Myths and Facts about Preamp Tuning

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Abstract: Even today the discussion about accuracy of noise figure measurements and the best method how to tune preamps does not stop. This article tries to recall some facts about these problems and to provide an answer to some of those beloved myths.

Introduction

These comments have been motivated by the recent the discussion in 'Tech Slot', VHF-UHF DXer 4/93, pp. 8, concerning the results on the last Martlesham VHF round table which took place in Great Britain. On this event there seemed to be a lot of interest to discuss the somewhat mystical observations on noise figure measurements and preamp tuning.

In fact the basic mathematical argumentation for a quantitative treatment of the phenomenon of gain error is available for amateurs since the articles in DUBUS 4/1988 and DUBUS 4/1990. It may make sense to raise these arguments again to avoid unnecessary or duplicate work.

The following observations and belief are typical for the state of discussion:

Observation:

Preamps with low input return loss or even return gain have erratic tuning behaviour. They require different tuning for minimum noise figure if pieces of cable or adapters were inserted between noise source and preamp. This is also true if they are tuned on a 40dB RL noise source.

1. Belief: It's believed that this behaviour should not happen when using a noise source with 40dB return loss. It's believed that the tuning sensitivity is inverse proportional to the goodness of match of the source.
2. Belief: A 15dB ENR noise source like the HP346B can serve as a useful indicator.
3. Belief: Source VSWR like antenna VSWR deteriorates noise figure of a preamp significantly even if the VSWR is small, i.e. 1.2:1 for example.
4. Belief: Most amateurs agree that they always have to re-tweak their preamps to the antenna after having optimised it on a noise figure meter. There seems to be no alternative to making the final tune up 'in situ'.

In the following I will try to raise some arguments against this belief by measurements and/or by a substantial theory about measurement errors. This will hopefully give some impression about the difference between true values and indicated values during any measurement.

1. Magnitude of Gain Error

Observation: Preamps with low return loss have erratic tuning behaviour, even if they are tuned on a 40dB RL noise source.

Erratic tuning behaviour and phase dependent measurement errors are caused by the gain error. It should be made clear that the magnitude of the so called 'gain error' is not determined by the magnitude of the return loss of the noise source used, but by the magnitude of the vector difference of the reflection coefficients between states ON and OFF.

I recall the exact equation for the gain error[1] (See Box about gain Error).

Equation [2] states, that the actual gain error during a measurement depends on the magnitudes of Γ_{ON}, Γ_{OFF}, S_{11} and the relative phase between the DUT and the noise source. The function DG versus the phase of S_{11} can be represented by a sinusoidal curve[2], which is unique for each noise source. Maximum gain error occurs at the extremes of this sinusoidal function but with opposite sign. The reference plane for the phase of S_{11} is the connector of the noise source. Any adapter or a lossless piece of cable will shift the phase and hence the actual gain error.

Gain error DG is 1 (0dB) under two conditions:

1. If $\Gamma_{ON} = \Gamma_{OFF}$ holds
2. If $S_{11} = 0$ holds.

In other words: Gain error will occur only if there is a **change in source impedance** caused by switching the noise source together with a non-zero S_{11} of the DUT.

Equation [1] tells, if $|S_{12}|$ of DUT or $|\Gamma_L|$ are not equal zero, the gain error gets even worse because of the feedback condition. Therefore it's good practice to control the load impedance of the DUT by means of an isolator between DUT and noise figure meter/converter to guarantee the same measuring conditions for different DUTs. Otherwise gain error would be dependent on the S_{12} of the DUT which is not desirable.

1 DUBUS 4/1988, pp.22 and DUBUS 4/1990, p.30
2 DUBUS 4/1990, p.20,21

Magnitude of Gain Error

[1] $$DG = \frac{G_{TON}}{G_{TOFF}} = \frac{1-|\Gamma_{ON}|^2}{|1-\Gamma_1\Gamma_{ON}|^2}\cdot\frac{|1-\Gamma_1\Gamma_{OFF}|^2}{1-|\Gamma_{OFF}|^2}$$

Γ_{ON}: Reflection coefficient of noise source in state ON
Γ_{OFF}: Reflection coefficient of noise source in state OFF
S_{11}: Input reflection coefficient of DUT

$$\Gamma_1 = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L}$$

If we assume that the following conditions hold:

$|\Gamma_{ON}|<0.03$ (30dB RL)
$|\Gamma_{OFF}|<0.03$ (30dB RL)
$|\Gamma_L|\approx 0.05$ (26dB RL)
$|S_{12}S_{21}|<0.1 \implies \Gamma_1 \approx S_{11}$

we can simplify to:

[2] $$DG = \frac{|1-S_{11}\Gamma_{ON}|^2}{|1-S_{11}\Gamma_{OFF}|^2}$$

Fortunately the organisers of the event in Martlesham were clever enough to check the two noise sources used for their S-parameters. They have the following worst case gain error, if $|S_{11}|$ is assumed to be equal 1 (0db RL), which is typical for normal 144MHz preamps:

HP346A:

$\Gamma_{OFF} = 0.0071@90$ (43dB RL)

$\Gamma_{ON} = 0.0089@116$ (41dB RL)

$|\Delta\Gamma| = 0.004$

This results in a gain error of $\pm 0.035dB$ for the HP346A noise source used in Martlesham.

HP346B:

$\Gamma_{OFF} = 0.02@11$ (34dB RL)

$\Gamma_{ON} = 0.03@-200$ (30.5dB RL)

$|\Delta\Gamma| = 0.048$

This results in a gain error of $\pm 0.42dB$ for the HP436B noise source used in Martlesham.

The worst case values above may be smaller for DUTs with better input return loss. Normal amateur style preamps don't have a better input return loss than say 3dB. This gives an improvement factor of 0.7 on the gain error.

By the way a fictive noise source with:

$\Gamma_{OFF} = 0.02@11$ (34dB RL)

$\Gamma_{ON} = 0.016@13.7$ (36dB RL)

has the same magnitude of gain error as the HP346A above, i.e. $\pm 0.035dB$, because it has the same magnitude of vector difference, i.e. 0.004. Please note that **good return loss** is **not a necessary** condition for a small gain error of a noise source! Of course it's easier to achieve a small $|\Delta\Gamma| = |\Gamma_{ON} - \Gamma_{OFF}|$ if the basic return loss of the noise source is large.

2. Tuning low return loss preamps

The observation on the tuning characteristic of the MGF-1801 preamp on 144MHz from G3LQR is fully explained by the gain error behaviour of the noise source used. Even if the maximum magnitude of the gain error is low, you will inevitably tune the DUT to a condition that a gain error occurs with positive sign. If you tune to minimum indicated noise figure you will maximize the measured Y-factor, which is equivalent. This will be done by adjusting the phase of the input matching circuit for higher gain of the DUT during noise source ON than during noise source OFF. This is exactly the condition of positive gain error. The magnitude of the actual gain error depends on the ideal phase of the true minimum noise figure matching condition, which sets the starting point on the gain error curve and the sensitivity of the DUT against mistuning. The latter is quite low, because the true noise figure minimum is quite tolerant against VSWR. This can be seen, if you calculate the noise figure circles. The main point is that gain error develops much faster than the noise figure deterioration from mistuning and that the indicated noise figure is some mixture of true noise figure and gain error.

The experimenter will suffer a mistuning in the order of the maximum gain error worst case, if he tunes to lowest **indicated** noise figure. In other words the **gain error prevents** him from finding the **true noise figure minimum** for non-impedance matched DUTs and real world noise sources. Also each noise source has it's own 'optimum' phase for maximum positive gain error, because the characteristic of gain error versus phase of DUT is unique for each noise source. Therefore it's very unlikely that two different noise sources will require the same tuning condition of the DUT to **indicate** minimum noise figure!

To show a numerical example I have simulated a WA5VJB type (4:1 XFR in the output) preamp with MGF1801 for its mistuning behaviour and the tuning error induced by the gain error of a HP346B (See Table Case Study). The simulation serves as an easy method to provide some substitution for the otherwise unknown true values. This is justified, because it's only a qualitative analysis to give an example for the phenomenon gain error.

