Characterization of Various Quasi-Optical Components for the Submillimeter Limb-Sounder SMILES

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Abstract

The submillimeter-wave limb-emission sounder called SMILES is currently being developed for the Japanese Experiment Module of the International Space Station. It will observe the spectral emission lines of several stratospheric trace gases related to ozone chemistry. We present transmission and reflection measurements with a submillimeter-wave vector-network analyzer of various optical sub-components of SMILES, which include corrugated feed horns and corrugated back-to-back horns, a novel single sideband filter and a conical calibration load.

1 Introduction

SMILES is a submillimeter-wave limb-emission sounder which is currently developed for the Japanese Experiment Module of the International Space Station [2]. It will obtain global maps of ClO, BrO, HCl, O_3 and other stratospheric trace gases related to ozone chemistry by observing their spectral emission lines in two frequency bands at 624.32–626.32 and 649.12–650.32 GHz. Two superconducting SIS mixers cooled by a mechanical cooler will guarantee the very highest sensitivity.

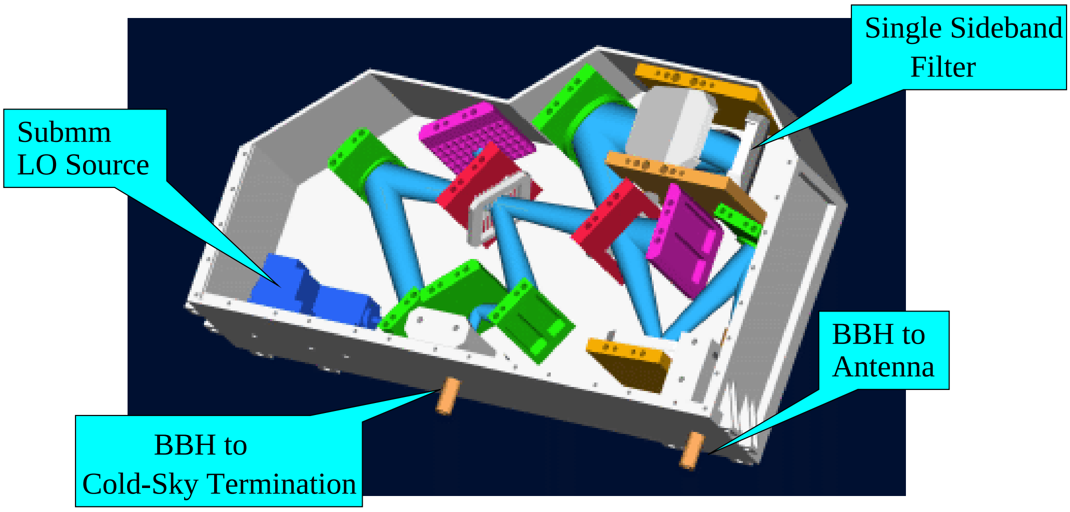


Figure 1: Ambient Temperature Optics (AOPT) module of SMILES. Submillimeter radiation from the cold sky and the atmosphere enters the AOPT through two corrugated Back-to-Back Horns (BBH). The output to the cryogenic mixers is hidden underneath the single sideband filter.

The Ambient Temperature Optics subsystem as shown in Figure 1 provides LO injection, single sideband filtering and EMC isolation for the radiometer. This is achieved by freestanding wire grids, a novel configuration of the Martin-Puplett Interferometer based on Frequency Selective Polarizers (FSP) and corrugated Back-to-Back (BBH) horns, respectively. Other optical elements outside of the AOPT are the corrugated feed horns of the SIS mixers and a black-body calibration load.

This paper reports on measurements of these critical quasi-optical components in the submillimeter range. Their transmission- and reflection characteristic were determined with a vector-network analyzer from the company *AB-Millimetre*[1]. In our configuration of this instrument coherent submillimeter radiation is generated from a phase locked Gunn oscillator using harmonic multiplication. A harmonic mixer with a second Gunn oscillator phase-locked to the same reference frequency as the first one is used for the detection and allows amplitude and phase measurements with high dynamic range [3].

