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Determining the Parameters of a Receive System in Conjunction with Cosmic Radio Sources

The editors would like to point out that the article (1) written by Guenther Hoch, DL6WU, provides an excellent basis for the following considerations. The following article is to describe antenna noise temperature and the "hot-cold noise figure measuring method", to discuss inaccuracies of sun-noise measurements, to introduce cosmic radio sources, and finally to describe measuring methods with the aid of these sources. The diagrams with measured values of the strongest radio sources at 144 MHz and 432 MHz form valuable reference information. A further diagram gives the data for the wider frequency range of 30 MHz to over 10 GHz.

1.
ANTENNA NOISE TEMPERATURE

One of the criteria of a receive system is its ability to receive very weak signals: its sensitivity. The sensivity is determined by only two factors:

Antenna gain (G)
System noise temperature (T_{sys})

The system noise temperature comprises the antenna noise temperature (T_a), the cable losses converted into noise temperature (T_{cable}), and the intrinsic noise of the receiver, or preamplifier (T_{rx}). The latter can be calculated easily according to equation 1 from the known noise figure F:

$$T_{rx} = (F - 1) \times 290\ K \qquad \text{(Eq. 1)}$$

In this case, F is used as factor (not in dB). The equivalent antenna noise temperature (antenna temperature) is the noise power received by the antenna, converted to the temperature of a resistor, whose value is equivalent to the radiation impedance of the antenna.

All objects with a temperature higher than absolute zero (0K), radiate electromagnetic waves due to this temperature. This radiation is well known in physics and can be expressed mathematically as "black-body radiation" according to Planck's law.

The antenna temperature is mainly determined by the noise temperature of objects within its beamwidth. If an object radiates noise due to its intrinsic temperature of due to other noise-generating mechanisms, the antenna will receive this noise and a certain noise power will be present at its connections. Since noise power and equivalent noise temperature are dependent on another according to Boltzman's constant, it is possible to express the received noise power as in increase in antenna noise temperature.

The antenna noise temperature has very little dependence on the physical temperature of the antenna itself that can be measured with the aid of a thermometer! The higher the efficiency of the antenna, that is the greater the ratio of radiation resistance to loss resistance, the less will be the dependence.

The received noise power, or the noise temperature of the antenna, does not only depend on the temperature T of the object, but also on how much this object is present in the antenna diagram. In order to calculate this, it is necessary to operate with the space angles of the object (Ω), and the antenna diagram (Ω_A). This is given in equation 2:

$$T_a = \frac{\Omega}{\Omega_A} T \qquad \text{(Eq. 2)}$$

If Ω is equal to Ω_A, or is greater, this will mean that the antenna will only "see" the object radiating with temperature T; and the antenna noise temperature will be equal to the temperature of the object:

$$T_a = T$$

However, all practical antennas have unwanted lobes and a finite front-to-back ratio. If these are not suppressed considerably, the antenna will receive additional noise power with them. In the case of conventional antennas with beamwidths of less than 25° in both planes, a rule of thumb is given in (2) that takes the effect of unwanted side and back lobes into consideration:

$$T_a = 0.82\,T_{sky} + 0.13\,(T'_{sky} + T_e) \qquad \text{(Eq. 3)}$$

T_{sky}: Mean value of the equivalent noise temperature of space within the main beam.
T'_{sky}: Mean value of the equivalent noise temperature of space within the side lobes.
T_e: Effective noise temperature of the earth (290 K).

Equation 3 is only valid for antennas that are facing towards the sky; it then provides good results.

2.
THE HOT-COLD METHOD

One of the most accurate methods of determining the noise temperature of a receiver is the so-called hot-cold method. This is achieved by connecting a resistor to the input of the receiver that has an identical value to the (transformed) radiation impedance of the antenna (usually 50 Ω), and varying its temperature over the widest possible range. The intrinsic room temperature of 290 K is usually used as "hot" temperature, and the "cold" temperature is that of liquid nitrogen (77 K), into which the resistor is placed.

If the noise power ratio Y that occurs between these two temperatures is measured at the receiver output, it is easily possible to calculate the equivalent noise temperature of the receiver in a very accurate manner:

$$Y = \frac{T_h + T_{rx}}{T_c + T_{rx}}$$

$$T_{rx} = \frac{T_h - YT_c}{Y - 1} \qquad \text{(Eq. 4)}$$

Y = Noise power ratio
T_h = "Hot" temperature
T_c = "Cold" temperature

The described hot-cold method can be varied by changing the noise temperature of the antenna instead of the temperature of the connected resistor. This is achieved by pointing the antenna towards the hot sun, and then to a cold point in the sky. The factor Y at the receiver output is measured for these two positions. If the antenna noise temperature T_a is known for these two positions, it is possible together with the antenna gain to calculate the noise temperature of the receive system T_{sys}, or vice versa. The problems involved herewith are to be discussed in the following sections. This is described in detail in (1).

2.1. Accuracy Problems in Conjunction with Solar Noise Measurements

If solar noise is to be used for measurements, it it necessary to know the solar flux S of the Sun. This possesses large fluctuations in dependence of solar activity (1).

On the other hand, the influence of the sky around the sun that is still "seen" by the antenna, is very low since solar noise is so high in comparison. It is only in December and January when the sun is located in front of the galactic center that the noise radiation around the sun can falsify the measurement.

