ALMA Memo 341

Selection of HFET or SIS Mixer for ALMA Band 3

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1. Introduction

The selection of an HFET amplifier or SIS mixer for ALMA Band 3 (nominally 89-116 GHz, with the option of extending the low end to 85 GHz) has been debated for several years. In this memo, I attempt to set forth the criteria on which the choice should be based and provide some of the information needed to make the final decision.

2. Criteria for Selection

The criteria I can identify which should be taken into account for the selection are:

- Performance
  - SNR for interferometric observations
  - SNR for single-dish observations
- Impact on other components
  - Cartridge design
  - LO generation
  - LO reference
  - Cryogenics
- Capital cost
  - Development cost
  - Production cost
- Maintenance cost

3. Performance

Receivers based on HFET amplifiers and SIS mixers have roughly comparable noise performance in Band 3, but they may differ in gain stability due to the 1/*f* gain fluctuation noise of the InP transistors which give the lowest amplifier noise temperature.

3.1 Interferometric observations

For ALMA's principal use in an interferometric array configuration, the most important performance measure is the receiver noise temperature. Since it is not generally possible to perform an absolute calibration of the system noise to much better than the target 1% for this band, gain fluctuations which are well below this level are not important for interferometry. For either receiver type, gain fluctuations will be well below this level and thus need not be considered for interferometry. Achieving a total of 8 GHz bandwidth per polarization is not a problem for either receiver type.

HFET amplifiers for Band 3 have been designed and built by M. Pospieszalski of NRAO using discrete transistors and chip-and-wire technology; MMIC amplifiers for this band have been designed and built by S. Weinreb of JPL. The receiver noise temperatures attainable are comparable for these designs, namely a minimum single-sideband (SSB) temperature of about 40K within Band 3, and an average of about 60K across the band. Two NRAO prototypes work from 68-116 GHz, and have a receiver noise temperature of about 100K at 115 GHz. It is believed that the top-end performance can be improved somewhat with a design optimized for Band 3, since the prototypes were designed to reach only 110 GHz and their top end was extended simply by doubling the number of gate bond wires. At the present time, the repeatability of the NRAO amplifiers in gain and phase is considerably better than that of the MMIC amplifiers, and the input return loss of the NRAO amplifiers is better. It takes much more technician time to assemble NRAO amplifiers, but it is much harder to get good MMIC chips than single good transistors.

SIS mixers for Band 3 have been designed and built by S.-K. Pan of NRAO, among others, and such mixers using moving backshorts have long been used on the 12-meter telescope. These mixers achieve a double-sideband (DSB) receiver noise temperature minimum of about 20K, with an average DSB noise temperature of about 25K. The comparable SSB noise temperature is about double that, or 50K. Fixed-tuned SIS mixers for Band 3 present some design challenges, particularly with the broad band IF. It may be more difficult to achieve a broad band noise match between the IF amplifier and SIS mixer for Band 3 than for Band 6, since the ratio of LO frequency to IF frequency is smaller. This effect may be somewhat overcome by restricting the IF band to 4-8 GHz for Band 3; this meets the ALMA specifications if both sidebands are available simultaneously, but means the LO tuning range must be larger. Fixed-tuned SIS mixers may also be slightly worse than tunable mixers due to design compromises needed to eliminate mechanical tuning. It is therefore expected that SSB receiver noise temperatures will be about 60K across Band 3.

Thus, on the basis of receiver noise temperature alone, the choice between HFET amplifiers and SIS mixers is a tossup. The SNR of interferometric observations with SSB Band 3 receivers will be essentially the same.

3.2 Single-dish Observations

For single-dish spectroscopic observations, the bandwidths of the individual frequency channels are so small (no more than a few MHz) that even with long integration times the only relevant parameter is the receiver noise temperature.

The major difference in performance between the two receiver types is in continuum single-dish observations and is due to gain fluctuation. In the case of HFET amplifiers, this arises from trap effects within the semiconductor and is intrinsic to the devices themselves. Measurements by E. Wollack show that a 6-stage Band 3 HFET amplifier using 50-micrometer gate width devices will have gain instability of about 3×10^{-4} for time scales longer than a few milliseconds; this is much worse than the noise of about 1×10^{-5} expected from an ideal radiometer of 8 GHz bandwidth in one second. ALMA has adopted a specification of 1×10^{-4} in one second on science grounds. It may be argued that 3×10^{-4} is close enough to this specification.

