The HIFI Focal Plane Beam Characterization and Alignment Status

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Abstract— **In this paper we present the results of the characterization program of the beams in the focal plane of the HIFI flight model. We discuss the beam properties, quality of alignment, instrument footprint, performance impact and compliance and compare the results to predictions based on lower-level characterization results and simulations. We finally conclude by presenting the expected properties at the sky by forward propagation through a telescope model.**

I. Introduction

Prior to final characterization of the flight model of the HIFI Focal Plane Unit [1-6], the design and sub-units have been thoroughly analysed and verified in several studies and measurement campaigns [7-12]. In the development model phase of HIFI the long wavelength limit of the instrument has been modelled and verified experimentally as part of an ESA-TRP study [13-17]. In these early activities we validated the design and green light was given for flight production, alignment and test of the flight hardware. A crucial part of the flight alignment and integration concerned the tests of the high-frequency bands of HIFI involving the measurement and mechanical corrections for the lens-antenna mixers employing small Si lenses [18-22]. Several corrections were applied to properly align and correct the optical interfaces of mixer-units in band 5, 6 and 7. These beam pattern measurements and shimming activities took place at sub-unit level where we tested individual Mixer-Sub Assemblies containing a single polarization flight mixer [6]. The final verification step carried out during the Instrument Level Test program was the experimental end-to-end verification of the optical chain from mixer-unit to the focal plane where the individual HIFI beams interface to the Herschel telescope. Since beyond this level no additional testing is planned involving the actual telescope, great effort was put to ensure proper mechanical referencing of the HIFI beams relative to optical alignment devices, which are later used by industry to align the FPU to the Herschel optical bench and telescope [7].

In this paper we provide a compact summary of the verification results obtained prior to flight tests. We then focus mainly on the results obtained during the ILT phase of HIFI [40], we shortly summarize the experimental system used, and present the measured footprint of the instrument in the focal plane. We discuss compliance and conclude by projected performance at the sky and a brief outlook at future pointing calibration activities planned in space [47].

II. Quasi-Optical Alignment Approach

The main philosophy behind the end-to-end alignment of the HIFI Focal Plane Unit (FPU) is to use visible laser light alignment methods whenever possible. This is driven by the complexity of the optics, consisting of a common optics assembly including the telescope pick-off mirror, the chopper mirror and relay optics to the individual mixer bands in a compact, wide-field and off-axis arrangement [5-7, 23-26]. Central to the instrument there exist an optical-mechanical interface at which the smallest self-contained receiver units, the Mixer Sub-Assemblies (MSA's), can be mounted [7]. The MSA optics only contains three off-axis mirrors in a compact near-field off-axis arrangement and finally the Mixer Unit (MU) in which the mixers are located [6, 9]. The beams from the mixer units hit in some cases as many as 15 optical elements before they interface to the Herschel telescope in the focal plane [7]. To get this complex system under full control we decide to first pre-align all mirrors but the mixer units by visual laser light. All the reflective elements are compatible with use of visible light and are of optical quality. The main optics of the FPU, containing the common optics to all receiver bands, are fully pre-aligned before being interfaced to individual MSA modules. The MSA modules are also fully pre-aligned prior to integration of the MU modules. The visual alignment can be done very accurately as the image quality is diffraction limited. This eliminates the need of adjustment of mirrors after integration of the mixer units. The measurement campaign then relies only on ensuring that a) the MU has a proper optical interface in terms of beam properties, location and direction, b) a properly mounted MU has still good performance when remeasured at MSA level and c) a verified MSA in terms of radio alignment and beam quality still show good performance after passing through the common optics of the FPU. The advantage of this modular approach is that once the smallest self-contained module is properly verified it can simply be mounted on the FPU and performance is ensured. This will in principle allow for easy exchange of Mixer Sub-Assemblies when necessary and is preferred in terms of project AIV logistics.

