Cryogenic operation of a mixer receiver

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Cryogenic operation of a heterodyne receiver

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1 Introduction

The reconstruction of the AMSOS microwave radiometer has recently begun. AMSOS was completely built at IAP Bern to retrieve millimeter wave emission of water vapor at 183 GHz. One part of the rebuilding includes the replacement of the old mixer and probably the first IF amplifier. During the discussions about possible improvements, a idea appeared, that should be discussed: is it worth while to apply cryogenic operation of the front end (mixer and first amplifier) in order to achieve a lower noise temperature of the system, and therefore a better sensitivity of the radiometer? Since the trade-off that would have to be done is not a very simple one, in the following chapters we will try to emphasize some aspects of the possible gains and losses by cryogenic operation of the receiver.

2 Noise temperature of a mixer receiver

Every receiver can be described by its noise temperature. For mixers, two different concepts are introduced, Single Side Band noise temperature and Double Side Band temperature, depending of the mode of the operation. Both concepts could be rather confusing, and a good explanation can be found in [MAAS86]. We will not deal with this matter in detail, and depending which concept is applied, overall noise temperature of a receiver (containing the mixer) can be calculated as follows. In Figure 2 there is a simple scheme of a mixer receiver. The mixer itself is shown as a noiseless device, with the equivalent noise generator in front of it.

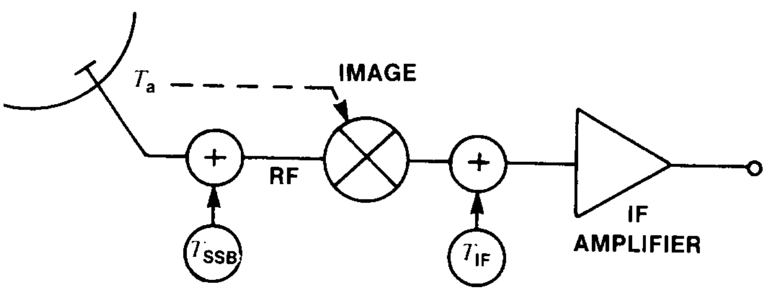


Figure 1: SSB noise model of a mixer receiver

T_A is the noise temperature of the antenna and it depends upon the noise level that is received. In general, the noise temperature of a directed antenna can be between a few degrees, when pointed at the cold sky, and a few hundred of Kelvin, when pointed at a warm source, the earth for instance. Therefore T_A must be taken into consideration when calculating the overall noise temperature. We assume that the antenna noise temperature is the same over the whole range of operation - indeed it is the same both at RF and image frequency. T_{IF} is the noise temperature of the IF amplifier. For single side band operation, the total input noise at the input of the IF amplifier (it is also shown as a noiseless device with the equivalent noise generator in front of it, Figure 2) will be:

$$T_{L,IF} = T_A G_{ci} G_{ci} + (T_{SSB} + T_A) G_{cr} + T_{IF} \tag{1}$$

Where G_{cr} and G_{ci} are conversion factors (less then 1) of the mixer at RF and image frequencies. We assume that they are equal and $G_{cr} = G_{ci} = 1/L$, where L is the conversion loss of the mixer. Therefore:

$$T_{L,IF} = (2T_A + T_{SSB})/L + T_{IF} \tag{2}$$

The overal noise temperature of the receiver will be:

$$T_{SYS,SSB} = 2T_A + T_{SSB} + LT_{IF} \tag{3}$$

For the double side band operation, DSB noise temperature at the input of the IF amplifier (Figure 2) is:

$$T_{L,IF} = 2(T_A + T_{DSB})/L + T_{IF} \tag{4}$$

Which makes:

$$T_{SYS,DSB} = T_A + T_{DSB} + LT_{IF}/2 \tag{5}$$

Both SSB and DSB concepts could be, as we said above, very confusing, but this is not the main interest of these chapters. From the equations above it is not clear whether to use the DSB concept or to apply a filter for removing the image response. It depends of the type of the receiver and its application, but from the equation for the overall noise temperature either SSB or DSB concept, it can be seen that there are two noise sources that can be influencd: the noise temperature of the mixer and the noise temperature of the IF amplifier. Noise sources in a mixer will be analysed in more detail, in order to realize how much of the mixer noise can be decreased by cooling.

