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Development of Mixer Block Production Technology for Radio Astronomy Receivers

Project report

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1. Summary

This report presents the first results of work done by the Kapteyn Institute/SRON for Witec Fijnmechanische Techniek B.V. for the development of series fabrication techniques of submillimeter-wave mixer blocks for ALMA.

ALMA - the Atacama Large Millimeter Array – is a new large observatory for millimeter and submillimeter wave radio astronomy and is being developed as a collaboration between institutes in Europe, North America, and Japan. ALMA will comprise at least 64 antennas of 12 meter diameter, and each antenna will be equipped with 10 receivers for different frequency bands. The crucial detection elements in each dual-polarization receiver are two high-sensitivity SIS mixers. Up to now, submillimeter wave mixers are usually hand-made by highly experienced and specialized personnel due to the required small mechanical structures (on the order of a few hundred micrometers). However, the large quantity of mixers (at least 128 per band) needed for ALMA calls for automatic ways of production without loss of quality.

The Kapteyn Instituut of the University of Groningen and SRON develop the submillimeter mixer for ALMA band 9 (602 to 720 GHz, or 0.41 to 0.5 mm). Over the past decade, SRON has accumulated significant design and fabrication experience for submillimeter wave SIS mixers.

A collaboration between Kapteyn Institute/SRON and Witec Fijnmechanische Techniek B.V., Ter Apel, has been set up with the aim to transfer the (manual) production expertise of SRON to Witec and develop a fully automatic production process at Witec suitable for series fabrication of submillimeter wave mixer blocks for ALMA.

This report describes the first results which can be summarized as follows:

- SRON fabrication expertise has been transferred to Witec.
- Witec has adapted and modified the SRON techniques for use on CNC machines.
- A first series of six mixer backpieces was fabricated at Witec.
- The results – and taking into account future improvements – seem to make the series production of the present mixer design viable.
- Some of the important mechanical parameters are within excellent control, while some others need improvement.
- Improvements can be achieved through modification of the production process, modification of the mounting structure, and better calibration of machining dimensions. All of these will be implemented in the next production run.

2. Introduction and background

2.1 Alma-the Atacama Large Millimeter Array

The project ALMA

The Atacama Large Millimeter Array (ALMA) is the name of a new large astronomical project of a truly global scale. It comprises an array of at least 64 telescopes, each equipped with 10 receivers. The project is at present a joint venture of Europe, North America (USA and Canada) and Japan. Within Europe, the participation is organised through the European Southern Observatory (ESO). The Netherlands is a member of ESO since its foundation in 1960. Other countries in Europe involved in ALMA, under co-ordination by ESO, are France, Germany, Italy, Spain, Sweden, and the United Kingdom.

The location of the ALMA array

The ALMA array will be located in Northern Chile in the Atacama Desert on the high-altitude (5000m) plateau named Llano de Chajnantor (Fig. 1). This site is selected because of its exceptional good atmospheric conditions that are required to carry out high-sensitivity astronomical observations at millimeter and sub-millimeter wavelengths.

Fig. 1: Panoramic view of the proposed site for ALMA at Chajnantor. This high-altitude plain (elevation 5000 m) in the Chilean Andes is an ideal site for ALMA.

ALMA's technical capabilities and challenges

The ALMA project will expand the aperture synthesis techniques into millimeter and sub-millimeter radio astronomy, which enable precision imaging. The ALMA facility will be particularly well suited to two domains that are major challenges in modern astrophysics: (1) the formation and evolution of galaxies and quasars in the early universe, and (2) the formation of stars and planets in the Milky Way and nearby galaxies. The collecting area (at least 7000 m^2), resolving power, excellent high-altitude site, better instrumentation, and the large number of baselines will give vastly increased sensitivity.

ALMA poses great technical challenges for development and fabrication. Up to now, millimeter wave instrumentation and telescopes have only been built as single units or a few units at most. ALMA requires many specifically designed and fabricated units of a certain kind. For example, 640 receivers are needed for 64 antennas (10 per antenna).