III. Pre-flight Model Verification Results

The suppliers of the mixer units carried out a unit level verification program verifying either by test and/or analysis [27-28] that the mixer units comply with their optical interfaces. In the high-frequency bands 6 and 7 the MU level verification was combined with the MSA level verification in close collaboration with the supplier [18-19]. The design of the MSA optics was verified independently by analysis and test prior to integration with the MU. For that purpose dedicated electromagnetic simulations were carried out by Neil Trappe, Massimo Candotti, Gary Cahill, Tim Finn, and Tully Peacocke using a variety of modelling techniques and simulation packages [8, 11-17]. A few striking simulation and measurement results obtained for the long wavelength limit of HIFI are shown in Fig. 1 to 4 and described in more detail and extent in [7]. In Fig. 1 the simulated beam pattern of a band 1 MU after passing through the three-mirror system of the MSA [7, 9] is shown. The beam map is obtained in a plane where we interface to the common optics of the FPU. The measured beam profile in the same plane is shown in Fig. 2. Both patterns are shown on a logarithmic scale. The apparent visual agreement is striking. When taking a closer look at the patterns and comparing two orthogonal cuts taken through the centre of the maps in phase and amplitude, this agreement can indeed be confirmed. In Fig. 3 the measured and simulated intensity is compared and quantitative agreement down to -40 to -50 dB is obtained. In Fig. 4 we see that also in phase there exists excellent agreement. The observed structure both in intensity as well as in phase matches nicely to the predicted shapes. The differences are believed to originate from the applicable manufacturing tolerances. Differences in for example coupling efficiencies calculated on the basis of measured and simulated patterns agree within tenths of a percent.

In [7] and [9] we present all results obtained for the long wavelength limit design verification at 480 GHz. This paper also includes measurements and simulation for the Local Oscillator path and includes the telescope optics.

From these verification activities we concluded that once a mixer itself is compliant to the optical interface good end-to-end performance for a perfectly pre-aligned optical chain can indeed be ensured and that powerful analysis tools are available to predict and simulate expected performance at higher level of integration. It is therefore safe to limit further testing to end-to-end verification at MSA and FPU level only.

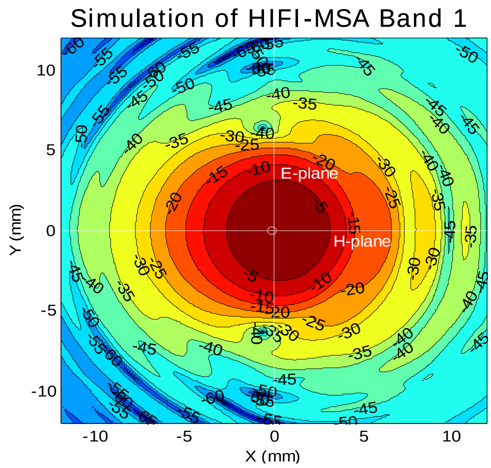

Fig. 1 Simulated beam pattern of HIFI MSA band 1 at 480 GHz.

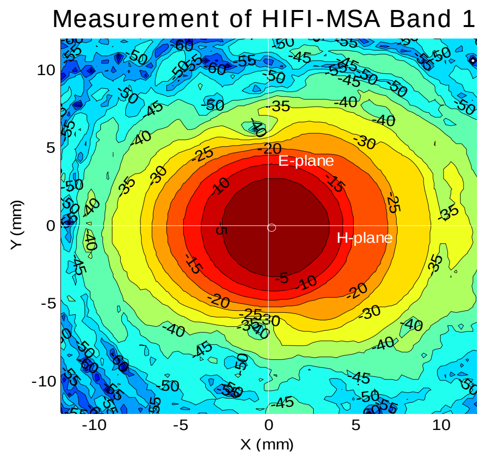

Fig. 2 Measured beam pattern of HIFI MSA band 1 at 480 GHz.

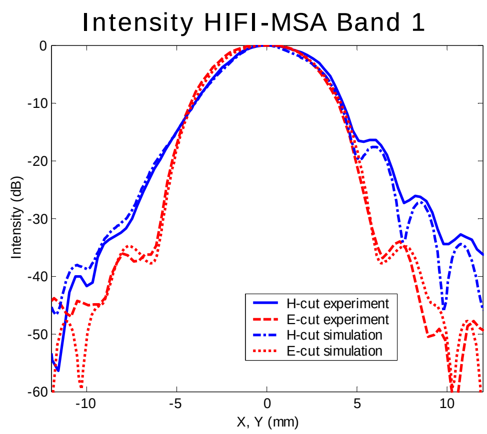

Fig. 3 Simulated and measured intensity along the E- and H-planes of the maps in Fig. 1 and 2.