3 Noise analysis of a mixer

Noise theory has been studied extensively in many semiconductor theory books. Basically, there are four different types of noise in semiconductor devices, two of which are of major importance, and two not that important. The less important ones are flicker noise and generation-recombination noise. Flicker noise in semiconductor devices results from fluctuations in charge carrier density, which in turn cause fluctuations in material resistivity. Fluctuating resistivity causes a fluctuating voltage to appear across the material. However, flicker noise is negligible in most applications (especially in radiometry). Its importance decreases dramatically above a few MHz, and at very high frequencies it makes no contribution to the overall noise temperature of the receiver. Generation-recombination noise derives from the random thermal ionization of impurity in the semiconductor body. The result is the random behavior of the conductivity of the semiconductor, which gives rise in voltage fluctuation, when direct current is passed. Although theoretically important, both of these noises are basically negligible in practical application, especially beyond 100 GHz. The two most important noise types are shot and thermal noise.

Shot noise is generated by the diode because the diode conducts current in pulses as each electron is emitted across the junction. Since the transit time is considered to be very short (compared to the inverse of the frequency), the current can be treated as a series of random impulses, each of which occurs as a single electron transits the junction. The average number of such pulses in each second is constant, and is proportional to the dc current. It can be shown that the mean square shot noise current in a forward biased diode is:

$$\overline{i_s^2} = 2qI_jB \tag{6}$$

where q is the electron charge, I_j is the junction dc current, and B is the bandwidth. As we can see, no temperature factor plays a role in the shot noise figure. Therefore, the cooling of the receiver (with a mixer and an amplifier being semiconductor devices) doesn't affect the amount of shot noise directly. On the other hand, due to the changes in current characteristics of the mixer's diode, dc bias current is usually decreased at cryogenic temperatures. This matter will be explained later.

As every resistance (at certain temperature above absolute zero) produces thermal noise, it is the same with the series resistance of the mixer diode. It arises from the random agitation of electrons, and is closely related to blackbody radiation. Thermal noise is frequency dependent. However, at 'low' frequencies and 'high' temperatures (below the submillimeter and above a few Kelvin), the noise power from a resistor depends on bandwidth and temperature, and not frequency. This estimation is extremely accurate in the above mentioned range, where hf$<<$KT, h being Planck's constant. In AMSOS's application this is valid. A resistor of resistance R could be equivalently replaced by a noiseless resistor and a noise voltage source in the series:

$$\overline{v^2} = 4KTBR \tag{7}$$

where K is Boltzmann's constant, T is absolute temperature in Kelvin. The noise power available in a bandwidth of B is:

$$P_n = KTB \tag{8}$$

Both thermal and shot noise are white Gaussian noise. In Figure 2 both noise sources are presented as noise generators. In Figure 2 (a), both generators are presented originally, and in Figure 2 (b) the voltage generator of thermal noise is transformed into a current generator source, using some elementary theorems of electrical circuits (Thevenin's theorem).

