# A Deployable 600–720 GHz ALMA-Type Sideband-Separating Receiver Cartridge

Ronald Hesper[1*], Andrey Khudchenko[1], Michel Lindemulder[2], Mariëlle Bekema[1], Rob de Haan-Stijkel[1], Jan Barkhof[1], Joost Adema[1] and Andrey Baryshev[1]
[1]*Kapteyn Astronomical Institute, University of Groningen, The Netherlands*
[2]*KVI — Center for Advanced Radiation Technology, University of Groningen, The Netherlands*
[*]Contact: R.Hesper@astro.rug.nl

***Abstract*—We designed, built and tested a new ALMA-type dual polarization, sideband-separating (2SB) receiver cartridge for the 600–720 GHz band (ALMA Band 9). It meets all the major technical specifications, most of them with ample margin. Key performance results: SSB noise temperature typically 200 K or better, with a slight upturn to about 250 K at the upper band edge; image rejection typically better than 15 dB with a few in-band excursions to about 13 dB; the IF pass-band ripple over any 2 GHz subband is about 3 dB. The four 4–12 GHz IF outputs provide a total of 32 GHz bandwidth.**

**Two copies are produced initially, one for deployment in the SEPIA front-end at APEX (Chile), the second for the future LLAMA telescope situated in Argentina. Apart from being deployable instruments in their own right, the two receiver cartridges act as prototypes and demonstrators for a future upgrade of the ALMA Band 9 array. In addition, the new cartridges are designed in such a way (including heritage from the ALMA Band 5 receivers built in collaboration with GARD, Chalmers University of technology, Sweden) that other high-frequency bands above, say, 200 GHz could be implemented with relative ease in the existing structure. This would enable, for instance, the production of 230 GHz receivers for various projected observatories that aim to participate in the Event-Horizon Telescope consortium.**

## I. Introduction

In atmosphere-dominated sub-millimeter wavelength ranges like ALMA Band 9 (600–720 GHz, $\approx$500$\mu$m) and higher, using sideband-separating (2SB) receivers can have major advantages for the observation efficiency when compared to doule sideband (DSB) ones. We estimated before, using typical “Band 9” atmospheric conditions at sites like ALMA and the typical noise performance of the currently installed receivers there, that integration times for spectral line observations can roughly be halved when going from the DSB case to 2SB [1]. This improvement applies both to single-dish telescopes and interferometers. For continuum observations (total power), there may be little gain for interferometers (everything else being equal) and possibly a slight loss for single dish observatories.

Of the ALMA-style receiver cartridge described here, two are being built for single-dish observatories: APEX in Chile, where it will be part of the triple-band SEPIA facility instrument [2] and LLAMA in Argentina, which is currently under construction. The first cartridge, for APEX, is undergoing final qualification at the time of writing, and is scheduled to be delivered mid-July 2018.

Apart from their purely scientific role in these two observatories, the receivers also act as demonstrators and test cases for the use of 2SB receivers at these high frequencies in general, as there are no other deployed receivers in this region to the best of our knowledge. From a technical point of view, there are several innovations in the cartridge design intended to facilitate future extensions to other wavelengths, and finally, they are also a test case (already successful, judging from the test results) of techniques that should help in making arrays of sideband-separating mixers.

## II. Construction

The base structural approach for the 650 GHz Cold Cartridge Assembly (CCA, the part residing in the vacuum of the cryo-

