ALMA Band 9 Sideband Separating Upgrade

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***Abstract*—We present a brief summary of a study, performed over the last few years, on the feasibility of upgrading the existing ALMA Band 9 receivers (602–720 GHz) along the lines of the ALMA-2030 roadmap. The goals: upgrading the mixer architecture from Double-Sideband (DSB) to Sideband-Separating (2SB); extending the IF bandwidth beyond the original 4–12 GHz; extending the RF bandwidth beyond the original Band 9 window; investigating whether the current stock of Band 9 SIS junctions is sufficient for the 2SB upgrade; investigating the possibilities of improving the polarimetric performance of Band 9; investigating upgrade roll-out strategies; and finally estimating the cost of such an upgrade. Most of the performance upgrades (IF bandwidth, RF bandwidth and polarimetry) are either demonstrated or are argued to be feasible. The number of available mixers may just be sufficient for an upgrade with similar noise performance.**

Keywords—Sideband-separating receivers, Sub-mm receivers

I. Introduction

The technical feasibility of an ALMA Band 9 mixer upgrade from the existing double-sideband (DSB) configuration to sideband-separating (2SB) was demonstrated in an ESO study by the NOVA Sub-mm Instrumentation Group several years ago [1]. Since then, the design of the sideband-separating mixer has been developed further with significant improvement of key parameters, namely sensitivity (noise temperature) and image rejection ratio (IRR) [2]–[4]. Subsequently, two left-over DSB Band 9 receiver cartridges were converted to 2SB operation [5], one for the SEPIA facility instrument [6] on the APEX telescope in Chile (“SEPIA-660”) and one for the future LLAMA observatory in Argentina. The former has successfully passed its commissioning phase, with several key performance parameters far exceeding the specification [7], and is in full science operation. These receivers both offer a total IF bandwidth of 4×8 GHz (configured as 4×(4–12) GHz), which is double the total bandwidth of the current ALMA DSB and 2SB receivers (with the exception of Band 6, which already exports 4×5.5 GHz).

In this paper, we summarize the main results of a recently concluded follow-up study that targetted both practical issues of such an upgrade (i.e., whether new SIS devices must be produced or how to perform an upgrade without disrupting observatory operations), as well as a boost in bandwidth, sensitivity and polarimetric performance to new levels, in line with upcoming demands to keep ALMA up-to-date for the coming decade. The full study report, with many more aspects than can even be touched upon here, is publicly available [8].

A. Goals of the study

The goals (or tasks) in the study, slightly paraphrased from their original definitions:

1) Investigate the feasibility of extending the IF bandwidth to at least 12 GHz (e.g., to 4–16 GHz or more) with the goal to achieve as broad a bandwidth as possible without compromising the other performance parameters;
2) Investigate the extension the RF bandwidth beyond the current edges of Band 9 (602–720 GHz) without compromising the other performance parameters (at least not in the original core RF range);
3) Verify the availability of a sufficient number of SIS mixer devices at NOVA to enable a 2SB upgrade of all 73 ALMA Band 9 receivers;
4) Investigate possibilities to improve the polarimetric performance beyond that of the currently installed Band 9 receivers;
5) Investigate the possibilities of performing the upgrade while keeping the majority of the old DSB and new 2SB Band 9 receivers in operation;
6) Determine the expected cost, both in new hardware and labour, to upgrade all existing ALMA Band 9 receivers, including the options for increased IF/RF bandwidth and optical performance mentioned above;

In the following sections we report on the results obtained within goals 1, 2 and 4. Goals 3, 5 and 6 will only be briefly summarized, since these are more programmatic than technical. The reader is referred to the full report [8] in case of further interest in these matters, as well as for the full technical details of the project.

B. Overall architecture

The architecture used to obtain sideband separation is the classical I-Q mixer setup shown in fig. 1. Also drawn are the cryogenic components after the IF hybrid. The LNAs amplifying the IF signals are critical for the noise performance, since they are the first elements in the signal chain providing gain, all preceding components being lossy to some extent. Critical for the IRR performance is the suppression of reflections in all

