Development of the HIFI band 3 and 4 mixer units

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ABSTRACT

We describe the current status of the HIFI mixer units for Band 3 and Band 4. The mixer units cover the 800-960 GHz and 960-1120 GHz frequency range and have a 4-8 GHz IF frequency band. The major requirements and the design strategy are described. Functional tests of the magnet, the de-flux heater, IF-circuit, and the corrugated horn were performed. Details of the design of the mixer units and the performance status are presented. The DSB receiver noise performance ranges from 210 K at 850 GHz to 430 K at 1075 GHz.

Keywords: SIS mixers, heterodyne receivers, space instrumentation

1. INTRODUCTION

The Herschel Space Observatory (launch date 2007) will fly two cameras/medium resolution spectrometers (PACS and SPIRE) and the heterodyne instrument HIFI[1,2,3]. An international consortium led by the PI institute, SRON, is building HIFI[4]. Within HIFI, 7 frequency bands cover the spectral range from 480-1250 GHz (SIS mixers) and 1.41-1.91 THz (HEB mixers). During observations a single frequency band will be operational. SRON is also responsible for the development of the mixer units for band 3 (800-960 GHz) and 4 (960-1120 GHz)[5]. Each of these bands contains two tunerless waveguide mixers to measure both signal polarizations simultaneously. The mixer units are mounted on a 2 K platform in a mixer console that thermally isolates the mixer units from the Focal Plane Unit (10 K ambient temperature). Within the Focal Plane Unit, each of the SIS mixer units is connected to a 4-8 GHz IF chain consisting of two isolators (one at 2K and one at 10 K) a low noise first stage IF amplifier close to the mixer unit, and a common second stage IF box. The second stage IF box provides further amplification, signal equalization, and finally power combining of the 10 separate SIS IF channels into two coax lines that run between the cold and warm (outside the dewar) IF back-end. In the back-end a Wide Band Spectrometer and a High Resolution Spectrometer are available for IF spectral analysis. During observations, the instrument will run in an autonomous mode. Optimal settings of the mixer units (bias voltage, magnet current, LO power) therefore have to be available from look-up tables or simple optimization routines.

The mixer unit development program is currently in the Qualification/Flight Model phase. Extensive environmental testing will prove the flight worthiness of the units. In this paper we present the mixer unit requirements, the current status of the mechanical layout of the mixer unit, the design strategy, the experimental results of its functional behavior, and the performance status.

2. REQUIREMENTS

A summary of the design drivers for the mixer units is given in Table 1. The two main requirements for the instrument are reliability and sensitivity. Note that the challenging goal sensitivities of the mixer units given in Table 1 are the sensitivities of the mixer unit only, without noise contributions from the optics and IF. Constraints on mass, envelope, magnet current, and heater current are mainly determined by the need to minimize the dissipation and heat load on the 2 K and 10 K level. The choice of materials and procedures in the assembly of the unit is driven by the environmental conditions of the instrument during shelf-life (several years), bake-out (80 degrees for 72 hrs), thermal cycling (approximately 25 times), launch (vibration levels, 20 G rms in qualification) and in-orbit operation (>3 years). To allow the use of a magnet current look-up table it is necessary to be able to remove trapped flux from the SIS device and

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superconducting electrodes. A de-flux heater that can warm up the superconducting layers above their critical temperatures (in Band 3 and 4 this is about 16 K) is therefore implemented.
The potential high levels of electromagnetic fields within the instrument (specified as 2 mV/m in 3-9 GHz range, 2 V/m outside this range) require that the mixer units have proper shielding for EMI, especially in the 4-8 GHz IF range. Protective circuitry to avoid ESD damage during handling and operation is also required.

T_{mix} DSB	Band 3		Band 4	
Frequency	*800 GHz*	*960 GHz*	*960GHz*	*1120 GHz*
Baseline	119 K	158 K	158 K	190 K
Goal	99 K	129 K	129 K	151 K

