Optics Design and Verification for the APEX **S**wedish **He**terodyne **F**acility **I**nstrument (SHeFI)

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***Abstract*—In this paper, we present the design and verification of the receiver optics for the Swedish Heterodyne Facility Instrument (SHeFI) of the APEX telescope. SHeFI is placed in the telescope Nasmyth cabin A (NCA). The receiver is designed to carry up to 6 frequency channels of which four receiver channels have been designed, built and characterized: 211-275 GHz (Band 1); 275-370 GHz (Band 2); 385-500 GHz (Band 3); 1250-1390 GHz (Band T2). Bands 1, 2, and T2 were installed in the telescope during Spring 2008 and are currently in operation. The first three bands use 2SB SIS mixer technology and Band T2 employs HEB mixers in a waveguide balanced mixer configuration. The entire optics design was driven by the requirement of frequency independent illumination of the secondary with -12 dB edge taper and the limitations imposed by the receiver position in the NCA. The optical system is designed to provide coupling of the SHeFI receiver channels and PI instruments placed in NCA to the common optics of the telescope and cover the wide frequency range from 210 GHz to 1500 GHz. In the paper, the design approach, optimization, and verification are described.**

I. INTRODUCTION

APEX, the Atacama Pathfinder Experiment [1], is a collaborative project involving Max Planck Institut für Radioastronomie (MPIfR), Onsala Space Observatory (OSO), and the European Southern Observatory (ESO). The telescope is located at latitude 23º00'20.8" South, longitude 67º45'33.0" West at an altitude of 5103 m in the Atacama desert, Llano Chajnantor, in the northern part of Chile Figure 1. APEX is a Cassegrain type telescope, manufactured by Vertex Antennenteknik [2], with a 12 m in diameter primary mirror, having a surface accuracy of 17 µm, and an antenna pointing accuracy of 2" rms. The telescope has, except for the Cassegrain cabin, two additional instrumentation cabins, Nasmyth cabin A and B. SHeFI was designed to be located in the telescope Nasmyth cabin A (right in the Figure. 1) and where it was installed during the Spring 2008. The optical system is designed to provide coupling of the SHeFI channels and the PI instruments residing in the NCA to the telescope and covering a very wide frequency operating range from 210 GHz to 1500 GHz. Detailed information regarding the complete receiver design is found in [3], while we focus exclusively on the optical design in this paper. SHeFI is designed to carry up to 6 receiving channels of which four frequency channels have been designed, built, integrated into the receiver and characterized: 211-275 GHz (Band 1) [4]; 275-370 GHz (Band 2); 385-500 GHz (Band 3) [6]; 1250-1390 GHz (Band T2) [7].

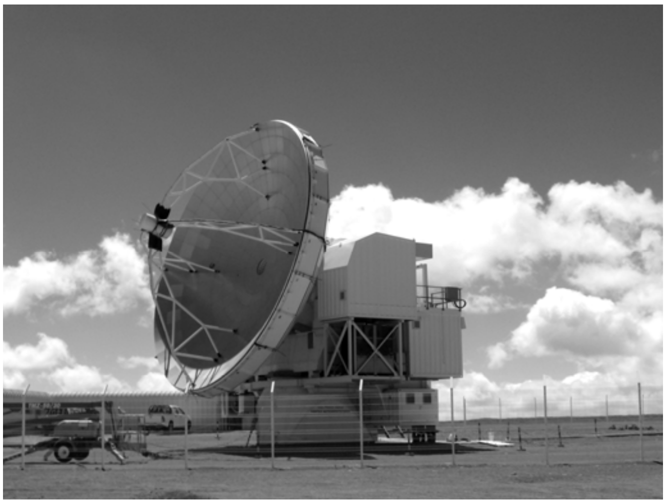

Figure 1. APEX telescope at 5100 m in the Atacama Desert, Llano Chajnantor, Chile.