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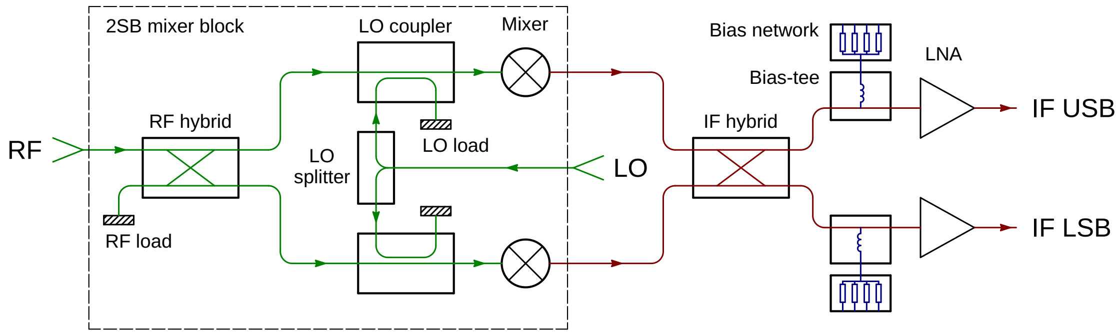

Fig. 1: Schematic diagram of the classical 2SB mixer architecture used in the study (as well as in the SEPIA/LLAMA receivers). Waveguides in green, IF coaxial cables/strip lines in red, DC lines in blue. Each "Mixer" denotes a single-ended (DSB) SIS device. A full receiver typically contains two such assemblies, for orthogonal polarizations. Further details in [8].

parts of the structure: not only the absorption of the waveguide loads which terminate the uncoupled LO power and any LO power reflected off the mixers ("RF load") is crucial, but also the impedance matching of the hybrids (RF and IF) and the LNA inputs [3], [4].

The SIS mixer devices require a DC bias voltage, which must be injected into the IF system somewhere by a bias-tee. In our case, this happens between the IF hybrid and the IF LNAs, which is possible because the IF hybrid is (crosswise) DC-transparent. In the case of SEPIA/LLAMA, the bias-tees (with their associated bias networks) were conveniently integrated into the IF LNAs; for the wide-band experiments presented in the current paper a discrete in-house produced bias-tee was used.

II. Extending the IF bandwidth

A. Scientific driver

Even without any further widening of the total IF bandwidth beyond the demonstrated factor of 2 in SEPIA-660, an upgrade like this would increase the ALMA sensitivity in Band 9 by 20–30% on average for spectral line observations [3]. This ties in with the Recommended Development Path number 2 ("Larger bandwidths and better receiver sensitivity: enabling gain speed") in the ASAC recommendations for ALMA 2030 [9]. It also fits in Pathway No. 04 ("2SB B9/B10") and Pathway No. 05 ("Sensitivity: Lower noise Rxs") in the ALMA Development Working Group Report "Pathways to Developing ALMA" [10] and in the ALMA Development Roadmap [11].

B. Technical aspects

The main technical questions and challenges are the following:

1) What is the actual maximum usable IF bandwidth of the existing Band 9 SIS devices?
2) What are the key performance parameters of the IF components, especially in the view of obtaining high ultra-wide band image rejection?
3) Can IF components be found with the needed bandwith, and if not, how can architectural workarounds be devised?

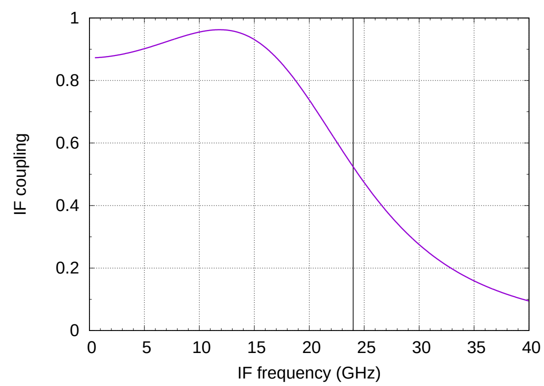

Fig. 2: Simulated IF power coupling of the Band 9 SIS junction at the operating point.

To answer the first question, the employed Band 9 SIS devices were resimulated, using tools that were unavailable at the time the devices were developed almost twenty years ago. We will not go further into the simulation here (details can be found in [12] and of course [8]), except to show one of the important results in this context, namely the mixer's IF power coupling to a 50 Ω coaxial port. This is shown in figure 2, demonstrating a good match up to at least 20 GHz. The -3 dB point in the power coupling is actually located at about 24 GHz. One of the two main aspects of the study was the experimental verification of these simulations.