2 Corrugated Feed Horns

The two SIS mixer blocks of SMILES will be equipped with corrugated feed horns that are known to produce symmetric Gaussian beam patterns with low side-lobes [9]. However they are not easy to manufacture for frequencies in the submillimeter region and detailed antenna pattern measurements are mandatory.

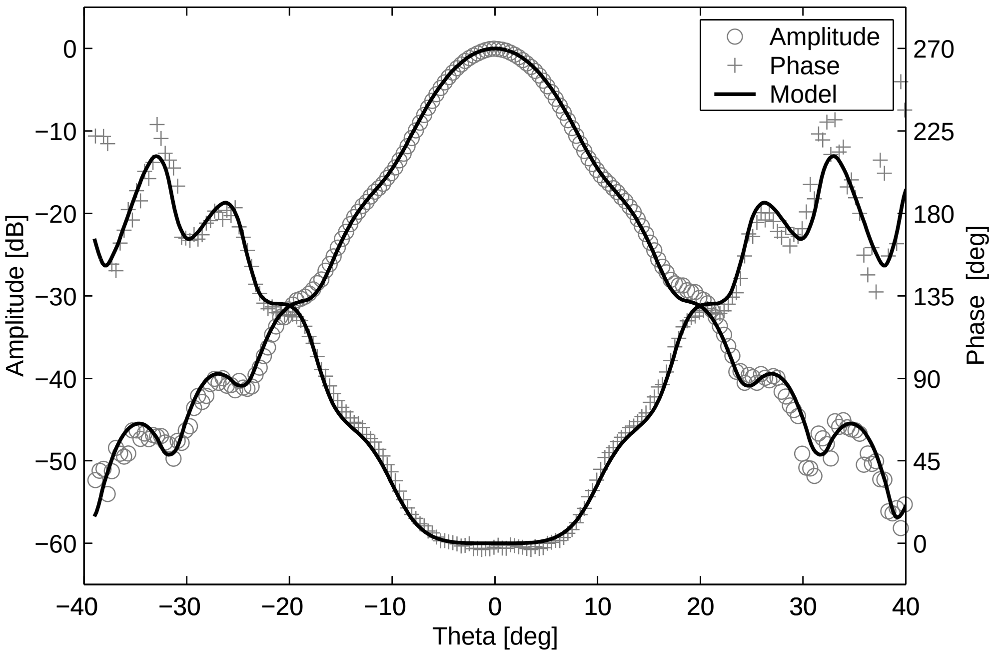


Figure 2: Measured amplitude and phase of the SMILES corrugated horn antenna together with model predictions. This measurement is a cut through the E-plane at a frequency of 602.5 GHz.

[1] *AB-Millimetre*, 52 rue Lhomond, 75 005 Paris, France, http://www.abmillimetre.com