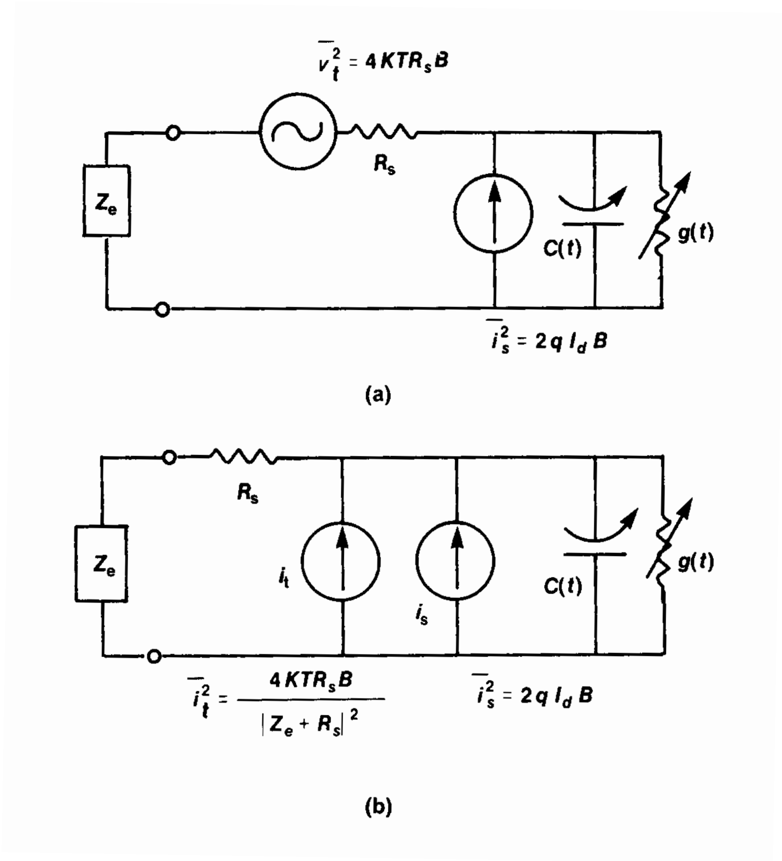


Figure 2: Equivalent noise circuit of the diode. (a) Thermal noise presented as a voltage generator; (b) thermal noise presented as an equivalent current source

Now, both sources can be treated equally, since they contribute (from the point of view of the electrical circuit theory) to the overall mixer noise in the same way. A very exact analysis of the influences of both noise generators and their behavior at mixing frequencies can be found in [MAAS86]. However, for us it is important to have an idea about the dependence of overall receiver noise on different parameters, like environmental temperature and diode's dc current.

4 Effects of cryogenic operation

As can be seen immediately, even at a glance on Figure 2, by changing the operation temperature, we can directly affect only the thermal noise amount. That is the only factor that depends directly on the temperature. However, the changes in the overall noise temperature of a receiver, caused by its cooling, could be considerable. On the other hand, changes in operation temperature usually cause changes in mixer diode characteristics that indirectly affect shot noise. Receivers for very low noise application (like radio astronomy) are often cooled to $12 - 15$ K using the helium closed Gifford-McMahon cycle, or even to 4.2 K using Joule-Thompson refrigerators. Some effects of low temperature on the mixer receiver will be discussed.

It is well known that diode (mixer diode) current is exponentially dependent on the diode voltage. The ideal diode equation can be derived relatively easily, and it is:

$$I(V) = I_0[e^{(qV/KT)} - 1] \tag{9}$$

However, behavior of the diode is usually not ideal, and in order to compensate, the ideality factor n is introduced. It is measured experimentally, and it is close to 1, usually between 1.05 and 1.25. With the ideality factor introduced, the diode equation becomes:

$$I(V) = I_0[e^{(qV/nKT)} - 1] \tag{10}$$

I_0 is the current parameter and its calculation can be difficult, since many parameters can influence on it, like tunneling, charge generation and leakage. The ideal expression for I_0 can be found in literature as:

$$I_0 = AT^2We^{(-qV_b/KT)} \tag{11}$$

where W is the junction area width, V_b is the voltage height of the junction barrier, and A is the modified Richardson constant, which is approximately 96 $Acm^{-2}K^{-2}$ for silicon, and 4.4 $Acm^{-2}K^{-2}$ for GaAs.

As we can see from the equations above, there are two effects: the diode current becomes more sensitive to voltage at lower temperatures, and I_0 has an exponential, but also a strong square law dependence on temperature. Both effects make the slope of I/V diode characteristic steeper, and its knee moves to higher voltages (Figure 4).

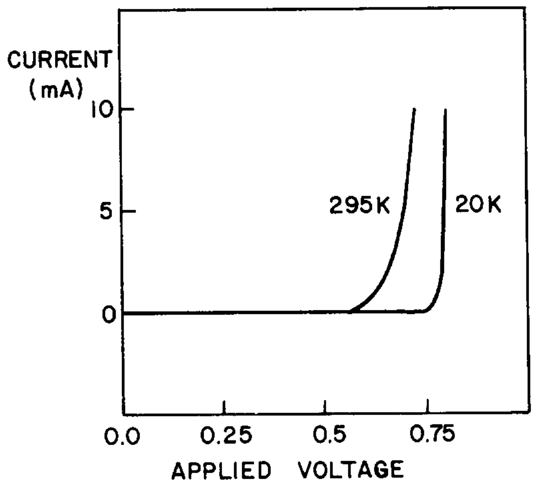


Figure 3: I/V characteristics of a GaAs Schottky diode at room and cryogenic temperatures. The knee moves to higher voltages at low temperatures