The second and third questions above are of course closely related. For instance, circulators, traditionally used to suppress standing waves between poorly matched mixers and LNAs, become impractical (or nonexistant) when an ultra-wide IF bandwidth (say 2–20 GHz) is pursued. This means in turn that either the mixer output or the LNA input (or both) should be well-matched. Since the SIS matching is hard to improve (and in our case, we intend to re-use the existing Band 9 mixers in any case), the focus must be on the input matching of the LNAs. For application in a 2SB receiver, the input matching becomes even more important [3], [4]. Apart from the matching, the noise temperature (as mentioned above) and

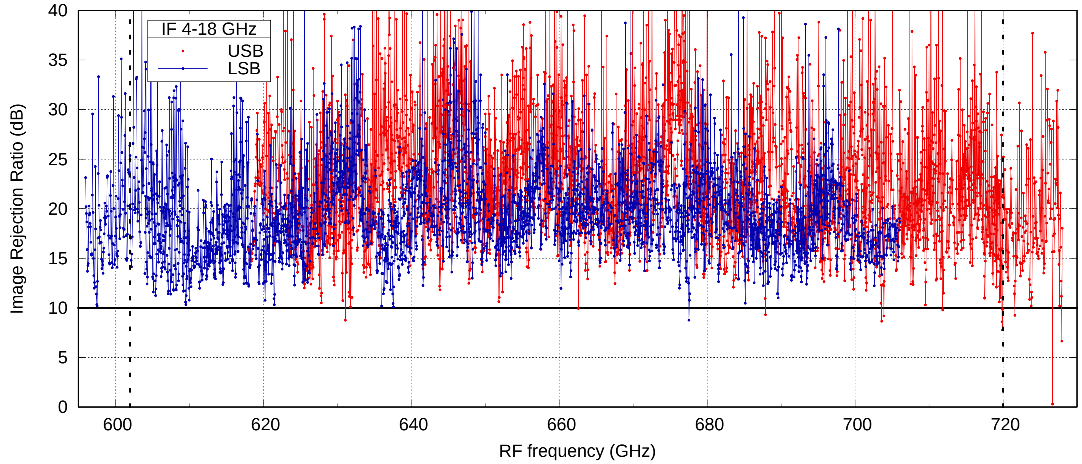

Fig. 3: The combined IRR data for the tested 2SB mixer with ultra-wide band IF infrastructure and 8 GHz-spaced LO settings, as function of the RF frequency. The IF range of each sub-trace is limited to 4–18 GHz. The horizontal black line at 10 dB indicates a typical specification of similar receivers.

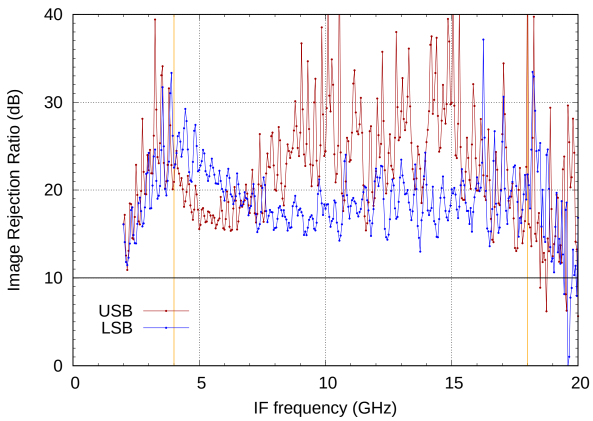

Fig. 4: The IRR singled out for one LO frequency near the middle of the band (662 GHz) over the full 2–20 GHz IF band. The vertical yellow lines indicate a usable band of 4–18 GHz.

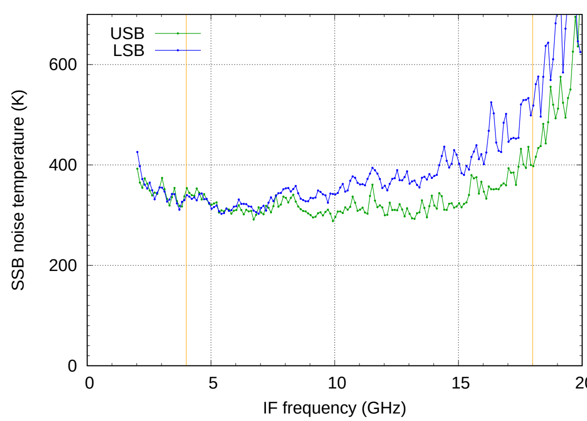

Fig. 5: The noise temperature for both sidebands at the same LO frequency as fig. 4. Note that this is the single-sideband (SSB), which is intrinsically double that of the individual DSB mixers, even any added components are lossless).

the gain flatness are critical.