ALMA at Chajnantor
(Courtesy NAOJ)
ESO PR Photo 14/01 (6 April 2001)
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Fig. 2: ALMA 12-m antennas placed on the Chajnantor site.

2.2 The importance of high quality SIS mixer fabrication

The astronomical signal received by the 64 ALMA antennas will be focused into receivers and ultimately detected with SIS mixers. Such high-sensitivity mixers are being developed for ALMA band 9 (600 to 720 GHz) at the Kapteyn Institute / SRON in Groningen. A major difficulty in the fabrication of these mixers is the machining of a mixer block containing very small structures (on the order of a few hundred microns), and the ultra-high precision required (a few microns). The quality of the mixer block fabrication has a direct influence on the sensitivity of the whole instrument. Up to now, mixer blocks are fabricated manually by very experienced mechanics. The large quantities of mixer blocks needed for ALMA call for a different, industrialized production process without compromising quality.

The development of such an industrialized production process for ALMA mixer blocks is the aim of the present project.

In general (not only valid for SIS mixers, but all ALMA parts and subsystems), these are the most important fabrication requirements:

- Production of state-of-the-art designs developed in scientific institutes
- Series production of about 150 units (128 plus spares)
- Low cost fabrication without compromising performance

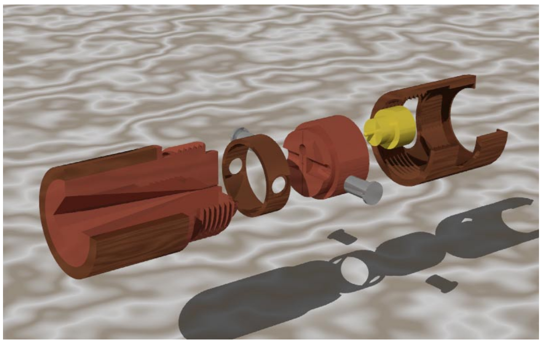
3. ALMA band 9 mixer design

3.1 Single-ended DSB mixer

Fig. 3 shows the design of an ALMA band 9 single-ended double sideband (DSB) waveguide mixer. The design goal was best possible performance combined with simplicity and series fabrication possibility. The mixer consists of several parts:

- a horn (1),
- a centering ring (2) aligning the horn with the backpiece,
- a mixer backpiece (3) which holds the superconducting detection element (an SIS tunnel junction) and an IF connector,
- a threaded cap to hold horn and backpiece together (4),
- a magnet consisting of a coil (not shown) and two pole shoes (5),
- a mounting structure (not shown).

The parts of the mixer which are most critical to the performance, and for which the new series-production procedures are developed, are the horn and the backpiece.



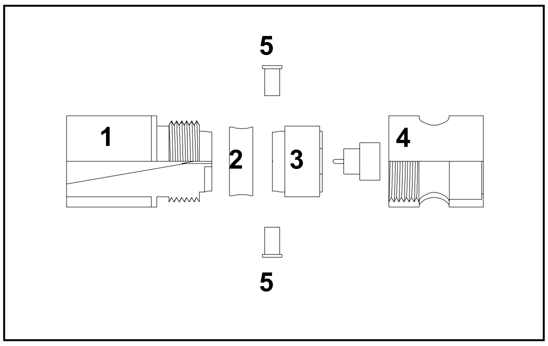


Fig. 3: Design of ALMA band 9 (602 – 720 GHz) mixer.

3.2 Horn

The function of the horn is the efficient coupling and matching of the free-space sub-millimeter wave coming from the secondary telescope reflector to the TE_{10} mode of the waveguide. The operational model will incorporate a so-called corrugated horn, which has very good beam properties, but since this is a very difficult and costly part to produce, initial tests will be performed with a much simpler diagonal horn. The waveguide itself is very short (a few millimeters) and is integrated into the back of the horn.

