NOISE FIGURE CALCULATION FOR SPACE SURVEILLANCE RADAR SYSTEMS

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ABSTRACT

The daily life on Earth more and more relies on satellites and space missions. These missions are increasingly at risk by the growing amount of space debris. As even small particles can destroy active satellites, it is necessary to build up an up-to-date catalog of all objects in space. While there are good results using optical systems for high altitude objects e.g. at geostationary orbits, for low earth orbit objects the use of highly sensitive radar sensors is necessary. For the proper design of these radar systems the signal-to-noise-ratio (SNR) is a key factor. While the SNR's signal part is mainly dependent on system parameters like transmit power or antenna gain, the system's noise figure is influenced by a multitude of parameters. For short range radar systems the receiver noise temperature dominates the calculation, whereas for space surveillance radar systems the calculation is more complex.

While the individual factors of a system's noise figure have been discussed in various publications, the combination of all these factors and their relative importance is considered only rarely. This paper provides an overview over all effects concerning the noise figure calculation for space surveillance radar. After a short introduction to the basic concepts of noise figure calculations, each effect influencing the noise figure is discussed in detail for two example radar systems, one for detection and another one for imaging. These calculations include external parameters like the noise effects of the sun or atmospheric losses as well as the system specific factors like feed line losses, noise figure of low noise amplifiers (LNA) and side-lobe effects.

The proper calculation of a system's noise figure plays an important role for the design of a space surveillance radar system.

Keywords: SSA; radar; noise figure, atmosperic effects, galactical noise.

1. INTRODUCTION

The noise figure of a radar system plays an important role as a performance parameter of a radar system. It occurs as linear factor in the radar-range-equation which is given in the following (1):

$$SNR = \frac{P_t G_t G_r \sigma \lambda^2 \tau}{(4\pi)^3 R^4 k_b T_s} \qquad (1)$$

where

- P_t is the transmit power of the system
- G_t and G_r are the transmit and receive gains of the antenna
- σ is the Radar-Cross-Section (RCS) of the observed target
- λ is the systems wavelength
- τ is the pulse length of the radar system
- R is the range between target and radar system
- k_B is Boltzmann constant
- T_s is the systems noise equivalent temperature

This means, a doubling of the systems noise figure means the system can detect targets of half of the size.

This noise figure consists of many parts and the calculation is especially dependent on the region the radar system is pointing at, since the temperature can be calculated as:

$$T_s = (1-\eta)T_{int} + \eta\xi T_{ant} \qquad (2)$$

where T_{int} is a antenna internal noise temperature, η is the directional dependent radiation efficiency of the antenna, T_{ant} is the actual temperature of the target scene and ξ is the emissivity of the target scene.

In general, the main contributions to the noise figure calculation are given by the following parameters:

- T_{int} noise temperature of internal antenna effects. Mainly dominated by systems Low-Noise-Amplifier (LNA)

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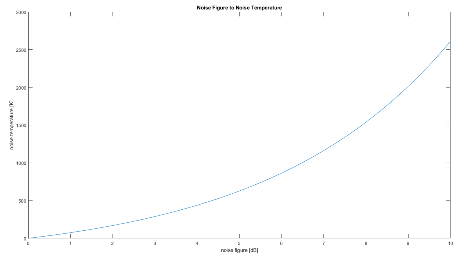


Figure 1: Conversion from receiver noise figure to equivalent noise temperature

- T_Ω noise contribution of all ohmic losses between antenna and LNA, including e.g. feed-line, adaptors and circulator
- T_{ant} noise figure of the antenna, contributions of all scene-effects. This includes noise temperature of the sky, the sun and other galactic sources as well as radome-losses, ohmic resistance of the antenna itself side lobes directed towards the ground

1.1. Different Definitions of the Technical Term Noise Figure

There are two completely different definitions of the technical term "noise figure" in the literature. The historical first measurement of noise was done by Bell in 1926 at Bell Labs and published two years later by Johnson [5]. The first theoretical definition of a noise figure is given by Friis [1]. Friis defines the terms "noise figure" (NF) and "noise figure" (F) as a measure of degradation of the SNR between input and output of a component or a signal chain. Within this definition, F is the quotient of input and output SNR and NF means the signals loss in dB between the two ports.

The second definition which is the standard today was introduced by IEEE in 1959 as the "Effective Input Noise Temperature [...] [is defined as] the input-termination noise temperature which, when the input termination is connected to noise-free equivalent of the transducer, would result in the same output noise power as of the actual transducer connected to a noise-free input termination" [3].

Since the aim of this paper is to give a proper calculation method for space situational awareness (SSA) radar receive systems, the IEEE definition is used. The reasons for this decision are:

1. the noise-figure is angle-dependent
2. for receive systems, you can not give any ration, since in absence of a target there is only an output
3. there is no unitless power gain like for a single amplifier

In some cases, a noise figure equivalent is given in dB (for transformation see Figure 1). The authors do this, when an equivalent noise temperature is totally unusual, like e.g. for ohmic losses.