It is the atmospheric conditions and the surface accuracy of the primary mirror that introduce general limitations for the upper observing frequency. The degradation factor of the antenna aperture efficiency with frequency and the surface accuracy can be estimated according Ruze formula $\eta_a(\lambda) = \exp(-16\pi^2\sigma^2/\lambda^2)$ [8] where σ is the RMS error of the antenna surface. According to this formula, at 1400 GHz, the APEX antenna keeps approximately 37 % of the initial aperture efficiency. Figure 2 illustrate simulated atmospheric transparency [9]. The location of the SHeFI receiver frequency bands coincide with the atmospheric windows [10].

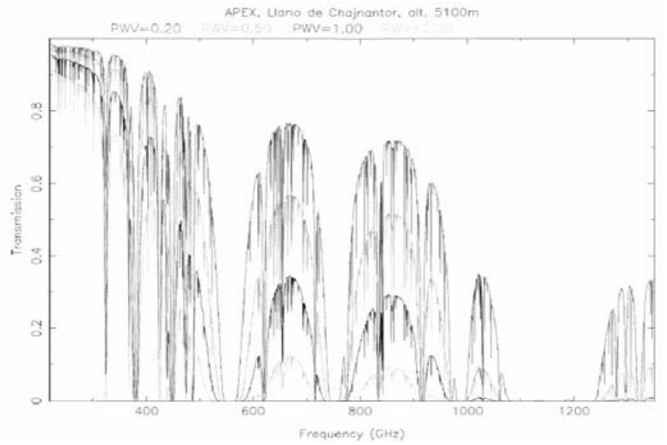

Figure 2 Atmospheric transparency at the APEX telescope site [9].

The objectives of this article are to summarize the design strategy and implementation of the optical system, to describe the integration of the receiver optics with the telescope optical system, and to explain the optics verification procedure and present results validating the design. A detailed description of the optical system in the Cassegrain cabin and NCA is presented below, Section II, where we present the design of the frequency independent optical system. Section III is dedicated to the description of the cold optics and the feed horn design. The verification and alignment of the cryostat optics is described in Section IV and the installation procedure at the telescope, including mechanical- and RF alignment is described in the Section V. Section VI presents results of the final verification of the optical design in terms of telescope pointing accuracy.

II. APEX CASSEGRAIN AND NASMYTH CABIN A OPTICS

The APEX telescope is a Cassegrain type telescope and is a prototype for the ALMA antenna. The antenna parameters are summarized in Table 1. However, in contrast to the ALMA antenna, containing all instruments in the Cassegrain cabin, the APEX telescope carries two additional instrumentation cabins, Nasmyth cabin A and B [11] [12]. The SHeFI receiver is located in the Nasmyth cabin "A" of the telescope, together with two PI instruments and is connected to the Cassegrain cabin by the Nasmyth tube. The optics layout of the Cassegrain, NCA, and SHeFI optical system is shown in Figure 3. The axial distance from the secondary focal point to the Nasmyth flange is about 3.2m and the antenna signal is guided to the Nasmyth cabin by the Nasmyth tube.

TABLE 10. ANTENNA PARAMETERS FOR THE APEX TELESCOPE.

Symbol	Description	Value
D	Primary aperture	12 m
fp	focal length primary	4.8 m
fp/D	ratio of primary	0.40
d	Secondary aperture	0.75 m
f/d	Final f/d ratio	8

The entire optics design was driven by the location of the receiver in the Nasmyth cabin, and consequent limitation of the aperture, Ø150 mm, introduced by the elevation encoder inside the Nasmyth tube A. Extremely wide frequency range of the instruments in the NCA, up to 32% of the center frequency, necessitates a frequency independent optical solution that should include the entire 8 mirror system. The broad frequency band, the location of the instrument, and the small clearance diameter of the elevation encoder exclude the use of ALMA type off-axis antenna illumination scheme [13].

