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Pre-amplifier – Pros and Cons

Perhaps the most serious competitor to the subject of antennas in the attentions of radio DXers is the receiver pre-amplifier. Whenever a problem is complex it gives greater scope for misconceptions, the spread of widely accepted so-called facts, pseudo-scientific folklore, all of which tends to cloud the issue in an aura of mystique.

It is common knowledge nowadays that the gain specification alone of a pre-amplifier is insufficient to assess its merit. Gain is easily achieved and an excess of it merely drives the following stages into producing intermodulation distortion under strong signal conditions. Likewise, it is also well-known that the noise producing qualities of a pre-amplifier, expressed by such quantities as noise-factor, noise-figure or noise temperature, are much more important parameters to be considered. The appendix gives the relationship between these quanties.

Now comes the questions: How low must the noise in a pre-amplifier be? Should one disregard cost and get the very lowest noise specified? Also, how much gain – if it is not the highest gain that to be striven for. What is the optimum gain and upon what does it depend?

1. MAXIMUM AMPLIFICATION?

The aim of this article is to point out a few common mistakes apparent in the employment of a pre-amplifier intended to improve a system and to suggest simple methods by which these mistakes may be avoided. The dilemma of how much gain will be unravelled first. Why not simply use as much amplification as possible in order to detect the weaker signals? Well, this obvious solution would be fine if the receiving system (aerial and pre-amplifier) itself did not generate noise. All the pre-amplifier would do is to amplify the noise along with the signal thus giving higher levels of both but with no greater discrimination between them. In order to obtain a higher signal level with lower noise, it is necessary to minimise the additional noise introduced by the receiving system during the process of amplification.

The noise introduced into the antenna is, however, unavoidable and nothing much can be done about it once the antenna has been erected with the due attention paid to the antenna elevation, location, working frequency and the gain. The signal-to-noise ratio (S/N) at the antenna output

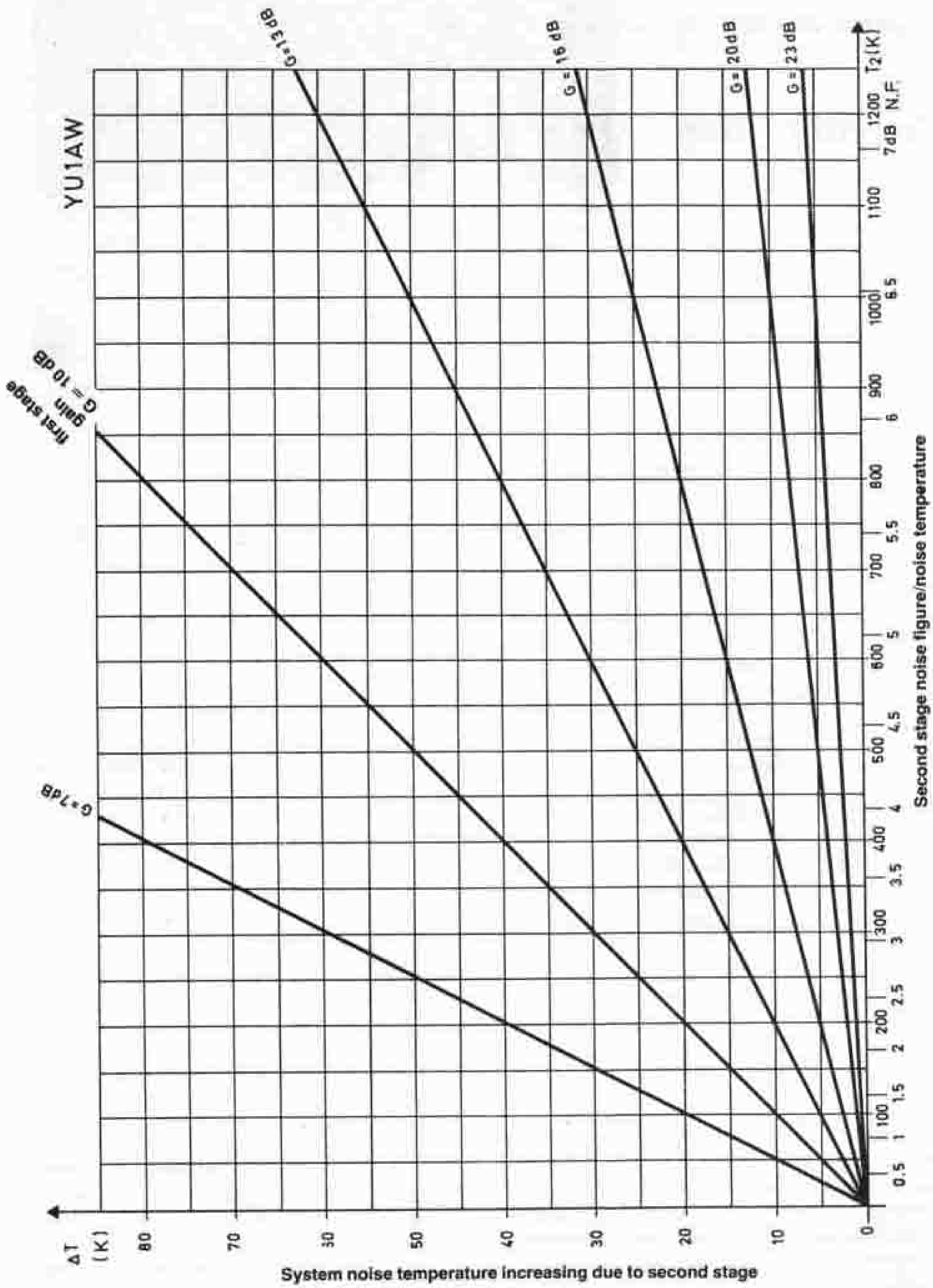

Fig. 1: The influence of the second-stage noise (T_2) on the total receiver noise (ΔT) for various values of first-stage gain (G)

