C147	05	38,7	+ 49	50	23	
3C196	08	10,0	+ 48	22	14	
3C273	12	26,6	+ 02	20	46	
3C279	12	53,6	− 05	31	11	
3C286	13	28,8	+ 30	46	15	
3C309.1	14	59,0	+ 71	52	9	
3C380	18	28,2	+ 48	43	14	
3C454.3	22	51,5	+ 15	53	11	

* for the wavelength of 20 cm

block diagram of the electronic assembly



3. Tasks

Notice: Tasks 1 and 2 are to be done before the day of the experiment

Task 1: Calculate azimuth and height of the Meteosat-satellite! This satellite is geostationary above 0. degree of longitude.
Annotation: Garching: lo = 11.6° (eastern longitude), la 48.2° (northern latitude).

Task 2: Calculate height and point in time (MEZ) of the Sun passing in front of the antenna on the day of your experiment!
Annotation for task 2: You can take (with interpolation) the right ascension and declination of the Sun on the day of your experiment from the table in the appendix. You have calculated the azimuth (identical to the azimuth of Meteosat) of the lab's antenna in task 1. You can obtain height and hour angle t from the transformation formulas between horizon and equatorial system. The sidereal time for the evening of the day of the experiment can be determined with the help of the table in the appendix. Assume the position of the Sun for the day of the experiment to be fixed and neglect the difference between sidereal time and civic time in the course of one day as well!

Task 3: Calculate the "antenna temperature" from the rise of the signal when the Sun passes. With the help of this value the flux of the Sun can be determined using $S = k*T_A / A$, where S is the flux density of a point source at the surface of the Earth in W Hz^{-1} m^{-2}, k the Boltzmann constant ($1.38*10^{-23}$ J/K), A the effective area of the antenna in m² and T_A the "antenna temperature" in K. What do you have to keep in mind when calculating the real flux of a source from the "antenna temperature" ? Map the obtained value in fig. 5 of the experiment's instruction sheet.

Task 4: Measure the "antenna temperature" by varying the elevation of the antenna from about –15° (ground) to 50° (cold sky) ! The noise temperature of the receiver was determined to be 64K by a hot/cold-measurement. Map the obtained values into a diagram! (The antenna temperature is not the physical temperature, but the effective temperature "seen" by the antenna. In addition, there are contributions to the temperature from side lobes and losses in the material of the antenna.)

Task 5: Measure the voltage at the antenna output (impedance 50 Ω) when receiving the signal from Meteosat (The measurements are performed with the "small" antenna. The diameter is 1.75 m, the illumination 55 %) !

Task 6: Evaluate the flux of the "milky way" from the recorder print-outs!

Task 7: Determine the opening angle θ of the radio telescope on the basis of the recorder print-out and compare θ to $p_{1/2}$ (see Section 2.3: About the devices) !

Task 8: Calculate the radiation temperature of the Sun at the observed frequency with the help of T_A and θ!

Literature:

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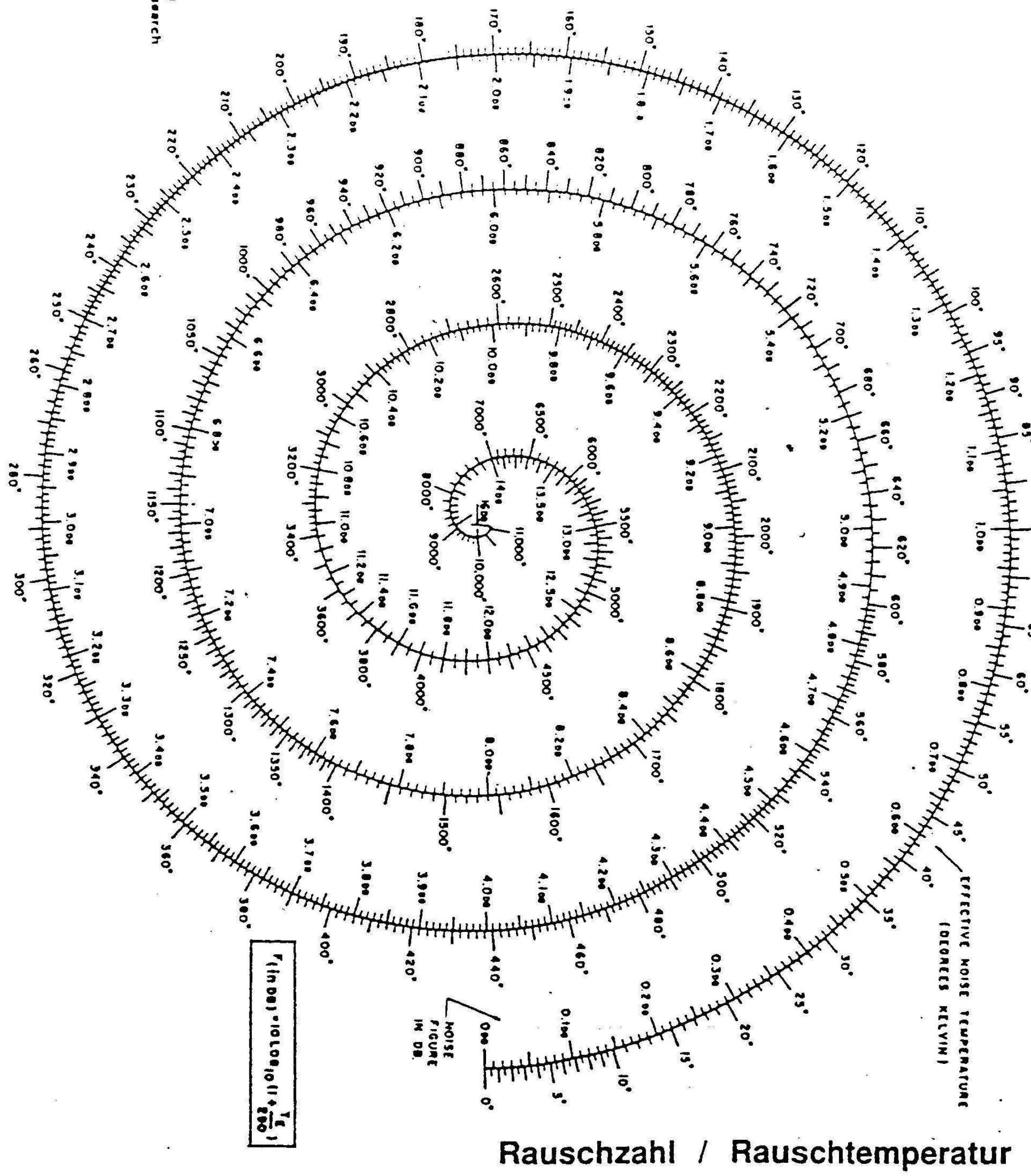
Rauschzahl und Rauschtemperatur

Spiral chart relates Noise Figure and Noise Temperature

This 40 inch long conversion chart for receiver and amplifier noise is rolled into a sprial to combine accuracy and convenience. The chart is arranged for maximum accuracy at the low-noise end of the scale.

A.C. Hudson, Radio and Electrical Engineering Division, National Research Council, Ottawa, Canada and Microwaves Magazine



Rauschzahl / Rauschtemperatur