Sensitivities, excluding contributions from IF chain and optics losses

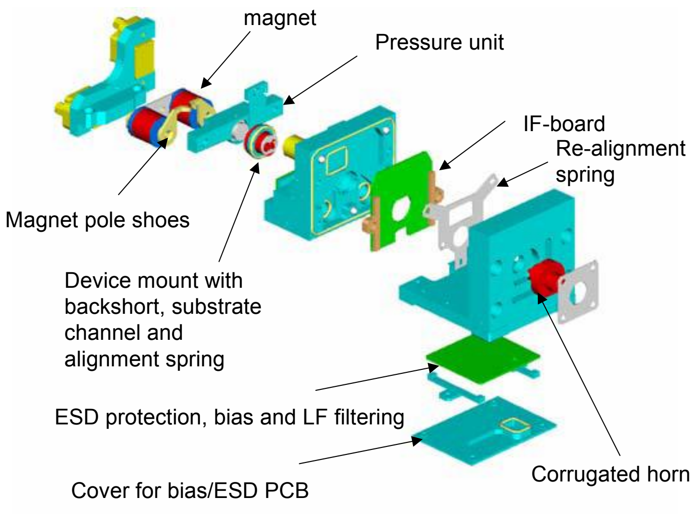
•Withstand shelf life, bake-out, launch and in-orbit operation (9 years)
•Mass < 75 grams
•Envelope 32x32x45 mm
•IF range 4-8 GHz, ripple < 2dB/1 GHz
•De-flux heater operating at current < 20 mA
•Magnet current < 10 mA for second minimum in the Fraunhofer pattern
•Beam quality
•Optical alignment tolerances (goal): x,y: 42 μm, tilt 0.2°
•ESD protection, EMC shielding
•Bias circuit isolation > 30 dB in IF range

Table 1 Summary of the main requirements of the HIFI band 3 and 4 mixer units

3. MAIN FEATURES

The current design of the mixer unit is shown in Figs. 1, 2, 4, and 7.
The unit consists of four sub-units:
The horn bracket. This bracket holds the horn, the low frequency filtering and ESD circuit board, and the bias connectors (type: Cannon MDM 3401 9 pins). Also on the horn bracket are the mechanical reference planes that define the position of the bracket on the mixer console. The alumina ESD/EMC filtering board is held in place with two aluminum springs to allow for thermal expansion and contraction.
The IF-box. This box houses the magnet, the IF circuit board, an auxiliary PCB, and the IF output connector (Radiall female bulkhead). The alumina IF circuit board is clamped with 2 titanium springs into the housing (Fig. 2).
The device mount. The SIS device and the heater are mounted in the device mount. Attached to the device mount is a leaf spring that is used for alignment purposes (Fig. 4).
The pressure unit. This unit holds a pressure plate that is pushed forward against the device mount. Releasing a stack of washer springs inside the pressure unit applies a controlled pressure to the waveguide/device mount interface (Fig. 4).

The mixer units for band 3 and 4 are identical, except for the dimensions of the waveguide, horn, and horn bracket. The assembly flow is such that all sub-units can be pre-assembled and the SIS-device is inserted only at the final stage of the assembly. In case of a failure or device upgrade, the mixer unit can be re-used without major disassembly or cleaning steps. This allows for a late stage device selection program (as long as the overall HIFI schedule permits) and the possibility to insert the best device available at the time of the delivery for further integration.



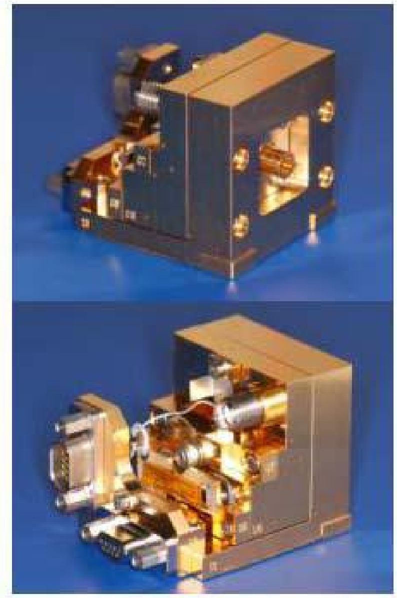


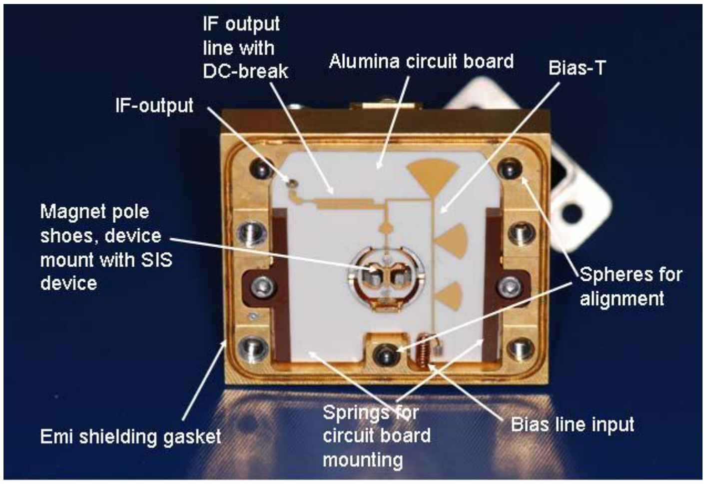
Figure 1 Left: Exploded view of the mixer block. Right: Front and backside view of an assembled mixer unit

4. DESIGN STRATEGY

Based on the specifications given above, the following design strategy was used to come to a final design:

4.1 Optical Alignment

The correct optical alignment of the mixer unit is of major importance for the assembly and operation of HIFI. All optical elements within HIFI, except for the mixer units, are aligned with visible light and therefore are positioned with high accuracy. An incorrect location of the quasi-optical beam of the mixer unit therefore is a potential source of misalignment, especially since there is no means for an in-situ adjustment of the mixer unit alignment (e.g. with moveable mirrors). The alignment can be adjusted with shimming, but it is practically undoable to correct the final instrument cryogenic alignment in this way (7 channels, 14 mixer units). For the waveguide mixers the mechanical position of the corrugated horn envelope is used to determine the position of the quasi-optical beam. It is assumed and actually experimentally shown, that a correct location of the corrugated horn corresponds to a correct location of the quasi-optical beam. Since the alignment is so critical, the design of the band 3 and 4 units is such that after initial mounting of the horn, and verification of its position (with a profiler), it is not necessary to remove the horn from the bracket again in subsequent device mounting assembly steps. The horn and bracket are manufactured with a tight tolerance and measurements with a profiler show that the horn position is indeed within the specifications stated above.



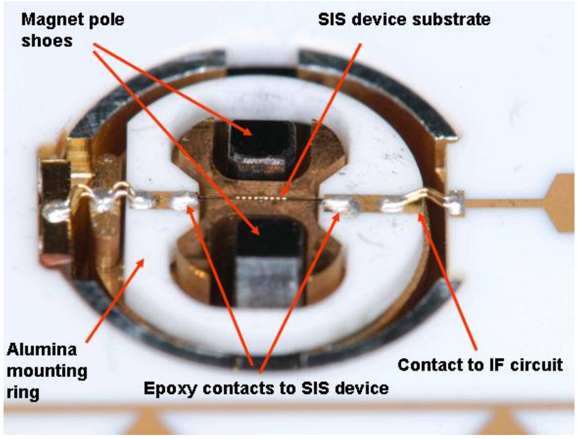


Figure 2 Details of the ‘IF-box’ of the mixer unit (left) and the device mounting and contacting (right)

4.2 IF and bias circuitry

The IF and bias circuit are fabricated on two alumina substrates. Alumina is chosen because of the compatibility with ceramic components and the heritage from previous cryogenic space missions (ISO-mission). The IF-circuit board is mounted parallel to the SIS device (see Fig. 2), to facilitate electrical contacting and to have a short distance between the device and the IF-circuit (impedance matching). In the initial design of the IF and bias-T board, ceramic capacitors were used for DC-blocking and filtering. In the final design both the bias-T and DC-blocking in the IF output line are implemented with planar circuitry. The planar circuit design improves both the reliability of the board (no components or electrical contacts that can fail) and the manufacturing (no need for electrical contacts).

4.2 EMI shielding

In order to comply with the high EMI shielding level, the SIS device and the IF circuit board are inside a Faraday cage, with only a filtered bias line entering this shielded compartment. The low frequency filtering of the bias line (< 3 GHz) is accomplished with a filter circuit on the DC-bias board, the high frequency filtering is in the bias-T circuit on the IF-board. The heater and magnet (and the necessary bias wiring) are located outside the shielded box. EMI measurements on initial mixer unit models showed that the flat mounting interface of the two metal parts forming the closed compartment gave insufficient shielding at frequencies above 3 GHz. The shielding improved dramatically after EMI gaskets (made of gold coated BeCu springs from BalSeal) were placed at all relevant interfaces. Fig. 2 shows one of the EMI gaskets, shielding the interface of the IF box to the horn bracket.

4.3 Electrical contacts

Important issues for the possible procedures to make electrical contacts (soldering, wire-bonding, conductive epoxy) are the cleanliness, reliability, the thermal compatibility with the part to be mounted (or with parts already mounted) and the reliability against repeated thermal cycling. For example, many conductive epoxies require curing temperatures of 150 °C for several hours, but this temperature would degenerate the SIS device characteristics and also the insulating layer of the superconducting wires of the magnet. Conductive epoxy with a low temperature curing schedule (like Epotek H20 E) is very attractive for SIS device mounting, because it can be used for both the mechanical mounting and the electrical contacting. Furthermore it requires no cleaning step after application (soldering would require removal of excess flux) and it applies no force on the ultra-thin (40 µm) device substrate. Conductive epoxy is also used for some of the other final electrical contacting steps, (e.g. device to IF-circuit, IF-circuit to IF output connector). Connectors, auxiliary circuitry (magnet, heater) and the components on the DC-bias board are all soldered. Flexible connections are used at those electrical contacts that are subject to thermal stress (see Figs. 2 and 7). For example the SMA IF output pin is not mounted directly to the IF-board, but via two gold wires.