terminals to the receiver, is then, the best that is available for that particular antenna and it is clear that in the subsequent processing of the signal by the receiver, nothing should be allowed to further deteriorate it. This cannot be achieved in practice and the design effort should be devoted to confine the noise to an acceptable level for the prevailing conditions. This is because the pre-amplifier not only amplifies the signal and the noise arriving at the antenna terminals but also adds its own internally generated noise. The signal-to-noise ratio of the output of an ideal amplifier is exactly the same as that at the input. An actual amplifier, unfortunately, always has a lower S/N ratio at its output than is presented to its input and it is logical to conclude that the merit of a pre-amplifier may be assessed by how low its internally generated noise is.

The pre-amplifier gain evidently, has so far played no part in the discussion. The previous discourse is valid only for the case where an ideal amplifier follows the subject pre-amplifier. As this can never be achieved in practice, it can be concluded that the pre-amplifier gain should only be high enough to prevent the noise from the second stage from sharply deteriorating the S/N of the overall system.

This point may be clarified by a numerical example. It will be assumed that the second stage of amplification has the same level of internally generated noise as that of the pre-amplifier. Also, the amplification of the pre-amplifier is 50 times (i.e. 17 dB of gain). The input to the second stage will then be the signal plus noise from the antenna together with first stage's own internal noise – all amplified by 50. The noise contributed by the second stage will then be only 1/50th (2 %) of the overall noise. This can be expressed in the following manner:

$$T = T_1 + \Delta T \text{ and } \Delta T = T_2/G$$

where

T = the overall noise temperature
ΔT = the noise contributed by the second stage
T_1 = the noise temperature of the first stage
T_2 = the noise temperature of the second stage
G = the gain of the first stage

From this example it is clear that the second stage will only deteriorate the overall S/N ratio by a very small amount. It is also apparent that amplification values of between 20 and 50 for the first stage will surfice to overcome the noise T_2 of the second stage as long as this noise is not excessively high (**see fig. 1**).

When a pre-amplifier is to be added to a receiver, it is the receiver itself which can be regarded as the second stage of the above example. The sensitivity of the overall system will be improved from the mediocre specification of the receiver alone but the gain of the pre-amplifier may not be sufficient to determine the second stage noise if, for example in the extreme case, that receiver employs a high-level ring-mixer in order to improve the intermodulation performance.

An important point has been arrived at and that is the decision to sacrifice pre-amplifier gain in order to preserve the higher level of signal handling properties of the receiver system or whether the circumstances dictate that the pre-amplifier be given a high gain in order that the overall receiver is as sensitive as possible.

There is no universal recipe and the receiving system must be tailored in order to meet the prevailing conditions as seen at the antenna output terminals. The first factor determining these conditions is the noise arriving with the signal noise which cannot be influenced by the operator but must be coped with by the receiver. This noise will now be analysed and each component of it examined.

2. ANTENNA NOISE

In the VHF range the **sky noise** is the **greatest contributor** to the total antenna noise and this is universally proportional to frequency. It cannot be influenced in any way but can be neglected at frequencies above 1 GHz (1).

Above 1 GHz, the **ground noise** is constant but decreases towards lower frequencies owing to the increasing ground reflectivity. But the total noise level is the sum of noise radiated from the earth and sky noise which has been mirrored from the earth's surface. When the antenna is directed skywards, as in earth – moon – earth (EME) or satellite communications, the contribution of this noise is small and is largely dependent upon the distribution of the side-lobes (1). The desirability for an EME antenna, to possess a clean lobe pattern, may now be appreciated.

When, on the other hand, "normal" VHF/UHF communication is carried out over the earth's surface, the antenna receives both ground and sky noise because the antenna lobes are directed to both, sky and earth in about equal amounts.

Two further contributions are: The **man-made noise from large cities and industrial areas** which vary according to location, and **atmospheric noise**. The later is very much smaller at VHF/UHF than at HF and dependent upon the prevailing atmospheric conditions.

The **thermal noise** across the radiation resistance of an antenna may be neglected owing to the very high efficiency of VHF/UHF antennas.

From what has been already said, it may be concluded that at the terminals of every antenna which is directed at the horizon, a noise power may be measured. When the antenna is directed towards the sky this noise power falls. The relationship of this noise to the working frequency is shown in **fig.2**.

Since it became known that the sky born noise fluctuated considerably, minimum values for certain areas were taken, other areas may have random noise power distribution (1). The objective values for antenna noise represent that of the absolute minimum because the urban noise was not taken into account and also there exists the possibility that the skyward directed antenna could be pointed to a particularly noisy part of the sky. The curves, then, can only indicate the minimum noise which may be expected under the most favourable environmental and space conditions.