In order to achieve 8 GHz IF bandwidth in an SIS mixer, an amplifier must be closely integrated with the mixer. This has been achieved at NRAO for a 211-275 GHz (ALMA Band 6) SIS mixer using a 3-stage InP IF amplifier in the ALMA IF band of 4-12 GHz. Use of InP devices is needed in order to make the power dissipation low enough so that the SIS junction will remain sufficiently cold. However, there will be $1/f$ gain fluctuation from this source, as well. It is predicted from Wollack's work that this effect from the IF preamp will be about 0.5×10^{-4} in one second, due to the amplifier having fewer stages and wider gates than the HFET RF amplifier. There will be a small additional contribution to the $1/f$ noise from following IF stages which will be about the same in both HFET and SIS receivers. Thus, if gain instability in the SIS mixer is small compared to amplifier gain instability, it is predicted that the SIS mixer receiver will be about 6 times more stable than the HFET-based receiver.

In the case of HFET amplifiers operated with constant-current bias at temperatures <20K, the gain is independent of device temperature to a very high degree. Thus, for an HFET receiver, the only important effect is $1/f$ noise. However, SIS mixers are very sensitive to temperature (the precise dependence depending strongly on the design). Gain changes in an SIS mixer receiver may be dominated not by $1/f$ noise of the preamp, but by other factors.

In summary, the single-dish continuum performance of an HFET receiver has known and calculable characteristics which can perhaps be addressed by receiver configuration (discussed later). The single-dish continuum performance of an SIS receiver will be dominated by factors such as cryogenic system performance. It is not clear without further laboratory work which system will work better in the field.

The final factor to consider is the effect of the atmosphere on single-dish continuum observations. If the fluctuations in continuum radiometer output for Band 3 are dominated by the atmosphere rather than the instrument, then it doesn't matter which one we pick. To my knowledge, there is no detailed prediction of the atmospheric effects which would permit this comparison.

4. Impact on Other Components

There is a considerable difference between HFET and SIS mixer receivers which will have an impact in several areas.

4.1 Cartridge design

There is an immediate difficulty with an HFET receiver which arises from the fact that the HFET amplifiers have a very large instantaneous bandwidth: it is difficult to choose a first LO frequency. There appear to be 3 alternatives:

1. Place the first LO well below the observing band and generate a first IF whose highest frequency is less than the total bandwidth of the HFET amplifier (the baseline

plan for the HFET receivers). This may also require a filter after the amplifier. Perform a second mixing in order to get down to the IF band. This requires a lot of components—many more than an SIS mixer receiver, in which the conversion to the IF band is done in one step.

2. Place the first LO within the observing band, identical to the configuration of an SIS mixer receiver, but use a sideband-separating conventional mixer composed of two DSB mixers and two hybrids. This requires good gain and phase match between the two DSB conventional mixers and hybrids. Again, more components are required than with an SIS mixer receiver.
3. Accept DSB operation over the lower part of the band by using only a DSB mixer and, for the high end of the band, a high-side LO. This destroys the performance equality of HFET and SIS mixer receivers over most of Band 3, making SIS mixers the more attractive option.

The second difficulty arises when single-dish continuum radiometer performance is considered, assuming that for Band 3 the atmosphere does not dominate. A straight-through total power radiometer using HFET amplifiers fails to meet the specification by a factor of ~3. Any correlation or switching scheme which could compensate for this would again increase the number of components required in the cartridge, making it more difficult and expensive to build and more difficult and expensive to maintain.

4.2 LO generation

The LO system uses a suite of phase-locked power drivers for Band 3 LO generation, regardless of whether an HFET or SIS mixer receiver is selected. There is so much power available for Band 3 regardless of the selection of LO frequency that this is not a consideration. However, if the LO is below the RF band rather than within it, a different set of components is required. It eases the design task of the LO group if the LO is chosen to lie within the observing band, as for an SIS mixer.