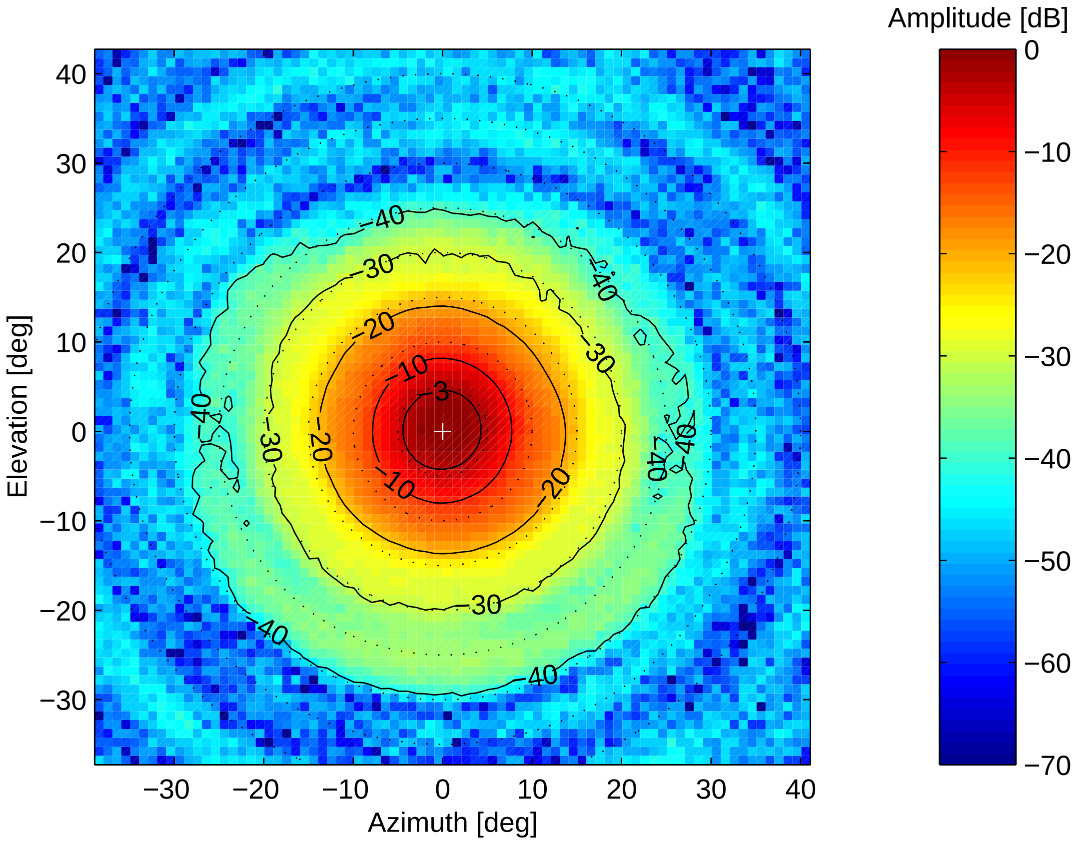


Figure 3: 2-D antenna pattern of the corrugated horn antenna. Solid lines represent the 3 dB and the first 10 dB contours of the measurement, dotted lines are circles with 5° difference between their radii.

A first prototype of the SMILES horn antenna was mounted on the harmonic detector of the *ABmm* system and rotated in azimuth and elevation using a motorized 2-axis rotational stage. The submillimeter source with another corrugated horn antenna was operated at a frequency of 602.5 GHz and remained fixed in a distance of 250 mm. Since the aperture diameter of the horn under test is 4.2 mm this distance is more than three times larger than the far field requirement $2D^2/\lambda$. Three micro-positioners are used to adjust the position of the phase center of the horn under test with respect to the rotational axes to achieve a flat phase response in the main beam.

Amplitude and phase of the 1-D antenna patterns in Figure 2 are in good agreement with the predictions of the mode-matching model CORRUG [1] down to the -50dB level. Other corrugated horns with a different design showed a similar good match between measurements and model.

The symmetry of the horn is revealed by the 2-D antenna pattern in Figure 3. Small deviations on the -40 dB level at elevations beyond 20° are caused by artifacts of the antenna test range. This is indicated by the fact that the asymmetry does not change when the horn is rotated by 180°.