3. SELECTING A PRE-AMPLIFIER

A simple method of selecting a pre-amplifier would be to estimate the noise arriving with the wanted signal and then aquiring a pre-amplifier which would develop an equal value of self-generated noise. This would result in a 3 dB deterioration in the S/N from the antenna as seen at the output of the pre-amplifier owing to the effective doubling of the total noise power. This may be acceptable, especially when it is to be compared against frequently occurring fades of below – 30 dB.

Using this method of assessment, a satisfactory pre-amplifier selection can be made which would be suitable for normal terrestrial communication purposes, assuming of course, that the receiving system's (pre-amplifier plus receiver) total noise contribution is equal to that of the antenna noise.

It is important for some communications applications to reduce the Δ(S/N) from 3 dB to 1 dB. This necessitates reduction in receiver noise by several times involving a further sacrifice of receiver dynamic range and also entails an extra expense.

Bearing this in mind, it may be concluded that the construction and employment of a pre-amplifier having a lower noise than that of the antenna does not make much sense for terrestrial work. The antenna noise is a relevant factor in the determination of other elements of the receiving system.

In order to illustrate this contention, an example will be taken from amateur practice.

Radio amateurs living in small country towns, away from motorways and industrial plants, can expect an antenna noise temperature of about 1000 K (Kelvin). The author has measured noise temperatures of around 800 K when a 2 m antenna was directed towards one of the quieter regions of Belgrade at about midnight.

Assuming that the amateur radio receiver has a 4 dB noise-figure – a typical enough value for a

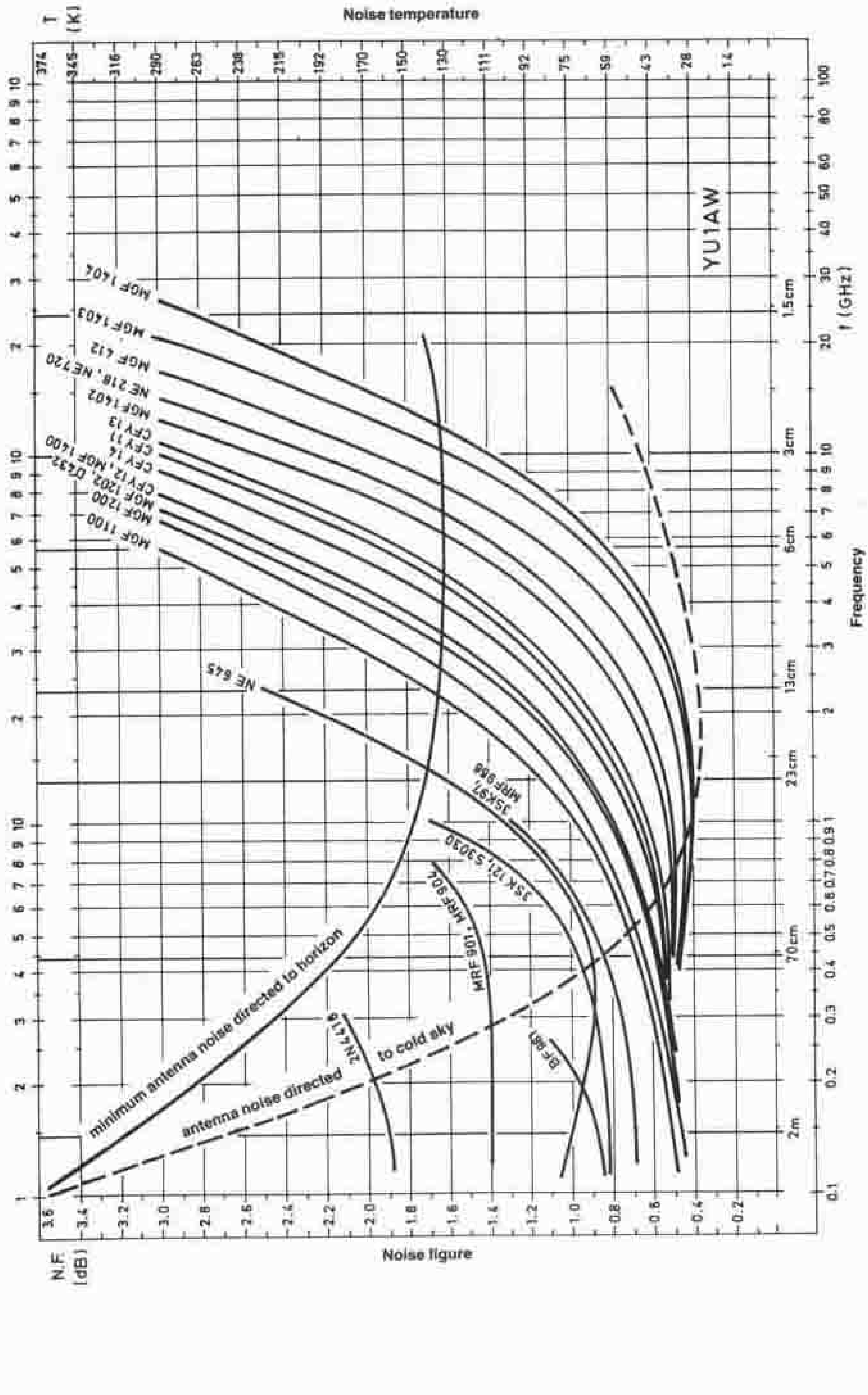

Fig. 2: Frequency dependence of the noise-figure of various well-known transistors and the minimum noise values to be expected from antenna noise.

commercial receiver – and that the antenna coaxial cable has a loss of 1 dB. If a CW or SSB signal, accompanied by noise of 10 dB lower, is induced into the antenna, the signal at the output of the receiver will have a lower value of signal-to-noise – namely 7.9 dB. This is a 2.1 dB deterioration of the signal when compared with the ideal (non-existent) receiving system.