4.3 LO reference

A two-conversion HFET receiver configuration requires both a first LO and a second (fixed) LO. The second LO requires additional components and there would be a cost savings if it were not required.

4.4 Cryogenics

There is some difference between HFET and SIS mixer receivers in requirements on the cryogenic system. The HFET receiver needs to be cooled only to below about 20K. Also, since the HFET amplifier is at the (nominally) 15K stage, residual IR radiation coming through the IR filter can be dumped on the 15K rather than the 4K stage.

Another advantage for the HFET receiver lies in the fact that it is expected that during fast switching for phase calibration the Band 3 receiver will be used for phase referencing. Thus, a large fraction of the time the Band 3 receiver will be continuously on. If the receiver uses SIS mixers, then the base cooling capacity for the 4K station must accommodate this configuration without impact on the junction temperatures of SIS mixers for other bands.

5. **Capital Cost**

5.1 Development Cost

The HFET amplifier design work needed for an ALMA Band 3 receiver is essentially done. It may be desirable to optimize the existing design for 89-116 (or 85-116) GHz in order to achieve somewhat better performance at the 115 GHz CO line, but this is probably not a big deal. The technical risk is zero. The cost is very small.

A preliminary fixed-tuned SIS mixer design investigation by S.-K. Pan indicates that an SIS mixer with the desired characteristics is probably practical. It would be in many respects a scaled version of the proven 211-275 GHz design. The required test equipment is in hand. The major costs would be masks and wafers, amounting to some $30K. The technical risk is small.

5.2 Production Cost

HFET amplifiers of the chip-and-wire technology for Band 3 require about 2 weeks of technician time for assembly; for the roughly 140 units needed (including spares), this means about 6 technician-years of labor. We would also need another InP wafer, since there are not enough 50 micron devices in stock for this many amplifiers; the cost is about $200K. For MMIC HFET amplifiers, the total labor is about 1 technician year, but several wafers might be needed, so the cost would not necessarily be a lot less.

Assembly of SIS mixers (including integrated preamp) requires less labor than HFET amplifiers, but several SIS wafers would be required in order to get enough good mixer chips. At the present time, testing SIS mixers takes considerably longer than testing HFET amplifiers, although this is expected to improve in production mode. It is impossible at this stage to say if the net cost of the SIS mixers would be significantly different from that of either style of HFET amplifier.

Except for the partial DSB configuration case for HFET receivers, the HFET receiver cartridge would in every case have more components than an SIS receiver cartridge. This would make it harder to package in the allotted space and raise the price. A believable cost estimate would require a real design and cost breakdown.

It is thus unclear which type of receiver would be less expensive to produce.

6. **Maintenance Cost**

Maintenance will consist of replacing defective components in the cartridge and repairing or replacing them. An HFET receiver, which is likely to have more components than an SIS mixer receiver, could possibly take more maintenance. Having more components, it will be harder to work on and require more time to replace defective pieces. On the other hand, the SIS mixer receiver will have some parts cooled to 4K, perhaps increasing the failure rate—although there is no clear evidence for this in existing receivers.

However, the failure rate of the active electronic components in either receiver is likely to be small, and in either case will be a small fraction of the total maintenance cost. Most of the cartridges will use SIS mixers, and we will have to deal with whatever failure rate we achieve on those systems—so adding one more is just an incremental burden.

7. **Conclusion and Recommendations**

The only thing which is clear is that the choice between HFET and SIS mixer receivers for ALMA Band 3 is unclear. There do not seem to be large performance, cost, or maintenance drivers which greatly favor one approach over the other. Each approach has its advantages and disadvantages.

I recommend three courses of action:

(1) Perform a detailed layout of an HFET receiver cartridge for Band 3 in order to demonstrate that such a receiver can fit into the space allotted.
(2) Continue the design work on a fixed-tuned Band 3 SIS mixer. If the computer model indicates that the design should work well, fabricate prototypes and test them for noise temperature and gain stability.
(3) Perform a detailed cost analysis of the two receiver types.