4.4 Mechanical mounting

The mechanical mounting methods should be compatible with the possible differences in thermal expansion coefficients of the parts to be mounted. This is mainly an issue for the alumina IF and DC-boards mounted in the aluminum housing. These boards are therefore clamped down with two metal springs (see Fig. 2).

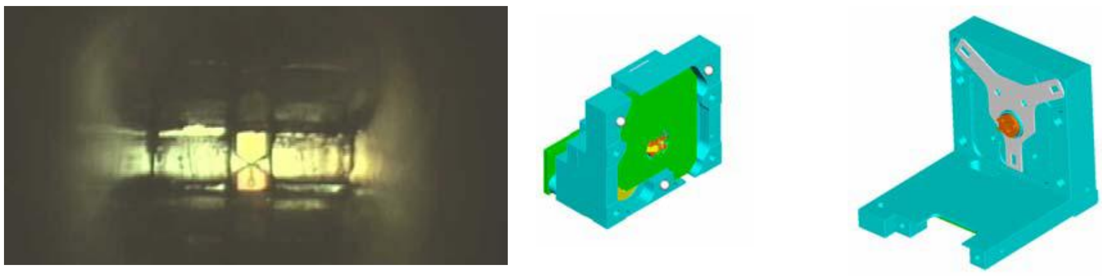


Figure 3 Left: View of the device mount to waveguide (300x75μm) interface, as seen through the corrugated horn. Note that the waveguide in the horn is slightly bigger than the waveguide in the device mount. Right: The alignment of the horn bracket to the device box is defined by three spheres in the IF box, and an alignment spring with three slits in the horn bracket.

4.5 Internal alignment

We make use of in-situ alignment of the device mount (that holds the SIS device) to the waveguide of the corrugated horn. To do so, we attach a leaf spring on the device mount to a custom made x-y stage and position the device mount while looking down the corrugated horn with a 100x magnification (see Figs. 3 and 4). After alignment, a spring (a stack of spring washers) inside a pressure unit is released and the device mount is pressed against the horn. This procedure is somewhat similar to the use of a mask aligner in optical lithography. The stack of springs ensures a repeatable and well-defined contact pressure of the device mount to the horn. Other advantages over conventional mounting methods with screws and mechanical references (dowel pins) are the ability to deal with slight tilt in the two mating surfaces and the absence of wear on precision fittings or reference planes. Furthermore it simplifies the manufacturing of the device mount considerably, since there is no need to position the waveguide and substrate channel very accurately within the device mount. The alignment method also adds flexibility in the device mounting procedure and IF design, since we do not need dowel pins or screws in the vicinity of the device. After the initial alignment, the leaf spring attached to the device mount is locked in position to the IF-box. To avoid the need for an alignment procedure after every disassembly of the mixer block, the IF-box and horn bracket are positioned with respect to each other by means of a three point alignment, making use of three alignment spheres in the IF box, and a Y-shaped alignment spring with three slits in the horn bracket (Fig. 3). The realignment accuracy of this method is better than 5 μm.

4.6 Device mounting

In our laboratory mixer designs at lower frequencies, SIS devices are mounted into the device mount substrate channel with (super-)glue, and electrical contact is made via silver paint or wire bonding on the device substrate. Direct bonding of 17 μm wires to the 40 μm contact pads on the thin (25-35 μm) substrates turned out to be a major cause of failure in the assembly procedure of the HIFI mixer units. We therefore developed an alternative mounting method in which the electrical contact to the device is made via silver epoxy (Epotek H20E). The device is mounted with the silver epoxy on a gold patterned alumina carrier. The carrier is then mounted with Scotchweld 2216 to the device mount (Fig. 4). A potential problem of this mounting method is breakage of the substrate, if it would touch the substrate channel bottom. It actually turns out to be advantageous to make use of a suspended substrate design in which the substrate is suspended about 15 μm above the channel bottom. Both Epotek H20 and Scotchweld 2216 have a flight record. Multiple gold wires are used for the electrical contact from the contact pads on the carrier to IF-board circuitry (see Fig 2).

During the test phase we make use of silver paint for the electrical contacting of the device. After noise performance testing the device is easily removed from the device mount and restored. This gives us the opportunity to characterize the device performance in a test unit and use the flight model mixer units only for the final assembly.

Figure 4 Left: Alumina device mounting ring with a SIS device mounted with two dots of silver epoxy.
Middle: device mount with alignment spring attached. The heater is mounted in the backside of the device mount.
Right: The pressure unit that pushes the device mount against the horn. The bullet-like part is pushed forward with an (internal) stack of spring washers.