The radio amateur realizes that he has a loss and tries to correct it by purchasing a GaAsFET pre-amplifier with a noise figure of 0.4 dB, a gain of 23 dB and costing a great deal of money – aha! This does the trick and brings the S/N up to 9.5 dB when connected at the receiver and when connected directly at the antenna terminals 9.8 dB. This represents an improvement of 1.6 dB or 1.9 dB in the latter case. The price in performance which has to be paid for this improvement is that the receiver's dynamic range has been drastically reduced making it useless for contest work.

The amateur manages to sell his dream performance pre-amplifier and obtains a much cheaper one with noise-figure of 2 dB and an amplification of 10 dB. He could have modified the input stage of his receiver as it is relatively easy to achieve noise figures in the region of 2 dB.

With this 10 dB pre-amplifier the dynamic range of the receiver is still somewhat reduced but by no means what it was when using the first pre-amplifier. Now, with the improved receiver, the original dynamic-range performance has been retained and a S/N of 8.9 dB at its output.

Was it really worth compromising the dynamic range of the receiver for a 0.6 to 0.9 dB increase in output S/N by using such a high performance pre-amplifier – not to mention the cost of the thing? Our radio amateur did at least realise his mistake and corrected it. The super-specified pre-amplifier failed to bring about the improvement in receiver performance which could have been expected from it – why? **Because no account was taken of the antenna noise.**

Only in space communications, and above all in EME work, is a pre-amplifier with the lowest possible noise figure justified. This is because the antenna is looking at the "cold" sky and the antenna noise is therefore much lower. Also, the wanted signal is mostly hovering at, or even under, the noise level so that an improvement in the system noise figure of 1 or 2 dB can bring about an improvement in reception of between 50 and 100 %.

Let's take a closer look at **figure 2**. It may be seen, that all GaAsFET amplifiers in both the 2 m and 70 cm bands have almost the same noise figures. The difference between the various types is that the expensive ones are specified at microwave frequencies as well (3). It does not make sense to pay twenty times the price for a microwave GaAsFET and then use it at VHF/UHF. All GaAsFETs have noise figures which lie under the 2 m aerial noise spectrum but the really high priced microwave types, on account of their narrow gate structure (0.5 to 0.2 μm), are liable to have a higher noise figure at the lower frequencies than at their specified microwave frequency band.

4. THE EFFECT OF CABLE LOSS

In the aforegoing discussion not much has been said about the effect of the coaxial cable on the receiving system. In reality, however, it is the coaxial cable and not the pre-amplifier which is the first element in the receiving system and always contributing a loss.

It has already been mentioned that the first component has a determining influence on the system noise figure. Generally it increases the system noise figure by the amount of attenuation in the antenna down-lead to the receiver pre-amplifier. Even a short length of low-loss cable increases the system noise figure by a few tenths of a dB. The best pre-amplifiers may not compensate for the use of long lengths of low-grade coaxial antenna down-lead, **see fig. 3**.

It follows, then, that a mediocre pre-amplifier located at the antenna terminals is a much better proposition than a high-performance pre-amplifier located at the end of a long length of lossy cable.