3.3 Backpiece

The backpiece has several functions. Apart from the precise mechanical positioning of the SIS junction substrate with respect to the waveguide, it provides the electromagnetic coupling of the waveguide mode to the SIS junction itself. For this it incorporates a rectangular resonance cavity just behind the substrate which defines the field distribution at the location of the waveguide probes that are integrated on the junction substrate. Especially the shape and dimensions of this cavity are of paramount importance to the performance of the mixer.

Further included in the backpiece are a sub-miniature coaxial connector to extract the intermediate frequency signal from the mixer, and a small heater to momentarily raise the junction temperature above the superconducting transition (this is necessary for getting rid of so-called "trapped flux").

4. Development of mixer block production technology at Witec B.V.

4.1 Project objectives

The objectives of the project *Development of Mixer Block Production Technology for Radio Astronomy Receivers* are:

- Transfer of experience about submillimeter mixer block production from Kapteyn Institute/SRON to Witec Fijnmechanische Techniek B.V. in Ter Apel, and
- Enable Witec to produce submillimeter mixer blocks with the required precision in larger quantities in an automatic way.

4.2 Project plan

In order to reach the project goals, the following steps were followed:

- Definition of specifications for the production process of an ALMA band 9 mixer block
- Discussion with Witec about the feasibility and possible production technologies
- Explanation of the mixer design and the of critical parameters to Witec
- Transfer of knowledge and production experience from SRON to Witec
- Adaptation and (if necessary) modification of the SRON (manual) production process to an automatic process at Witec
- Fabrication of the required special tools
- Experimental machining of a substrate groove and refinement of tooling and machining technique
- Establishing the stamping procedure for a backpiece cavity
- Fabrication of several complete mixer block backpieces by Witec

- Tests of the fabricated backpieces with respect to fabrication accuracy, tolerances and repeatability at Kapteyn Institute/SRON

- Recommendation of further steps

Due to the machining difficulty and the special tools and techniques employed, it was clear from the beginning that the project needs to be carried out in very close collaboration between Kapteyn Institute / SRON and Witec. This close interaction was ensured by regular meetings, working visits both to SRON and Witec, and close collaboration at the working level.

5. Production process specifications

5.1 Mixer block fabrication requirements

The design goal is best possible performance combined with the possibility of series fabrication and ease of assembly. The requirements for mixer block fabrication to meet these goals are as follows:

- **Best possible performance**: Optimal high-frequency performance requires machining tolerances and surface smoothness better than a few percent of the typical dimensions of the microwave structures (which are of the order of 100 µm) i.e., in the range of a few micrometers.
- **Possibility of low cost series production**: All parts should be produced on CNC (Computerized Numerically Controlled) machining equipment. The machining operations should be performed in such a way that, once established in the CNC program, they require as little manual intervention as possible. It is especially important that the part under construction does not need to be removed from its machining clamp before it is completely finished, since doing so would require a time-costly realignment procedure. An optimization and automatization of the production process is also mandatory to keep the fabrication cost as low as possible.
- **Ease of assembly**: Because of the large number of mixer units that have to be assembled (on the order of 150), and also to facilitate field-serviceability, the various parts of the mixer should be self-aligning with respect to each other. No manual adjustments should be needed, alignment should be defined purely by the machining accuracy.

For the finished product, the following mechanical parameters are tested and measured to assess the product quality:

- Surface finish
- Width, height, depth and shape of backpiece cavity
- Width and depth of substrate groove
- Alignment of cavity with respect to the reference circle (which is the outer edge of the backpiece)
- Outer dimensions of backpiece

- Reproducibility of dimensions and alignment

5.2 Machining techniques

An important starting point in the series production process was that the techniques for manual single-piece production that have been developed at SRON over the past 20 years should be retained as much as possible, while adapting them for use on modern CNC machining equipment.

The outer shapes of the parts are made by conventional CNC milling (in contrast to the originals that were made on a lathe), which poses no great technological difficulties, except for the requirement of rather tight tolerances. Also the diagonal horn can be made by milling. For the waveguide and the cavity, two less conventional techniques have to be used: cutting and stamping.