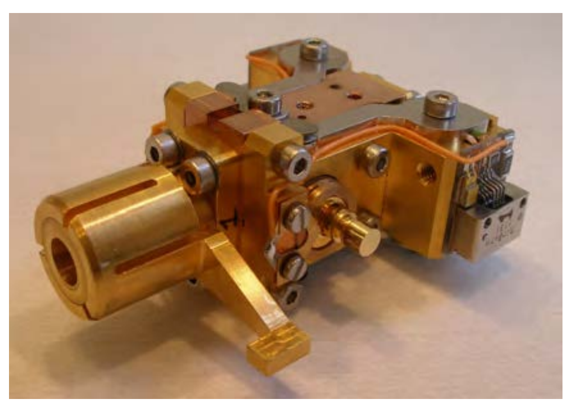

Fig. 1. The Band 9 sideband-separating mixer (excluding the IF hybrid) that was used in the new cartridge. An interface “collet” (left), which comes in place of the original mixer holder, interfaces the horn mechanically and thermally to the optics assembly. On the opposite end another horn (not visible) couples in the LO signal. In the center, one of the two backpieces containing the SIS junctions is visible, here with a protective short on the GPO-type IF connector. Magnetic field for Josephson suppression is supplied to the junctions by magnet coils housed in the two bulges left and right on the far end of the block, transported by magnet conductors visible on the top surface (and, symmetrically, on the bottom).

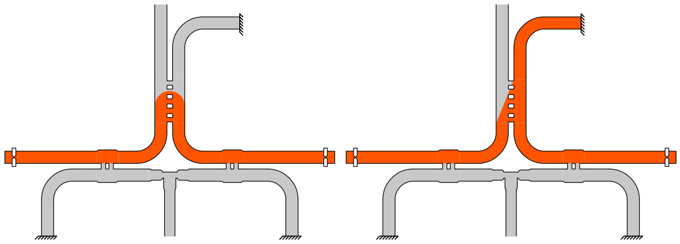

Fig. 2. The two reflection paths in the RF waveguide structure, "U-turn" (left) and "Y-branch" (right), that cause most of the deterioration of the image rejection once the contributions of the amplitude and phase balance are minimized. Similar paths exist in the IF system, as discussed in the main text, where the same labels are used for the analog cases.

genic front-end) is very similar to the Band 9 ones produced in series for the ALMA observatory [3]. Apart from the mixers themselves, there are modifications to the optics block, optics support structure and LO injection optics. Another important change is the doubling of the IF transport channels, from two to four, across all temperature levels. The most important design features are discussed in the following sections.

One of the new developments in this receiver's design, compared to the currently operational ALMA Band 9 receivers, is the direct coupling of the SIS mixer outputs to the cryogenic low-noise amplifiers, without intermediate circulators to suppress standing waves, but at the same time without tightly integrating the mixers and amplifiers. This leads to a certain deterioration of the image rejection ratio (IRR), as explained below, but because of the mixer's good performance and the greatly improved performance of some IF components, we still obtain a quite acceptable IRR (better than 15 dB for most frequencies). The fact that the IF components are not tightly integrated allows for convenient independent testing, while the ability to place the IF amplifiers a good distance away from the mixers will be beneficial in the development of 2SB mixer arrays.

### A. Mixers

The receiver is based on the 2SB SIS mixers developed in our group over the last few years [4], shown in Fig. 1. The RF quadrature hybrid is optimized for high isolation (a.k.a. directivity) and input return loss, as these parameters are the main limiting factors in obtaining good image rejection once the phase and amplitude are adequately balanced. The other waveguide components (LO couplers, LO splitter and matched loads) received similar optimizations. Apart from the waveguide design, it was also found that the right choice of material and first-class machining are instrumental for obtaining the theoretically expected performance[1]. With this design and an IF system incorporating circulators to isolate the mixers from the LNA input reflections, image rejection ratios in excess of 20 dB over most of the band were demonstrated [4].

[1]The operational RF hybrid blocks were machined by GARD, (Group for Advanced Receiver Development), Chalmers University of Technology, Gothenburg, Sweden. The material used was a copper-tellurium alloy, *not* gold plated.

### B. IF System

After optimization of the RF part of the 2SB mixers as mentioned in the previous section, the next limitation of the image rejection ratio (IRR) is mainly due to the performance and matching of the components in the IF system. Although the frequencies are much lower, very similar arguments apply here, namely that once the phase and amplitude balances are adequate, the IRR is dominated by the return losses of the components at the end-points of the chain, and the isolation of the, in this case, IF hybrid.