The first two columns show the simulated (SUPERCOMPACT PC) values for the true noise figure and the corresponding input

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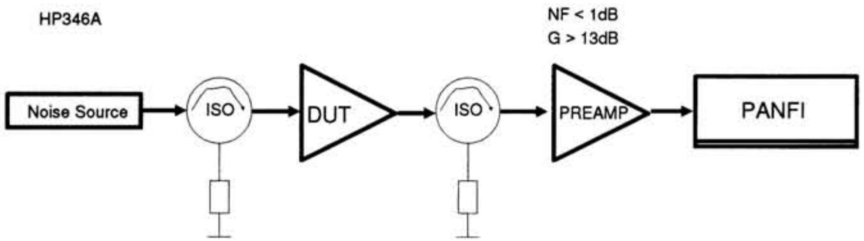
Case Study: Tuning Behaviour of MGF1801 preamp on 144MHz using a HP346B Source

MGF-1801 Preamp for 2m Simulated NF and Input Phase		Case 1 (Preamp on noise Head)		Case 2 (Preamp with 65° phase delay in front of noise head)	
True NF (dB)	φ_{11} (deg)	Gain Error (dB)	Indicated Noise Figure (dB)	Gain Error (dB)	Indicated Noise figure (dB)
0.553	5	0.419	0.13	0.196	0.357
0.369	15	0.415	-0.05	0.13	0.24
0.298	25	0.398	-0.1	0.059	0.24
0.262	35	0.371	-0.11	-0.012	0.27
0.239	45	0.333	-0.09		
0.225	55	0.283	-0.06	-0.154	0.38
0.216	65	0.227	-0.01		
0.211	75	0.163	0.05	-0.277	0.49
0.209	85	0.095	0.11	-0.327	0.54
0.216	105	-0.048	0.26	-0.397	0.61
0.224	125	-0.186	0.41	-0.419	0.66
0.243	145	-0.304	0.55	-0.389	0.63
0.265	165			-0.311	0.58
0.286	185			-0.193	0.48
0.302	195			-0.125	0.43
0.320	205	-0.401	0.72	-0.052	0.38
0.340	215			0.022	0.32
0.364	225	-0.335	0.70	0.095	0.27
0.392	235			0.167	0.23
0.425	245			0.230	0.20

phase φ_{11}. It's assumed that the preamp is retuned for each phase value (Parallel-C and Series-C), because this is exactly what is done when tuning to a noise head. The optimum tuning point from simulation is a noise figure of 0.209dB at 85° input phase. Don't bother about any numbers of the simulation, it's just an example to show the tuning behaviour of a 144MHz preamp based on the noise parameters of the MGF1801 and with a typical input circuit compromising a Series-C and Parallel-C and parallel fixed inductance. Case 1 shows the **indicated** noise figure based on the gain error[3] calculated according equation [2] for the HP346B used in Martlesham. The preamp is mounted directly on the noise head. Now case 1 shows that the minimum of **indicated** noise figure will occur at 45° input phase. This point of course is randomly dependent on the tuning characteristic of the LNA measured and the gain error characteristic of the noise source used.

3 Situation may have been worse in reality because this type of preamp has K ~ 0.05, large feedback and may have some return gain up to 4dB dependent on the load impedance. Therefore assumptions underlying equation 2 may not be satisfied.

Fig. 1: Optimum Noise Figure Measurement System



At this point you will indicate the minimum noise figure and of course tune for this condition. Whilst the indicated noise figure is -0.11dB the true noise figure would be 0.262db, not far - only 0.05dB - away from the true minimum which is located at an input phase of 85˚ and 0.209dB. But this is just a random configuration and we had good luck. Therefore to show what can happen we introduce a phase shift of 65˚ between DUT and noise source, for example a cable. This can also happen by choosing a different noise source whose gain error curve is shifted by 65˚. Case 2 shows that the minimum **indicated** noise figure of 0.19 dB will be found at an input phase of 255˚ with a true noise figure of 0.48dB. The true minimum of 0.209 dB at 85˚ input phase will be missed by 0.27dB in this case. It's obvious that the HP346B noise source will enforce very different tuning positions for minimum indicated noise figure.