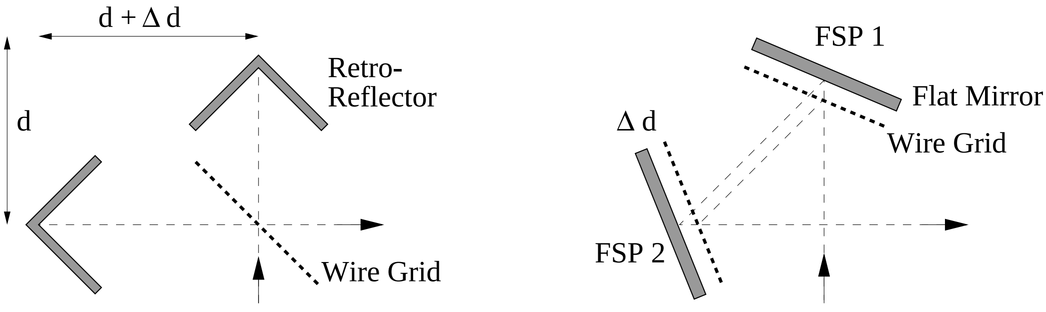


Figure 4: Schematic setup of a conventional MPI and a pair of FSP's. The wires of each grid have an orientation of 45° with respect to the polarization of the incoming radiation.

3 Sideband Filter

Many millimeter- and submillimeter-wave receivers make use of the Martin-Puplett interferometer (MPI) to achieve single sideband operation [7]. The frequency characteristic of a MPI can be easily tuned by changing the optical path difference in one of the two interferometer arms. For fix-tuned applications in space this has the disadvantage that the dimensions of the whole interferometer have to be machined to an accuracy in the order of 1μm and that these tight tolerances have to be maintained over the whole temperature range of operation. Another drawback is that residual reflections due to the imperfect performance of the grid cause standing waves in the optics which could limit the accuracy of the instrument.

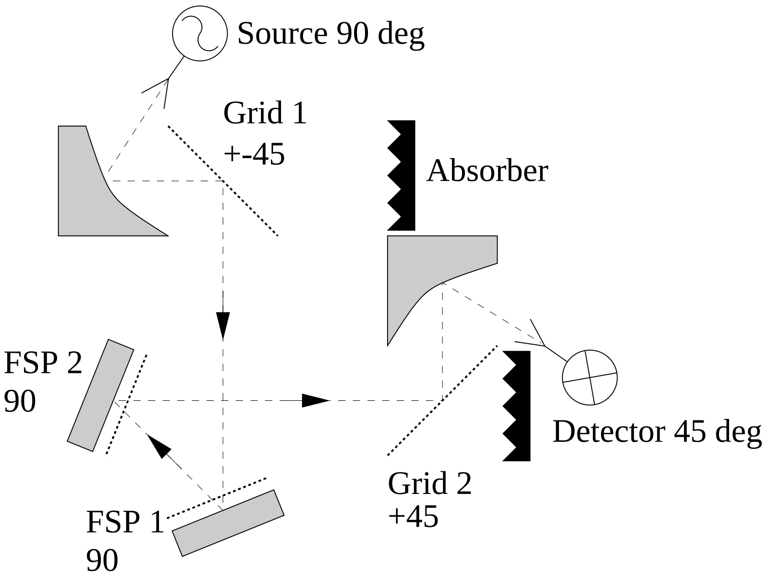


Figure 5: Quasi-optical network for transmission measurements through a pair of FSP's