Another effect of the temperature drop are changes in the value of the ideality factor. It remains reasonably constant at temperatures as low as 100 K, and then rises as temperature drops further. At 30K or below, its rise almost completely compensates any further temperature reduction, keeping the slope of the I/V curve nearly constant. One of the reasons for the disappointing rise of the ideality factor at low temperatures is that conduction is no longer dominated by thermionic emission, but by quantum-mechanical tunneling. When thermionic emission dominates, the tunneling component of current varies exponentially with the square root of doping density. Therefore, this effect can be minimized by designing diodes for cryogenic operation with reduced doping density. For instance, GaAs Schottky diodes used at room temperature usually have doping densities around $2x10^{17}cm^{-3}$. For cryogenic operation, doping may be as low as $10^{16}cm{-}3$. This may be a serious hurdle for the application of mixers designed for operation at ambient temperatures - the ideality factor of heavily doped diodes can rise considerably even at temperatures above 100K. It is very difficult to explain the dramatical rise of the ideality factor, and the theory of tunneling is probably not a sufficient mean. However, based on experiences, it can be seen that the ideality factor reaches the value of n=5-10 at very low temperatures ($< 20K$).

Despite the rise of n, the diode characteristics remains exponential (see Figure). Therefore, the mixer conversion loss (but not the noise temperature, of course) remains essentially constant over a very wide range of temperatures, as long as the diode bias and LO power can be modified to compensate changes in the I/V shape. Consequently, the key to optimizing mixer performances over environmental temperature variations is to change the bias and LO power level in accordance with the temperature.

Series resistance R of the diode is affected both by changes in semiconductor mobility and the quality of the ohmic contact, although at very low temperatures the latter dominates. Ohmic contacts are more difficult to produce on GaAs then silicon because it is difficult to find metals with the appropriate work functions and to dope the semiconductor heavily. This may result in a very slight rise in R, but may also result as a complete failure in diode conducting.

The knee of the I/V curve rises with temperature decrease, so the diodes must be biased to a higher voltage for optimum mixer performance. This may have as an effect the increase in average junction capacitance in operation. This capacitance increase may cause a small increase in the mixer's conversion loss (0.1-0.3 dB) on cooling.

All these factors affect that, according to [MAAS86], it has been observed that, if a *convetnional* Schottky diode is used, the reduction in mixer noise temperature on cooling is at most a factor of 2.0-2.5, although its physical temperature may be reduced by a factor of 20 or more. Two phenomena are responsible for this situation. One is the effect of tunneling, described previously, which becomes worse at low temperatures and high doping densities. Reducing doping densities can help, but in that case, the serial resistance can be increased substantially. The second phenomenon is that the volatage-variable junction capacitance causes minimum conversion loss and minimum noise temperature to occur under different conditions of tuning, bias and LO power level. The result is that mixers with very low conversion loss often have disappointingly high noise temperatures. So, the reduction in the variation of the junction capacitance would result in significantly better noise performance. Some of these problems are solved with Mott diodes.

A Mott diode consists of a metal contact to a semiconductor with a thin, lightly doped epitaxial layer that is grown on a very heavily doped buffer layer. The epitaxial layer is, for an order of magnitude, thinner than at Schottky diodes. Also, the technology of building is different from the one used at Schottky diodes. The light doping of epitaxial layer helps prevent tunneling at low temperatures. The Mott diode's ideality factor at very low temperatures is often not significantly different from that of Schottky diodes, for unknown reasons. Even in this case, the Mott diode exhibits substantially better performance at low temperatures than Schottky diode. The essence of this better performance is the well reduced junction capacitance.