Several conclusions can be drawn:

1. Tuning a DUT to minimum indicated noise figure is equivalent to 'detune' the input matching circuit for the maximum positive gain error condition. The difference between the noise figure in tuned position and the real minimum of noise figure will be the magnitude of the gain error worst case.
2. The amount of the actual mistuning depends on the random properties of the gain error characteristic of the noise source and the tuning characteristic (Noise figure versus input phase) of the preamp investigated and cannot be predicted.
3. Any cable or adapter introduces only some phase shift - if loss can be neglected-, which only changes the current magnitude or sign of the gain error but not the maximum magnitude. Therefore it's always possible to retune for maximum positive gain error, i.e. for lowest noise figure indication. To state it clearly: Any difference in tuning positions when introducing phase shifts between DUT and noise source are pure artefacts caused by the gain error, which is a function of noise source quality and input return loss of the DUT.
4. For accurate tuning to the true minimum of noise figure the use of a HP346A is mandatory, because the mistuning behaviour of the HP346B stated above will be typically reduced by a factor of 10. But be aware that all tuning artefacts will remain as a phenomenon even with a HP346A:

For example, if you calculate the values given in the table above but based on the gain error characteristic of the HP346A, you will get the indicated noise figure minimum at 0.21dB and 125˚ input phase for case 1- the 'true' value at 125˚would be 0.224db, i.e. only a 0.015dB mistuning- and at 0.184dB and 95˚ input phase for case 2, which is very near the 'true' minimum tuning condition - only 0.002dB mistuning! The necessary shift in input phase from 125 to 95 degrees requires a considerable change in input tuning (Cp=1.87pF ==> 2.17pF) of the preamp however. In neither case you will achieve the 'true' tuning position, if only input phase is considered! But the magnitude of mistuning will be virtually eliminated for nearly all practically cases even if the indicated noise figure may vary with full swing of gain error. To compare the two noise sources, two tables are given for the indication behaviour and the tuning behaviour.

Perfect tuning assumed (True Noise Figure is 0.209dB@85˚ input phase), the noise heads will indicate some different noise figure in dependency of the gain error:

Indication Behaviour of HP346B & A						
	Case 1			Case 2		
Source	**Ind.**	**True**	φ_{11}	**Ind.**	**True**	φ_{11}
HP346B	0.11	0.209	-	0.54	0.209	-
HP346A	0.22	0.209	-	0.19	0.209	-

After tuning to minimum indicated noise figure:

Tuning Behaviour of HP346B & A						
	Case 1			Case 2		
Source	**Ind.**	**True**	φ_{11}	**Ind.**	**True**	φ_{11}
HP346B	-0.11	0.262	45	0.19	0.48	255
HP346A	0.21	0.224	125	0.18	0.211	95

The only method to **reduce the gain error** even further is the **insertion** of an **isolator** in front of the HP346A. With only 20dB isolation the gain error will be reduced to 0.0035dB. This magnitude can be neglected for all practical purposes.

The best measurement system today would be (Fig. 1):

1. HP346A Noise Source
2. Low Loss Isolator with better than 26dB output RL and 20dB isolation
3. DUT
4. Isolator with 26dB input RL and 20dB isolation
5. Preamp with 13dB gain and less than 1dB noise figure for reducing 2nd stage error
6. Noise Figure Meter or Converter

3. HP346B as an indicator

Statement: The HP346B, 15dB ENR, noise source can serve as a useful indicator.

I don't agree that the HP346B is a useful indicator, because with this source you even cannot tune to the true minimum of noise figure. As explained above, when tuning to minimum noise figure with a HP346B, the DUT could be fully misaligned, because you will detune the DUTs input match away from the true noise figure minimum condition in order to maximise the gain error!

Therefore it doesn't make sense to compare tuning positions for minimum indicated noise figure between the HP346B and the HP346A source. It's better to use a 10dB PAD in front of the HP346B and to neglect the loss of ENR-calibration. In this case you will find the true minimum of noise figure with a relative accuracy of +–0.042*dB* worst case for this noise source.

4. Tuning Preamps 'In Situ'

Statement: Most amateurs agree that they always had to re-tweak their preamps to the antenna.

I disagree with the general opinion that tweaking a preamp in the antenna is a good method to achieve lowest possible **system noise figure** and that the tuning points for best noise figure must differ when changing the test set-up from bench to the antenna. To my opinion this is a artefact caused by inappropriate measurement techniques.

Observations which support the general belief stated above stem mainly from the past, when inadequate noise sources like the HP346B or AIL 7615 have been used. These introduced a gain error of say +–0.42*dB*, which led to misaligned preamps. This of course can produce a significant change in sun/CSG noise observed.