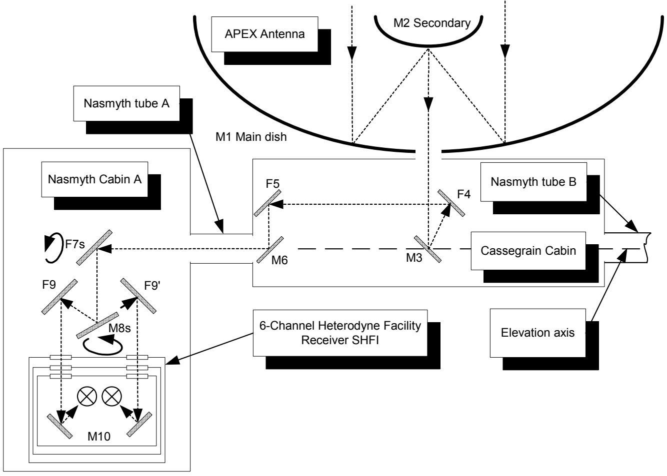

Figure 3. Optical layout of the Cassegrain and Nasmyth cabin A facility receiver.

Instead, we use two precision rotating flat mirrors to provide switching between PI instruments and SHeFI and also between the different receiving bands of SHeFI [14] and bringing the input receiver beams at the axis of elevation (coincides with the center of the Nasmyth tube A). The complete optical path, coupling the receivers to the Cassegrain sub-reflector, works as a re-imaging system, transferring the image of the secondary onto the aperture of the corrugated horn for each receiver, keeping the illumination of the secondary at -12 dB edge taper.

The Cassegrain and NCA optics consists of the three offset ellipsoidal mirrors, M3, M6, M8s, and three flat mirrors, F4, F5, and F7s, Figure 3. The combination of the M3 and M6, with flat F4, F5, forms a Gaussian telescope, providing frequency-independent re-imaging of the antenna focal plane from the Cassegrain cabin into the Nasmyth Cabin A [15],

[16], [17]. The M3 and M6 focal lengths were optimized in terms of minimizing distortion and providing beam clearance on the encoder position. The flat mirrors F4 and F5 are used to fold the beam in the Cassegrain cabin in order to avoid interference with multi-pixel bolometric instruments and their respective optics. The flat mirror F7 (see Figure 3) is the optical switch between SHeFI and the PIs [18]. Switching between SHeFI channels is achieved by the precision rotating of the active mirror M8s [14]. The mirror M8s in combination with each channel active mirror M10 have been chosen in such a way that they provide re-imaging of the secondary onto the feed horn aperture of the selected channel. Compared to the ALMA optical solution [16] and [17], the APEX Cassegrain and NCA optics requires a more complex optical path, including 8 mirrors coupling the secondary image to each mixer horn.

The idea of the frequency independent illumination [15], [16], [17], can be illustrated by utilizing the ray matrices for paraxial beams in conjunction with the complex beam parameter q [21]. As example, the mirror M10 in Figure 4 is described by the distribution matrix (1) for a single optical element with the focal distance f1. The associated reference cross-sections are at the horn aperture, at the distance L1 (the lens position), and at an arbitrary distance L2 from the lens position as indicated in Figure 4.

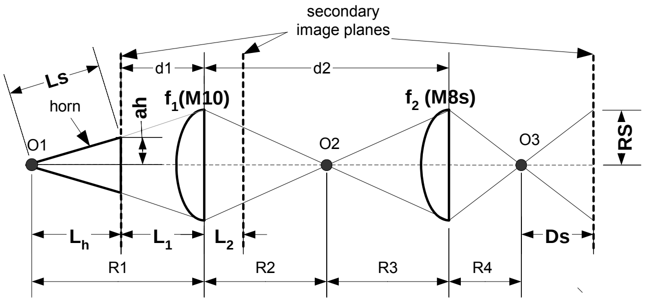

Figure 4. Nasmyth cabin equivalent optics scheme. Points O1,O2,O3 refer to the focal points, traced from the original Cassegrain focal point. M8s and M10 – off – axis ellipsoidal mirrors with focal distances equal f2 and f1 respectively. Dashed lines refer to the secondary image planes. Ls- horn slant length, ah- horn aperture radius.