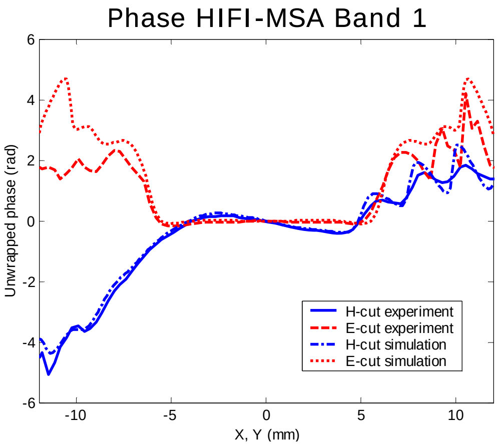

Fig. 4 Simulated and measure phase cuts of MSA band 1 at 480 GHz.

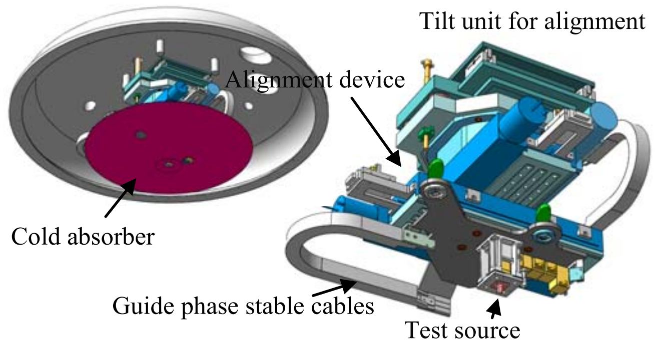

Fig. 5 Artist impression of vacuum scanner system used for the measurement of the focal plane beams of HIFI.

IV. Experimental System

We measure the HIFI beams in phase and amplitude as becomes clear in Fig. 3 and 4. This has the clear advantage that all information is contained in a single planar measurement[36-38]. From the measured complex field distribution the relevant parameters such as beam width, phase centre location and direction of propagation can be determined. Furthermore measured datasets can be included in electromagnetic simulation software and forward propagated to a higher level of integration. The measurement technique and system architecture employed is described in detail in [29-38]. We obtain a signal-to-noise ratio over 90 dB and phase resolution below 5º at frequencies as high as 1.6 THz.

For Instrument Level Tests at Focal Plane Unit level we use a rather involved system. Since the Herschel telescope has a focal ratio of 8.7 the spatial extent of the HIFI beams is already significant at the gate valve flange on the FPU cryostat which is roughly at half a meter from the optical bench. In order to reduce the heat load on the instrument we developed a vacuum scanner system which is mounted on top of the FPU cryostat. Once pressures at both sides of a gate valve system are equalized, the gate valve is opened and the scanner system can see the FPU. The scanner system is composed of a X- and Y-stage for horizontal and vertical translation, contains mechanical interfaces for coherent test sources and alignment devices and a cold absorber screen [39] which is cooled by liquid nitrogen. The cold absorber screen is mechanically supported from the moving stage and moves with the test source and is contained in a floating thermal shield construction in the vacuum scanner box. An artist impression of this system is shown in Fig. 5. See also section III of the paper by Teyssier et al in these proceedings [40]. In Fig. 6 we show the FM FPU as it would sit on the baseplate of the FPU cryostat. The scanner system shown in Fig. 5 scans the beam in a radial pattern in an on-the-fly-mapping mode measuring the two polarization channels in each mixer band simultaneously. We finally show a close-up of the actual scanner system in which a test source and the thermal-mechanical interface to which the cold absorber screen is mounted can be seen.

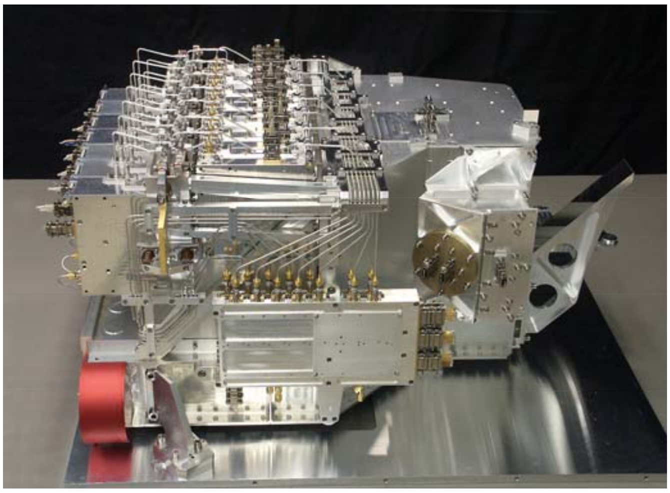

Fig. 6 Flight model FPU of HIFI. On the right hand side the telescope pick-off mirror M3 can be seen. On the top of the instrument the alignment cube used for Herschel optical bench integration and telescope alignment is visible.