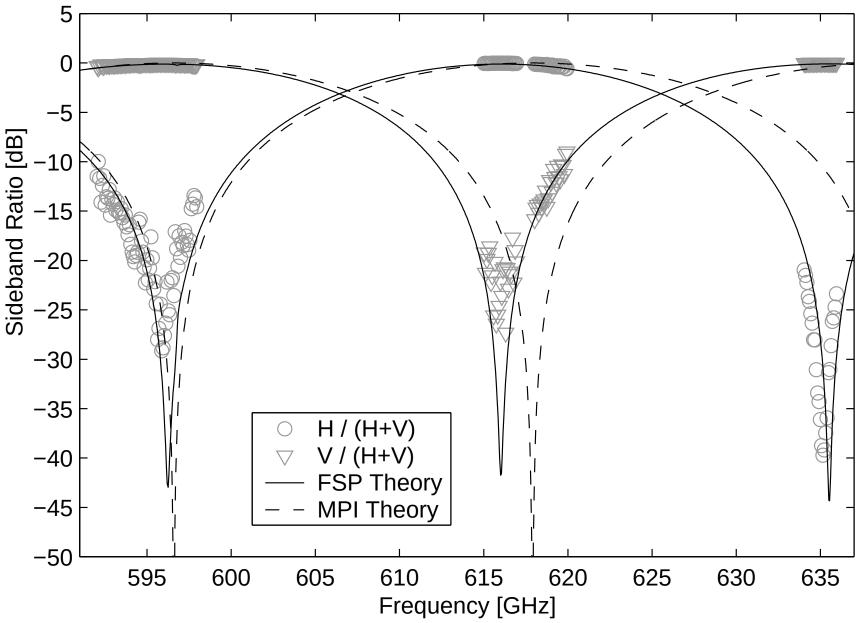


Figure 6: Transmission measurements through a pair of FSP's with $\Delta d = 1.9$ mm together with the theoretical curves for the corresponding MPI and FSP interferometers.

To avoid these problems a new configuration of the MPI as show in Figure 4 will be used for SMILES [4]. It is based on two Frequency Selective Polarizers (FSP) which consist of a wire grid placed in a specific distance Δd parallel in front of a flat mirror. This device is free of residual reflections and more suitable for fixed-tuned applications since the critical tolerances have to be met only within the FSP.

When the theoretical transmission through such a device is calculated the non-ideal behavior of the wire grids has to be modelled in detail because it has a significant influence on the frequency characteristic of the FSP's. As discussed in [6] the cross-polar components of the signal transmitted and reflected by the grids shift the frequency of the bandpass minima and maxima of the FSP filter compared to a conventional MPI with similar path difference.

The transmission through a first prototype of two FSP's with $\Delta d = 1.9$ mm was measured on a quasi-optical test bench using the network analyzer (Fig. 5). Two elliptical mirrors produce a Gaussian beam with a beam-waist radius of $\omega_0 = 10$ mm between the FSP's. The wires of both FSP's have a vertical orientation, while the wires of the reflecting grids are set for 45° polarization. The first grid after the vertically polarized source can be rotated by 90° to obtain two measurements H and V.

The normalized ratios $H/(H+V)$ and $V/(H+V)$ as displayed for different frequency bands in Figure 6 are a measure for the sideband suppression. The transmission minima are already below the noise floor of this measurement and can be smaller than the observed values. This figure also shows the expected characteristics of a conventional MPI and of the FSP filter with the same nominal path difference. The frequency shift between the theoretical FSP curve and the measurement is about 300 MHz, which corresponds to 1 μm machining accuracy of Δd.

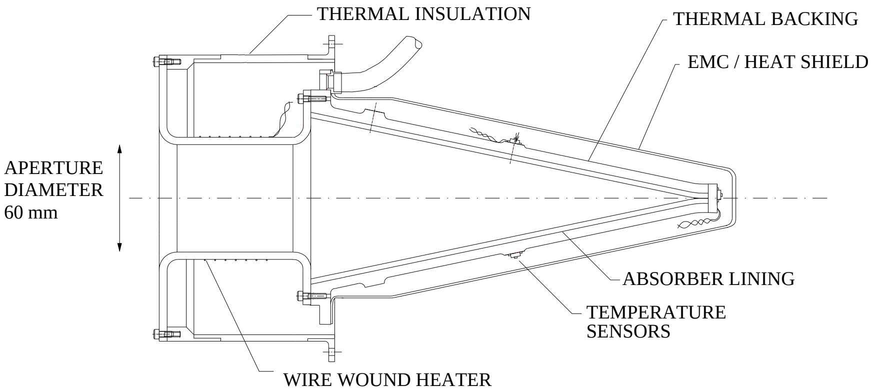


Figure 7: Design of the Calibrated Hot Load CHL. The aperture has a diameter of 60 mm, total length is 317 mm.