To recapitulate, in the RF part of the 2SB system, imperfections in these properties cause image band leakage mainly by two parasitic signal paths from mixer to mixer (illustrated in Fig. 2): one by way of the hybrid and the RF load that terminates its idle port ("Y-branch"), and the other ("U-turn") directly mixer-to-mixer because of the finite isolation of the hybrid. Both of these paths lead to the presence of an error signal at the mixers that is always in counter-phase with the direct signal, and therefore maximally destructive to the image rejection. To mitigate this, we focussed on optimizing the RF load and the isolation of the hybrid, keeping an eye on the phase and amplitude balance al well, of course.

As mentioned before, similar mechanisms play a role in the IF system, and if we want to get rid of the circulators (which are bulky, lossy and expensive, as well as limiting in bandwith), while keeping high IRR values, these should be addressed. The main qualitative difference in the IF case is that U-turn and Y-branch paths are present on *both* the mixer-side and amplifier-side of the hybrid, yielding two U-turns and four Y-branches, because both the reflections of the mixer outputs and the amplifier inputs are typically non-negligible. In contrast, in the RF part, when the feedhorn is well-matched to the hybrid, all but one of each kind of reflection path are eliminated.

The IF hybrids were developed and produced by Centro Astrónomico de Yebes (CAY) [5]. The hybrid's isolation has not been measured cryogenically, but at room temperature it is reported to be very similar to the input reflections ($S_{nn}$) [6], something we also found generally the case when designing the RF hybrid. There is no reason to believe that this changes at low temperature. The $S_{nn}$ parameters *were* measured cryogenically, and shown to be below $-24$ dB almost everywhere, with a few points touching $-22$ dB. Because the U-turn reflection paths also depend on high reflection coefficients of both the mixers and amplifiers, we conclude that with this isolation performance of the hybrid their contribution to the IRR is minor.

On the mixer side, new electromagnetic simulations of the SIS devices [7], which come from the same batches as the DSB production mixers, show them to be much better matched on the IF side than previously estimated. Typical values around $-8$ dB were found. We plan to verify these calculations experimentally in the near future, but until new Band 9 junctions can be produced there is not much we can do to improve this, and the obtained performance shows it to be adequate.