The mixer block containing a waveguide of dimensions 400 μm x 100 μm is made as a split-block, i.e., a rectangular groove of width 100 μm and depth 200 μm is cut into each half of the metal block, which are then joined together so that a single closed waveguide is formed. The grooves are cut with a sort of paring chisel of exactly the width of the waveguide, shaving off a layer of a few microns at a time until the required depth is reached. The same technique is used to cut the substrate-groove in the backpiece.

The rectangular resonance cavity in the backpiece is stamped with a precisely shaped tungsten-carbide punch. Since the resulting cavity is a direct imprint of the punch, the quality of the result is to a large extent determined by the shape and surface finish of the punch. The extremely fine punches (100 x 400 μm footprint, with a shaft length of about 200 μm), as well as the chisels for cutting the grooves (also made of tungsten-carbide), were hand-made at Witec using diamond-abrasive tools, building on the procedures developed at SRON.

The backpieces still require one manual intervention during machining: after punching the cavity, it has to be filled with a hard material to avoid creating a burr when the chisel for cutting the substrate groove is drawn over it. Although undesirable, it seems that at the moment there is no better alternative for this. However, the impact on production throughput is limited by the fact that it is a room-temperature operation (unlike, e.g., soldering) that can be performed in the machining clamp without breaking the alignment.

6. Results

6.1 Produced parts

After fabricating the required tools and gaining experience with the implementation of the above mentioned techniques on the 5-axis CNC milling machine at Witec, an initial test run of six backpieces was produced. The backpiece was chosen over the horn because it is the most difficult of the two to produce, and because it requires both techniques (cutting and stamping), whereas the horn only needs cutting.

Fig. 4 (left) shows the resulting series of backpieces as they come out of machining, still attached to the raw copper rods that they were made of. Four of these were produced in a single unattended run. An enlargement of a single backpiece is shown in Fig. 4 (right).

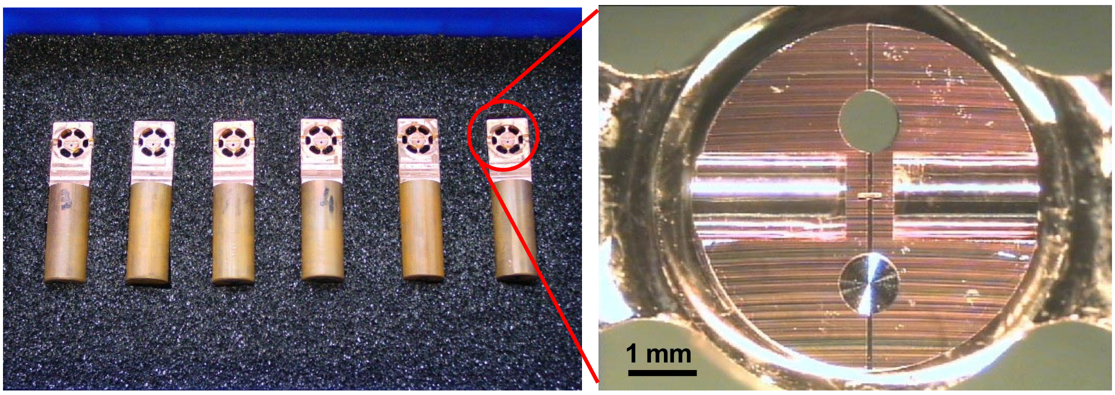


Fig. 4: Left: First production run of six mixer backpieces (before removing them from their mounting structure). Right: Enlarged view of a single backpiece.

6.2 Quality of produced parts

A first check of the quality of the produced backpieces was made by visual inspection through a microscope (Fig. 5). Although quantitative results are not available yet, it seems that the quality of the surface finish is comparable to that of typical hand-made SRON mixers and thus sufficient.