4 Calibration Load

The radiometric on-board calibration of SMILES will be realized by alternate observations of the cold sky and of a black-body calibration target at ambient temperature. The design of this load will be based on the Calibrated Hot Load (CHL) which was developed by *Thomas Keating Ltd.* and *AEA Technologies* within an previous submillimeter limb-sounder study of the European Space Agency ESA [5]. Figure 7 displays the design of the CHL based on a tapered aluminum cone lined with microwave absorbing material.

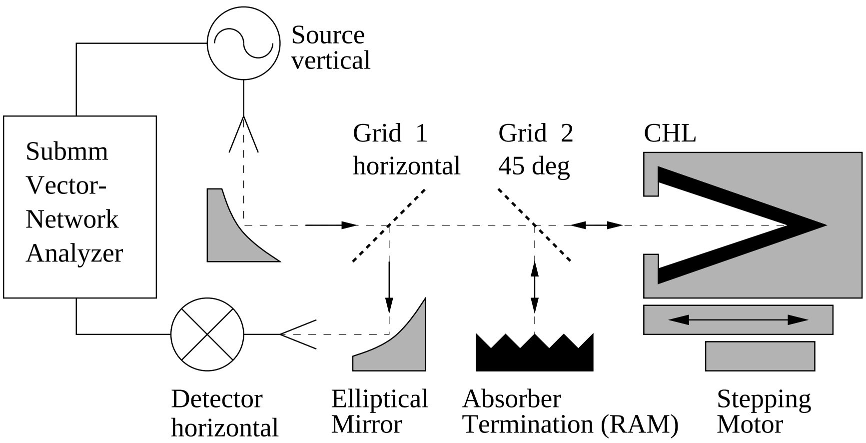


Figure 8: Setup of the quasi-optical reflectometer. Device Under Test is the CHL mounted on a motorized translation stage which allows to alter the phase of the reflected signal.

A quasi-optical reflectometer was used to measure the monostatic reflectivity of the CHL. This property is of special interest because it determines the amount of standing waves between the load and the receiver and thus the baseline ripple of the calibrated spectra. The schematic diagram of the reflectometer setup is given in Figure 8. The vertically polarized beam from the *ABmm* source passes

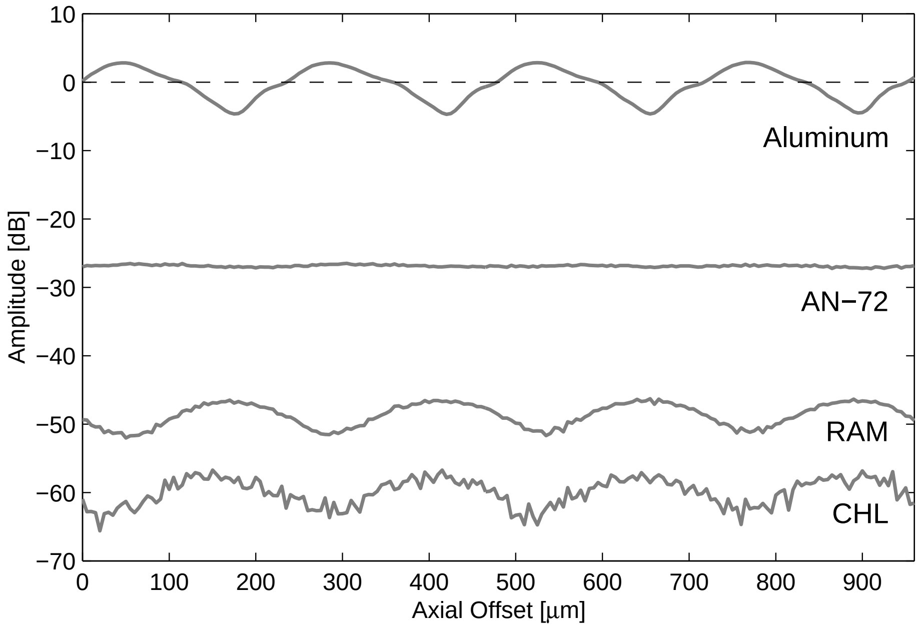


Figure 9: Reflection measurements at 625 GHz of the CHL and other absorbing materials at different axial offsets.