Sensitivity of noise figure versus source VSWR

The sensitivity of noise temperature versus source mismatch for a noisy twoport is

$$T_n = T_{min} + 4R_N T_0 \cdot \frac{|\Gamma_G - \Gamma_{OPT}|^2}{(1-|\Gamma_{OPT}|^2)(1-|\Gamma_G|^2)}$$

Γ_G: Actual Source Reflection Coefficient

Γ_{OPT}: Optimum Source Reflection Coefficient for minimum noise figure

R_N: Normalised Equivalent Noise Resistance

which reduces to

$$T_n = T_{min} + 4R_N T_0 \cdot \frac{|\Gamma_G|^2}{(1-|\Gamma_G|^2)} \quad \text{if } \Gamma_{OPT} = 0 \text{ (50 ohms for a tuned preamp)}$$

With $VSWR = \frac{1+|\Gamma_G|}{1-|\Gamma_G|}$, $|\Gamma_G| = \frac{VSWR-1}{VSWR+1}$ and $F = \frac{T}{T_0} + 1$ we can conclude

[3] $$F = F_{min} + R_N \cdot \frac{(VSWR-1)^2}{VSWR}$$

To measure R_N, first tune the LNA to F_{MIN}, then insert a tuner (for example antenna combiner 2x50->50 provides VSWR=2.0:1 or 4x50->50 provides VSWR=4:1), measure F and calculate R_N:

[4] $$R_N = \frac{(F - F_{MIN}) \cdot VSWR}{(VSWR - 1)^2}$$

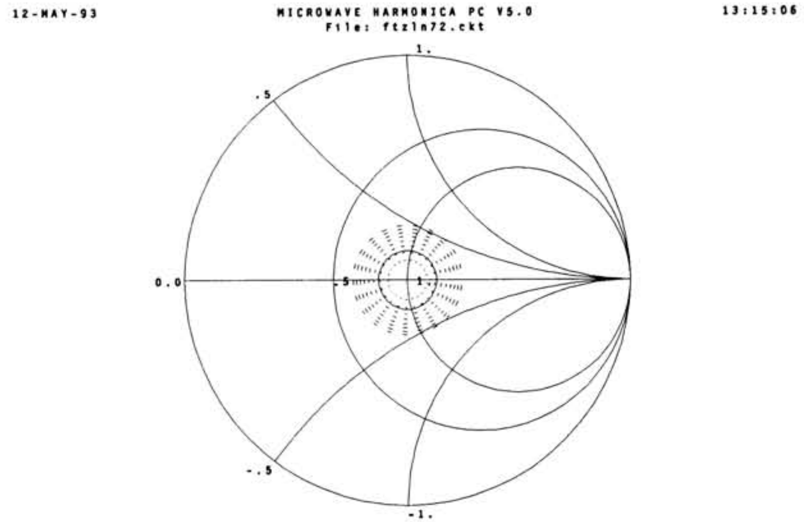
On 432MHz a change of 0.1dB in RX-noise figure produces a change of 0.5dB in sun/CSG noise in a good system ($T_{SYS} \approx 75K$). With a gain error of $\pm 0.035dB$, the system noise temperature will be within $\pm 0.18dB$ of the optimum value if you tune your preamp on the bench provided that the source VSWR of the antenna does not deteriorate the measured noise figure (See remark below).

On the other hand sun/CSG noise (Y-factor method) can be measured with an accuracy of $\pm 0.5dB$ at best. When calculated backwards this is equivalent to a $\pm 0.1dB$ error in noise figure. Situation gets even worse if the antenna impedance changes when moving from the celestial source to cold sky. In this case you will suffer the equivalent of a gain error but much more than with a good noise source, because VSWR of the antenna normally is large compared with a good noise source and also the vector difference can be large very likely. All this is rather unpredictable and even not quantified! Or do you know an amateur who inserts an isolator between antenna and preamp to get rid of the impedance change for minimizing a possible gain error? Did you hear of an amateur who measured the impedance of his antenna system when changing the pointing to be able to quantify his gain error? In my view all these **amateur measurements** with antennas involved are **obsolete** and governed by **wishful thinking**.

Therefore I think generally the 'bench' method is superior to the 'in situ' method. The only motivation for antenna measurements should be:

1. The unavailability of a noise figure meter
2. The unavailability of a good noise source
3. An antenna VSWR of greater than 1.5:1.