5 PERFORMANCE

5.1 Corrugated horn

The mixer unit uses a corrugated horn antenna, tapering down to a reduced height waveguide of 300x75 μm (Band 3) or 240x60 μm (Band 4). The horn design is equal for all bands (except for a scaling factor). For the band 3 horn (with a center frequency of 880 GHz) the aperture radius is 1.6 mm and the horn slant length is 9.8 mm. At 880 GHz the far field divergence angle is 8.46 degrees and the waist size is 0.729 mm. Band 3 and 4 horns are fabricated at RPG and Thomas Keating. Results of amplitude measurements on an RPG horn at 890 GHz and a Thomas Keating Horn at 1030 GHz are shown in Fig. 2. The experiments show that both manufacturers can fabricate horns with a well predicted and symmetric beam pattern at these high frequencies.

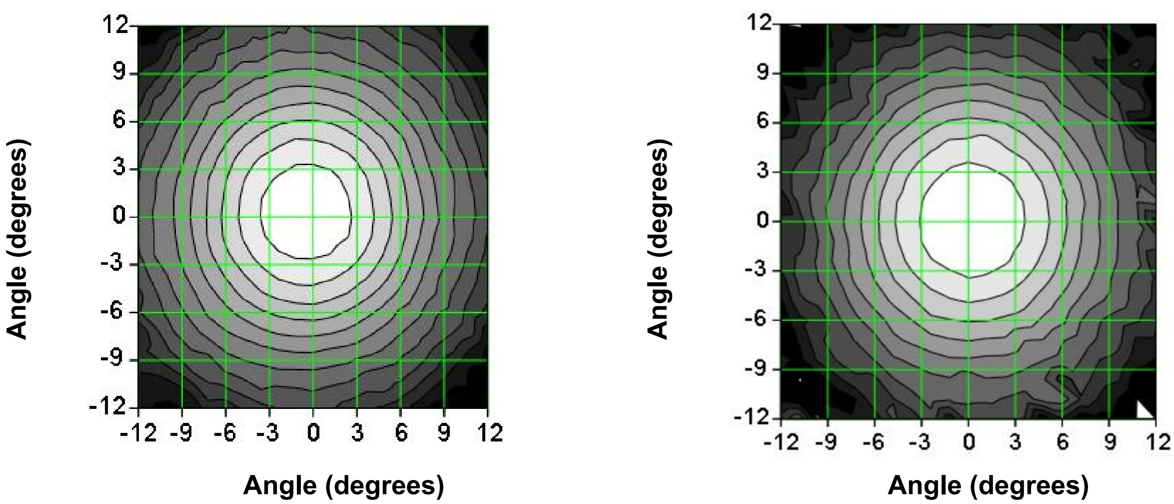


Figure 5 Measured far field beam patterns for a RPG horn at 893 GHz (left) and a Thomas Keating horn at 1030 GHz (right). Contours are at 2 dB spacing.

5.2. Magnet and de-flux heater

The magnet consists of two superconducting coils and a (multi-element) core of Vacuflux 50. The coils are fabricated using an ortho-cyclic winding technique by which the 64 μm diameter wires (fabricated by Supercon) are packed as densely as possible (see Fig. 6). The gap between the pole pieces at the position of the device is 1 mm. A 10 mA magnet current results in approximately 400 Gauss at the junction position. The amplitude of the Josephson super-current versus magnet current for a typical twin junction device is shown as the dashed line in Fig 3. This behavior approximately follows the predicted super-current versus magnetic field (proportional to the magnet current) behavior. For this particular device the receiver can be operated with a magnet current of approximately 6 or 11 mA. It is well known that due to external disturbances (e.g. switching of power lines) flux quanta can be trapped near the junction, thereby