Two deficiencies are visible however: 1) there is a clear burr at the bottom edge of the cavity, produced by the chisel cutting the substrate groove. The reason is that the procedure to fill the cavity with a hard material between punching and cutting was not yet implemented. 2) the cavity is slightly barrel-shaped at the top (Fig. 5, central image). The latter is a known problem that also occurred in the past with hand-made mixers, and that should be solvable by a slight modification of the shape of the punch.

The shape of the cavity at the bottom looks excellent (Fig. 5, right image), as does the overall shape of the substrate channel (straight and parallel).

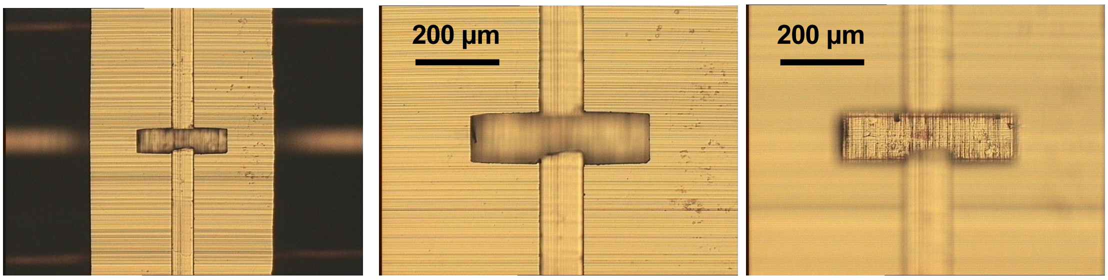


Fig. 5: Microscope images of a mixer backpiece cavity and substrate channel. The focus was adjusted to the top (center image) and the bottom (right image) of the cavity, respectively.

6.3 Reproducibility of dimensions

The most important check, needed to verify the viability of series production on CNC equipment, is the reproducibility of dimensions and alignments. For this, several key parameters, such as the size of the cavity and its position within the reference circle, were measured at Kapteyn Institute/SRON and compared to the intended values. The most important ones are shown in Figs. 6 and 7 (all dimensions in micrometers).

The width (Fig. 6a) and height (Fig. 6b) of the cavity are very close to the specified value (line) at the cavity bottom, which shows the accuracy of the hand-made punch. At the top of the cavity, due to the barrel-shaped distortion, the width and height are off by 10-20 µm. As mentioned before, this should be correctable by a slight modification to the punch.

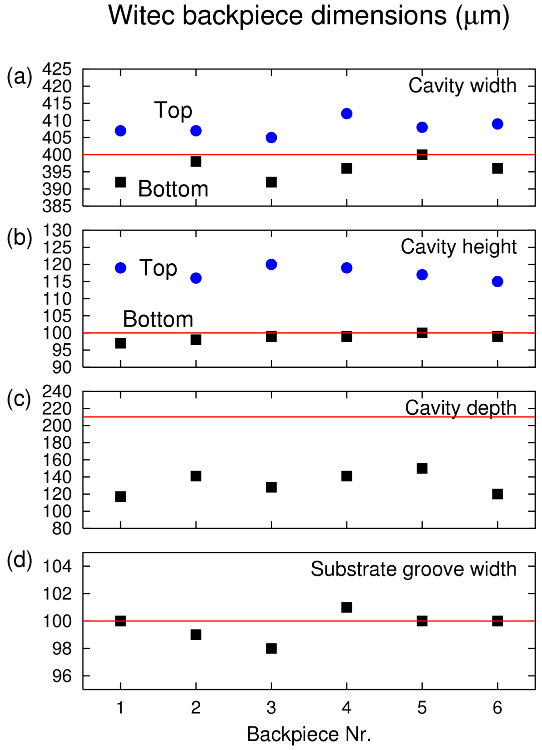


Fig. 6: Dimensions (in µm) of critical structures in the six fabricated backpieces. Cavity width (a) and height (b) were measured both at the top (●) and the bottom (■). The horizontal lines indicate the target values.