Figure 2: Noise Figure Circles of LNA-432-1302
$NF_{MIN} = 0.35dB$; $R_N = 0.19$
Dashed Lines: Noise Cigure Circles in 0.025dB Increment
Solid Line: VSWR Circle 1.3:1



4. Regular checks of the consistency in system performance.

What should be stated is that preamps with low return loss or even return gain[4] exhibit a larger gain error during bench measurements and likely will have oscillation problems when placed into the real world, i.e. into an antenna with some complex source impedance. Therefore it's **good engineering practice** to design **stable preamps** with **a good return loss** in the input. Remember that with an input return loss of 10dB all effects discussed will be reduced by a factor of 3. These preamps are 'noise source tolerant' and 'antenna match tolerant'.

5. The sensitivity of noise figure on source match

Statement: Antenna VSWR detoriorates noise figure of a preamp heavily.

Measurements and simulations indicate that a typical preamp on 144MHz with a MGF1302 will suffer only a 0.05dB increase in noise figure, when the source impedance has a VSWR of 1.3:1 instead of 1:1!!! Even with this rather poor matching condition there is no sense for changing the preamp tuning when going from bench to the antenna. The explanation is, that the noise figure minimum is rather broad in terms of VSWR. This is true for all GaAs-FETs in the range between 144MHz and 10GHz with a decreasing sensitivity for the higher frequencies. You can easily see this by drawing noise figure circles for those devices on a Smith chart. This explains why semiconductor companies have great difficulties to accurately measure the noise parameters of their devices.

Another practical proof is the fact that fixed tuned preamps with low noise figures can be

4 This is not uncommon for some well known commercial preamps

successfully constructed in spite of the device and circuit tolerances. The input matching circuit has the only purpose to transform the centre of the device noise figure circles to the centre of the Smith chart, i.e. to a source impedance of 50 ohms! The basic sensitivity of a preamp to source match is given by the normalised noise resistance of the device and the type of input matching circuit. On 144MHz the value for R_N is about 1.5 for a MGF-1302. For the complete preamp this will be reduced by the finite loaded Q of the input matching circuit to $R_N < 0.1$! This has been simulated by means of SUPERCOMPACT. Similar values I have simulated for preamps on 432MHz.

Practical measurements on source match behaviour have been made in 1985, when I started to investigate stability, tuning behaviour of preamps and gain error. I built a small low-loss airline quarter wave transformer for 432MHz, which provided a reflection coefficient of 0.176. On this defined mismatch I measured a series of 432 preamps with and without tuner. It's easy to get a value for R_N from these measurements for each preamp (See equations below). At that time I got a mean value for R_N of 0.21 with 11 different single gate GaAs-FET preamps (MGF1400, MGF1402, NE218, D432 types) measured. Fig.2 illustrates the sensitivity for source VSWR of a 432MHz preamp. Maybe that simulation is a bit optimistic about R_N, but the simulated values are in the right order of magnitude.

The simple equation [3] describes the behaviour of a preamp in case of source VSWR, if it has been tuned to 50 ohms for optimum noise figure. It's only dependent on the normalised noise resistance of the preamp and the source VSWR, i.e. the antenna VSWR. Of course it's not dependent on the relative phase. Such a dependency, if observed, would be the result of a gain error during measurement. A prerequisite of this equation being valid is that the preamp is really tuned to $\Gamma_{OPT} = 0$, i.e. 50 ohms. Otherwise the sensitivity gets larger. This optimum tuning condition is only achievable by using the appropriate noise source of course. In other words if you use an already mistuned preamp in a system with source VSWR, the sensitivity for source mismatch gets larger and you may think about retuning it to this source, but probably with a high risk to arrive at a mistuned condition again.

The influence of antenna match on noise figure is overstated by nearly all amateurs. I disagree with the general opinion that the antenna has to be pure 50 ohms resistive. In fact it's allowed to have an 'acceptable' VSWR, which should be some value below 1.3:1. In this case the total RSS (Root of Sum of Squares) error for gain error and VSWR deterioration would be $\pm$ 0.06*dB*.

The source VSWR sensitivity will get even smaller at higher frequencies, because the normalised noise resistance of GaAs-FETs is lower on higher frequencies.