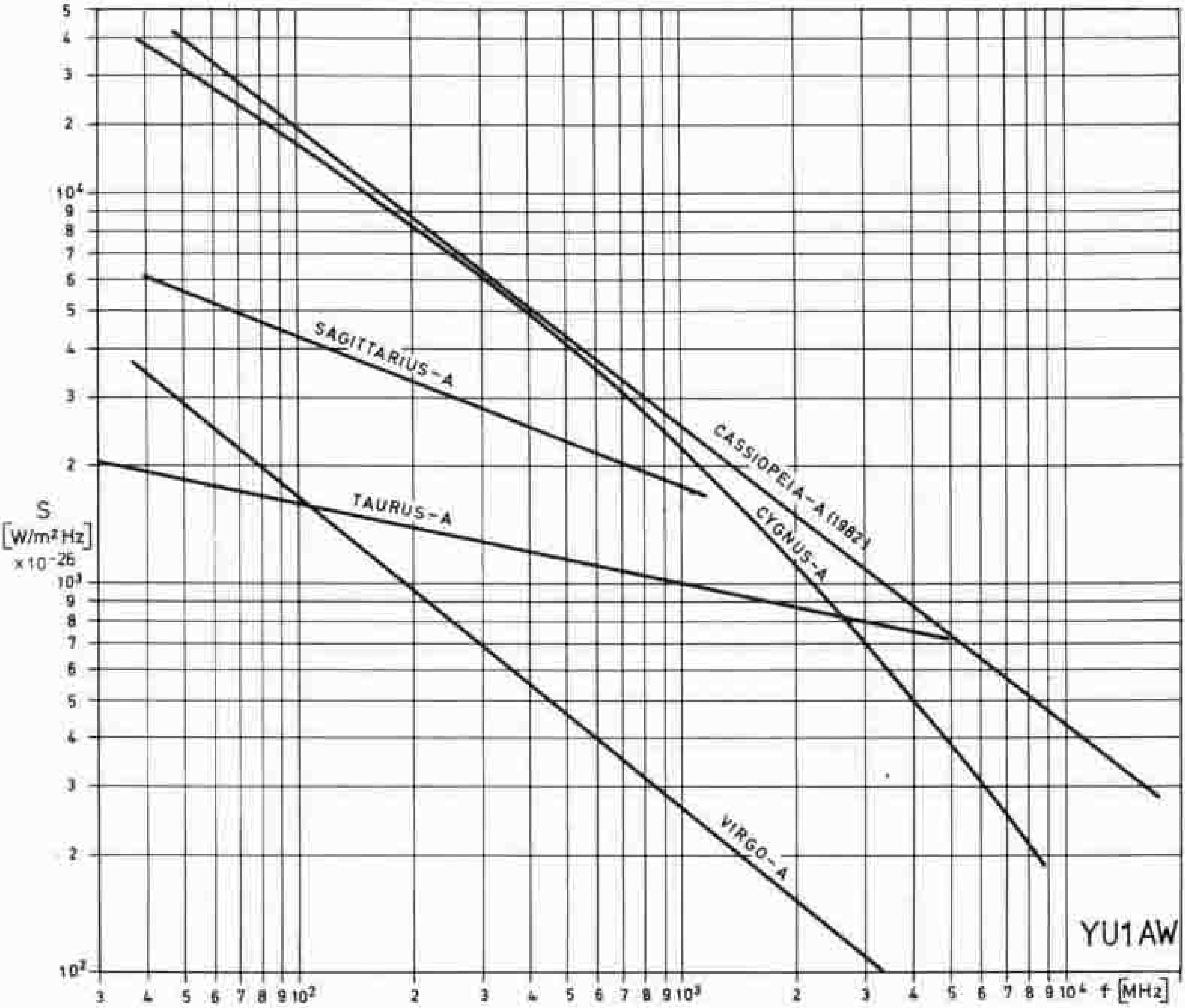

Fig. 1: Noise flux S (× 10^{-26}) of the strongest radio sources (excluding the sun) over the frequency range of 40 to 10000 MHz

Galactic radio sources on the other hand, provide a very much lower, but considerably more constant flux. This means that they can be used instead of the sun to solve problems of inaccuracy. However, their size is so minute in comparison to the beamwidth of conventional antennas, that they represent point sources. The noise temperature of the sky around the radio sources therefore often has a considerable effect on the noise temperature of the antenna. **In order to avoid considerable measuring errors, it is necessary to consider the sky noise around the radio source. This is the reason why one will obtain such inaccurate – or even false – results when the solar noise measuring method is used unchanged with other cosmic noise sources!**

3.
GALACTIC RADIO SOURCES

We know the galaxy to which our solar system belongs as "Milky Way". It comprises an immense number of stars, and new stars appear and old stars disappear all the time. These processes are especially frequent in the central regions of the approximately lens-shaped Milky Way and for this reason a relatively very strong noise arrives at the earth from this direction that covers virtually the whole radio spectrum. In addition to this diffuse radiation, there are descrete sources, so-called radio stars, with very strong radiation. The strongest are Cassiopeia-A and Taurus-A. These two radio sources are the remains of Supernova explosions. When viewed through an optical telescope, they are seen as foggy areas, and are therefore called "Nebulars".

There is an infinite number of other galaxies outside our Milky Way, in which enormous processes are taking place, and therefore transmit considerable radiation. These are known as "Radio-Galaxies" and the strongest in the northern hemisphere are Cygnus-A und Virgo-A.

A very strong radio source is located in the core of the Milky Way: It is Sagittarius-A, and is possibly the active core of our galaxy.

Figure 1 shows the noise flux S of the previously mentioned, strong radio sources as a function of the frequency. The curve shows the astrophysisists that the nature of the radiation is not thermal, but is dependent on synchrotron processes (spiral-shaped movements of very fast electrons in strong magnetic fields).

4.
SKY TEMPERATURE AROUND THE RADIO SOURCES

As was previously mentioned, the accuracy of the hot-cold method using cosmic radio sources is dependent on the exact knowledge of the mean noise temperature around these radio sources. For this reason, noise power profiles were measured around all the previously mentioned strong radio sources, and a systematic calculation of the mean values was made.

During this process, we soon found that the beamwidth of the main lobe must be taken into consideration, since a different temperature mean value will result for each beamwidth due to the non-constant distribution of the temperature around the sources.

Therefore, the sky temperature was determined as a function of the antenna beamwidth, in steps of 1 dB antenna gain. In the case of the 144 MHz amateur band, a beamwidth range of 25° to 10° was selected which corresponds to gain values of 18 to 26 dB_i. Measured values of the sky temperature were available for 136 MHz and 160 MHz. They were interpolated to obtain values for 144 MHz.

We then noticed that small sky areas, spaced several 10 degrees, are present in the vicinity of the radio sources Cassiopeia and Cygnus, and partly also near Taurus, that have a higher temperature than the direct vicinity of these sources. If one points his antenna simply to the highest noise amplitude, one will obtain false results since one will then be pointing to a position somewhere between the radio source and the "hot" part of the sky. Logically, antennas of differing gain (beamwidth) will be pointing to slightly different directions when aligned for maximum noise level. We have agreed to accept this directional error.

After taking all these things into consideration, very accurate data was obtained for the mean sky temperature around the previously mentioned radio sources, and for the various beamwidths of the antennas. The diagram for T_{sky} at 144 MHz is given in **Figure 2.** In order to make the diagram more usable, the antennas gain in dB_i (isotropic radiator) is also given.