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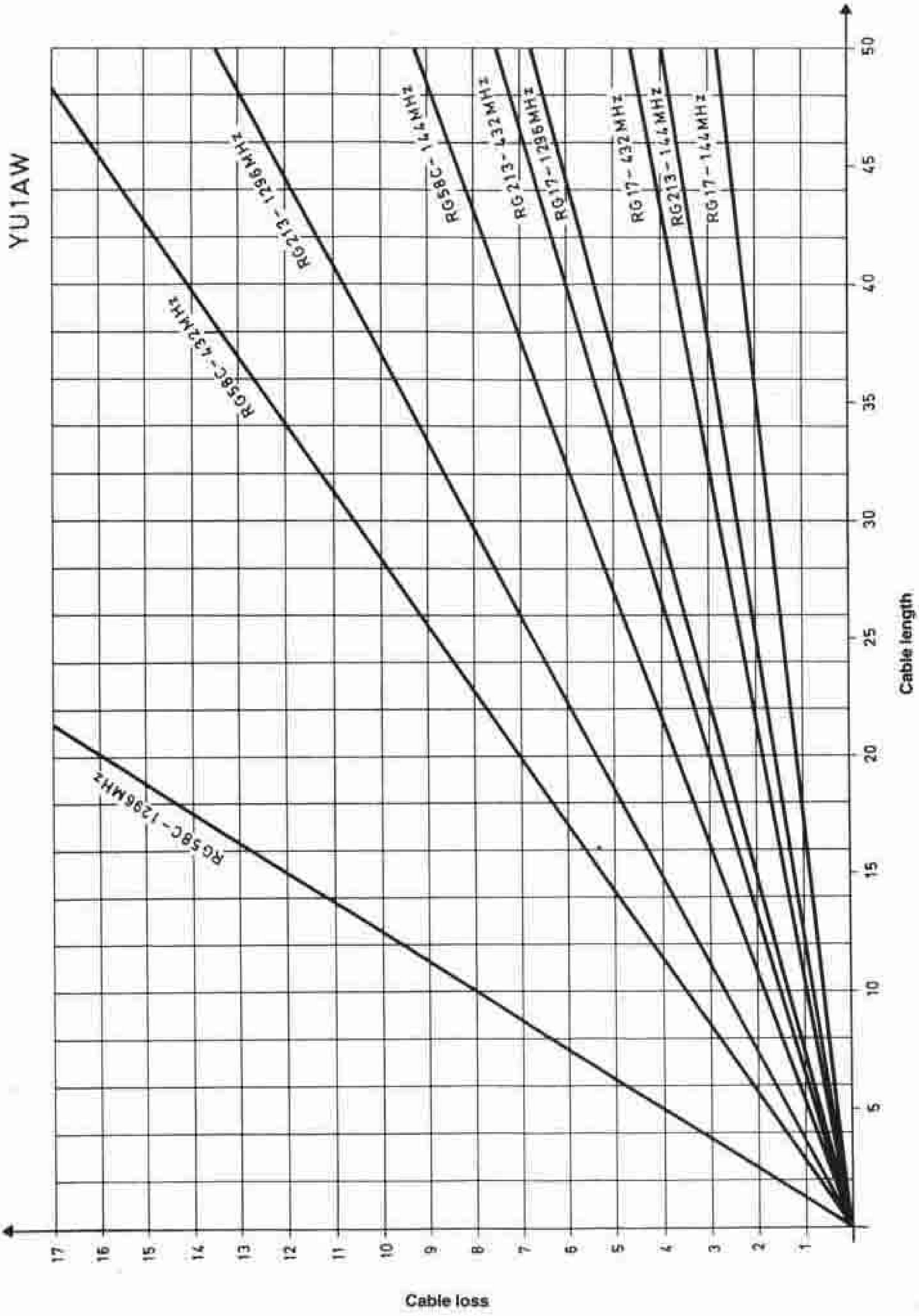

Fig. 3: Cable loss L_r as a function of length for a few well-known types and the most popular VHF/UHF amateur band.