	300K Schottky	*20K Schottky*	*300K Mott*	*20K Mott*
Conversion loss	6.2dB	6.2dB	6.6dB	6.6 dB
$T_{mxr,SSB}$	600K	300K	800K	200K
LO power	2.5mW	1.0mW	1.0mW	0.15mW

Table 1 - Comparison of a Schottky and a Mott diode at room and cryogenic temperatures

The Mott diode shows poorer ambient temperature performance than the Schottky, but a much better one at low temperatures, and requires up to 8 dB less LO power, which can be crucial at very high frequencies, where LO power could be poor. [MAAS86], according to Keen, compares properties of a Schottky and a Mott diode, operating at room and cryogenic temperatures. His results are summarized in Table 4

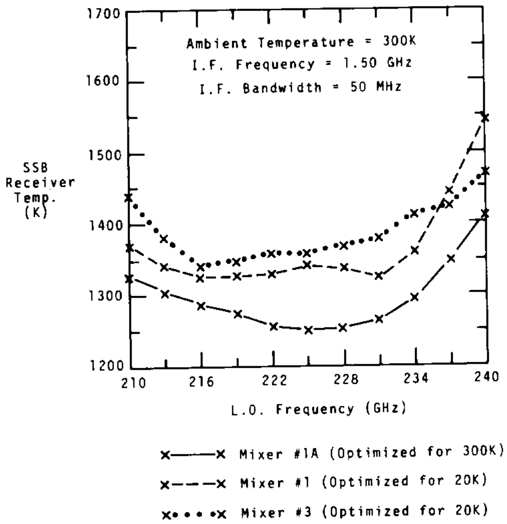
The improvement in performances at cryogenic operation of a Mott diode is obvious, but the noise temperature of the mixer with the Schottky diode is decreased by a factor of two, when it is cooled from 300K to 20 K. This could mean the following: if a receiver is to be designed, one should decide in advance which type of operation will be applied, and consequently, the type of mixer. Cooling down the existing mixer doesn't bring too many advantages.

Another similar experiment was introduced by Archer [ARCH82]. This paper provides some very useful data that are highly important in this matter. Archer compared a receiver (a mixer receiver with a Schottky-diode mixer) at ambient and cryogenic temperatures. He came to the conclusion that an improvement of a factor of three of the noise temperature could be achieved by cooling the receiver to a temperature of 20K. However, the increase in complexity and decrease in portability are significant.

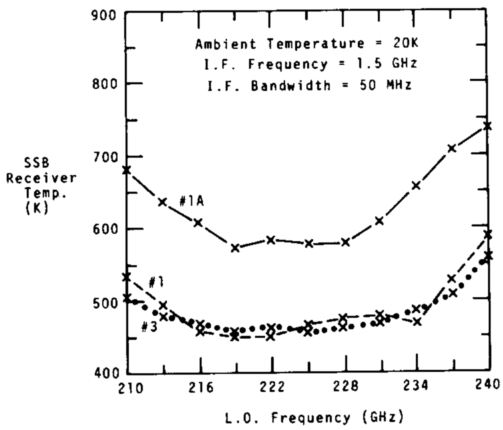
The receiver that he used in his experiment was the one for the frequency range of 210-240GHz. The complete scheme and description of the receiver is given in his paper. A series of measurements were done upon the whole operational range of the receiver, at an ambient temperature of 300K, and at 20K. The set-up of the mixer diode had to be optimized for two different temperatures. Archer used three different mixers, and for every one of them the measurements were done at room temperature, as well as at cryogenic temperature. Every mixer was re-adjusted and re-biased for any of the two operation environments. At 300K, dc bias voltage for one of the mixers (1A), for instance, was normally fixed to a value of 0.620V, ant LO power was adjusted to give a mixer current of 1.10mA. At 20K, dc bias voltage had a value of 0.89V, and 0.40mA for the diode current.

In Figure 4 (a) and 4 (b) the noise temperatures of these three receivers (with three different mixers) at 300K and at 20K are presented. We can see that for the room temperature receiver, the SSB receiver noise temperature with mixer 1A varies between 1400K at the band edges, to a minimum of 1250K at the band centre. At 20K the SSB noise temperature of the receiver with mixer 1A varies between 700K and approximately 600K at the band centre. For mixers 1 and 3, the decrease in the noise temperature is more emphasized, but the ratio of noise temperatures at 300K and at 20K doesn't exceed 2.5-2.8. However, mixers 1 and 3 had been made for 20K operation, and therefore their performance at 300K was a bit worse than with mixer 1A. On the other hand, mixer 1A had been made for room operation, and the decrease in receiver noise at cryogenic operation was not dramatic, with the ratio of noise temperature decrease of around 2.