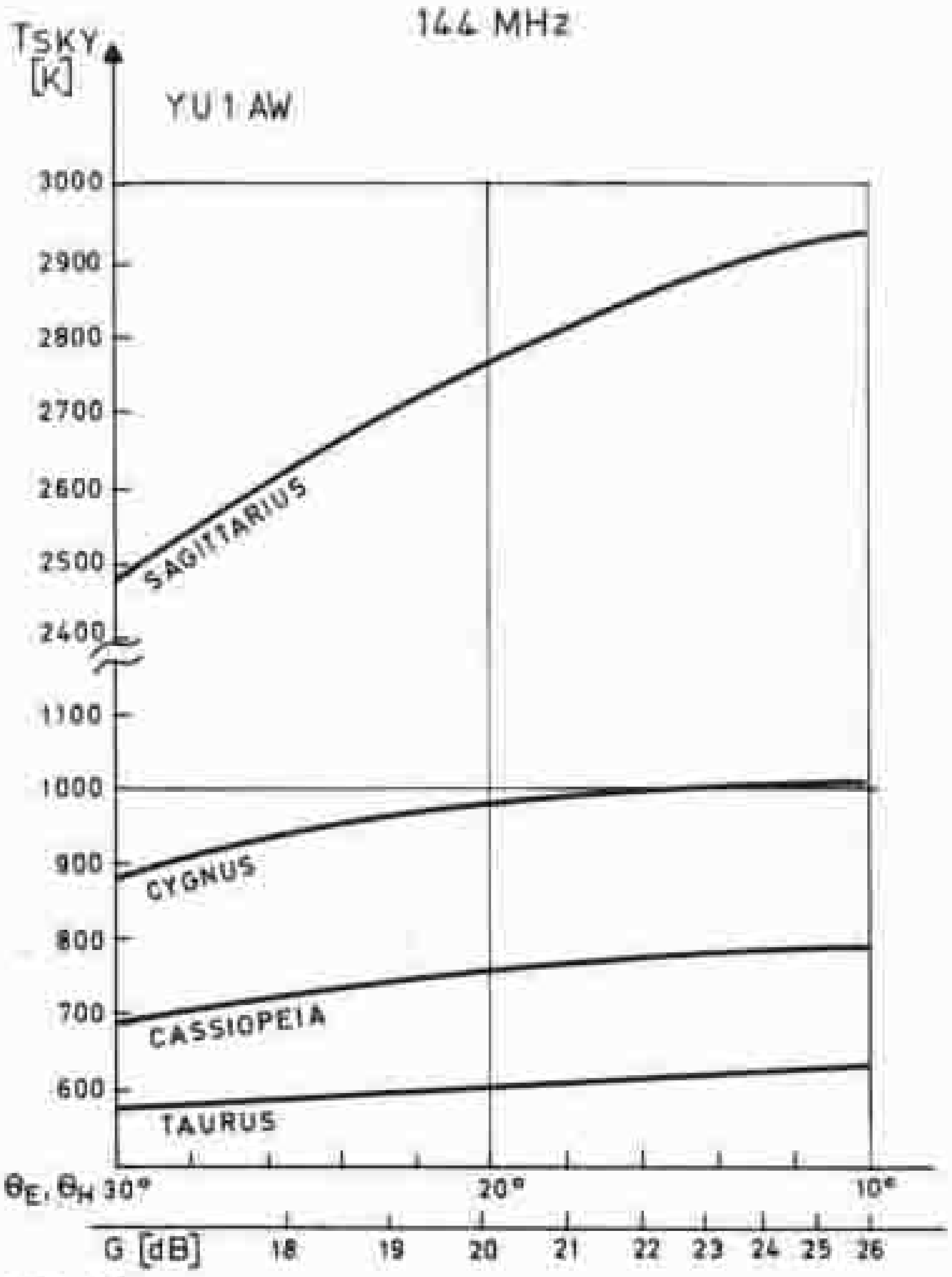

Fig. 2:
Mean sky temperature T_{sky} around five radio sources at 144 MHz

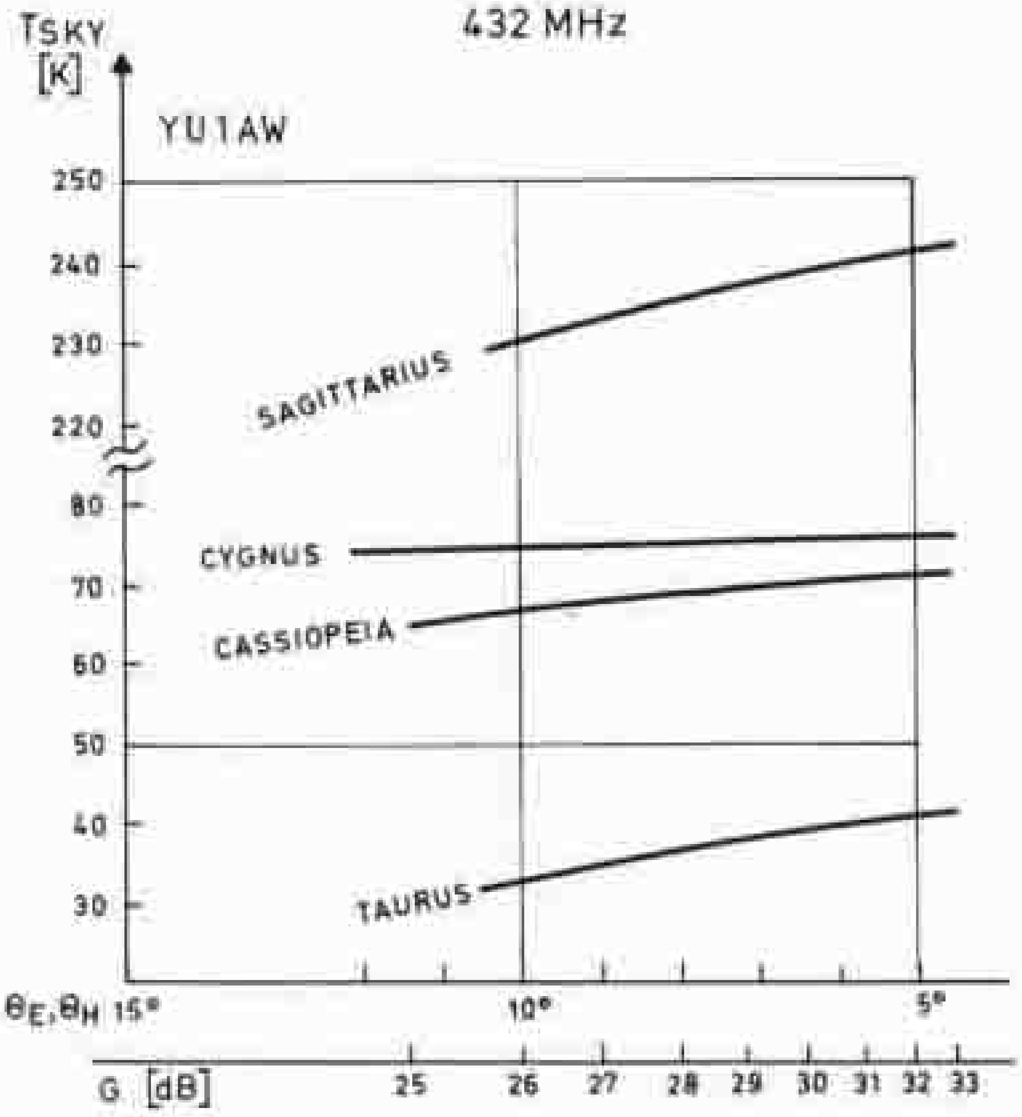

Fig. 3:
Mean sky temperature T_{sky} around five radio sources at 432 MHz

The same process was also made for the 70 cm band, only that the beamwidths were in the order of 10° to 5°, corresponding to a gain of 26 to 32 dB_i. The interpolation for 432 MHz is based on measured values for 400 and 480 MHz. The results are shown in **Figure 3.**

5.
DETERMINING THE TEMPERATURE OF THE "COLD" SKY

The knowledge of the temperature of the "cold" points in the sky are just as important as the temperature of the sky around the radio sources. Careful interpolations had been carried out for this, especially for two different "cold" areas of the sky:
In constellation Leo (α = 09:30; δ = 40°) and in constellation Aquarius (α = 22:30; δ = 0°)

The coldest points in these areas have temperatures of 195 K, or 275 K at 144 MHz. Mean temperature values as a function of the various antenna beamwidths were found for both "cold" areas. In the case of 432 MHz, the difference between Leo and Aquarius is only 5 K, which means that both areas can be classed as being equally cold, namely 20 K.

With the aid of the Tailor-equation (Eq. 3) we determined the temperature of a directional antenna (T_{acs}), pointing towards this position, from the temperature of the cold sky (T_{cs}). In this case, the mean value of the noise temperature of the visible half of the sky T'_{sky} is 400 K at 144 MHz, and 40 K at 432 MHz. A value of 290 K is assumed for T_e. It is interesting to find that the values of T_{acs} obtained using the Tailor-equation virtually coincide with the values obtained from practical measurements.

Finally, the T_{acs}-values were calculated for various antenna beamwidths. The antennas used for 432 MHz have a narrower beamwidth than the areas of the cold sky region, which means that no dependence of the antenna temperature on the beamwidth results.

6.

TEMPERATURE CALCULATION FOR AN ANTENNA POINTING TO A RADIO SOURCE

Based on the T_{sky}-data, it is possible using equation 3 to obtain T_{asky}, which is the temperature of an antenna that is pointed to the sky around a radio source but **without** the radio source itself. In order to obtain the total antenna temperature T_a **with** radio source, it is necessary to add T_{asky} and the temperature increase caused by the radio source.

The intensity of a radio source, that is its flux, is determined from the equivalent noise temperature T of the source, its spatial angle Ω_s, and the wavelength of the radiation:

$$S = (2kT\Omega_s)/\lambda_2 \text{ in W/m}^2\text{Hz} \qquad \text{(Eq. 5)}$$

The flux density-values (S) of certain radio sources were measured at various frequencies. Figure 1 is the result of these values.