Several cryogenic wide-band LNAs were used in the course of the study. These were supplied by the Observatorio Astronómico de Yebes (Spain), who have their own program to develop amplifiers along these performance lines. Yebes also supplied us with a cryogenic 4–20 GHz quadrature hybrid for the 2SB demonstration mixer. The LNA type (Y420G) used in he final phases of this study, namely for construction of the single-polarization 2SB receiver has a full gain bandwidth of 4–20 GHz with an input return loss better than 15 dB in at most frequencies, and better than 10 dB overall. The noise temperature is in the range of 5–6.5 K. In the mean time, the development process at Yebes progressed [13], with further improvements in noise performance and matching characteristics.

C. Results

We can only present here a small selection of the experimental results, to show that a wide-band 2SB receiver is indeed feasible at this frequency, using the existing Band 9 mixer devices. It should be noted that these results are a proof of concept, and were not extensively optimized.

Figure 3 shows the obtained image rejection ration (IRR), synthesized out of traces 8 GHz in LO frequency apart. The IF band here is limited to a practical 4–18 GHz. Even with the non-optimized system, the IRR is above 10 dB (a typical specification for the existing ALMA 2SB bands), while in many places 15 dB is obtained. Because the contributions of the different LO settings overlap in fig. 3, for clarity one trace (LO 662 GHz) is singled out in fig. 4, where the IRR can clearly be observed as better than 14–15 dB up to about 18 GHz IF.

The noise temperature at the same LO setting is plotted in fig. 5. As mentioned above, this system was not optimized yet. The best part of the USB is just above 300 K (SSB), while with SEPIA660 values around 150-200 K were obtained [5]. Since the main losses are located in components before the mixer (which did not fundamentally change with respect to SEPIA660), we expect that with careful optimization similar noise performance can be obtained.

III. Extending the RF bandwidth

A. Scientific driver

The reason that ALMA Band 9 originally was chosen to be 602–720 GHz is the presence of strong pressure-broadened water vapour absorption lines at 557 and 750 GHz. In practice, however, very dry conditions still allow useful observations slightly outside of this range, especially if the source is sufficiently bright. A good example, obtained with the SEPIA660 2SB receiver at APEX, is a spectral line survey of the Orion-KL star-forming region [14], with the focus specifically on the frequency ranges around and just outside of the ALMA Band 9 band edges (viz. 581–607 GHz and 701–727 GHz). Even with non-ideal atmospheric conditions, over 100 lines of various molecular species were observed in just minutes of integration time. Although many of these molecules can also be observed in the current ALMA Band 9 frequency range (or in other bands) [15], this clearly demonstrates the feasibility of such observations, especially when combined with a high image-rejection ratio (better than 20 dB at most frequencies for SEPIA660).

Another scientific driver is the expanded access to atomic cooling lines of, e.g., [CII] and [OIII] in distant galaxies over a larger range of redshifts. The mentioned lines appear in Band 9 around $z = 2$ and $z = 4$, respectively, just about bracketing the peak of star formation, making this aspect relevant in the realization of one of the three ALMA 2030 science goals (Origins of Galaxies) [11].

B. Technical aspects

As demonstrated in SEPIA660, the Band 9 SIS junctions typically have an RF bandwidth extending significantly beyond the 602–720 GHz range of the Band 9 specification. Also the reflective optics in the receiver as well as the corrugated feedhorns have much wider relative bandwidths than the specification ($\sim$25–30%, rather than 12%). In the scope of this study, apart from the mixers qualified for SEPIA and LLAMA, about 28 extra SIS mixers have been tested successfully in the extended RF band. We therefore assume that this is representative for all Band 9 mixers.

Since the junctions and surrounding components already have sufficient RF bandwidth, the only modification needed is the extension of the local oscillator (LO) tuning range. Most of the LO resides in the Warm Cartridge Assembly (WCA) just outside the vacuum flange of the front-end cryostat, consisting of a YIG-tuned oscillator (YTO), an active multiplier chain (AMC) and a power amplifier (PA). The final part, the $\times 9$ multiplier, is located in the cryogenic part. It was demonstrated before [5], during the construction and technical commissioning of the SEPIA and LLAMA receivers, that AMC, PA and multiplier are indeed usable beyond the ALMA band edges. For these two receivers, a new LO tuning range of 586–730 GHz was defined. With an IF band of 4–12 GHz, this yields an RF band of 574–742 GHz. Since the edges of this band lie deep within the pressure-broadened tails of the water vapour lines, we can state that the receiver RF bandwidth is then totally atmosphere-limited. In fact, the SEPIA660 receiver has recently been used over this extended range to perform a high-resolution study of the atmospheric transmission itself [16].