$$M = \begin{bmatrix} 1-\frac{L_2}{f_1} & (1-\frac{L_2}{f_1})\cdot L_1 + L_2 \\ \frac{-1}{f_1} & \frac{-1}{f_1}\cdot L_1 + 1 \end{bmatrix} \tag{1}$$

It is assumed that the reference plane is the horn aperture with a Gaussian beam distribution parameter equal to

$$q_0 = \left[\frac{1}{R_i} - j\frac{\lambda}{\pi\cdot\omega_i^2} \right]^{-1} \tag{2}$$

where λ- wavelength, ω_i -beam radius , R_i- radius of the phase curvature, referred to the horn aperture according to [21]. For an initial optics designing stage, those parameters could be related to the horn's geometry as: R_i=Ls, ω_i=0.64 ah.

$$q_2 = \left[\frac{M_{0,0}\cdot q_0 + M_{0,1}}{M_{1,0}\cdot q_0 + M_{1,1}} \right] \tag{3}$$

Choosing $M_{0,1} = 0$, results in

$$L_2 = \frac{-L_1\cdot f_1}{f_1 - L_1} \tag{4}$$

and is associated with the geometrical optics image position of the horn aperture. In our case it also coincides with the secondary image plane and it can easily be shown that by substituting (1) and (2) into (3).

$$q_2 = \left[\begin{array}{l} (R_i + f_1 - L_1)\cdot\frac{f_1 - L_1}{R_i\cdot(f_1)^2} - \ldots \\ \qquad\qquad \ldots - j\frac{\lambda}{\pi\cdot\left(\omega_i \frac{f_1}{f_1 - L_1}\right)^2} \end{array} \right]^{-1} \tag{5}$$

This gives the relation between the initial beam parameters, ω_i and R_i, and the transformed beam parameters, ω_2 and R_2 as following:

$$R_2 = \frac{R_i\cdot(f_1)^2}{(f_1 - R_i + L_1)\cdot(f_1 - L_1)} \tag{6}$$

and

$$\omega_2 = \frac{f_1}{f_1 - L_1}\cdot\omega_i \tag{7}$$

Equation 6 and 7 show that the Gaussian beam parameters (the phase curvature and the beam radius) at the image planes of the optical system are frequency independent and coincide with the geometrical optics solution describing single - lens transformation. This means that the geometrical optics approximation can be used to perform beam tracing and determine the position of the image plane cross sections. The results also implies that, in the assumption of frequency independent field distribution on the horn aperture, an optical re-imaging technique can be used for transferring the horn aperture image onto the secondary to provide frequency independent antenna edge taper illumination .

When designing the SHeFI optical system, a two-mirror re-imaging scheme (M8 and M10 in Figure 4) was investigated under the assumption of the fundamental Gaussian beam mode propagation while the mirrors were represented as ideal quadratic phase transformers. The design parameters and design equations are presented in Table 2, where Lh and ah is the length and aperture radius of the feed horn. All parameters in Table 2 can be seen in Figure 4 where the example two-mirror system is illustrated.

TABLE 2. DESIGN PARAMETERS OF THE TWO-MIRROR RE-IMAGING SCHEME, SEE FIGURE.

Parameters	Equations
Variable parameters	Lh, ah, f_2, R_4
Scale parameter K	$\frac{Lh}{ah} \cdot \frac{Rs}{Ds}$
R_1	$Ds \cdot Lh \cdot K \cdot \frac{K \cdot (f_2 - R_4) - f_2}{Ds \cdot K^2 \cdot (f2 - R_4) - (f_2 - R_4 - Ds) \cdot Lh}$
d2	$f_2 \cdot \frac{R_4 \cdot K + R_1}{(R_4 - f_2) \cdot K}$
L_1	$R_1 - Lh$
f_1	$f_2 \cdot \frac{R_1}{(R_4 - f_2) \cdot K + f_2}$

The optimization goals for the optical design were chosen as following: **i.** minimum distortions, **ii.** minimum cross-polarization, **iii.** minimum dimensions for all optical components and horn. Because of severe space limitation for placing SHeFI, constrains of geometry implementation were imposed. In order to optimize to minimum possible distortion and cross-polarization level, formulas presented by Murphy [23] were used. In order to keep the cross-polarization and beam distortion from the corrugated horns under control, we used the bending angle of the horn with respect to the off-axis elliptical mirror (M10, Fig. 4) as small as possible [23] for given geometrical constrains. The full bending angle between the incoming and the reflected beam is 25°.