The noise power that an antenna receives from a radio source is to be designated P_{as},

G(dB)	18	19	20	21	22	23	24	25	26
	CASSIOPEIA-A								
T_{as}(K)	87	109	138	173	218	275	346	435	550
T_{asky}	684	695	705	713	717	721	725	728	730
T_{sky}	725	738	750	760	765	770	775	778	780
T_a	771	804	843	886	935	996	1071	1163	1280
	CYGNUS-A								
T_{as}	84	106	134	169	211	268	336	423	536
T_{asky}	852	873	889	895	902	906	908	910	910
T_{sky}	930	955	975	982	990	995	998	1000	1000
T_a	936	979	1023	1064	1113	1174	1244	1333	1446
	SAGITTARIUS-A								
T_{as}	28	35	45	56	70	89	112	141	178
T_{asky}	2238	2296	2349	2381	2418	2443	2460	2476	2492
T_{sky}	2620	2690	2755	2795	2840	2870	2890	2910	2930
T_a	2266	2331	2394	2437	2488	2532	2572	2617	2670
	TAURUS-A								
T_{as}	12	15	18	23	29	37	47	59	74
T_{asky}	571	578	582	586	588	590	594	597	593
T_{sky}	587	597	600	605	607	610	615	618	620
T_a	583	593	600	609	617	627	641	656	672
	VIRGO-A								
T_{as}	9	12	15	19	23	30	37	47	59
T_{asky}	329	326	324	321	319	317	316	315	315
T_{sky}	292	288	285	282	279	277	276	275	275
T_a	338	338	339	340	342	347	353	362	374
	COLD SKY (LEO)								
T_{acs}	266	263	260	257	255	253	251	250	250
	COLD SKY (AQUARIUS)								
T_{acs}	331	328	325	322	320	318	316	315	315

Table 1: The temperatures of five radio sources and two "cold" points at 144 MHz

and is dependent on the flux density S of the source, as well as on the effective aperture of the antenna A. Furthermore, it is necessary for a factor 1/2 to be inserted, since most antennas only receive a certain polarization, whereas cosmic radio sources usually radiate unpolarized waves.

It is now possible for us to make a formula for T_{as}, which is the increase of the antenna temperature due to the reception of noise power from a radio source:

$$P_{as} = \frac{S \times A}{2} \quad \text{with}$$

$$A = \frac{G \times \lambda^2}{4\pi}$$

$$P_{as} = k \times T_{as}$$

$$T_{as} = \frac{P_{as}}{k} \quad \text{or}$$

$$T_{as} = \frac{S \times G \times \lambda^2}{8\,k\pi} \qquad \text{(Eq. 6)}$$

G(dB)	26	27	28	29	30	31	32	33
				CASSIOPEIA-A				
T_{as} (K)	26	33	41	52	65	82	103	130
T_{asky}	97	98	98	99	99	100	100	100
T_{sky}	66	67	67	68	68	69	69	70
T_a	123	131	139	151	164	182	203	230
				CYGNUS-A				
T_{as}	25	32	40	50	64	80	101	127
T_{asky}	104	104	104	104	104	105	105	105
T_{sky}	74	74	74	74	74	75	74	75
T_a	129	136	144	154	168	185	206	232
				SAGITTARIUS-A				
T_{as}	13	16	20	25	32	40	50	64
T_{asky}	232	233	235	237	238	239	240	241
T_{sky}	230	232	234	236	238	239	240	241
T_a	245	249	255	262	270	279	290	305
				TAURUS-A				
T_{as}	7	8	10	13	17	21	26	33
T_{asky}	70	71	72	73	73	74	75	76
T_{sky}	33	34	35	36	37	38	39	40
T_a	77	79	82	86	90	95	101	109
				VIRGO-A				
T_{as}	3	4	4	5	7	9	11	14
T_{asky}	60	60	60	60	60	60	60	60
T_{sky}	20	20	20	20	20	20	20	20
T_a	63	64	64	65	67	69	71	74
				COLD SKY				
				$T_{acs} = 60$				

Table 2: The temperatures of five radio sources and the cold sky at 432 MHz

Since the noise powers are added in the antenna, and after taking into consideration that the noise power divided by the Boltzman constant results in the equivalent noise temperature, a simple addition of T_{asky} and T_{as} will result in T_a. This is the temperature of an antenna pointing towards a cosmic radio source together with the "hot" sky around it, and including a pointing error (see section 4), as well as considering the effect of sidelobes facing towards the "warm" earth, and to the side. All these components were determined as a function of the beamwidth of the main lobe of the antenna. The results are given for each radio source separately in the tables. **Table 1** shows the temperature values for 144 MHz, and **Table 2** the same for 432 MHz.

The flux density values for all sources were obtained by arranging the measuring results given in the references. The values for Cassiopeia-A were obtained from the values from previous years calculated together with the known reduction rate for 1982. This reduction of the flux density of Cassiopeia-A is caused by the rapid expansion, and thus cooling of this residual part of a Super-Nova of approximately 400 years ago **(Table 3).**

Since the accuracy of the whole method is dependent on exact flux density values, these must be checked in several ways. For instance, the values for 144 MHz were obtained from measured values for 136 and 160 MHz by interpolation, however, this was not made in a linear manner, but after taking the spectral distribution of the radio source in question into consideration.

7.
USING THE TABULAR VALUES

With the aid of the hot/cold method, it is possible to calculate the noise temperature of a receiver T_{rx} very exactly, if one uses the T_a of a certain radio source as hot, and T_{acs} as cold temperature. In order to do this, however, it is necessary to know the gain of the antenna.

$$T_{rx} = \frac{T_a - Y \times T_{acs}}{Y - 1} \qquad \text{(Eq. 4a)}$$

Firstly point the antenna to one of the cold regions of the sky, and then to one of the radio sources, after which the difference in the noise power between both antenna settings is measured. This is the factor Y for the above equation, and must not be inserted in dB. The same precautions (3) must be made when measuring Y, as with normal noise figure measurements.

The value for T_a is taken from Table 1, or Table 2 for the selected radio source, after taking the gain of the antenna used into consideration.

The receiver noise temperature T_{rx} in Kelvin can be converted easily into the usual noise figure after transposing equation 1:

$$F = 1 + \frac{T_{rx}}{290} \qquad \text{(Eq. 1a)}$$

and $$NF = 10 \log F$$

Radio source	Flux 10^{-22} (W/m²Hz) 144 MHz	432 MHz	1296 MHz
CASSIOPEIA-A*	1.11	0.47	0.20
CYGNUS-A	1.08	0.46	0.17
SAGITTARIUS-A	0.36	0.23	0.14
TAURUS-A	0.15	0.12	0.095
VIRGO-A	0.12	0.05	0.02

* 1982

Table 3: Flux density values for five radio sources at 144, 432, and 1296 MHz

8.
USING THE DIAGRAMS

In order to find T_{rx} with the aid of the tables, it is necessary to know the gain of the antenna used. It is possible, in the opposite manner, to calculate the antenna gain if T_{rx} is known – calculated from the measured noise figure NF, or the noise factor F.

In order to make this simpler for the user, and especially to allow the calculation with intermediate values of G and T_{rx}, diagrams have been drawn. They show T_{rx} as a function of Y for the four strongest radio sources, and for the cold sky using the antenna gain as parameter.

Since two cold points in the sky are available for 144 MHz, namely in the vicinity of constellation Leo and Aquarius, the diagram lines for this frequency are plotted twice.

Figure 4 shows the values of the strongest radio source, Cassiopeia-A, referred to the cold sky in Leo, as well as for Cygnus-A, referred to Taurus-A. (These lines fit into this diagram without interfering – see 8.1.)

Figure 5 shows the lines for Cassiopeia-A, referred to the cold sky in Aquarius, as well as Cassiopeia-A, referred to Taurus-A. The way to work with these diagrams is to be described later.

Figure 6 shows the lines for the other three strong radio sources, Cygnus-A, Sagittarius-A, and Taurus-A, referred to the cold sky in Leo, and, **Figure 7** finally shows the same three radio sources, referred to Aquarius.