Concludingly, we can state that the only technical intervention needed is the modification of the YTO, which is a relatively minor operation.

IV. Improving the polarization purity

A. Scientific driver

In discussions with members from the astronomical community, two science cases were identified that would benefit greatly from improved polarimetric performance of Band 9:

- The study of magnetic fields in very dense environments of circumstellar envelopes around evolved stars and high mass star-forming regions through the vibrationally excited water maser line at 658 GHz (see e.g., [17]).
- The study of dust polarization at high frequency, in combination with similar measurements at low frequency (ultimately down to Band 1), provides a powerful tool to constrain the sizes of dust grains, and thus to study processes such as dust settling and grain growth in protoplanetary disks around young stellar objects.

To a certain degree there may be a chicken-and-egg situation here, as there are hardly any facilities in the world, including ALMA, that *can* do high-quality polarimetry on extended sources at these frequencies. This also means that compelling science cases will rarely be considered by the community. It is very well conceivable that an offer of this capability may bootstrap further interest in it.

B. Technical issues

An internal study at ESO pointed out that the polarimetric performance for extended sources is typically not dominated by the cross-polar level of the receiver, but by station-to-station variations in the the misalignment (the "beam squint") of the two orthogonal polarizations on sky. For meaningful polarimetry, the spread in beam squint for Band 9 (although formally within specification) would have to be reduced by an order of magnitude.

Based on on-sky observation of point sources, it turns out that there is a clear division between the beam squint of the bands employing a grid for polarization splitting (Bands 7, 9 and 10), and the ones using a single feedhorn coupled to a waveguide orthomode transducer (OMT), the latter being better by an order of magnitude or more; exactly the improvement that is needed, as just mentioned.

The question is if such an horn-OMT combination is feasible for Band 9. Not only the required tolerances (of the order of 1.5 μm) are challenging, but especially the extra losses incurred must be minimized at all cost. The double-ridged septum

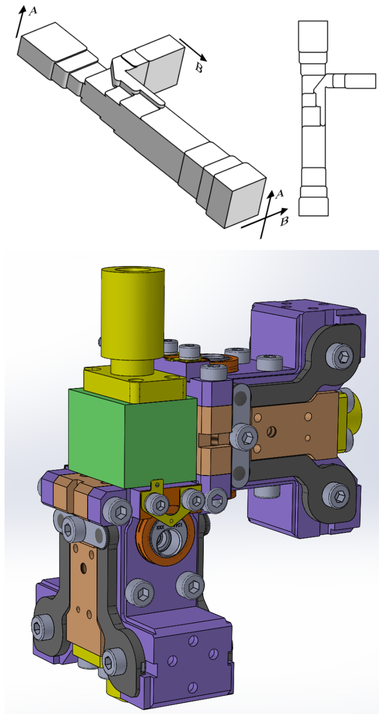

Fig. 6: Top: structure of the OMT by Dunning et al. (image from [18]). Bottom: the basic geometry of two SEPIA660-type Band 9 2SB mixers around a block (green) that could contain a Dunning-type OMT. The OMT structure itself will be about 2 mm long in the Band 9 frequency range and will certainly fit in a block like this.

OMT used in Band 5 (based on NAOJ's Band 4 design [19]) gives excellent cross-polar performance (26-27 dB typically). However, its long internal waveguide runs are estimated to cause an unacceptible increase in noise temperature. As an alternative, we propose the use of another OMT structure, invented by Dunning, Srikanth and Kerr [18], represented in the top panel of fig. 6. This OMT looks pretty much like a minimum-length T-splitter, and a more compact design can hardly be imagined. Since waveguide losses are the main argument against using an OMT at our frequencies, a design like this seems a good candidate for a Band 9 single-feedhorn architecture. In the bottom panel of fig. 6, a straw-man design is shown of how two Band 9 2SB mixer could be fitted around such an OMT.

A simpler (and definitely cheaper) solution is to try and improve the beam squint in the existing optics assemblies. For this, we simulated the Band 9 optics again, with wider fields of tolerance than before. The most likely cause of the large spread in beam squint was pinpointed to the polarization grid itself, rather than machining tolerances of the mirror surfaces or their alignment structures. Perhaps the deviations are stable enough to enable shimming based on beam pattern measurements in the lab (possibly with some iterations). Whether this is doable is unknown at the moment, but could be established in a few test cases. A definite disadvantage is that this method would preclude any improvement of the cross-polar level, so that the total improvement in polarimetric purity is limited.

