On the Instantaneous SIS Receiver Bandwidth

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I. Introduction

This document reviews measurements and analyses concerning the limits on the maximum desirable instantaneous SIS receiver bandwidth which is limited by IF amplifier bandwidth. Wider bandwidths result in a larger frequency "grasp" per unit time, thus increasing the efficiency of our telescopes, but at the cost of an increase in the receiver noise. Currently, the maximum ALMA bandwidth is 8 GHz per sideband per polarization for a sideband-separating SIS receiver and this appears to be a good compromise between divergent sensitivity and instantaneous bandwidth requirements [1], [2].

There are two types of IF amplifier that have been employed in SIS receivers, InP HEMTs (for example [1], [2]) and more recently SiGe hetero-structure bipolar transistors (HBT) [3]. The best SIS receivers so far have employed InP HEMT amplifiers [1] [2]. In fact, at cryogenic temperatures SiGe HBTs might be competitive in noise with InP HEMTs only for lower IFs [4]. Consequently, only InP HEMT IF amplifiers are considered in this memorandum.

Making a science choice is not within the purview of this memo. We only wish to point out the hardware limitations of using larger IF bandwidths on ALMA. Science-related choices should take these into account when considering the overall relative merits of wide- versus narrow-band science.

II. IF Amplifier Noise and Bandwidth Performance

The arguments which drive the choice of intermediate frequency (IF) at Band 6 given in Section 3 of Kerr *et al.* [1] are relevant to all millimeter and submillimeter frequency bands. As pointed out in this report, the IF input is the point of lowest signal level in the entire receiver system, making the noise temperature at this stage of utmost importance. In fact, the IF amplifier noise temperature as a function of frequency is the fundamental limitation driving the maximum bandwidth for an SIS receiver.

The average noise temperature of an IF amplifier over a given bandwidth is determined by the minimum noise measure of the device used and how well this device can be "noise matched" to the driving impedance over this bandwidth [5],[6]. In case of a direct integration of IF amplifier with SIS mixer (as is the case for ALMA band #6 receivers), this driving impedance is the output impedance of an SIS mixer [2] [7].

The minimum noise measure of modern InP HEMTs is practically equal to the minimum noise temperature for frequencies up to W-band [5], [6]. For state-of–the art devices the minimum noise temperature is about 4hf/k (4 K at 20 GHz) [4], [6]. In spite of expectations this value has not been reduced by further scaling of gate length from about 100 nm fifteen years ago to about 30 nm today. Although the reduction in gate length leads to significant improvements in signal properties of a HEMT device (transconductance, cut-off frequency, maximum frequency of oscillations), it does not improve the minimum noise temperature due to an increase in drain noise, counteracting the beneficial effect of increased gain [4] [6]. Consequently, current state-of-the-art values of minimum noise temperature should be considered to be a practical limit for cryogenic InP HEMTs. The minimum noise temperature due to the nature of heat removal mechanism from InP HEMTs under bias is practically independent of ambient temperature between 4 K and 15 K [11].

Currently there are two laboratories which have demonstrated the best performance of cryogenic amplifiers in the frequency range of interest for SIS mixer IF amplifiers: NRAO CDL using devices from the so-called cryo3 wafer produced by NGST for JPL DSN [8], and Low Noise Factory [9] using InP HEMT technology developed at Chalmers University (for example [10].

Fig. 1 shows noise temperature measurements provided by the manufacturer of three InP HFET amplifiers from Low Noise Factory (LNF) covering frequency ranges 4-8 GHz (measured at 5 K), 4-12 GHz (measured at 6 K) and 4-16 GHz (measured at 12 K) [9]. The minimum noise temperature of a device is also shown, which for the ambient temperature range involved is practically independent of ambient temperature [11]. It means that if the measurements for all three amplifiers were done at the same ambient temperature they would differ from those presented in Fig.1 by only a small different contribution due to the ohmic losses of the noise matching circuits.