2. NOISE FIGURE OF THE RADAR SCENE

All noise figure contributions of the scene are affected by atmospheric attenuation. A detailed discussion of all aspects of this is presented in [8]. The atmospheric attenuation is strongly dependent on the elevation of the radar beam. It can be calculated as

$$A_{atm} = \frac{0.042}{\sin\theta} \tag{3}$$

where θ is the elevation angle and $\theta = 90°$ means pointing the radar to the zenith. The numerators value is dependent on the climatic situations at the location of the radar system. The value of 0.042 is a literature value and is calculated for Madrid, Spain. All other values mentioned in [8] are in North America. For the most observations in the SSA context, the elevation angle should be greater than $30°$, thus the attenuation should not exceed 0.084 dB. The influence can be much bigger, if you are planning to start a tracking task with very low elevation, this can increase drastic and reach a value of 2.4 dB for $1°$ elevation angle.

All this values add to the losses caused by the radars radome A_{rad}. This radome losses can be in the range of 0.1 dB up to 1 dB. For an L-Band System as well as mmWave systems for imaging, a loss of 0.4 dB should not be exceeded for a dry and clean radome [7]. The attenuation will increase much, as the radome is covered with rain [6].

This values can be used, to calculate the noise figure caused by these atmospheric attenuation and radome effects. The equation used is based on a calculation in [8] and completed by radome effects:

$$T_{atm} = T_M \cdot (1 - 10^{-\frac{A_{atm}+A_{rad}}{10}}) \tag{4}$$

where T_M is the effective noise temperature of the atmosphere on the earth and thus chosen as 255 K–280 K depending on the humidity.

2.1. Noise Figure of the Sky

T_{sky} is often stated as the cosmic background radiation of the sky and stated in the order of 2.8 to 4 dB. This background radiation is only part of the total noise temperature of the sky. There are additional noise sources caused by different radiating astronomical objects like quasars. A contributor with much influence is the black hole in the center of the milky way. Established literature values for the noise temperature of the center of our galaxy are in the order of $15\,\mathrm{K}$ to $20\,\mathrm{K}$ for an L-Band radar [4]. Values for other galactic sources and frequencies can be seen in Figure 2

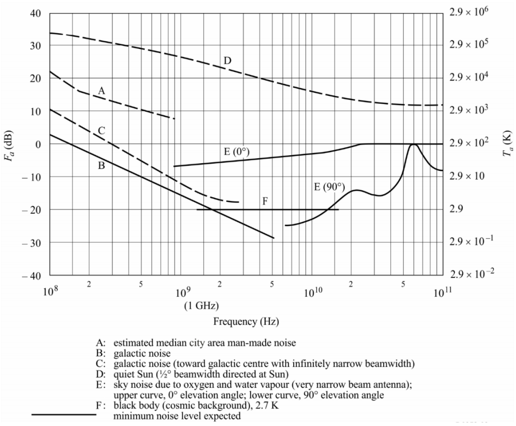


Figure 2: Sources of galactic noise by frequency, reprinted from: [4], Copyright: ITU

Another fraction of the noise temperature of the sky is caused by the sun which can be seen in Figure 3. The sun can be identified as a strong noise signal in a circle of about $4°$ and additional effects of side-lobes and ambiguities in a much bigger region around the main region. Common literature values for sun noise temperature vary by aspect angle and frequency and differ from only few Kelvins up to a region of some thousands of Kelvins [2].

To calculate a mean over all this effects caused by the sky, we recommend not to use only the cosmic background radiation, but build some sort of pessimistic medium value which we choose in the order of the radiation of the center of the milky way to be safe for realistic SNR computations. Summarizing we get the temperature of the sky as:

$$T_{sky} = T_M + T_{atm} \cdot (T_{sun} + T_{sp}) \tag{5}$$

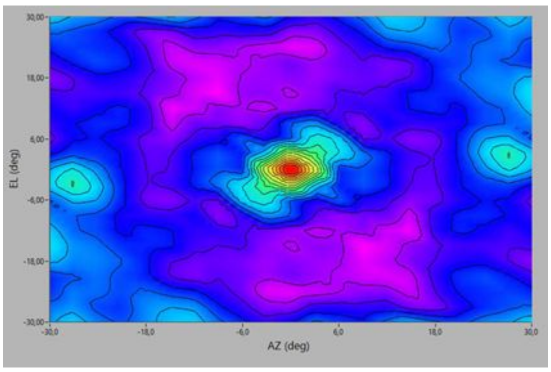


Figure 3: Radar measurement of the sun with GESTRA Phased Array Radar System

where T_{sun} and T_{sp} are the mean noise temperature of sun and space. The sum of these can be estimated pessimistic with a value of $21.5\,\mathrm{K}$.

2.2. Final Calculation of the Antenna Noise Figure

The noise figure of the sky consists of the previously calculated noise temperature of the sky, as well as some radiation of the earth surface which has a temperature of $290\,\mathrm{K}$. This radiation is collected via side- and back-lobes. While the back-lobes are very hard even to simulate and can not be specified exact, the effect of side-lobes is strongly angle dependent. While steering at broadside has a very good side-lobe suppression (see Figure 4a), the suppression is much lower for big off-broadside angles (Figure 4b).