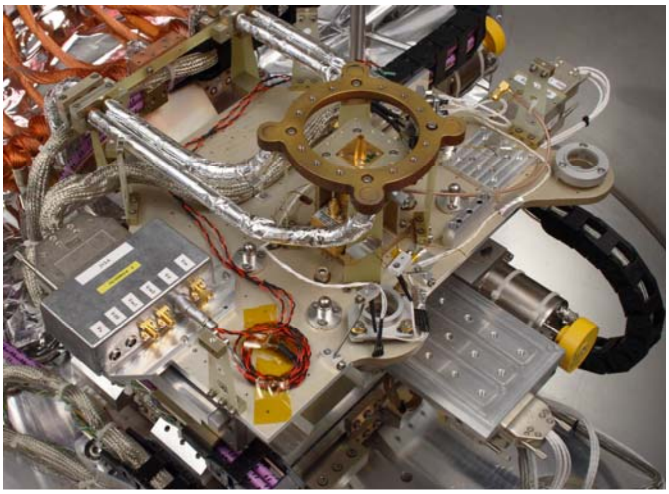

Fig. 7 View on the vacuum scanner system. In the centre the horn of a coherent test source and the thermal interface to the cold absorber screen are visible.

V. ILT RESULTS AND FOCAL-PLANE FOOTPRINT

During the ILT test campaign we measure the HIFI focal plane beams in 4 clusters. By using a test source that operates at the edges between bands a simultaneous measurement of 4 mixers can be done in one cooldown. For band 1 we use a source operating at 480 GHz and measure the beams of mixers 1H and 1V. Using a test source at 800 GHz we measure the beams of 2H, 2V, 3H and 3V resp. A source tuned at 1128 GHz is used to measure 4H, 4V, 5H and 5V. Finally we measure 6H, 6V, 7H and 7V at a frequency of 1619 GHz. Note that for band 7 this is formally an out-of-band frequency and some care has to be taken when interpreting the beam characteristics. Note that in all cases we use phase-locked or direct multiplied lab LO sources instead of the FM Local Oscillator Unit.

An example of a measurement for mixer band 5H is shown in Fig. 8 and 9 in amplitude and phase respectively. We obtain excellent signal-to-noise ratio, however the measured profiles show some scatter due to multiple reflections from shiny thermal shields in between the source and instrument. These multiple reflections can be partially removed by frequency switched measurements as well as in the analysis software. In our analysis we find that the scattering effect does not bias the determined beam properties. We observe that high spatial frequencies are filtered out by propagating the raw data to the focal plane.

We obtain identical results when fitting a fundamental Gaussian beam mode to our data, both in the initial measurement plane as well as in the focal plane after field propagation. The result of the propagation [44-46] of the measured field shown in Fig. 8 and 9 to a reconstructed distribution in the focal plane is shown in Fig. 10. In Fig. 10 we show the reconstructed field of mixer band 5H.

The fitted Gaussian beam that provides highest coupling to the complex field distribution is shown in Fig. 11. In Fig. 11 we show two orthogonal cuts through the field and compare the measured and fitted intensity and phase. The Gaussian fit provides the beam width, the propagation direction and the location of the phase centre and is used to verify compliance with the telescope interface. The Gaussian fitting procedure is explained in detail in [7]. In all cases we measure excellent Gaussian beam coupling well above 90% and in most cases between 93% and 95% We furthermore find that analysis on the measured maps yields similar numbers as compared to analysis on forward propagated model data taken from MSA measurements assuming perfectly aligned FPU optics. Differences we find can be understood in terms of alignment errors, both in the actual flight hardware as well as in the relative alignment between scanner system and FPU.

Finally we directly measure the co-alignment between the mixers operating on orthogonal polarizations. As both mixer are sampled simultaneously the co-alignment can be measured very precisely independent of alignment errors in the scanner system and FPU optics. We find that co-alignment is best in HIFI bands 6 and 7, reflecting the great effort that was put in shimming these lens-antenna based mixers. We discuss compliance further in section VI.