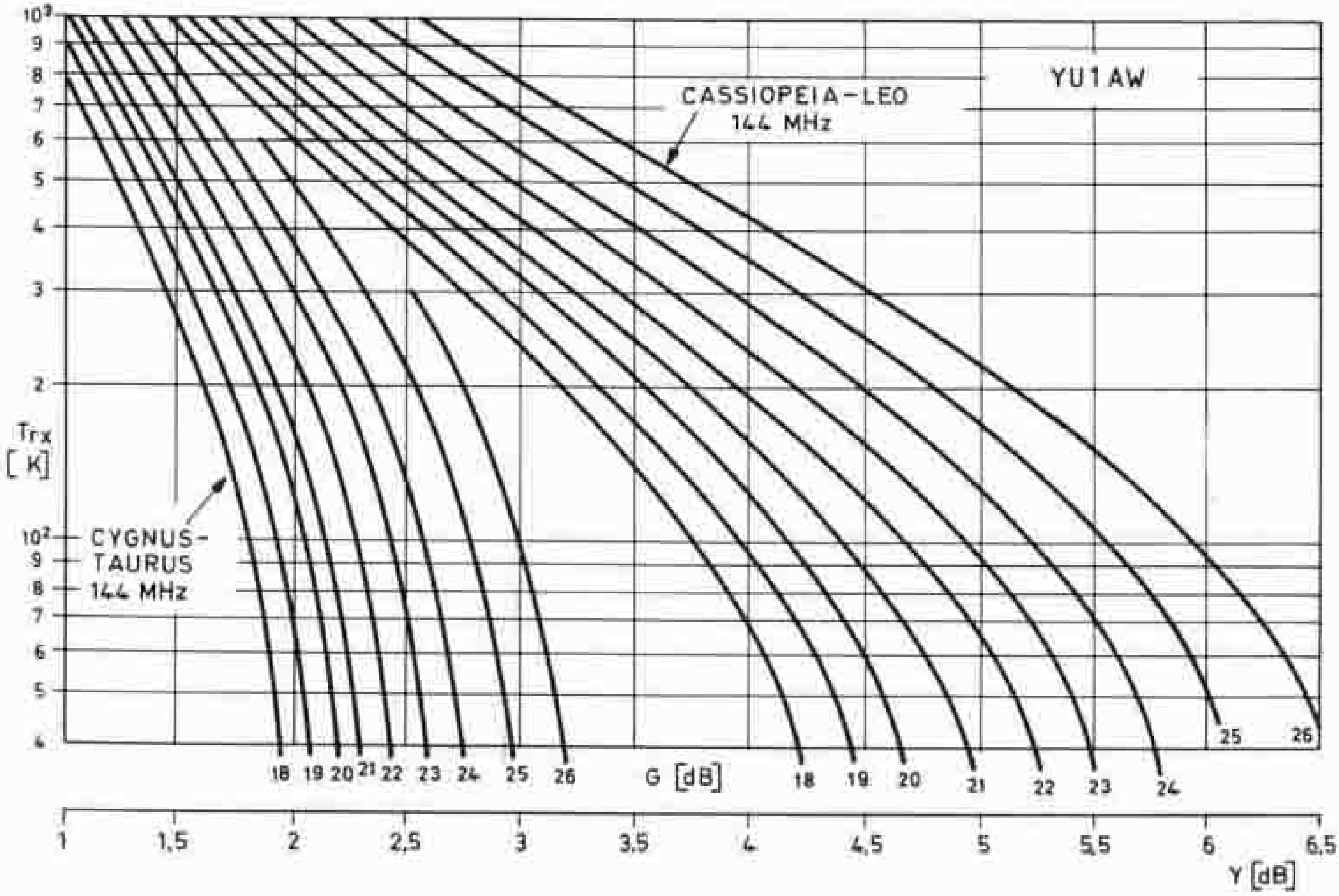

Fig. 4: Receiver noise temperature T_{rx} in Kelvin at 144 MHz using the Y-factor with the antenna gain as parameter. For Cassiopeia/Leo and Cygnus/Taurus

The most important thing is that one firstly uses the correct diagram, and secondly the correct scale. It could have been arranged more clearly if each group of parameters had its own diagram, but that would take too much space in the magazine.

In the case of 432 MHz, the diagram given in **Figures 8, 9, and 10** are valid. They contain the values for the same four radio sources, referred to a cold sky at 432 MHz.

One uses these seven diagrams firstly by simply inserting Y in dB (measured with the radio source in question as noise increase with respect to the appropriate cold sky). If T_{rx} is already known, it is possible for the antenna gain to be read off directly, and vice versa.

8.1. Ratio Measurement using Two Sources

If one compares the T_a-values of the various radio sources to another, one will see that they can be split into two groups: "hot" and "cold". Cassiopeia-A, Cygnus-A, and Sagittarius-A can be classed as "hot", whereas Virgo-A and Taurus-A are relatively "cold". Considering the importance of T_{cs} for the accuracy of the measurement, it is logical, not to point the antenna towards a cold region of the sky (Leo, Aquarius), but to one of the relatively cold radio sources. Figures 4 and 5 therefore contain two such pairs for 144 MHz.