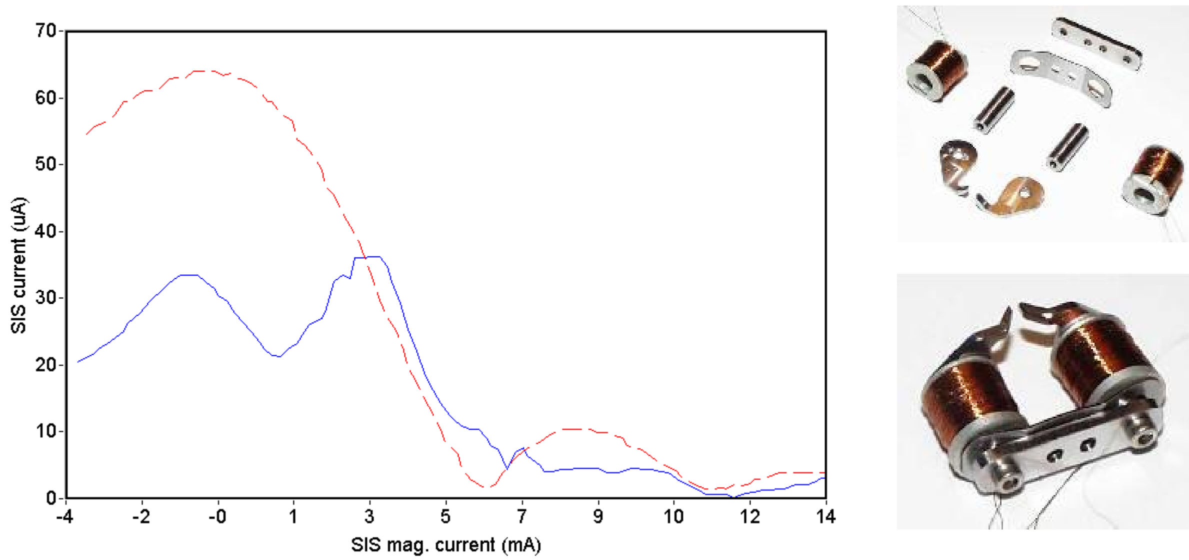


Figure 6 Left: SIS supercurrent versus magnet current for a device with trapped flux (solid line) and the same device after application of a de-flux pulse. Right: Parts of the magnet circuit and an assembled magnet circuit.

changing the dependence of the super-current suppression versus magnet current. An example of this is shown as the solid line in Fig. 6. For autonomous operation of the receiver it is preferable to have repeatable magnet current settings and therefore a flux-free state. The mixer units therefore have a heater to get the SIS device and the superconducting electrodes above their superconducting transition temperature (approximately 16 K with NbTiN layers). The de-flux heater is an 1150 Ohm miniature resistor mounted in a hole in the device mount (see Fig. 4). The heater resistor is in close proximity to the junction. The typical energy needed for heating the device to 15 K is 300-600 mJ. A heater cycle takes about 30 seconds from warm-up to cool-down. The two curves in Fig. 6 actually show the effect of a heater pulse on a SIS device with trapped flux.

5.3 IF circuit

The mixer units have an internal 4-8 GHz bias-T and an IF output circuit with a DC-break. The IF-box with the device mount and the 625 μm thick alumina board with IF circuitry are shown in Fig. 2. The IF circuit contains a bias-T with three radial stubs and an IF-output coupling line with a planar 4-8 GHz band-pass filter. The co-planar 4-8 GHz band-pass filter provides the DC-break. It is based on the work of Zhu et al.[6] and was developed at SRON with help of HFSS simulations by J. Kooi. The advantage of this filter in comparison with a traditional DC-blocking capacitor is the reliability (no components to be mounted) and the low loss. Results of noise measurements within the IF band are shown in Fig. 7. The figure shows results from mixer units in the development phase, and the final result as it will be in the

Flight Model mixer units. It was found that a proper ground return path of the IF signals was far more critical than originally anticipated. For reasons of cleanliness, flexibility and ease of assembly, the IF board is mounted with spring clamps in the housing. EMI gaskets underneath the board are used to achieve a proper ground contact between the housing and the board (Fig. 7). Traditionally one would use epoxy or a conductive sticky film for proper grounding of the IF board in its housing, but in the event of a failure this would make re-use of the mixer unit impossible. The most critical part of the ground return path is at the interface between the moveable device mount and the IF-box housing. Because of the in-situ alignment of the device mount, there has to be a gap between the IF-housing and the device mount, but at the same time this gap has to provide a proper ground in the 4-8 GHz frequency range and sufficient EMI shielding. A ring with two EMI gaskets is used to provide both the mechanical flexibility and the electrical continuity. After several experimental iterations it was found that the compression of the EMI gaskets was insufficient to provide a proper ground return path, especially in the 7-8 GHz range. Adjustment of the gasket compression solved the problem.