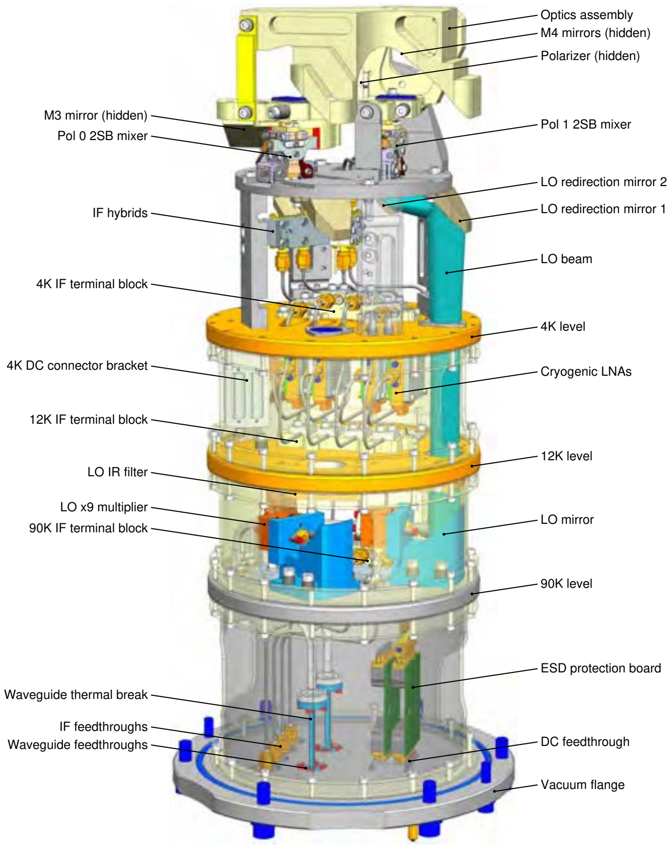


Fig. 3. Annotated 3D model of the Band 9 sideband-separating cartridge (with the fiberglass thermal insulation rings rendered transparant). The basic structure is derived from the Band 9 DSB production cartridge. The optics assembly is retained (with slight reworking to make space for the larger mixers), although it now contains two superfluous LO mirrors that originally projected the LO beams by way of beamsplitters into the mixers. Instead, each LO beam is now re-focussed into the bottom of the mixers by a combination of ellipsoidal and hyperboloidal mirrors. To facilitate later re-use of the cartridge structure for other frequencies, the LO and IF regions are spatially separated as much as possible.

This leaves the input matching of the cryogenic LNAs as the main target for optimization. The LNAs used here, also developed and produced by CAY, are a further evolution of the three-stage discrete HEMT amplifiers used in the ALMA DSB Band 9 receivers [8]. The main improvement is in the input reflection, which was decreased from about $-4$ dB to better than $-10$ dB over most of the band.

These three factors together make that the total image rejection is only slightly reduced with respect to the former configuration with circulators, to about 15 dB in the lowest points over most of the band (see section III-B).

In the DSB Band 9 cartridge, the SIS mixers were biased through the load ports of the circulators (which were DC-transparent) by resistive bias networks housed in small boxes mounted on the 4K level. In order to improve the integration of IF components, the new LNAs feature not only a bias-T but also the SIS bias network. The (high level) bias voltages are supplied to the same connector as the bias for the LNA HEMTs, greatly simplifying the DC cable harness as well.

Fig. 4. Left: the completed Band 9 2SB cartridge from roughly the same angle as Fig. 3. Top right: detail of the 4 K level with the two 2SB mixers just below the optics assembly and one of the IF hybrids clearly visible in the center. On top of the 4 K plate is the thermally anchored IF terminal block, that allows easy mating and de-mating of the IF connection between the 4 K and 12 K levels. Bottom right: detail of the 90 K level with the two LO multipliers and a similar IF thermal anchor block. On all levels the interconnects to the underlying level are accessible from above.

## C. Cartridge

Because of the doubling of the number of IF channels, the IF system was mechanically completely redesigned compared to the DSB case. Some design features were kept, especially the interstage couplings, which are always above the temperature plates and double as thermal anchors, facilitating easy disassembly of the cartridge for modification or repair.

The two produced 2SB cartridges are partially constructed out of left-over components of the DSB production cartridges, so not all original features are functional anymore. For instance, the optics block could be simplified considerably, as the LO mirrors and beamsplitters are superfluous now. As an aside, while re-use of the old optics would save a certain amount of cost if a full ALMA Band 9 upgrade is undertaken, there is also an opportunity to redesign the optics completely with a much improved polarisation purity compared to the original Band 9 optics.

In the new design,the IF components are clustered in the core cylinder of the cartridge, while reserving the outer space to the LO components. This should make the cartridge more or less universal from the 4 K level downwards, allowing us to reuse large parts of the design for other frequency bands, for instance 230 or 345 GHz for use in the Event Horizon Telescope effort or any other observatories using ALMA-style front ends.

An annotated 3D model is shown in Fig. 3, and a few photographs of the completed cartridge in Fig. 4.

### D. SIS Device Selection

As important as the phase and amplitude balance within the RF waveguide structure is the matching between the SIS mixer devices. The phase behavior of the mixers is likely to be quite uniform within one design and wafer run (or batch). The gain, however shows more variation, even within one batch. The gain of the mixers as function of RF frequency was determined during their DSB testing with a standard hot-cold load measurement, and candidate pairs selected by eye.

Besides the mixer's gain, another important parameter is their LO power requirement. With the LO splitter integrated in the hybrid block, there is no way to level the LO power to the mixers individually. Since the required LO power depends, within one design, largely on the normal-state resistance $R_N$ and the RF coupling coefficient (and hence the noise temperature $T_N$), both were additional criteria for mixer pairing. Finally, there are considerations of tunability, especially important for a facility instrument. Since the mixers were harvested from left-over production junctions, it may be obvious that the ones easiest to operate were already gone. Nevertheless, a sufficient number of candidate pairs were identified.