In order to avoid truncation losses along the optical path, a clearance of $5\omega_o$, where ω_o is the 1/e Gaussian radius, was used for all cryostat windows, IR filters and passive and active optical components ensuring the truncation loss of less than 1% [24], [16].

All receiver channels of the SHeFI are cryogenically cooled down to 4 K, which imposes additional uncertainty for final RF optics alignment because of the thermal contraction of the optical components and support brackets and impossibility to verify / measure the receiver optics geometry under operation. In order to address this uncertainty, angular position of the flat mirrors F9, Figure 3 and Figure 5, was made adjustable. That gives additional possibility of the beam alignment fine-tuning for every SHeFI receiver channel independently.

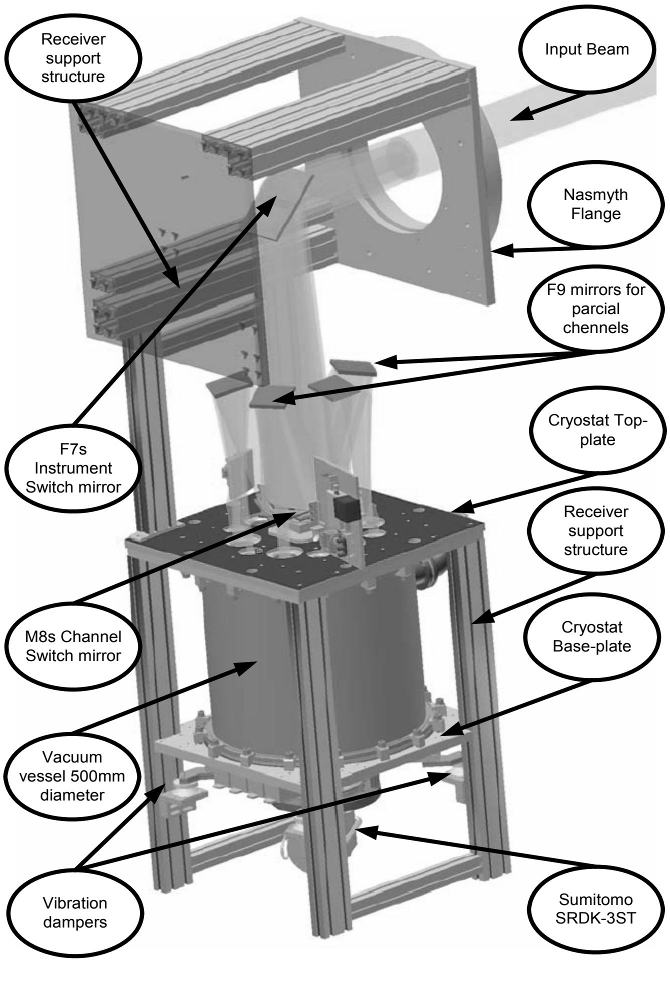

Figure 5. Nasmyth Cabin A optical system.

III. COLD OPTICS AND CORRUGATED HORNS

The space in the Nasmyth cabin A is limited and requires a very compact design in order to fit the 6 channel receiver and the PI instruments. To achieve the compact design, the receiver was built around the vertically positioned cryo-cooler [19], where all receiver channels are interfaced to a common reference plate, the mixer assembly interface plate. The common reference plate is linked to the 4K stage by flexible copper braids to provide cooling as well as vibration damping. The very compact design and radial placement of the mixer assemblies provides easy access to all receiver channels, once the cryostat vessel is opened and two thermal shields are dismounted.