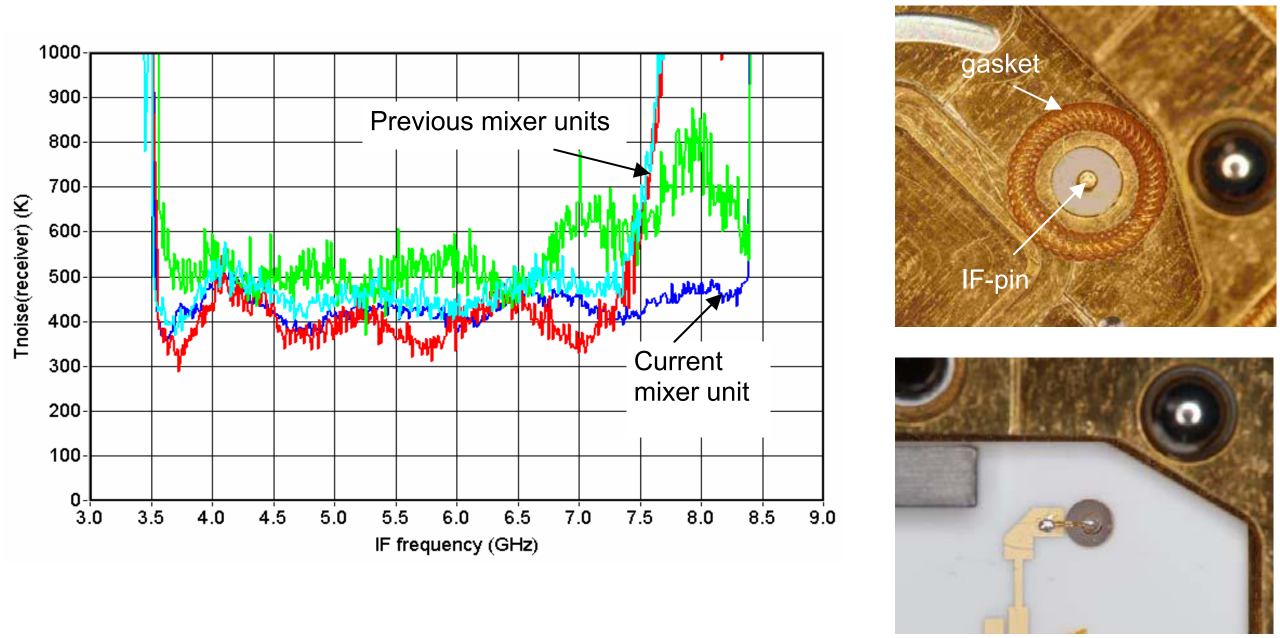


Figure 7. Left: Noise temperature within the 4-8 GHz IF band, of various mixer unit models. The increase in noise temperature in the 7-8 GHz range with the early models is due to an increase in resistance of EMI gaskets at these frequencies. Upper right: One of the EMI gaskets used for grounding the of the IF board to the metal housing. The picture is a top view of the IF-output connector pin. Lower right: top view of the IF output connector after mounting of the IF-board.

5.4 Sensitivity status

The heterodyne elements in the mixer units are Nb/Al_2O_3/Nb SIS twin junctions with Al and NbTiN top and bottom electrodes, respectively. The devices are fabricated at DIMES[7,8]. For band 4 we use NbTiN films grown at the Jet Propulsion Laboratory by J. Stern. Some typical receiver DSB Noise Temperatures versus RF frequency of band 3 and 4 mixer units are shown in Fig. 5. The figure shows noise measurements performed at 2 K with a thin 14 µm thick Mylar beam splitter. The noise temperature is measured with the full 4-8 GHz IF-band. The overall receiver noise temperature ranges from 240 to 450 K DSB. The receiver noise temperature in HIFI will be considerable lower (approximately 100-150 K) than our laboratory receiver, since HIFI will operate with a 15 K cooled diplexer and without vacuum windows or heat filters in the signal path. Data at the lower end of band 3 and the upper end of band 4 are missing because of lack of LO-power. The direct detection response of the mixer units is shown in Fig. 9. The centre frequency and bandwidth of the units corresponds well with the band 3 and 4 requirements.

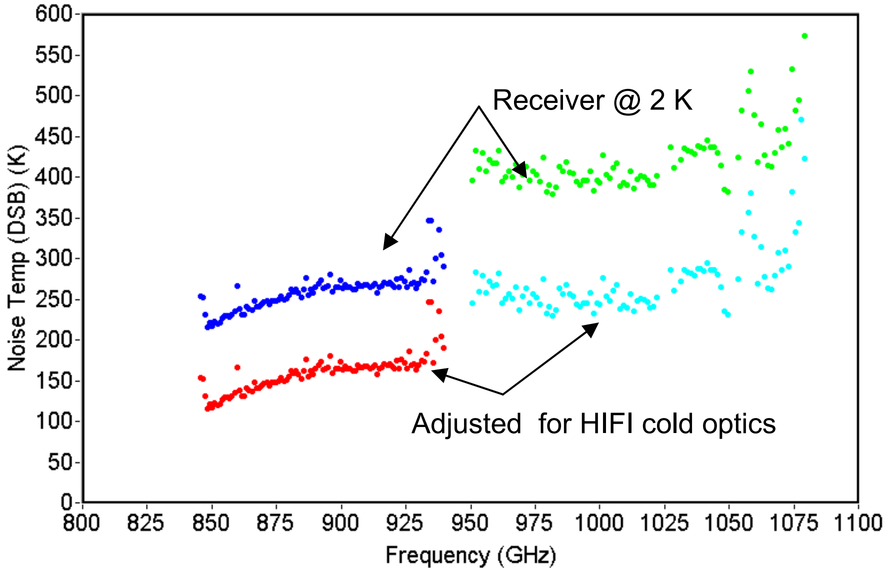


Figure 8 DSB receiver noise temperatures of band 3 and band 4 mixer units, measured with a 14 µm beam splitter (85 % transmission, 300 K ambient temperature) and at 2 K He bath temperature. Also shown are the corrected noise temperatures as expected in the HIFI environment. The noise contribution of the HIFI optics will be very low because of the high transmission of the Martin-Pupplet diplexer and the low ambient temperature (15 K) of the optics.