through a first horizontal grid. The second grid, set for a polarization of 45°, acts as a 3 dB beam splitter. Half of the power is transmitted to the device under test (DUT), in this case the CHL, while the other half is reflected to a beam termination made of the submillimeter-wave absorber RAM[2]. The returning signals, which were reflected at the termination or at the DUT, are then recombined with the 45° grid and partly routed to the detector by the horizontal grid. Two elliptical mirrors are included in the reflectometer to form a beam-waist with $\omega_0 = 10$ mm close to the aperture of the CHL.

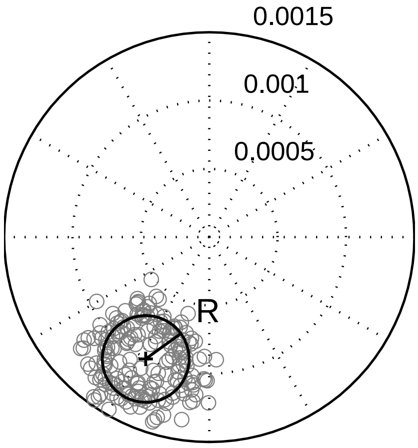
Amplitude and phase of the detected signal are determined by the reflectivity of the DUT and the absorber termination and by the path difference in the two arms of reflectometer. To separate the two components the DUT is mounted on a motorized translation stage which allows to move it parallel to the beam axis over a distance of one or more wavelengths.

Figure 9 shows such a measurement of the CHL and of two other commercial absorbers RAM and AN-72[3]. The measurement of a flat aluminum plate, also shown in this figure, was used to establish the 0 dB reference. Multiple reflections between the Aluminum and the reflectometer are causing the distinct periodic modulation when this plate is moved. In the case of the CHL and the RAM the modulations are due to the interfering signals of the DUT and the absorber termination. AN-72 produces a flat response because its reflectivity is much higher than that of the RAM termination, but still low enough to avoid a significant contribution from the multiple reflections.

In polar coordinates and on a linear scale the data points of each target lie on a circle due to the phase change from the moving DUT (Fig. 10). The radius of these circles is a measure for

[2]RAM: submillimeter-wave absorber with a pyramidal surface from *Thomas Keating Ltd.*

[3]AN-72: flat foam absorber from *Emmerson&Cuming*



DUT:	CHL
Frequency:	625 GHz
Radius R:	$3.17 \cdot 10^{-4}$
Reflectivity:	-70 dB

Figure 10: The same CHL measurements as shown in Figure 9, but on a linear scale and in polar coordinates.

the monostatic reflectivity of the DUT. The signal reflected at the fixed absorber termination has a constant phase and is responsible for the offset of the circles. From this measurement of the CHL an outstandingly low reflectivity of -70 dB at 625 GHz can be deduced. Similar results at other frequencies between 200 and 700 GHz are reported in [8] together with passive reflection measurements of the CHL at 278 GHz.

5 Back-to-Back Horn

To avoid EMC problems the sensitive receiver of SMILES has to be isolated from the low frequency RF contamination of the space station. This will be achieved by two corrugated Back-to-Back horns (BBH) which couple the atmospheric signal and the cold space view of the sideband termination into the shielded enclosure of the AOPT module. The BBH's have a total length of 130 mm and act as overmoded waveguides for the submillimeter waves while RF radiation with a longer wavelength is prevented from entering the receiver. A major concern are reflections at the BBH's which would cause standing waves in the optics. For that reason different BBH prototypes were tested in a reflectometer setup similar to the one shown in Figure 8. A third elliptical mirror after the second grid has to be added to image the source and detector horns onto the input of the BBH. The lateral position of the BBH can be adjusted manually using two micro-positioners to optimize the alignment for minimal reflections. Another motorized positioner moves the BBH parallel to the beam axis.