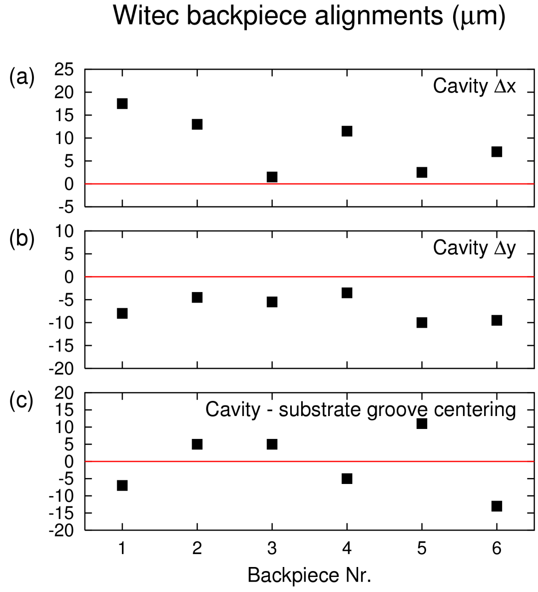


Fig. 7: Alignment deviations (in µm) of the cavity with respect to the reference circle (a and b) and relative to the substrate groove (c) for the six fabricated backpieces.

The largest error appears to be in the depth of the cavity (Fig. 6c), which is almost a factor of 2 too small. Similar deviations are observed in the depth of the substrate channel. The main cause is the absence of a suitable measurement microscope at Witec, so that it is impossible to perform a good depth calibration. For this reason, Witec recently invested in such a microscope, which should be delivered at about the time of writing. Another problem which was found, probably causing the large spread in the values, is the flexibility in the used clamping system. A much stiffer construction has been devised in the meantime, and the next run will show whether this is adequate to improve the reproducibility.

The substrate groove (Fig. 6d) has precisely the correct width, and the deviations (+/-2 µm) are negligible.

6.4 Positioning accuracy

The most important parameter from the alignment point of view is the centering of the cavity with respect to the reference circle, since this will determine the efficiency of the electromagnetic coupling to the waveguide. The measured horizontal and vertical deviations from the center are shown in Figs. 7a and 7b, respectively. Apart from a systematic error that should easily be correctible in the CNC program, a spread of 10-15 μm is visible, possibly also caused by the flexibilities in the mounting of the work piece. At present, it is not clear whether this will impair the performance of the mixer, so experiments are needed here. It is likely however, that a somewhat better positioning is desired.

The outer shape of the backpiece also contains a few systematic errors due to the microscopic bending of the tools during machining. This can easily be solved by some small adjustments in the CNC program.

7. Conclusions and recommendations

7.1 Conclusions

The following conclusions can be drawn from the results presented in Section 6:

- Witec has started to use production techniques developed at SRON for the fabrication of high-precision submillimeter wave mixer blocks.
- The very first test run of several CNC machined mixer backpieces gave promising results.
- The substrate groove width and the cavity footprint are within excellent control.
- Improvement is needed in the shape of the cavity top (including the burr at the edge of the substrate channel), and especially in the control of the depth of both the cavity and the substrate channel. The latter seems to be a calibration problem rather than a fabrication issue. A microscope is needed at Witec for proper measurement of the cavity depth.
- The alignment of the cavity relative to a reference circle is satisfactory. A systematic offset can be corrected easily, while a scatter may need a different mounting of the work piece.
- These results – and taking into account future improvements – seem to make the series production of the present mixer design viable.

7.2 Recommendations

Based on the conclusions, the following recommendations are made:

- In order to avoid a burr at the edged of the substrate channel, the cavity should be filled with a hard material between punching and cutting.
- The substrate channel and cavity depths should be adjusted after measurement and calibration at Witec. This requires a measurement microscope.

- A stiffer mounting construction during machining should be employed to attempt to decrease the scatter of parameters.

- The shape of the punch for the backpiece cavity should be modified based on the experience with the present results. This should improve the quality of the cavity.