Hence we get a final formula for the calculation of the antenna noise temperature:

$$\begin{aligned} T_{ant} =& ((1 - F_{SL}) \cdot T_{sky} + F_{SL} \cdot T_{env}) \cdot 10^{-\frac{R_\Omega}{10}} \\ &+ (1 - 10^{-\frac{R_\Omega}{10}}) \cdot T_{ant2} \end{aligned} \tag{6}$$

with the symbols

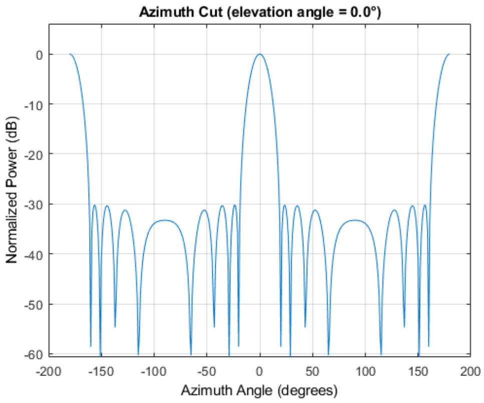
- F_{SL} fraction of the energy in side-lobes compared to the total received energy. This is very system specific and depends for example by the kind and arrangement of the used antenna (dish antenna vs. phased array)
- T_{env} temperature of the environment, usually $290\,\mathrm{K}$
- R_Ω ohmic losses of the antenna
- T_{ant2} physical temperature of the antenna, usually $290\,\mathrm{K}$

3. NOISE FIGURE OF INTERNAL SOURCES, FOR EXAMPLE FEED-LINE AND RECEIVER

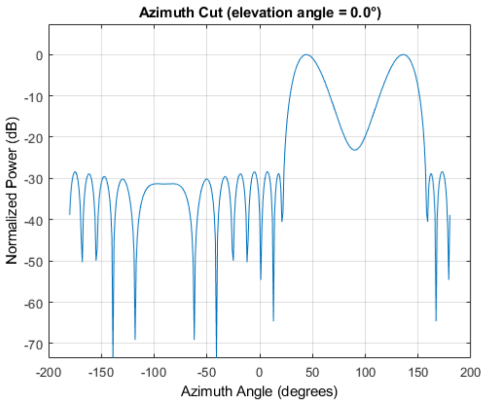
On the way from the antenna through the systems until the RF-signal reaches the LNA in the Receiver, every part contributes via ohmic losses to the noise figure.

In a usual system this feed line consists of some plugs and adapters, which each one contributes with about $0.1\,\mathrm{dB}$ and possibly a circulator. All this is in the order of less than one dB for an L-Band System and some dB for a W-Band system. This all contributes to the feed-line temperature as

$$T_{line} = T_{env} \cdot (10^{-\frac{\sum_i L_i}{10}}) \tag{7}$$



(a) antenna pattern steering broadside, good suppression of side-lobes



(b) antenna pattern steering at $45°$, high side-lobe level at $135°$ with hardly any suppression of the side-lobe

Figure 4: antenna patterns for different steering angles considering a ULA-Array antenna with 11 elements arranged in 0.5λ-spacing in L-Band

where L_i is the loss of the single component.

Last the LNA of the system has a large effect on the systems noise figure. Typical values for LNA noise figure T_{rec} in an L-Band System are between 0.7 and 1.4 dB and up to 5 dB for higher frequency systems in W-Band.

These internal effects alone lead to noise temperatures of about 100 K in L-Band and several hundred Kelvins for W-Band imaging systems.

4. NOISE FIGURE OF THE RADAR SYSTEM

To get the radar systems noise figure you have to sum up the previously discussed summands. This leads to the formula:

$$T_{sys} = T_{ant} + T_{line} + T_{rec} \tag{8}$$

5. CONCLUSION AND FUTURE WORK

The system noise figure of a space surveillance radar system of in general any radar system used for SSA topics is strongly dependent on the steering angle of the system. While all system internal effects are the same as for every other radar system, the contributions of the scene are much more complicated. The factors of atmospheric attenuation as well as radiation effects from the ground can increase drastically for very low elevation angles, whilst for high elevation angles, the influence of galactic radiation and the sun may have big influence. Additionally for ground-measuring radar systems it is usually guaranteed, that the internal receiver noise is strictly dominated by the noise figure of all effects of the scene. This assumption does not necessary hold for SSA radar systems, since the noise temperature of the sky can be in the order of less than 50 K and the antenna temperature is in the order of up to 100 K.

Without a proper calculation of these effects consider the following scenario: The radar system is programmed for to initialize a tracking task. For the first elevation angles no observations can be achieved due to the high noise collected by side-lobes. During long parts of the pass the radar system is possible to detect and track the debris particle. Then the system looses the particle because the radar is pointing to the direction near to the sun. When the steering direction diverges from the suns direction the radar can track and detect the particle again.

Other SSA specific influences in the field of radar systems are effects regarding space weather and ionospheric activity. This will be a part of future research to get a complete understanding of SSA radar systems.

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