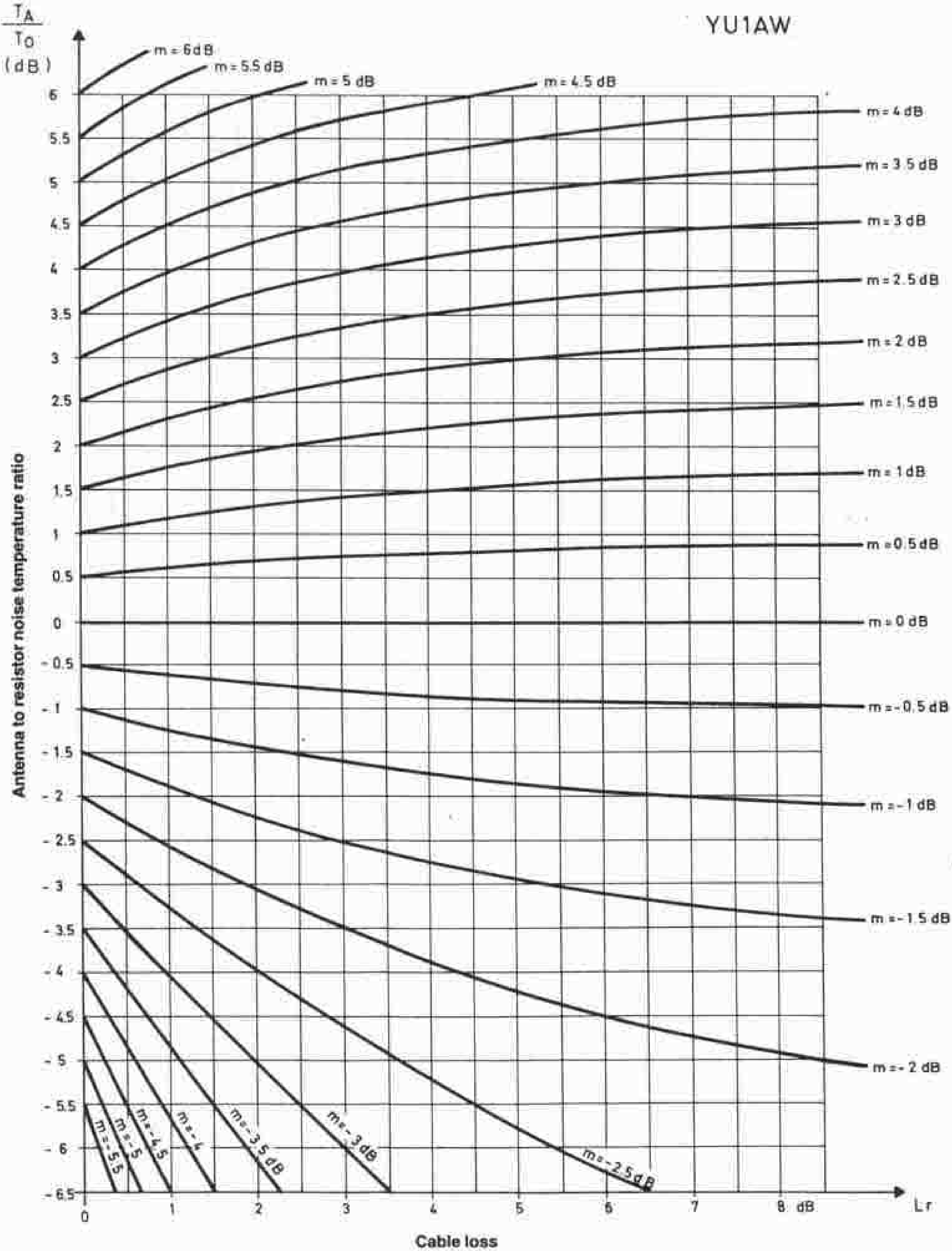

Fig. 4: Correction for the value of antenna noise-temperature T_a depending upon cable loss and the measured value of m.

The noise figure that a pre-amplifier should have for a specified case is then determined by the antenna noise (dependent upon location, antenna elevation, frequency etc.) as well as the allowance for second stage deterioration upon the overall system noise figure. But how can the antenna noise be quantified in order that a pre-amplifier noise figure may be arrived at?

5. MEASURING THE ANTENNA NOISE

The measurement of the antenna noise power is most simply accomplished by measuring the noise voltage across the receiver output and then substituting the antenna with a 50 Ω non-inductive resistor and comparing the two computed powers at 290 K, i.e. room temperature. The output voltmeter can be of any type from an electronic AC millivoltmeter to an ordinary multimeter (2) and (4).

The method is to terminate the antenna input terminals of the receiver/pre-amplifier with a 50 Ω pad of at least 10 dB attenuation, or a metal-film 50 Ω resistor or two 100 Ω MF resistors in parallel. The connecting leads, however, should be as short as possible. Connect the AC meter to the receiver AF output terminals and adjust the receiver gain for a reference voltage. Now replace the dummy 50 Ω antenna with the real thing and note the increased reading. Compute the two readings into decibels i.e.

$$m = 20 \log V2/V1$$

where V2 is the output voltage when the antenna is connected. V1 is the output voltage when the antenna input is terminated.

If there is a length of coaxial cable between the antenna and the receiver system's antenna input, the value of m must be corrected (fig 4).

With the knowledge of the type of cable, the frequency of interest and the cable's length, the cable loss can be arrived at by **fig. 3**. This cable loss (dB) is then used in **fig. 4** to obtain the corrected figure for m by seeing where the cable loss value on the X-axis intersects the computed value for m. The corrected value lies on the Y intersect expressed as a temperature ratio T_a/T_o (dB) where T_a is the antenna noise temperature and T_o the 50 Ω termination's noise temperature. This corrected noise temperature ratio T_a/T_o (dB) is then used in the characteristic of **fig. 5** in order to arrive at the required system noise figure or temperature. This, of course, includes the cable loss, so to find the figure required for the receiver itself the cable loss should be subtracted from it. Now it can be assessed what measure of pre-amplification – if any – is to be provided by the first stage of the receiving system.

6. PRACTICAL CASE

Taking a practical case: Assume that the antenna noise test described above gave a result of m = 3.5 dB. The fact that the antenna noise can be measured using the receiver is proof enough that its noise figure is pretty reasonable and that it is the antenna noise which is the limiting factor.

From the X-axis of fig. 5 it can be seen that the m value of 3.5 dB corresponds to a noise temperature T_a of 650 K. The cable loss L_r (25 metres of RG 8/RG 213) can be obtained from fig. 3 as 2 dB at 144 MHz. With this, the correct value of m can be read from fig. 4, T_a/T_o = 4.3 dB. Taking this value to the X-axis of fig. 5 gives the corresponding noise temperature of T_a = 780 K.

If it is known that the receiver itself has a noise figure NF = 3 dB, then the overall NF is 5 dB (taking into account the 2 dB cable loss) it can be seen from fig. 5 that the S/N deterioration is only 2.5 dB. It is then apparent that the greater proportion of the 780 K noise temperature is in fact urban noise and that under these circumstances the receiver has a satisfactory noise figure.

If it is required to improve the S/N ratio deterioration from 2.5 dB to 0.5 dB, the corresponding noise-figure is NF = 1.2 dB (found from fig. 5). As the cable has a 2 dB loss, an NF = 1.2 dB can only be achieved by locating a suitable pre-amplifier directly at the antenna terminals.

Taking another example: A quiet situation with low antenna noise as befits a country QTH. The antenna noise tests, this time, gave an m of 0 dB. Using 13 m of RG 213 (i.e. L_r = 1 dB) yields T_a/T_o = 0 dB from fig. 4. If a S/N degradation of not more than 2 dB is required then the total noise figure (from fig. 5) should be 2 dB. From this must be subtracted the cable loss and the second stage degradation.