After this pre-selection, no sure-fire way for mixer pairing based on DSB data has been found yet, as described in [4]. More than a dozen candidate combinations were tried, and finally four sets with both good noise temperature and image rejection, and decent tunability, were set apart for the deliverable receivers.

## III. Measurement Results

### A. Noise Temperature

The SSB noise temperature of the first Band 9 2SB receiver cartridge, measured above the front-end window and heat filters, is shown in Fig. 5. For the deliverable to the SEPIA instrument, a request was made to investigate the performance in an extended band, 6 GHz beyond both edges of the original ALMA specification (602–720 GHz). Especially the low-frequency extension, which is interesting for high-redshift observations of several spectral lines, shows quite a usable performance. In fact, the noise temperature over an even larger range (say, 580–730 GHz) stays fully within the ALMA specifications. Since the measurements were performed in the lab at about sea level, a significant part of the upturn beyond the ALMA band edges is likely to be due to the deep and broad water vapor absorption lines at 570 and 750 GHz. At the observation site, the extended band performance is expected to be better still.

### B. Image Rejection

Figure 6 shows the image rejection ratio as function of input (on-sky) frequency for both polarizations. In most places,

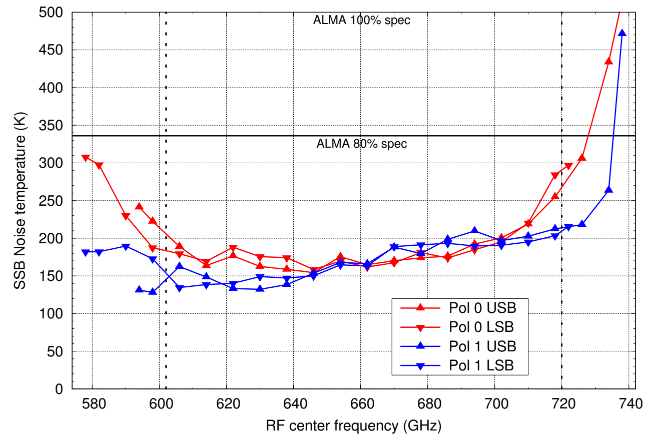


Fig. 5. The SSB noise temperature as function of input frequency of the first Band 9 2SB receiver cartridge. The regions outside the 602–720 GHz range (vertical dashes) form the extended band. The two levels are indicated below which, respectively, 80% and 100% of the points have to be below in order to meet the original ALMA Band 9 DSB specification (doubled to represent corresponding SSB values).

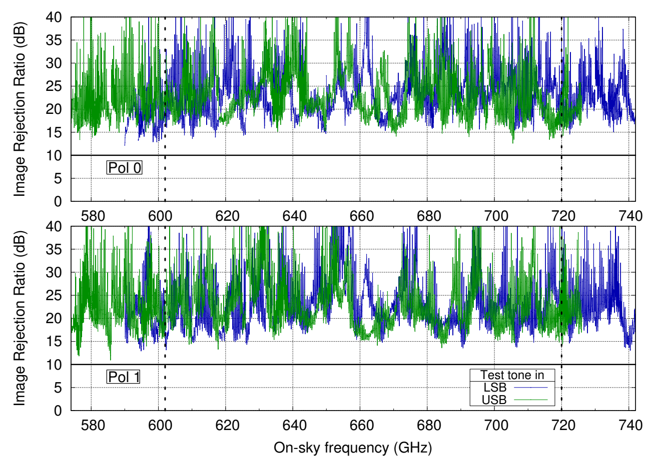


Fig. 6. The image rejection ratio as function of input frequency for both polarizations, and over the extended frequency band (vertical dashed lines). The horizontal axis refers to frequencies within the sideband that does *not* contain the test tone, *i.e.*, the sideband used for observation. The ALMA specification is 10 dB (horizontal line).

the rejection is above 15 dB. Also here, the band is extended beyond the original ALMA limits with quite usable results. Although the *average* IRR is definitely lower than the one obtained with IF circulators [4], the baseline values are actually very comparable. It is mainly the variations upwards that are much faster now, being dominated by the long IF runs.