The noise penalties as one increases the IF and/or the IF bandwidth are very apparent and to a first approximation they scale in proportion to the highest IF frequency. The noise penalties are also on the average higher for increased frequency ratio f_{max}/f_{min}. That is, at 4

GHz, a 4–16 GHz amplifier would have a higher T_n than would a 4–12 GHz amplifier and a 4-12 GHz amplifier would have a higher T_n than would a 4–8 GHz amplifier.

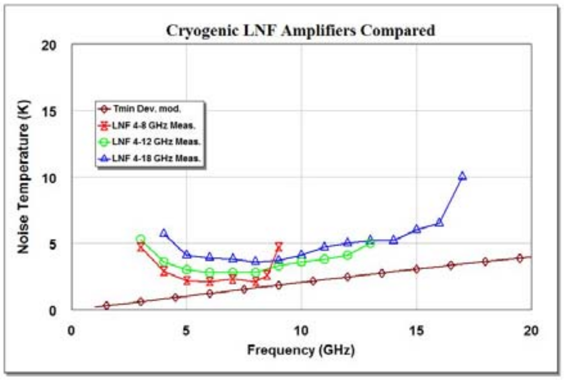

Fig. 1. Measured performance of Low Noise Factory (LNF) IF amplifiers (from company data sheets) compared with the minimum noise temperature of a state-of-the-art InP HEMT .

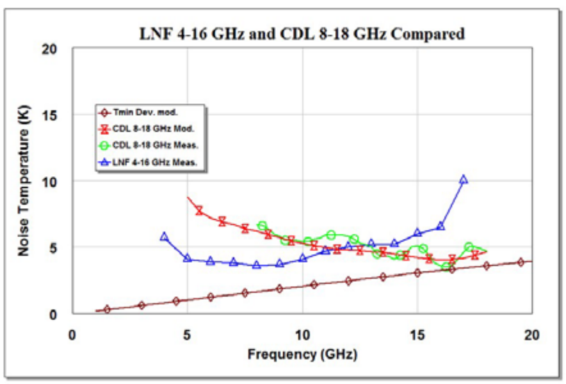

Fig. 2. A comparison between measured and modeled noise temperatures of a CDL 8-18 GHz and a LNF 4-16 GHz amplifier. See text for additional comments.

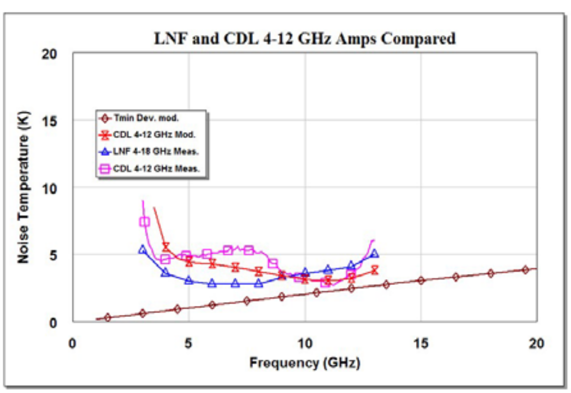

Fig. 3. A comparison between measured and modeled noise temperature of CDL and LFN 4-12 GHz amplifiers. The LNF amplifier was measured at 6 K ambient temperature while the CDL amplifier was measured at 15 K ambient. See text for additional comments.

These dependencies are also very well illustrated by comparisons between the measured and modeled data of CDL 4-12 GHz and 8-18 GHz amplifiers with relevant examples from Low Noise Factory as shown in Figs. 2 and 3. These comparisons between different amplifiers demonstrate the effect of using slightly different design approaches; LNF's tend to follow minimum noise measure of the device with some constant noise penalty while the CDL's exhibit lowest noise at the highest frequencies within the band. The lesson learned from these examples is that an increase in the IF range from 4–12 GHz to 8–18 GHz for a CDL designed amplifier results in approximately 3K IF noise penalty at the low-frequency end of the IF band. Similarly, the LNF amplifiers, due to their different noise matching circuit, might exhibit smaller noise penalties at low IFs while paying much larger penalties at higher IFs. This IF noise is multiplied by the SSB mixer conversion loss, which is a factor of 3–10 for ALMA (dependent upon receiver band). The end result is an additional receiver noise of 6–20K.