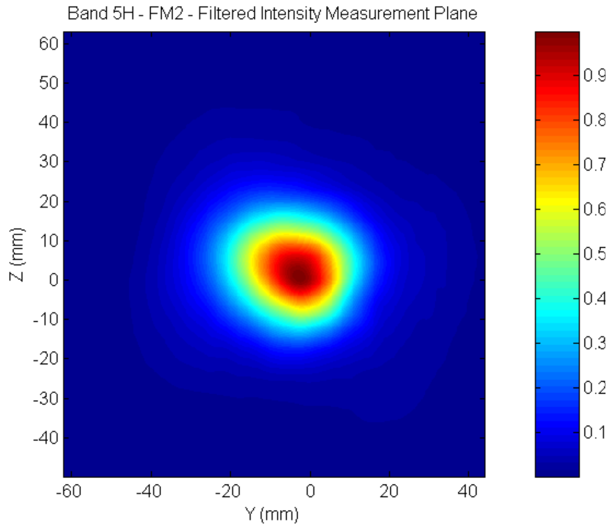

Fig. 8 Measured intensity distribution of band 5H.

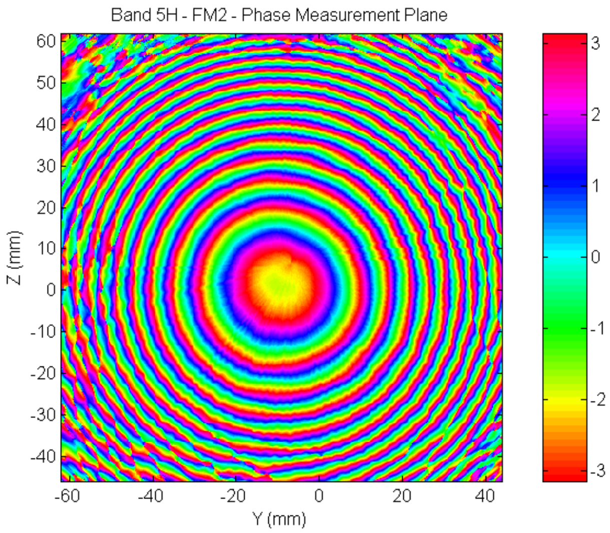

Fig. 9 Measured phase distribution of band 5H.

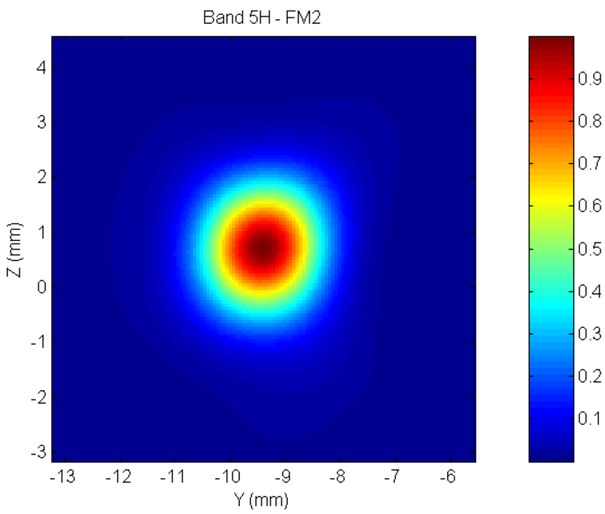

Fig. 10 Reconstructed focal plane field distribution in band 5H.

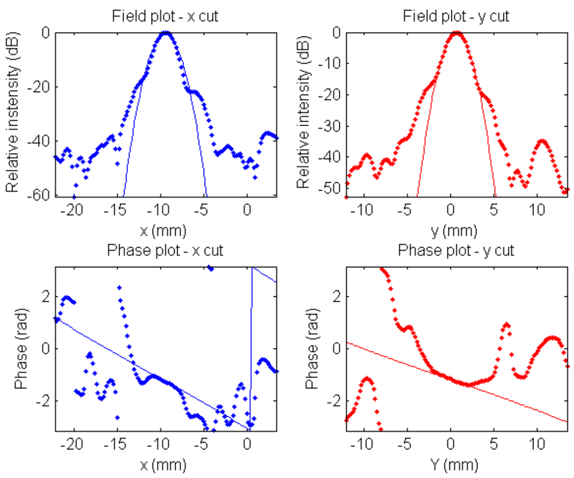

Fig. 11 Measured and fitted intensity and phase cuts in the focal plane for mixer band 5H.