Diagonal horns were used for the LO signals, except for the THz band where a corrugated horn is also used to couple the LO signal to improve the efficiency of the LO power guiding. For the RF signal coupling, all SHeFI receiver bands employ corrugated horns given that this type of feed provides nearly ideal performance with a very symmetric beam pattern, spherical wave fronts, low cross-polarization, good matching to waveguide, wide bandwidth, and up to 98% coupling efficiency with the fundamental Gaussian mode [20], [21].

IV. BEAM MEASUREMENTS

In order to characterize/verify the quasi-optical design and to align the receiving beams of the SHeFI, we performed vector-field measurements in the laboratory. This is done by performing vector field measurements of the receiver output while scanning a probe (point) source in the plane transverse to the beam propagation. The receiver input beam could be fully characterized by appropriate data processing [21]. Such procedure provides estimates for the direction of propagation (beam axis 3D position), the size and position of the beam waist, as well as the shape of the beam. The measured data are fit in 3D to the fundamental Gaussian beam to the measured by optimizing the power coupling coefficient. The measurement system is designed in such a way that it can perform vector field measurements within 211-500 GHz band, by only switching two filters and LO units, thus covering APEX Band 1 to Band 3. The LO- units were later installed in the telescope. In Figure 6 a two-dimensional amplitude map of the APEX Band 1 beam at 221 GHz is shown. The measured beam is fit to the fundamental Gaussian mode very well (estimated coupling efficiency ~98%) and it appears circular above -20 dB level.

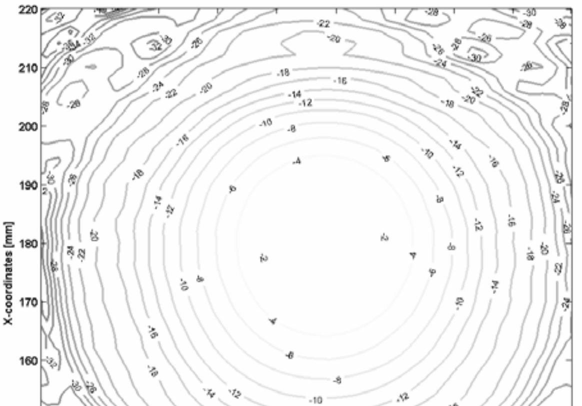

Figure 6. Power distribution of the beam pattern of the receiver measured for APEX Band 1 at 221 GHz. The beam pattern is circular down to -20 dB relative to the on axis value.

It needs to be pointed that at the same time as the vector field measurement system provides an extremely wide frequency range, it is limited to a number of discrete frequency points within each band, since a combination of a single frequency source and a comb generator is used to generate perfectly phase-coherent RF and LO signals. A detailed description of the vector measurement system can be found in [25].

In order to characterize the T2 band, scalar measurements were conducted, since the regular test source for the vector measurement system did not provide enough output power at those frequencies even though the measurement system flexibility allowed us to try the vector measurements as well though with a poor signal – to – noise ratio. In order to generate sufficient power, we employed the LO-source for Band 3 as a test source and the third harmonic was used to generate a RF-signal > 1300 GHz. In this case several transverse planes along the signal path were scanned in order to determine the position and the size of the beam waist [26]. Any possible tilt of the beam is determined by fitting a line through the amplitude centers. A map of the power distribution of the receiver beam, measured at 1334 GHz is shown in Figure 7.