A simple calculation can be applied on Archer's results. If we take into consideration the values of the diode dc current of mixer 1A at 300K and 20K, and noise temperatures given in Figure 4, we come to an estimation of the ratio thermal/shot noise. At 300K, it can be calculated that shot noise contributes by around 11% to the overall noise temperature. At 20K it is to be expected that this ratio rises in favor of shot noise (since thermal noise power is directly proportional to the absolute temperature), and really, shot noise contribution rises to around 21% in overall noise temperature. However, at these temperatures, the influence of shot



(a) Performance at 300K



(b) Performance at 20K

Figure 4: (a) Receiver performance at 300K for three different mixers. Mixer 1A was optimized for 300K operation, and mixers 1 and 3 for 20K operation. (b) Receiver performance at 20K

noise didn't rise dramatically, because of the fall of diode dc current at 20K. As we remember, the diode dc current of 1A mixer at 300K was 1.10mA, and it dropped to 0.40mA at 20K. Only at very low temperatures, shot noise becomes dominant. Of course, these numbers are only valid for this particular receiver, but they can give us an idea of the ratio of shot and thermal noise abundance.

It can be concluded that with the full optimization of receiver performances (bias etc.), the most that can be achieved is a reduction by a factor of three. The reduction of thermal noise has been achieved, as well as shot noise, due to lower bias current. However, Archer suggests that the complexity of the receiver increases dramatically by the application of cryogenic operation. When a receiver has to be cooled, mechanical refrigerators have to be used. However, they have poor reliability and high power requirements (several kW), which makes them unsuitable for some kinds of application - especially for a spacecraft. On the other hand, the same factors can be critical for airborne operation of the instrument. Normally, there are two possible kinds of refrigerators: those with liquid nitrogen and liquid helium. Liquid helium allows us to go to temperatures even lower than 4K, but it is very expensive and difficult to handle. Problems experienced with He refrigerators were mainly of mechanical nature, often related to compressor failures. Liquid nitrogen can be used to achieve temperatures below 60K, it is less expensive and much easier to handle.

All the components of the system have to be well insulated, and basically it is not possible to use normal components - for high frequency connections special kind of connectors and cables have to be applied, like stainless steel semirigid coaxial cable, with silver-plated current-carrying surfaces. Also, a thin wall stainless steel waveguide, with a gold or silver-plated insides could be used for high frequency interconnections. Also, a mechanical design of all the parts of the cooled part of the system has to be designed separately. Every part of the system must have good thermal expansion coefficients. Especially, the diode mounting inside the mixer must be well designed, in order to prevent poor mixing performances, or even the complete failure of the operation. On the other hand, operation of the mixer itself could be critical. Archer suggests that a typical mixer can stand (at least) five sequntional immersions in liquid nitrogen followed by its warming to the room temperature. However, beyond this number, the behavior of the device is not easy to predict.

5 Conclusions

As we have already said several times throughout the text, by cooling the receiver, better noise temperature figures can be achieved. However, the complexity of the system increases, and maintenance becomes one of the crucial factors. If one has to design a new instrument, it is a good idea to decide at the beginning, which kind of operation is to be applied. For cryogenic operation, many parts of the system have to be built carefully, and the choice of the mixer is the most crucial part of the design. The mixer has to be chosen at the beginning to match cryogenic operation requirements, and the rest of the receiver should be appropriate to the mixer choice. The cryogenic operation of an existing receiver could still be a matter of a discussion.

In the case of the AMSOS interment, which is designed for airborne operation, cryogenic operation could certainly bring some advantages in sensitivity. However, we believe that in that case, the instrument would lose two of its crucial good properties: its (relative) simplicity and reliability.

6 References

The analysis presented in these chapters are (heavily) related to Stephen A. Maas' book 'Microwave Mixers', which contains a very detailed and competitive analysis of all aspects of microwave mixers, including functional descriptions, technology and applications. A very useful reference for this issue is a paper by John W. Archer.

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