A composite plot showing the results of all beams propagated to the focal plane are shown in Fig. 12. From left to right the bands 1 to 7 are covered. The size of the plot area reflects the actual size of mirror M3 as shown in Fig. 6. Indicated in the plot are the clusters of beam measurements. Within each cluster excellent relative alignment accuracy is available. Between clusters the reproducibility of the alignment procedure between scanner system and FPU optics is applicable as carried out for different configurations and time intervals. For all clusters the absolute alignment between scanner and FPU optics is dominant and is of order of a few mm. Note that a lateral error of a few mm in the focal plane only presents initial pointing inaccuracy but is insignificant as far as the alignment to the secondary mirror of the Herschel telescope is concerned. The systematic nature of alignment errors in the beam measurement is reflected in the pointing calibration plan [47] which we shortly outline in section VIII.

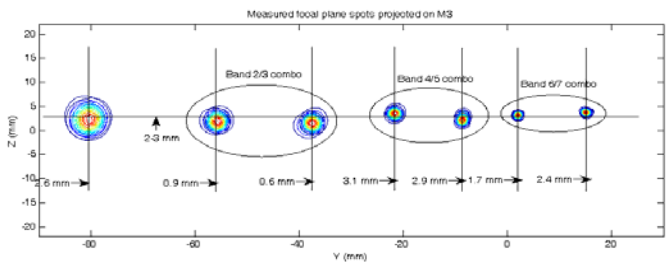

Fig. 12 Measured HIFI beams propagated to the focal plane.

VI. Compliance of Optical Performance

The Gaussian beam fitting results provide propagation direction and location of phase centre as well as the beam properties of the measured field. We compare the measured position (X, Y and Z coordinates) of the waist to the design values. We find that the location of the phase centre nicely follows the focal plane curvature and conclude that all beams are within focus of the Herschel telescope within the wavelength dependent tolerances [42]. Losses due to defocus are generally below 1%.

As explained in the previous section a direct comparison between measured and predicted lateral positions in the focal plane fails because of alignment errors between scanner plane and instrument. On the basis of forward propagated data obtained at MSA level, and knowledge of the visual laser light alignment of the FPU optics, we belief that the absolute errors of the beams in the focal plane are as small as 0.5 mm which corresponds to 3.5” at the sky. The absolute positions of the HIFI beams will anyhow be calibrated in-orbit as described in section VIII. As far as compliance is concerned the observed lateral deviations are insignificant as compared to the pupil alignment requirement [42] (illumination of the secondary mirror of the Herschel telescope).

As far as co-alignment is concerned we observe in general that mixer bands 6 and 7 show best co-alignment figures. This reflects the mechanical shimming corrections applied at MSA level [19]. For band 1 to 4 no mechanical corrections have been applied and co-alignment figures are generally worse and do not generally satisfy a 10% of waist radius co-alignment goal. We therefore decide to make default use of a telescope pointing in between the sky positions of the two polarizations. Worst-case coupling losses for a point source are then reduced by a factor of 4 as compared to using one polarization only. The co-alignment results are summarized in Table I. For each band we list the measured lateral offset in Y and Z (spacecraft coordinates) in mm. The fourth column indicates the total lateral offset. Note that 1 mm in the focal plane corresponds to roughly 7” at the sky. The waist radius is listed in the fifth column followed by the co-alignment error as a fraction of the waist radius. The last two columns indicate the coupling loss for a point source. $L_{H,V}$ indicates the coupling loss observed for one polarization channel when pointing the telescope at the other polarization. The last column indicates L_S, the coupling loss for synthesized pointing, where the telescope is pointed in between the H and V sky positions. As can be seen from the table the associated coupling losses are a factor of four lower, but losses are now present for both polarizations. When co-adding spectra, which is the default mode of scientific operation, there is a clear advantage to use a synthesized pointing approach.