These measurements clearly suggest that, for a total IF bandwidth of 8GHz, the optimum IF amplifier frequency range is 4–12GHz.

If, for some scientific reason, larger IF bandwidth is required, the penalties to the receiver and system noise can be reliably investigated in a computer model. As a general rule, the noise temperature of an IF amplifier in the frequency range we are considering is determined primarily by the highest frequency. This point is clearly illustrated in Figs. 2 and 3. This observation is further supported by a comparison of noise performance of VLA amplifiers compared with that which is achievable from a state–of-the-art InP HEMT shown in Fig. 4 [6].

III. Sideband Separation

A side-effect of increasing the IF, for a given bandwidth, is the increase in the size of the "hole" in sky frequency one must tolerate. For example, in ALMA Band 6, with a 4–12 GHz IF, there is no LO setting for which you get the 12CO, 13CO, and C17O 2−1 lines simultaneously. One also misses CS and SO (near 244 and 246GHz). If one increases the IF to 6–18GHz, one can find an LO setting (237.5GHz) where one gets all of the 12CO, 13CO, C17O, C18O, CS, and SO simultaneously, as well as a few other lines, but at the expense of higher receiver noise. As stated above the penalties in receiver noise can be reliably investigated in a CAD model. The examples shown in Figs. 1, 2 and 3 show that average noise temperature ratio of different IF amplifiers is very close to the ratio of the highest IF band frequencies.

IV. Microwave Circuit Limitations

There is a good reason for not extending the upper IF band edge while keeping the lower edge at 4GHz. The difficulty of designing microwave circuits (other than low noise amplifiers) in the frequency range we are considering (say 0–40GHz) depends more on the fractional bandwidth than on the highest frequency involved. For hybrids, isolators, bias networks etc., one octave is relatively easy, and 3:1 (e.g., 4–12GHz) is more difficult but still practical. For circuits beyond 3:1, it is more difficult to achieve flat noise and gain performance. Also, any commercial components needed to complete a receiver design are not generally available with good match and loss for bands greater than 3:1.

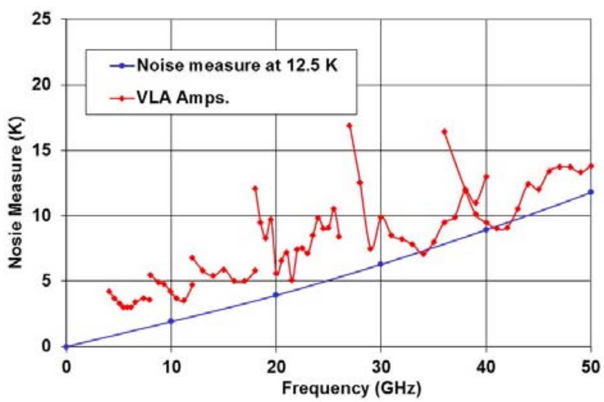

Fig. 4. VLA amplifier performance compared to that which is possible from a state-of the art InP HEMT device. From Pospieszalski [6].

V. IF Quantization

An additional consideration which may become significant at very high IFs is quantization of the IF signal. This has been investigated by Pan [12], who shows that for $f_{IF}/f_{LO} < 0.1$, the effects of IF quantization should be negligible, but for $f_{IF}/f_{LO} > 0.2$ the conversion gain and noise temperature of the upper and lower sidebands will differ, and the output impedance of the mixer will no longer be real but will have a reactive component which is a function of the IF.

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