Subtracting the cable loss first leaves a receiver system noise figure of 1 dB (= 75 K). This includes the second stage contribution and this has an NF 2 of say 3.5 dB and the first stage gain G1 is 13 dB. Referring to figure 1 gives a second stage noise temperature of 18 K. Deducting this from the total receiver noise temperature i.e. 75 K - 18 K gives the required first stage noise temperature of 57 K or NF 1 = 0.8 dB. The receiving system would be better served if the pre-amplifier was placed at the antenna terminals. The second stage loss then increases by the cable loss i.e. 1 dB plus 3.5 dB = 4.5 dB (530 K). The first stage amplification of 13 dB reduces the effect of the second stage noise ΔT to 27 K.

As an overall noise figure of 2 dB (= 175 K) is required, the noise temperature that the pre-amplifier must have is 147 K i.e. NF 1 = 1.8 dB.

From this second example it may be seen that for the same output S/N deterioration, locating the pre-amplifier in the most strategic position, will limit the demands upon its performance and thereby its cost.

7. HIGHER FREQUENCIES

At higher frequencies the value for m can become negative especially when the antenna is pointed shywards. Here is an example for 432 MHz.

The measurement of antenna noise yielded a result of m = − 1.5 dB when the antenna was directed at the horizon. The cable loss (6.5 m RG 213) was 1 dB. With fig. 4 T_a / T_o = − 1.9 dB. Fig. 5 indicates that this corresponds to a noise temperature of 185 K. The second stage noise contribution was held to 1 dB resulting in an overall noise figure of 0.7 dB (50 K).

If the receiver had a noise figure of 5 dB – typical for a proprietry amateur receiver – then the necessary pre-amplifier noise figure may be determined as follows:

With a first stage gain of 16 dB and a second stage noise figure of 5 dB and a feeder loss of 1 dB the second stage influence is found to be 22 K. It will be recalled that an overall noise figure of 0.7 dB (50 K) was required. Now taking into account the 22 K, the first stage NF 1 (i. e. the pre-amps NF) must be 0.4 dB at the antenna terminals. Placing the pre-amplifier in the station at the end of the 1 dB feeder loss would make it impossible to realise the 1 dB S / N degredation limit.

This example shows that at 430 MHz and higher, especially for space communications, the utmost in pre-amplifier noise performance is required. The reason lies in the very much reduced antenna noise at these frequencies.

8. CONCLUDING REMARKS

Pre-amplifier gains of 23 dB, which are so agressively aclaimed in amateur radio magazine adverts, have already been discussed. The receiver subjected to such a high gain input device would shatter into intermodulation distortion unless, of course, that it was used before a high loss (10 - 15 dB) feeder. Then it would represent a good solution as the 23 dB gain at the antenna would bring the overall NF to the same order as that of