TABLE VI
Co-alignment Results Obtained During ILT

Band	ΔY	ΔZ	ΔR	W_0	$\Delta R/W_0$	$L_{H,V}$	L_S
1	2	0.2	2	3.87	0.52	0.27	0.07
2	0.6	0.2	0.6	2.32	0.26	0.07	0.02
3	0.7	0.6	0.9	2.32	0.39	0.15	0.04
4	0.2	0.3	0.4	1.65	0.24	0.06	0.01
5	0.1	0.6	0.6	1.65	0.36	0.13	0.03
6	0.1	0	0.1	1.15	0.09	0.01	0.00
7	0.1	0.1	0.1	1.15	0.09	0.01	0.00

Next we discuss the alignment on the secondary mirror of the Herschel telescope. Alignment on M2, or pupil alignment, is important for the aperture efficiency and sidelobes of HIFI. The general requirement is to satisfy pupil alignment within

10% of the beam radius. Measured in the focal plane, M2 pupil alignment errors translate to tilt errors of the propagation direction of the beams. We observe that M2 pupil alignment generally satisfies 10-15% of the waist radius [41].

Finally we find that the measured waist size is within 10% from the design value. We conclude therefore that all HIFI bands are compliant with the quasi-optical alignment budget [42-43]. Expected aperture efficiencies, assuming an ideal telescope, should be within 10% from the design values.

VII. Beam Properties at the Sky

Finally we simulate the expected beam patterns at the sky by propagating [44-46] the measured results through a telescope model and applying a pupil mask representing the obscuration by the secondary mirror and support structure. An example of the masked telescope aperture field is shown in Fig. 13. The example is given for band 7 at 1.8 THz. An example of the wavefront error map in band 1 is shown in Fig. 14. By a Fourier Transform of the complex aperture field distribution at the primary mirror we obtain the far-field distribution.

The as-determined far-field profiles show generally good performance. We find highly symmetric beams which nicely follow a Gaussian distribution down to -20 dB. Sidelobes usually appear at the -20 dB level. Sidelobes are not always symmetric. Aberrations, astigmatism and coma originating from the focal plane beams causes this asymmetry [24-25]..

An example of a far-field cut obtained for band 1 is shown in Fig. 15. In this figure we show two orthogonal intensity cuts obtained in the principal planes of the satellite coordinate system together with the expected pattern on the basis of a truncated Gaussian beam. Although there are some differences in the sidelobes, the general agreement is excellent.

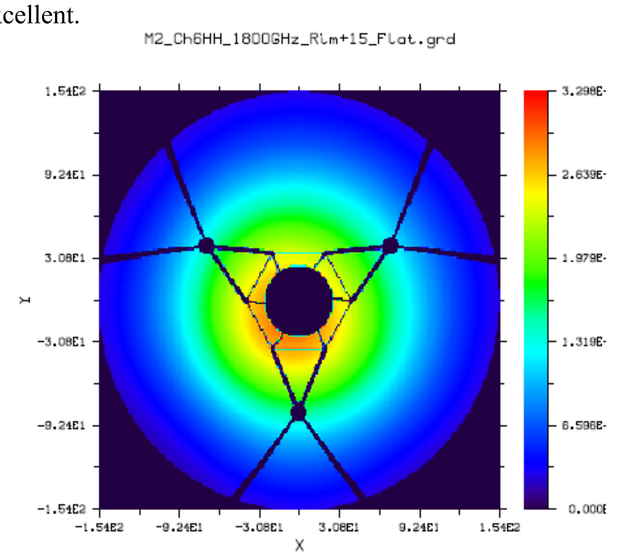

Fig. 13 Example of an obscured telescope aperture field.

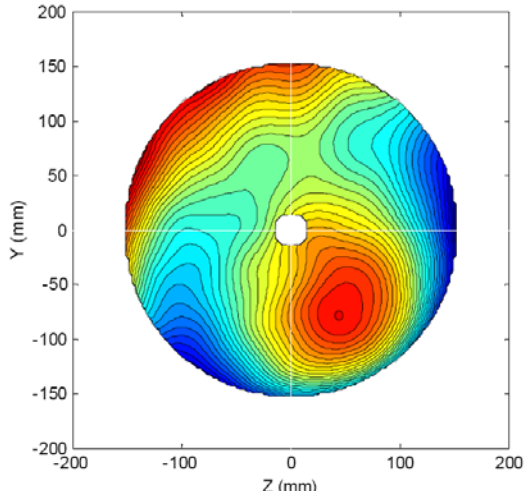

Fig. 14 Example of a measured wavefront error map in band 1.