8.2. Measuring Procedure

The most important thing is that no single

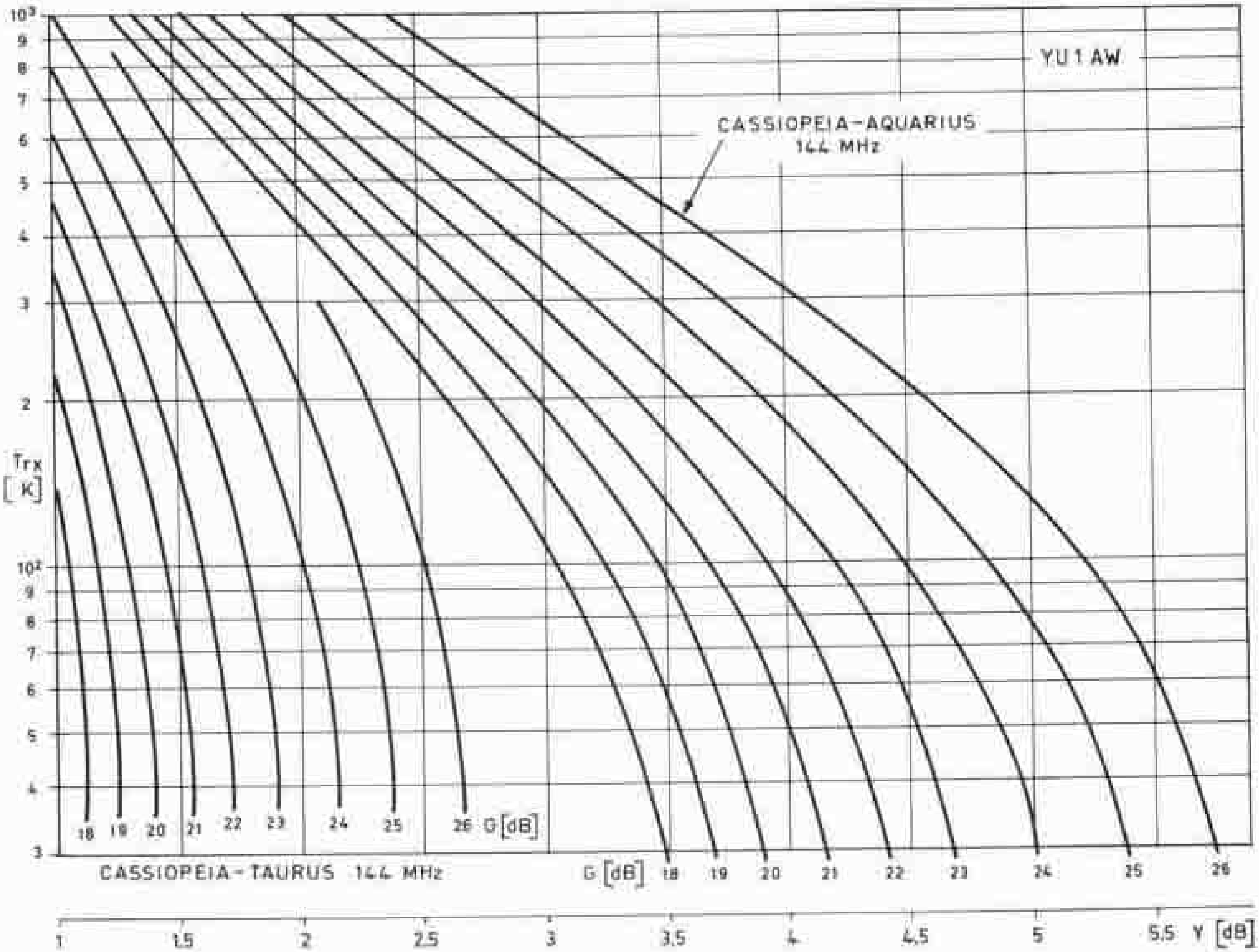

Fig. 5: as Fig. 4, but for Cassiopeia/Aquarius and Cassiopeia/Taurus

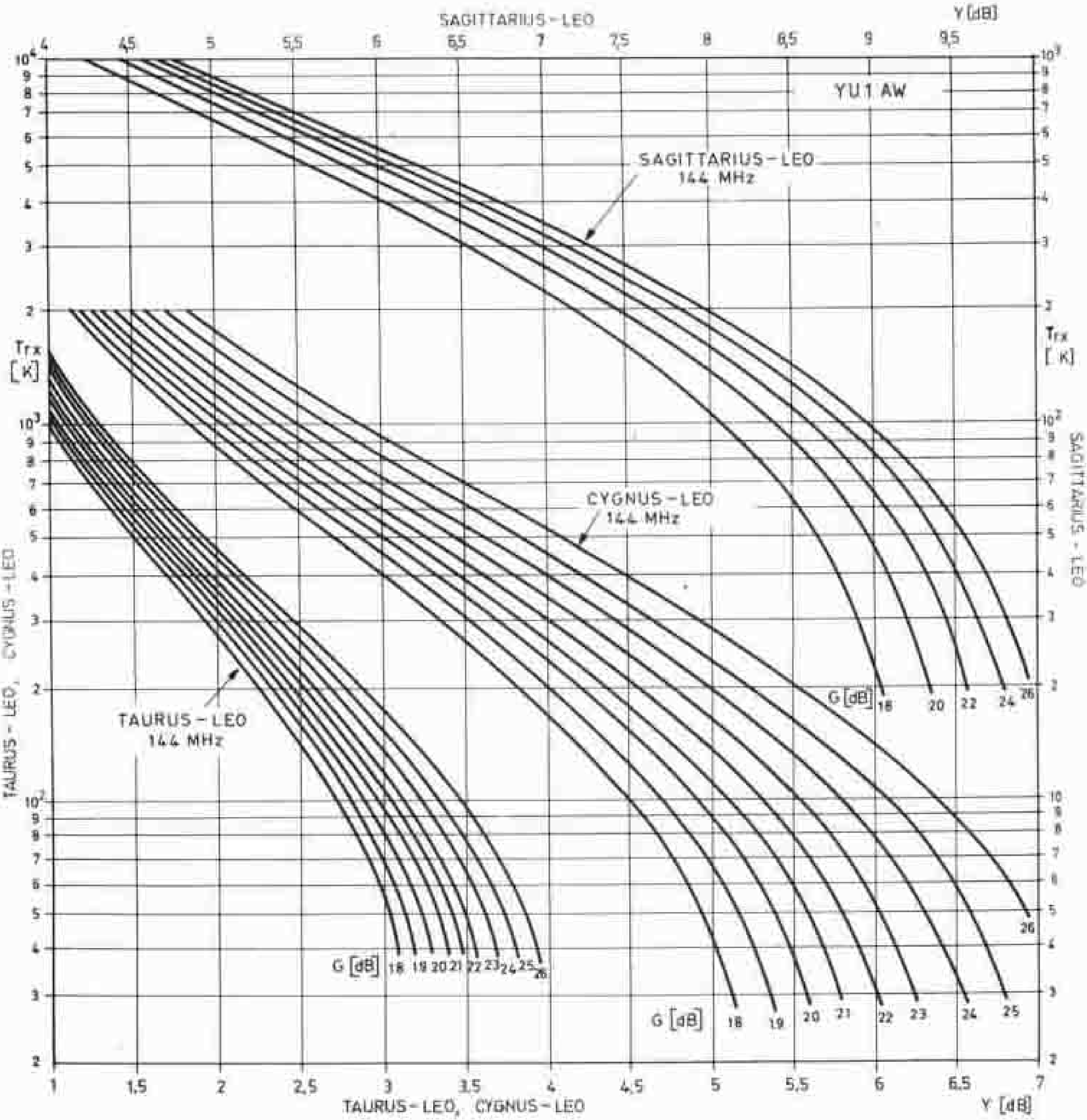

Fig. 6: as Fig. 4, but for Sagittarius/Leo and Taurus/Leo

stage of the complete receive system including all preamplifiers and converters is operating in a non-linear range. Once again, we would like to draw your attention to the article given in (3). The receiver is aligned to the widest bandwidth, SSB-mode, and the automatic gain control switched off. The noise voltage is now measured at IF-level, or, if not possible, at AF-level, according to the measuring equipment available. The accuracy of the measurements is dependent on the linearity and stability of the receive system, as well as on the precision of the calibrated attenuator and reading, and also on the accuracy of the antenna pointing system (rotators). The diagrams and calculations are very accurate, which means that any errors caused by them will only amount to a few Kelvin.

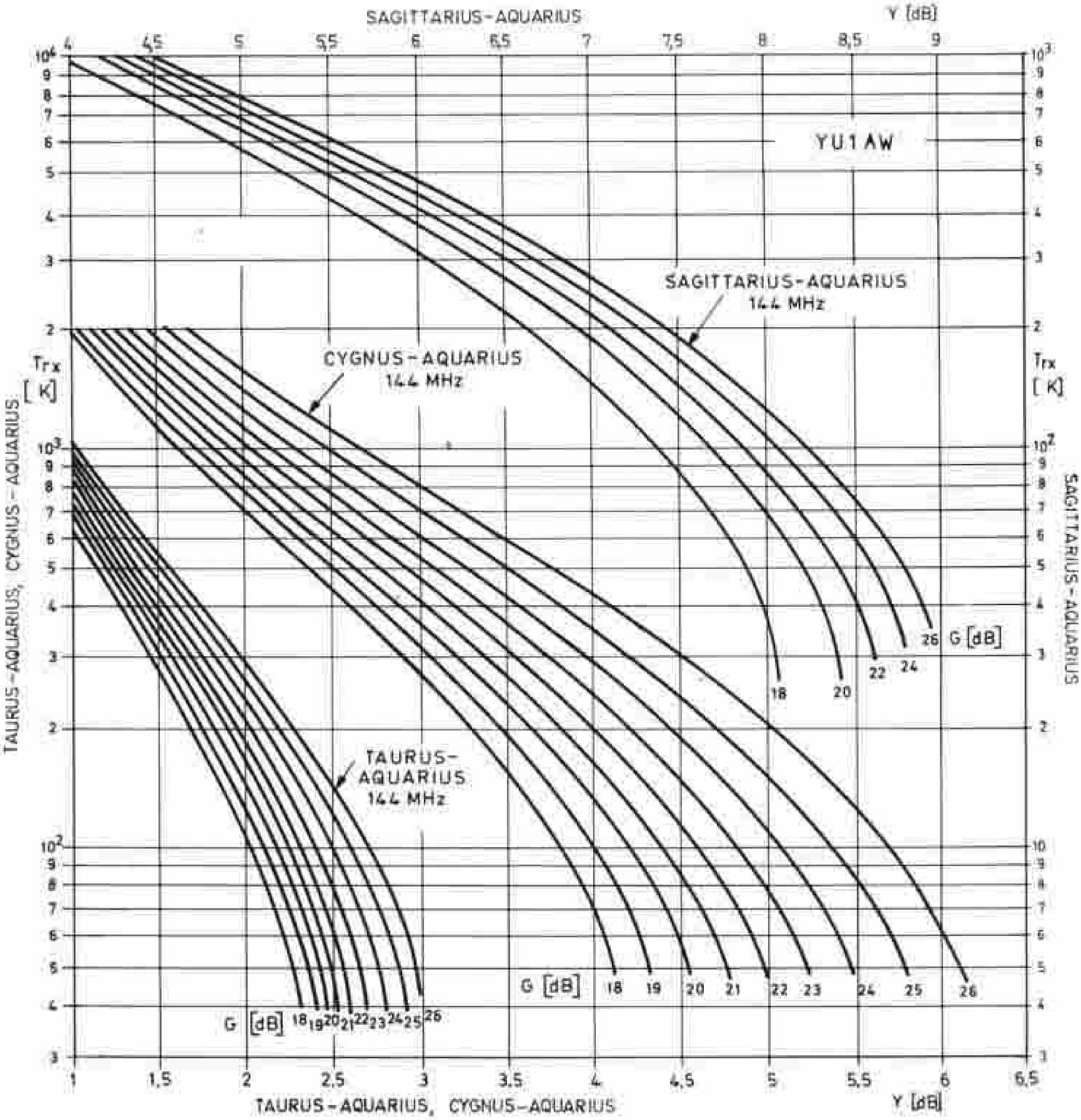

Fig. 7: as Fig. 4, but for Sagittarius/Aquarius, Cygnus/Aquarius, and Taurus/Aquarius