V. Programmatic issues

Here we present briefly the outcome of the other study goals, listed in section I-A. As usual, the reader is referred to [8] for the full account.

A. Availability of SIS mixer devices

An extensive statistical data-mining operation was undertaken, together with a small remeasurement campaign, to determine whether a sufficient number of SIS juncions are still available.

For a full Band 9 2SB upgrade a total of about 320 pair-matched SIS devices are needed. For the matching, in order to optimize the image rejection ratio, we expect to need up to 50% more, i.e., a worst-case maximum of 480. The actual number needed for the upgrade will most likely be in between these two extremes. The intention is to re-use as many of the mixers from the existing DSB Band 9 receivers as possible, as well as the delivered spares. Besides that, we will have to produce new mixers from bare SIS chips. We found that our current stock of SIS junctions is probably just enough to achieve this with an average noise temperature very close to the current average in the Band 9 array.

It should be noted that, although efforts are ongoing, e.g., at GARD in Sweden to re-establish Band 9 SIS production, any remanufacturing of these will be quite cosltly. For that reason, our baseline goal is to work with the existing SIS devices. On the other hand, for a significant *improvement* in the overall noise temperature, the complete remanufacturing of the SIS junctions remains the only option.

B. Upgrade strategies

A discussion was held between stakeholders from NOVA, ESO and JAO/OSF concerning the possible on-site strategies to upgrade the existing Band 9 DSB receivers to a 2SB configuration. The main issue here is the availability of Band 9 during the upgrade, which is likely to take at least 2–3 years. Three global options can be envisioned:

- Take Band 9 completely off-line for the duration of the upgrade;
- Recombine the LSB and USB of the upgraded 2SB Band 9 receivers before the IF switch for (part of) the duration of the upgrade, remove upon completion;
- Let the 2SB and DSB CCAs coexist and only use either the USB or LSB of the 2SB CCAs (switchable by bias-inversion) for the duration of the upgrade.

The first one is obviously highly undesirable, and will not be considered further. Also, during the discussion it became clear that the temporary addition of combiners in already-upgraded receivers (to be removed later) would pose significant obstacles for operations and maintenance of the array.

From the front-end point of view, the simplest solution therefore is to let a growing population of 2SB receivers co-exist with a shrinking number of DSB ones. In this case, the already upgraded receivers would always export both USB and LSB, but when correlated with the DSB receivers, only one of the sidebands would be used. Two operation modes could be offered: full 2SB with the growing number of upgraded receivers, or the full array with reduced sensitivity due to the missing sideband in part of the receivers. An advantage of the latter mode is that, although the sensitivity is reduced, all baselines contribute to filling the U-V plane. Apart from a mechanism to flag the data as coming from either DSB or 2SB receivers, the correlator and data pipeline should have no fundamental problems handling the mixed array.

Logistically, since significant re-use of components is taken into account, for a "rolling" upgrade scheme, an upgrade pool of the order of 10 receivers is expected to be required to enable a smooth flow. This could be accomodated by a temporary reduction of the number of operational receivers in the array.

C. Upgrade costing

Any estimate for the total cost of an upgrade is by nature a snapshot. Especially with the current economical developents, a time-stable estimate is hard to give. Nevertheless, the costing exercise performed during the study indicates that a full upgrade of Band 9 (or any other band for that matter) will be dominated by labour costs. Furthermore, the components that have to re-purchased are typically the more expensive in the receiver (e.g., mixers, cryogenic amplifiers). Even while we can re-using several expensive key components (LOs, including cryogenic multipliers, corrugated horns, etc.), an upgrade will likely to come out at 60–80% of the price of a totally new band, depending on chosen upgrade options.

VI. Conclusions

We demonstrated a proof-of-concept side-band separating ALMA Band 9 mixer with an IF band extending up to at least 18 GHz. The RF bandwidth can also be extended beyond the Band 9 limits, up to the very edges of the blocking water vapour lines. With a single-feed architecture, the polarimetric performance (mainly limited by the beam squint) could be improved significantly, probably to a lesser extent by simply shimming the existing grids. The number of remaining SIS devices may just be sufficient to upgrade the array while maintaining the noise performance. For a real improvement of noise temperature, new mixer devices are most likely needed. Finally, upgrade logistics and costing were explored.

It is our intention to build and characterize a full side-band separating ultra-wide IF Band 9 demonstration receiver with improved polarimetric performance in the coming few years.

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