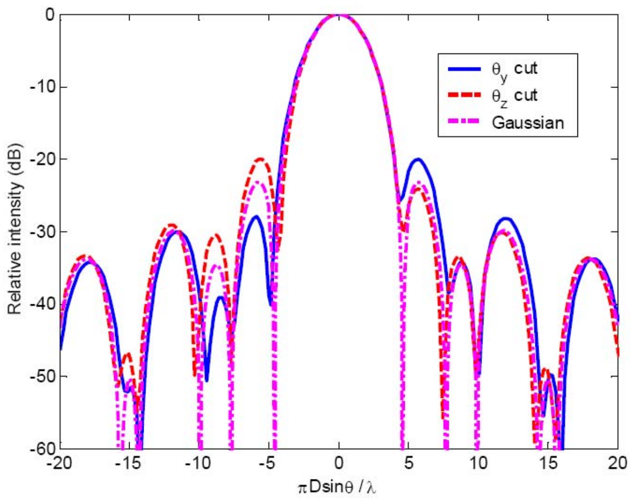

Fig. 15 Example of a far-field cut obtained for band 1

VIII. In-Orbit Calibration

In the previous sections it is explained that the absolute knowledge of initial pointing performance is limited by the metrology available during ILT. Consequently our initial estimate is not better than 3 to 4". This is however a fairly good number to start with given the size of the FWHM beam width ranging from typically 40" in band 1 to 10" in band 7. In close collaboration with the other Focal Plane instruments PACS and SPIRE on Herschel, the Herschel pointing calibration working group has issued a calibration plan in which a procedure is presented to calibrate the pointing direction for each individual aperture in HIFI [47]. For HIFI two Focal Plane Geometry calibration activities are foreseen. In the initial step a relatively large beam map is taken for one band at one frequency in each cluster mentioned in section V. Together with the results obtained in ILT, the relative knowledge of the other beams in each cluster is used to refine the initial estimate for a second calibration step. In the second finer calibration measurement, a smaller map of two times the FWHM is taken to obtain the final pointing calibration. For pointing calibration we will use planets as test sources. An example of the planned coarse and fine maps is illustrated in Fig. 16. In Fig. 16 all apertures of HIFI are shown, from right to left bands 1 to 7 projected on the sky can be recognized. The central row is for the central position of the focal plane chopper, the upper and lower rows correspond to the chopped positions which are separated by the chopper throw of 3'. The raster for the FPG coarse calibration is shown on the top row, whereas the final FPG fine calibration is shown on the bottom row.

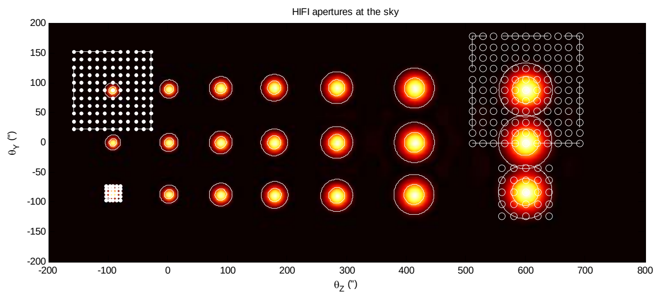

Fig. 16 Focal Plane Geometry calibration rasters shown on top of the nominal aperture positions for HIFI.

In addition to in-orbit pointing calibration we eventually measure in detail the beam patterns of all HIFI beams and determine aperture efficiencies at a number of frequencies as part of the spatial framework calibration activity for HIFI [48].

SUMMARY AND CONCLUSIONS

In this paper we provide an overview of simulation, alignment and beam measurement results obtained for HIFI. We present the alignment approach adapted and pre-flight model verification results supporting the selected verification method. We present the experimental setup and summarize results obtained during the Instrument Level Test program. We conclude that HIFI is fully compliant with the quasi-optical alignment budget. This implies that the total loss due to optical coupling loss is limited to 6% and the aperture efficiency for a nominal telescope is within 10% from the expected value. We furthermore observe that co-alignment is generally within 20-30% of the waist radius or within 10-15% of the FWHM. When pointing at the average sky position the loss per polarization channel is worst-case 7% and more typically 2-4%. In band 6 and 7 we achieve nearly perfect co-alignment, reflecting the careful mechanical shimming work done at Mixer Sub-Assembly level. We furthermore predict expected beam patterns at the sky by propagation of measurement results through a telescope model. Final pointing and beam pattern calibration will be carried out in space.

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