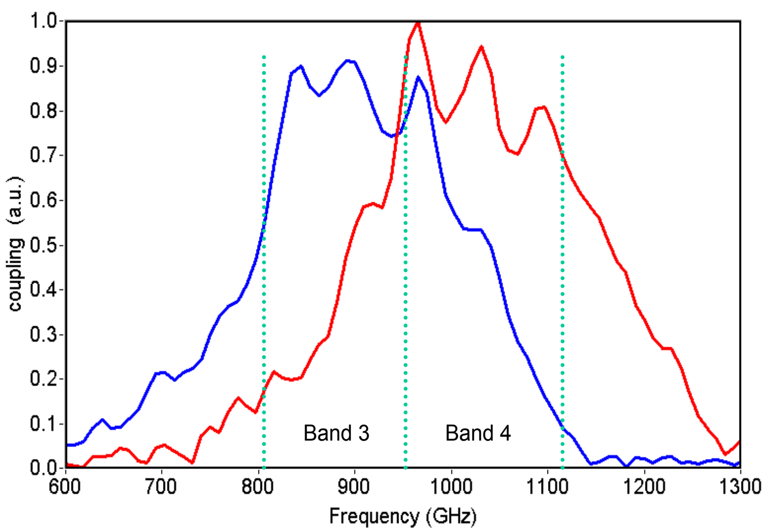


Figure 9 Fourier Transform Spectrometer measurements of the band 3 and 4 mixer units shown in Fig. 8. Note that 70 GHz ripple in the measurement is due to an artifact in the FTS set-up.

6 SUMMARY

We have presented the status (in May 2004) of the band 3 and 4 mixer units for HIFI. The mixer unit is complying with the mechanical, electrical and optical interface requirements. The mixer magnet, the de-flux heater, and the novel IF circuit board are operating as required. Measurements on the beam quality of the corrugated horns, the RF sensitivities and the mixer unit bandwidth are very promising.

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REFERENCES

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1. T. de Graauw, F. P. Helmich, "Herschel-HIFI: The Heterodyne Instrument for the Far-Infrared", in *The Promise of the Herschel Space Observatory*, edited by G. L. Pilbratt et al., ESA SP-460, pp. 45-51, 2001.
2. B. D. Jackson, K. J. Wildeman, N. D. Whyborn on behalf of the HIFI Focal Plane Consortium, "The HIFI Focal Plane Unit", *Proc. 13th International Symposium on Space Terahertz Technology*, pp. 339-348, 26-28 March 2002, Harvard University, Cambridge, Massachusetts, USA.
3. Web site at *: http://spdext.estec.esa.nl/home/herschel/*
4. Web site at: *http://www.sron.nl/divisions/lea/hifi/*
5. G. de Lange , B.D. Jackson, M. Eggens, H. Golstein, W.M. Laauwen, L. de Jong, S. Kikken, C. Pieters H. Smit, D. Van Nguyen,, "Development of the HIFI band 3 and 4 mixer units", *Proc. 13th International Symposium on Space Terahertz Technology*, pp. 359-368, 26-28 March 2002, Harvard University, Cambridge, Massachusetts, USA.
6. L. Zhu, H. Bu, K. Wu, "Aperture compensation technique for innovative design of ultra-braodband microstrip bandpass filter ", *IEEE Inter. Microwave Symp. MTT-S*, 2000, Boston, pp 315-318.
7. B.D. Jackson, G. de Lange, W.M. Laauwen, L. de Jong, T. Zijlstra, N.N. Iosad, and T.M. Klapwijk, "THz SIS mixer development for HIFI", *Proc. 13th International Symposium on Space Terahertz Technology*, pp. 561-570, 26-28 March 2002, Harvard University, Cambridge, Massachusetts, USA.
8. B.D. Jackson, A.M. Baryshev, G. de Lange, S.V. Shitov, J.-R. Gao, N.N. Iosad, and T.M. Klapwijk, "Low-noise 1 THz superconductor-insulator-superconductor mixer incorporating a NbTiN/SiO_2/Al tuning circuit", *Appl. Phys. Lett.*, vol. 79, no. 3, pp. 436-438, 16 July 2001.