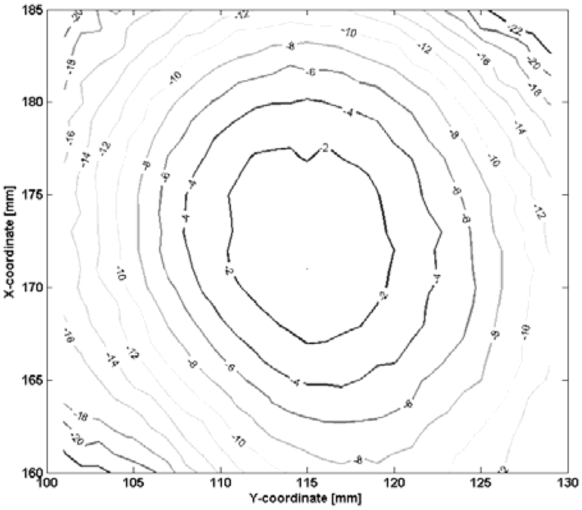

Figure 7. Power distribution of the beam pattern of the receiver for APEX Band T2 measured at 1334 GHz.

V. INSTALLATION AND VERIFICATION AT THE APEX TELESCOPE

The installation procedure at the telescope has been taken in two phases, the mechanical alignment of the SHeFI receiver and the RF alignment of each individual receiving beam for optimum coupling to the common optics of the telescope. The mechanical reference in the NCA is the flange at the Nasmyth tube on which the whole receiver support structure is attached, see Figure 5. The goal of the mechanical alignment was to align the receiver warm optics plate (see Figure 5) with respect to the Nasmyth flange. During the mechanical alignment the receiver warm optics is separated from the cryostat in order to ease the handling and hence the alignment (see Figure 8). The mechanical alignment is done by placing a laser at the center of the Nasmyth flange in combination with a flat mirror on the receiver warm optics plate. The laser shines via the PI switch onto the flat mirror and is then reflected back to the laser as schematically illustrated in Figure 8). The receiver warm optics plate is adjusted until the reflected laser beam coincides with the laser aperture. A Position Sensitive Detector (PSD) [27] is then used for precision centering of the receiver warm optics plate in the horizontal plane.

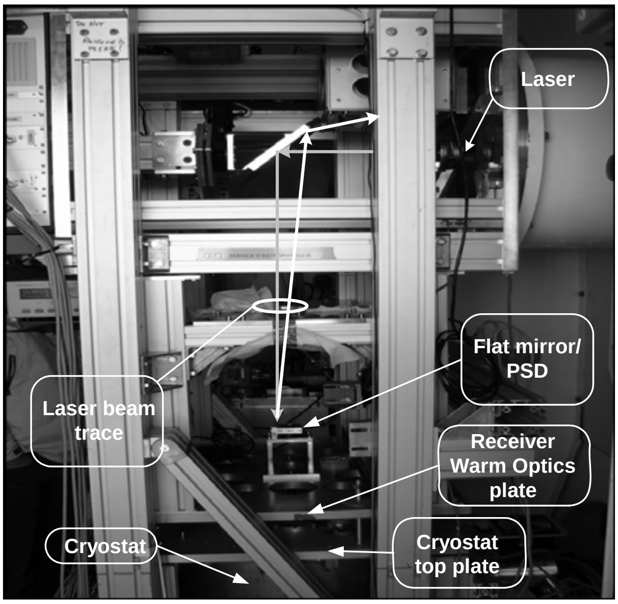

Figure 8. Mechanical alignment procedure with the laser bracket in the NCA flange.

Once the mechanical alignment is done the cryostat is lifted up and the top plate is bolted to the receiver warm optics plate and the support structure.

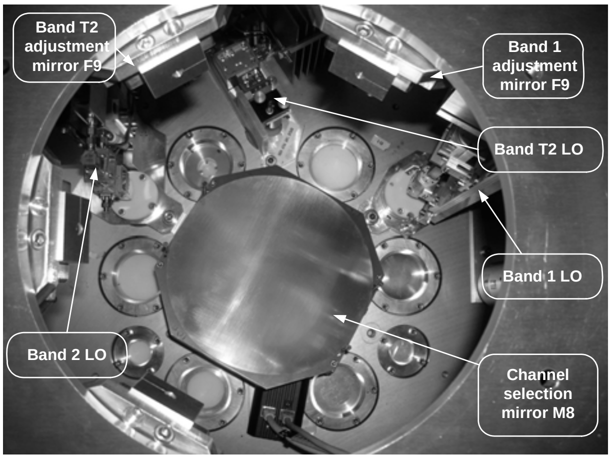

Figure 9. Top view of the channel switching mirror and the flat adjustment mirrors.