In order to average the statistical fluctuations of noise measurements, it is very necessary to carry out several measurements, preferably using various radio sources and "cold" points. Finally, one should form a mean value of all measurements.

9.
FINAL NOTES

The given data allows exact measurements of the receive system parameters to be carried

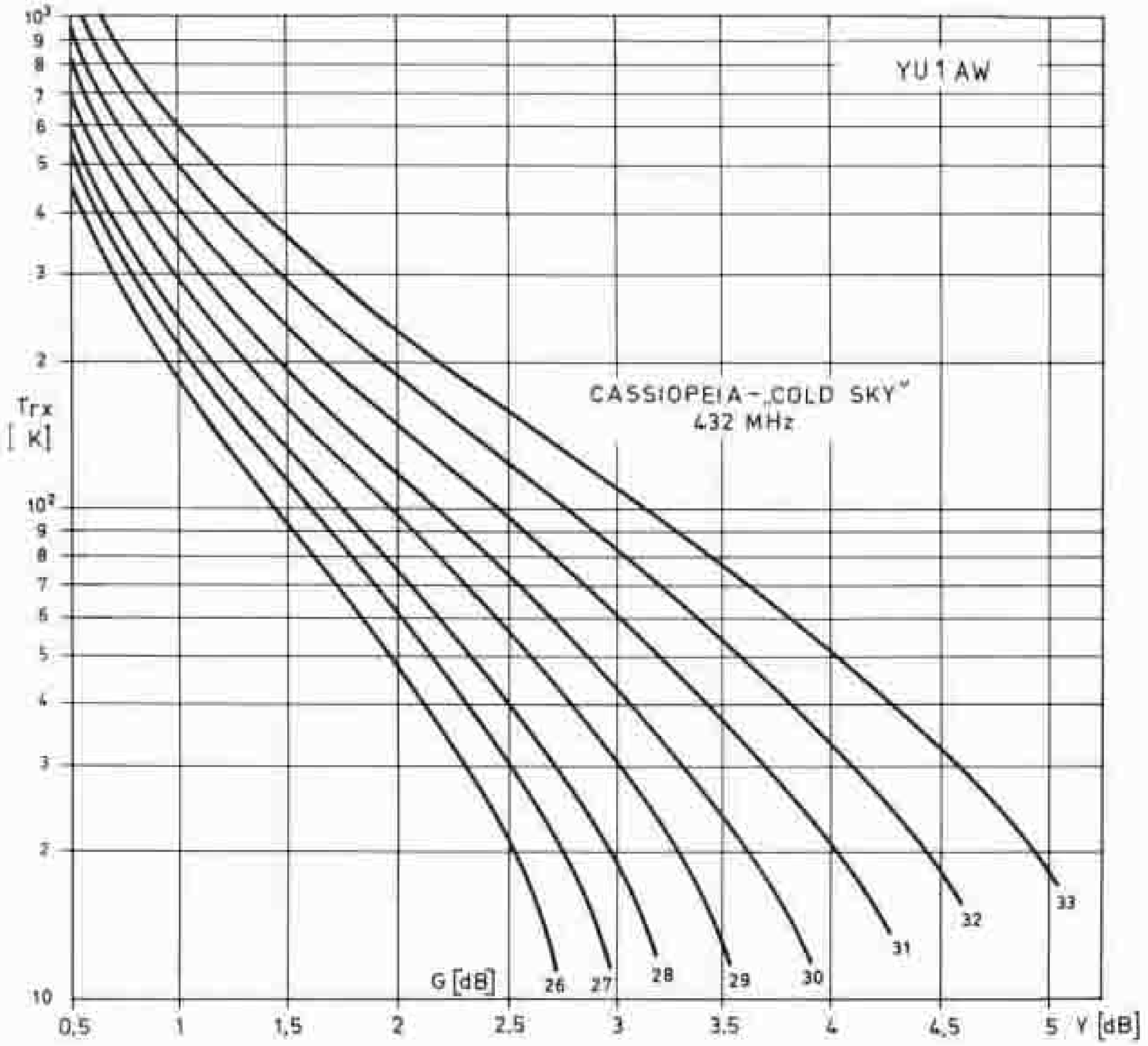

Fig. 8: Receiver noise temperature T_{rx} in Kelvin at 432 MHz using the Y-factor with the antenna gain as parameter for Cassiopeia/cold sky

out by using cosmic radio sources as references. The accuracy of this method is directly dependent on the accuracy with which one measures the ratio of noise powers between the hot and cold points in the sky.

During the preliminary phase, the assistance and literature published by Mr. Aleksander Tomik, Director of the Astronomic Observatory in Belgrad, was very helpful.

The practical application and checking of the method was made by Mr. Teodor Mrksic, YU7AR, and others. He made his array of four YU0B-antennas (4 × 22 el.) available for all measurements at 144 MHz. Also recently published measured values together with other EME-antennas were a great help in order to check the method.