### C. IF Spectrum

Because of the absence of IF circulators, the IF ripple is of special concern. A typical IF output spectrum is shown in Fig. 7. Despite the absence of circulators, the IF ripple due to standing waves (the 0.5–1 GHz periodicity visible in the figure) is not much larger than, say, 1.5 dB.

Since most current back-ends digitize the IF signal in 2 GHz subbands, the maximum ripple over *any* 2 GHz interval within

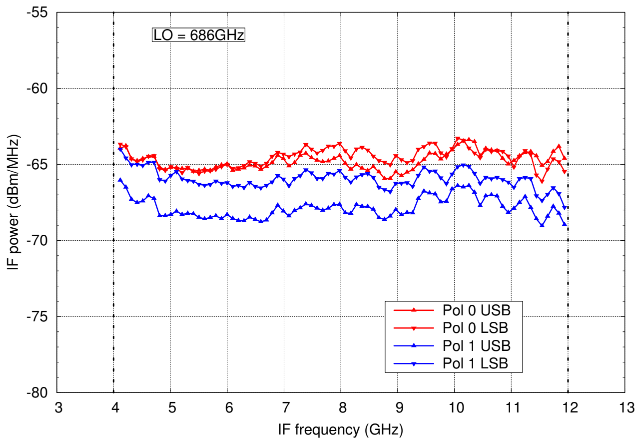


Fig. 7. IF output spectrum with the mixer looking at a 300 K load. The LO frequency is 686 GHz, which puts the $CO_{6–5}$ line (691 GHz) in the USB. Despite the absence of circulators between the mixers and the LNAs, the IF ripple due to standing waves is not much larger than about 1.5 dB.

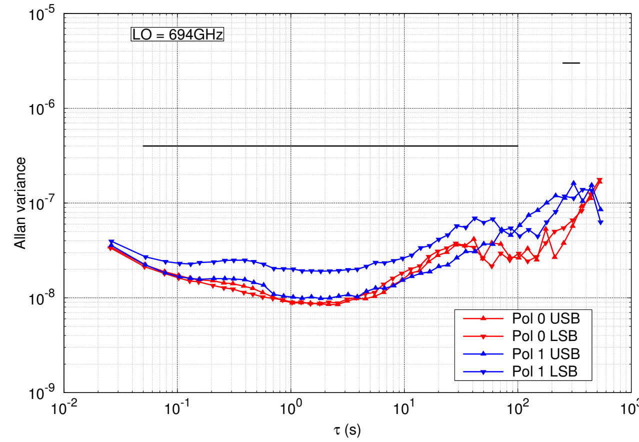


Fig. 9. Allan variance of the IF output power as function of integration time, looking at a 300 K black-body load. The LO frequency is 694 GHz. The horizontal bars indicate maximum allowed values in the ALMA specifications.

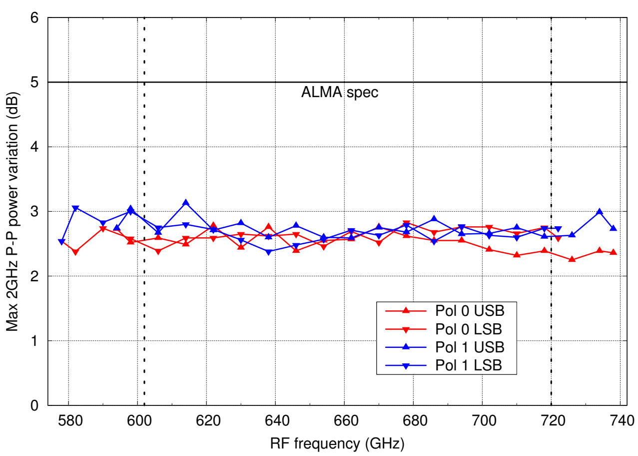


Fig. 8. The maximum peak-to-peak IF ripple in any 2 GHz subband of the IF band, for all tested (extended range) LO settings. The ALMA specification allows 5 dB of ripple.