The RF beam alignment is carried out by introducing a piece of a cold absorber (dipped in liquid nitrogen) at the center of the Nasmyth flange while observing the receiver IF output power level. The individual receiver beams between the channel selection mirror (M8, in Figure 3) and the mixer horn aperture are aligned by adjusting the flat channel mirrors (F9, in Figure 5) until the largest drop in the output IF power observed when the absorber is centered at the Nasmyth flange. Figure 9 shows the channel selection mirror, M8, and the individual channel tuning mirrors, F9s. The procedure is then repeated with the absorber inserted close to the telescope focal plane to verify the alignment throughout the whole optical path.

VI. FIRST LIGHT RESULTS

After completing the mechanical and RF beam alignment, the exact offset and tilt of the beams with respect to the telescope focus have to be established. This was done by pointing the telescope at well known sources on the sky and measuring the offset and tilt. The telescope adjustable secondary can compensate for small offsets, ±15 mm for the z-offset, ± 10 mm for the x- and y-offset, and once the offsets and tilts are determined the values are used to calibrate the pointing during observations. The pointing is continuously recalibrated, since the offsets may vary with temperature and elevation of the telescope. For calibration of the APEX Band 1 and Band 2 Mars and Saturn were used as such calibration sources. Mapping of the planets were performed in order to find the azimuth-, elevation-, x-, y-, and z-offsets. The measurement results for azimuth and elevation offsets measured from continuum pointing on Mars can be seen in Figure 10 with the secondary wobbled to improve accuracy of the measurements.

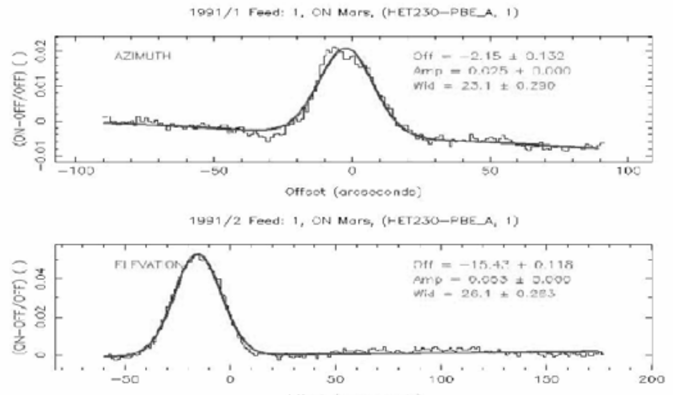

Figure 1014. Measured results for azimuth and elevation offsets measured from continuum pointing on Mars at 230 GHz.

Through these measurements it was verified that the optical alignment had been very successful and the offset in azimuth and elevation was less than 16 arc seconds and the telescope focus in z-direction was offset by 100 µm only!

CONCLUSIONS

In this paper, we present the optical design and experimental verification of the APEX 6-channel facility instrument, SHeFI. Currently three receiving bands are installed in the APEX telescope, Band 1 (211-275 GHz), Band2 (275-370 GHz), and T2 (1250-1390 GHz). The implemented optical design is optimized to fulfil, requirement of a frequency independent illumination of the secondary at -12 dB edge taper for each frequency band, the constraints with respect to the placement of the instrument in the APEX telescope Nasmyth cabin and consequently the RF beam clearance limitation by the elevation encoder. The entire design was optimized to fit the limited space available inside the APEX telescope Nasmyth cabin A. The procedures for the optical design and the optical components optimization, including the corrugated horns, are described. Laboratory pre-shipment vector beam measurements as well as the installation procedure and verification results at the telescope are presented. The telescope pointing results confirms that the optical design and SHeFI receiver performance is up to expectations.

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