Figure 11 displays the amplitude of the detected signal for different axial positions. The modulations again are caused by the superposition of the reflected signals from the BBH and the absorber termination and can be removed by applying the technique described in the previous section on neighboring data points. The resulting monostatic reflectivity of the BBH given by the black line in Figure 11 has a minimum value below -65 dB in the optimum focal position. The lateral position of the BBH is more critical than the axial position since a 1 mm horizontal or vertical offset of the BBH already leads to reflections at the -30 dB level.

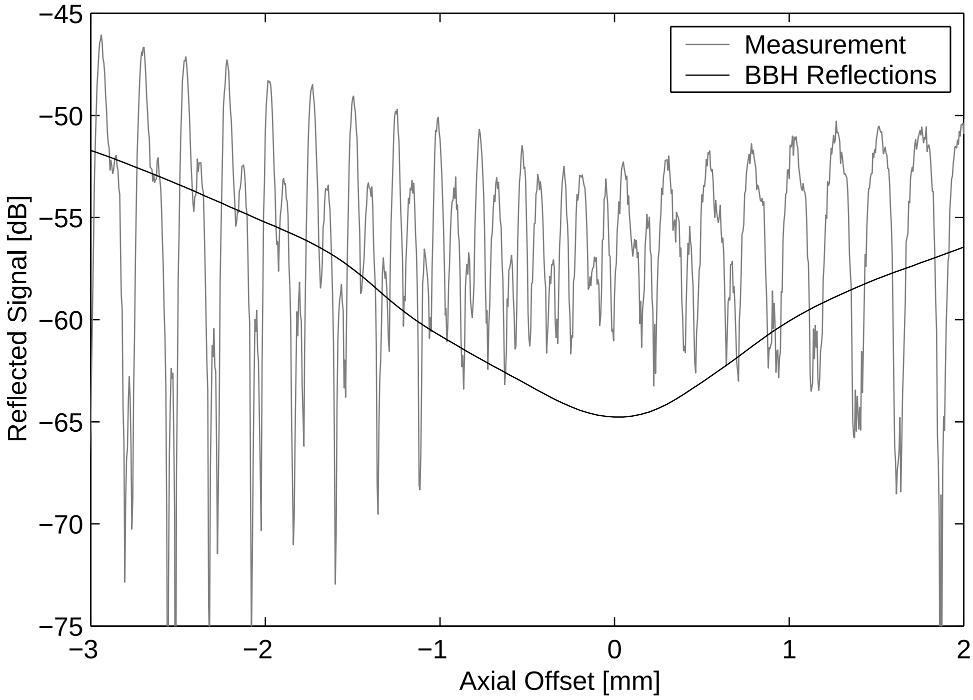


Figure 11: Reflectometer measurement of the BBH for different axial offsets from the optimal focal position and the retrieved BBH reflectivity (black line).

6 Conclusions and Outlook

We have described transmission and reflection measurements of critical quasi-optical components for SMILES in the submillimeter region which were obtained with a vector-network analyzer. Summarizing we conclude:

Antenna patterns of the corrugated feed horns are very close to the predicted values. This is a good proof for theory, manufacture process and measurement technique. Measurements of a novel FSP sideband filter showed that a sideband suppression of more than -40 dB can be achieved with such a device. Only a small frequency shift between the measured and the predicted transmission minima was observed. This shows that the non-ideal characteristic of the grids can be modelled correctly and that the FSP's can be machined with the required μm tolerances. The Calibrated Hot Load CHL has a very low monostatic reflectivity of -70 dB in the frequency bands of SMILES. This will lead to less standing wave problems than with other load designs. Reflections from the Back-to-Back Horns can be as low as -65 dB. However this requires a high accuracy in the alignment of the optics.

Currently an engineering model of the complete AOPT module is manufactured. The electrical characteristics of the whole module will be measured before and after vibration and thermal cycling as soon as it is available.

Acknowledgements
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