the IF band is an important specification, as it determines the loss of effective number of bits (ENOBs), and therefore dynamic range, due to IF baseline ripple. In Fig. 8 this is plotted for all tested LO frequencies. As can be seen, the ripple is of the order of 3 dB, resulting in about 1/2 bit loss, and quite constant over the band. Of course, when quantization happens with a sufficient number of bits, a larger part of the IF band (or even the entire band) can be digitized in one go without the need of equalization of the subbands. It is likely that upcoming back-ends will have this capability.

### D. Stability

Amplitude stability is an important parameter to determine the optimum on-source integration time, especially in a single-dish telescope where random gain fluctuations are not correlated away. The Allan variance as function of integration time is shown in Fig. 9, and turns out to be roughly an order of magnitude better than the ALMA specification. This is also a good indication of the quality of all active and passive parts of the signal chain (mixers, hybrids, LO, amplifiers), as all of them have overriding influence on the Allan variance.

### E. Performance Overview

The 2SB Band 9 cartridge went through the full set of qualification measurements, in this case to be delivered to APEX for the SEPIA front-end[2]. Not all results are detailed here, but Table I contains the most important specifications, along with the obtained results. Where several resulting values or ranges are given, these pertain to different polarizations or IF channels. To enable direct comparison with the ALMA specifications, the results do not include the extended RF frequency range. However, *all* specifications are also met in the extended range. One small exception is the beam squint, which is marginally out of spec, but has been accepted by the SEPIA project nonetheless.

## IV. Conclusion

We produced a fully deployable ALMA Band 9 (602–720 GHz) sideband-separating receiver cartridge with a total IF bandwidth of 32 GHz. Apart from some minor optical issues due to the use of a reject optics block, it meets all ALMA specifications, and in case of the crucial ones (sensitivity, image rejection, IF passband ripple and stability), with large margins, and even over an extended frequency range of about 580–730 GHz. It proves that removing the IF circulators, even when the mixers and amplifiers are far apart, can still meet state-of-the-art specifications when careful matching of the IF components is observed, which is important for future array applications. The cartridge design is modular, easy to service and designed with the adaptation to other bands in mind.

[2]These results were obtained during the in-house commissioning phase. Since then, some modifications have been made to the cartridge configuration to ensure long-term stability, and the tabled values may deviate slightly from those at final delivery, which were still being measured at the time of writing.

After commissioning in August 2018 on APEX, it should start proving its worth on the sky.

TABLE I
KEY SPECIFICATIONS AND RESULTS FOR THE 2SB BAND 9 RECEIVER.

| Requirement | Specification | Result |
|---|---|---|
| RF frequency range | 602–720 GHz | 586–730 GHz |
| IF frequency range | 4–12 GHz | |
| Number of IF channels | 4 | |
| Polarizations | 2 (linear) | |
| Noise temperature | | |
| 80% of the RF band | $\leq 335\,\text{K}$ | $\leq 200\,\text{K}$ |
| 100% of the RF band | $\leq 500\,\text{K}$ | $\leq 284\,\text{K}$ |
| Image rejection | | |
| 100% of the RF band | $\geq 7\,\text{dB}$ | $\geq 12.6, 13.3\,\text{dB}$ |
| $\geq$10 dB | 90% of the RF band | 100% |
| $\geq$15 dB | goal | 96%, 93% |
| IF ripple | | |
| 4–12 GHz | $\leq 7\,\text{dB}$ p-p | $2.8 - 3.8\,\text{dB}$ p-p |
| any 2 GHz subband | $\leq 5\,\text{dB}$ p-p | $2.8 - 2.9\,\text{dB}$ p-p |
| Amplitude stability $\sigma^2_{\text{Allan}}$ | | |
| $0.05 \leq \tau \leq 100\,\text{s}$ | $\leq 4 \times 10^{-7}$ | $5.5 - 7.1 \times 10^{-8}$ |
| $\tau = 300\,\text{s}$ | $\leq 3 \times 10^{-6}$ | $1.1 - 1.5 \times 10^{-7}$ |
| Gain compression | | |
| 373 K vs. 77 K | $\leq 3\%$ | $\leq 0.6\%$ |
| Beam performance | | |
| Aperture efficiency | $\geq 80\%$ | $\geq 81.2\%$ |
| Polarization efficiency | $\geq 97.5\%$ | $\geq 97.5\%$ |
| Beam squint | $\leq$ 10% FWHM | $\leq$ 10.2% FWHM |