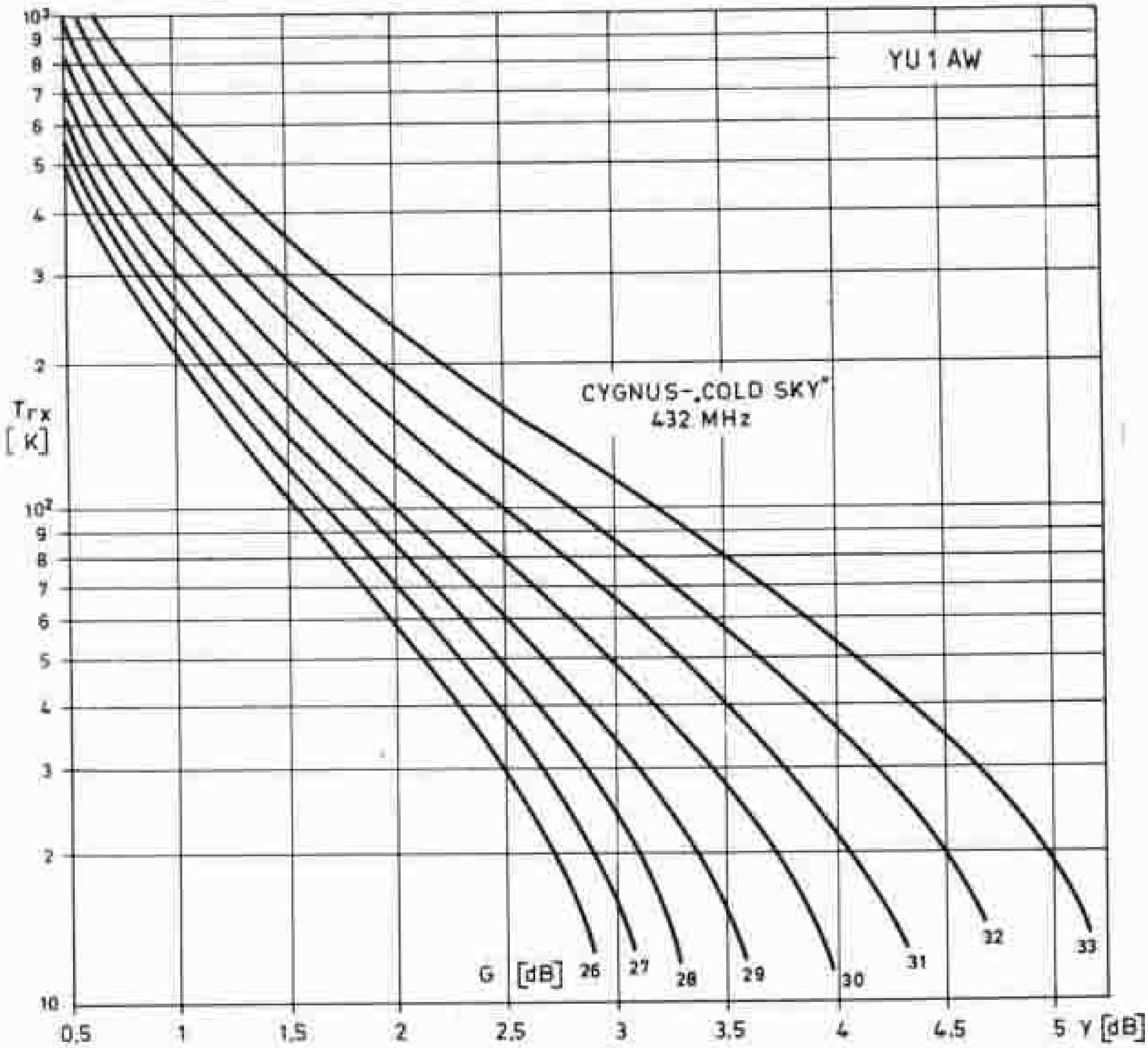

Fig. 9: as Fig. 8, but for Cygnus/cold sky

Only the strongest radio sources were considered in this article, since it is only possible for these to be used with relatively inexpensive equipment. In the references, it is possible for data to be obtained for the nebulars Omega and Aquila, which were measured by several owners of large EME-antennas, both at 144 MHz and at 432 MHz. These two nebulars generate, however, such a low flux density that (amateur) measured values for them are actually measurements of the sky around them. Since both are also in the vicinity of the center of the Milky Way, the noise temperature of the sky around them is relatively high, which means: $T_a = T_{asky}$.

Special care is always necessary when carrying out measurements in the sky in the vicinity of the center of the galaxy, due to the strong radiation from this area. This is especially so when using antennas with relatively low gain (large beamwidth).

In the frequency range in excess of 1 GHz, the flux density of most radio sources is very low **(Table 3)**, which means that the measurements described in this article will provide very inaccurate results inspite of the very low temperatures of the cold points in the sky. For

Radio source	Rectascension α	Declination δ
CASSIOPEIA-A	$23^h 21^m$	$+58° 32'$
CYGNUS-A	$19^h 57^m$	$+40° 36'$
SAGITTARIUS-A	$17^h 44^m$	$-29°$
TAURUS-A	$05^h 31^m$	$+22°$
VIRGO-A	$12^h 28^m$	$+12° 40'$

Table 4: Sky coordinates for the five radio sources used

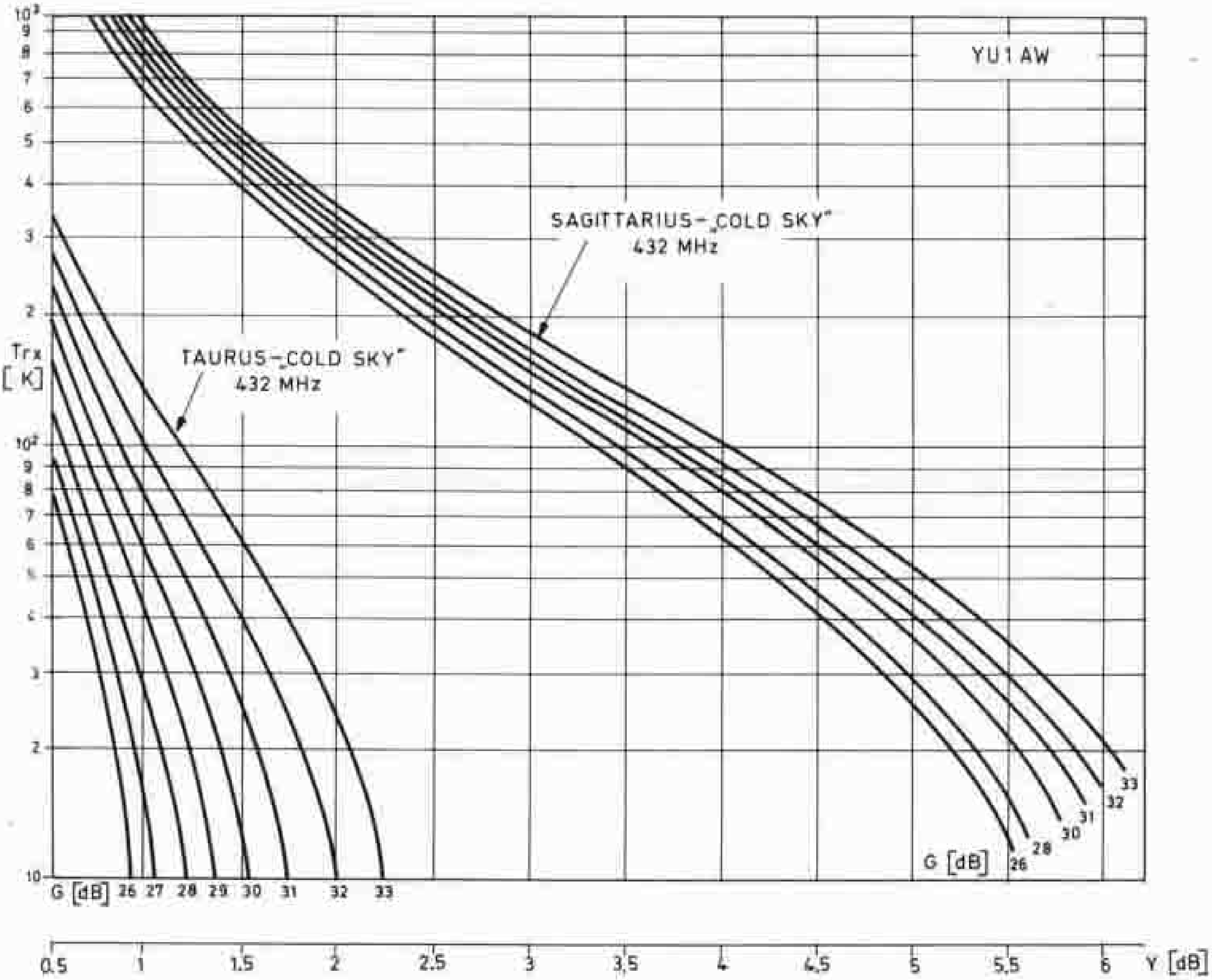

Fig. 10: as Fig. 8, but for Sagittarius/cold sky, and Taurus/cold sky

higher frequencies, it is therefore advisable to use the earth as source of the "hot" temperatures (290 K) and to measure it against the cold sky (T_{cs} = 10 K; T_{acs} = 30 K).

Attention should be paid when pointing the antenna to the earth surface that this does not deteriorate the matching, and that the antenna only "sees" the warm earth.

Cold sky Constellation	Rectascension α	Declination δ	Temperature T_{cs}	
			144 MHz	432 MHz
Leo	09ʰ 30ᵐ	+ 40°	195 K	15 K
Aquarius	22ʰ 30ᵐ	0°	275 K	20 K

Table 5: Sky coordinates for the two "cold" points

Tables 4 and 5 finally give the sky coordinates for the radio sources and cold points used.

10. REFERENCES

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