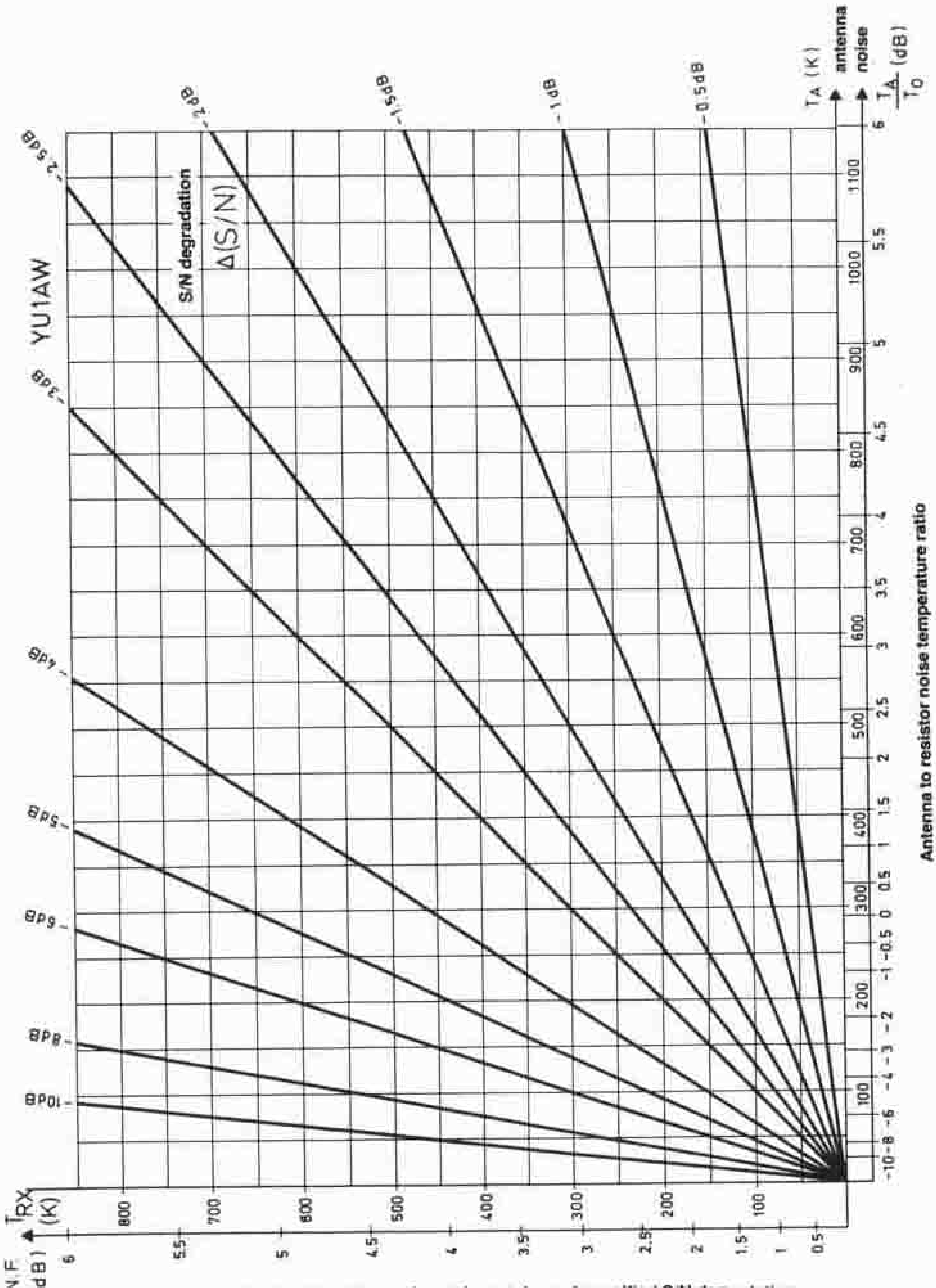

Fig. 5: Signal to noise degradation Δ(S/N) in relationship to the overall receiver's NF and the antenna noise temperature T_A

the pre-amplifier. It is the only case where such a high pre-amplifier gain is useful.

This, of course, begs the question of what such a high-loss cable is doing on an amateur station – especially during periods of transmission! The answer lies in the purchase of low-loss cable and the disposal of the 23 dB pre-amplifier.

Finally, a few more words on the measurement of antenna noise. It is important that during the measurement, none of stages are saturated with noise i. e. the whole receiving chain is working linearly. The receiver mode switch should therefore be turned to CW or SSB and not FM (limiters and saturated detectors). The AGC must be switched off and the RF gain turned down in order to avoid overloading effects. If this is not possible – as some receivers do not have the facility of RF gain control and AGC on / off switches – the results may be acceptably accurate as only low levels are involved in the measurement. The AF indicator must be sensitive to show the noise when the antenna is terminated in 50 Ω. The L. S. should be cut out of circuit and replaced with a terminating resistor (2). Local interference noises from vehicles, arc-welding and on-frequency signals should be avoided and to this end several measurements should be carried out.

The measurement error, even with a linear system, is compromised by the fact that the antenna almost never matches the receiver exactly and the antenna VSWR is higher than unity.

The autor hopes that this article will bring some enlightenment to a subject which has puzzled many amateurs over the years. Finally, the old axiom will again be recalled:
The best signal frequency pre-amplifier is the antenna!

9. APPENDIX

Only an ideal amplifier which generates no noise of its own is able to amplify without deteriorating the input S / N ratio. This is the same thing as saying that the signal-to-noise at the input is exactly the same as that at the output i. e. $S_i / N_i = S_o / N_o$. The noise factor can therefore be defined as that factor can therefore be defined as that factor by which the S / N at the output is more than that at the input of a device, i. e.

$$F = \frac{S_o / N_o}{S_i / N_i}$$

The ideal device amplifier / receiver etc. has a noise factor of unity. Actual devices all have a noise factor of greater than unity. The noise factor F allows the possibility of comparing one receiver's measured performance directly against another's as long as the measurement circumstances remain equal for both receivers. The noise factor F may be expressed in decibels in which case it becomes the noise figure NF.

$$NF = 10 \log F \text{ (dB)}$$

conversely,

$$F = 10 \text{ antilog } NF / 10$$

The noise generated within a receiver / amplifier can be expressed as an equivalent noise temperature T which is considered to be the temperature of a resistance at the input of the device which develops the same noise power at the output as the device itself – the device being considered as noiseless.

$$T = (F - 1)\ 290 \text{ K}$$

or

$$T = (10 \text{ antilog } NF / 10 - 1)\ 290 \text{ K}$$

Since the noise factor F is referred to the thermal noise at room temperature, i. e. 290 K, then by definition it may be written:

$$F = 1 + T / 290$$

or

$$NF = 10 \log (1 + T / 290) \text{ (dB)}$$

The (fictitious) ideal receiver has an equivalent noise temperature T = 0 K, all other receivers have a noise temperature of greater than 0 K.

10. LITERATURE

(1) D. Dobričič, YU 1 AW:
Determining the Parameters of a Receive System in Conjuction with Cosmic Radio Sources
VHF COMMUNICATIONS, Vol. 16, Ed. 1/1984, P. 35 - 50

(2) D. Dobričič, YU 1 AW:
Amaterske radio komunikacije preko Meseca.
Radio-amater 12/1979

(3) Mitsubishi Application Notes for GaAs-FETs

(4) J. Gannaway, G 3 YGF/D. Holmes, G 4 FZZ:
Some Pittfalls in Noise Figure Measurements
VHF COMMUNICATIONS, Vol. 13, Ed 1/1982, P. 44 - 48