## ACKNOWLEDGEMENT

This work was supported by the Netherlands Research School for Astronomy (NOVA) under a NOVA-IV ALMA R&D grant.

## REFERENCES

[1] A. Khudchenko, R. Hesper, A. M. Baryshev, J. Barkhof, and F. P. Mena, "Modular 2SB SIS receiver for 600–720 GHz: Performance and characterization methods," *IEEE Transactions on Terahertz Science and Technology*, vol. 7, no. 1, pp. 2–9, Jan 2017.

[2] Belitsky, V., Lapkin, I., Fredrixon, M., Meledin, D., Sundin, E., Billade, B., Ferm, S.-E., Pavolotsky, A., Rashid, H., Strandberg, M., Desmaris, V., Ermakov, A., Krause, S., Olberg, M., Aghdam, P., Shafiee, S., Bergman, P., Beck, E. De, Olofsson, H., Conway, J., Breuck, C. De, Immer, K., Yagoubov, P., Montenegro-Montes, F. M., Torstensson, K., Pérez-Beaupuits, J.-P., Klein, T., Boland, W., Baryshev, A. M., Hesper, R., Barkhof, J., Adema, J., Bekema, M. E., and Koops, A., "SEPIA — a new single pixel receiver at the APEX telescope," *A&A*, vol. 612, p. A23, 2018. [Online]. Available: https://doi.org/10.1051/0004-6361/201731458

[3] A. M. Baryshev, R. Hesper, F. P. Mena, T. M. Klapwijk, T. A. van Kempen, M. R. Hogerheijde, B. D. Jackson, J. Adema, G. J. Gerlofsma, M. E. Bekema, J. Barkhof, L. H. R. de Haan-Stijkel, M. van den Bemt, A. Koops, K. Keizer, C. Pieters, J. Koops van het Jagt, H. H. A. Schaeffer, T. Zijlstra, M. Kroug, C. F. J. Lodewijk, K. Wielinga, W. Boland, M. W. M. de Graauw, E. F. van Dishoeck, H. Jager, and W. Wild, "The ALMA band 9 receiver - design, construction, characterization, and first light," *A&A*, vol. 577, p. A129, may 2015.

[4] R. Hesper, A. Khudchenko, A. M. Baryshev, J. Barkhof, and F. P. Mena, "A high-performance 650-GHz sideband-separating mixer — design and results," *IEEE Transactions on Terahertz Science and Technology*, vol. 7, no. 6, pp. 686–693, Nov 2017.

[5] I. Malo-Gómez, J. D. Gallego-Puyol, C. Diez-González, I. López-Fernández, and C. Briso-Rodríguez, "Cryogenic hybrid coupler for ultra-low-noise radio astronomy balanced amplifiers," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, no. 12, pp. 3239–3245, Dec 2009.

[6] I. Malo-Gómez, *private communication.*

[7] K. Rudakov, *private communication.*

[8] R. I. Amils, J. D. Gallego, C. Diez, I. López-Fernández, A. Barcia, S. Muñoz, J. L. Sebastián, and I. Malo, "Low input reflection cryogenic low noise amplifier for radio astronomy multipixel receivers," *Journal of Instrumentation*, vol. 11, no. 10, p. P10018, oct 2016. [Online]. Available: http://stacks.iop.org/1748-0221/11/i=10/a=P10018