# Design and Test of the Optical Adapter used for Near-Field Measurements of TELIS

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# Summary

The following report describes the work done regarding the planned nearfield measurements of the Telis telescope optics [2]. Telis is a balloon-borne limb-sounding experiment with the aim of retrieving the height distribution of atmospheric traces gases such as ozone, water vapour etc. It will be operated at three frequency bands with center frequencies of 500GHz, 650 GHz and 1.8THz. The instrument optics consists of specific components for each channel and a telescope which is used by all channels. For reference on Telis see [1].

The work is divided in two parts. The first part deals with the design of a quasioptical adapter, which will be used for these measurements. Since we only want to test the telescope optics used by all channels we have to build an optical component which simulates the beam produced by the part which is not used in the measurements. The optical adapter was designed using extended gaussian optics, which takes higher order gaussian modes into account. The second part deals with the near-field measurement of the optical adapter.

# Literatur

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# Guoy-Phase Analysis of a two-mirror Optical System

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#### Abstract

In this report we analyse the radiation characteristics of a two-mirror optics regarding the total Guoy-Phase of the entire system. Non-ideal feed systems such as corrugated horn antennas cannot be described with a single zero-order Gaussian beam only. The phase relation of these higher order modes has to be taken into account designing an optical system. In this report we analyse a two-mirror optical system focusing on the total Guoy-Phase. Computations using physical optics and gaussian beam analysis are presented. It has been shown that the gaussicity of an optical system can be slightly increased by adjusting the total Guoy phase.

### 1 Introduction

Due to it's simple mathematical description Gaussian Beam Optics is nowadays successfully applied for the design of optical systems at submillimeter wavelengths. While for electrically large system the description of the field with geometrical optics/and or the fundamental Gaussian Beams is sufficient for electrically small systems the presence of higher-order Gaussian Modes has to be taken into account. Higher order modes are excited in a system due to nonideal feeds, limited-size optical components and spatial aberrations at focusing elements. These unwanted higher modes can degrade the performance of the optical system due to spill-over signals.

In this report we apply the analysis and optimisation scheme to a two-mirror antenna test feed optics for the TELIS project. The aim of this optics is to synthesise a Gaussian beam with a beam-waist of 3.2 mm at 625 GHz. TELIS contains highly sophisticated quasioptics which need beams with a very high gaussicity. The optics consists of one parabolic mirror with a focal length of 11 cm, which is given by the TELIS optical design and a ellipsoidal mirror which needs to be optimized. For the feed a corrugated horn antenna originally designed for the SMILES instrument is used.

### 2 Theory

For state-of-the-art submillimeter optical systems the corrugated horn antenna is commonly used as a feed. It has very good polarisation properties and a symmetrical radiation pattern which is described with

$$E = \begin{cases} J_0(r2.405/a) \exp(ik_o \sqrt{R^2 - r^2}) & \text{if } r < a \\ 0 & \text{else} \end{cases}$$
(1)

 $J_0$  denotes the Bessel function of the first kind of order 0, a is the aperture radius and R the horn slant length. Throughout the report  $k_0$  denotes the free space propagation constant. This aperture field distribution can be expressed as a superposition of either Gauss-Laguerre or Gauss-Hermite modes. Both mode sets are solutions of the paraxial wave equation in the the rectangular and cylindrical geometry respectively. Since the aperture field of a hybrid mode has a cylindrical symmetry we will use the Gauss-Laguerre mode set. The field distribution of the cylindrically symmetric Gauss-Laguerre modes read

$$E_{p0}(r,z) = \sqrt{\frac{2}{\pi}} \frac{1}{w(z)} L_{p0}\left(\frac{2r^2}{w^2(z)}\right) \cdot \exp\left(\frac{-r^2}{w^2(z)} - ik_0 z - \frac{i\pi r^2}{\lambda R(z)} + i(2p+m+1)\phi_0(z)\right).$$
(2)

with w(z), R(z) and  $\phi_0(z)$  denoting the beam waist, the phase curvature Radius and the Guoy phase

$$w(z) = w_0 \sqrt{\left(1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2\right)} \tag{3}$$

$$R(z) = z \left( 1 + \left(\frac{\pi w_0^2}{\lambda z}\right)^2 \right) \tag{4}$$

$$\phi_0(z) = \tan^{-1}\left(\frac{\lambda z}{\pi w_0^2}\right). \tag{5}$$

Since the Gauss-Laguerre mode set is a solution of a linear differential equation they are orthogonal over the the scalar product of the function space

$$\langle E_1 | E_2 \rangle = \int_0^\infty E_1 E_2^* r dr = \delta_{12}$$
 (6)

where  $E_2$  and  $E_2$  represent two Gauss-Laguerre modes. The phase contribution are the phase curvature which depends on r and z, the free-space propagation term kz and the Guoy phase  $\phi_0(z)$ . In order to create an accurate image of a given source field distribution the Gauss-Laguerre mode set needs to have the same phase relation on the image plane as on the source plane. Therefore the phase relation also has to be satisfied at r = 0 where the phase curvature term vanishes. The phase difference between a higher mode with index pm and the fundamental mode with index 00 reads

$$\Delta p = (2p+m)\Phi_0(z) \tag{7}$$

where  $\Phi_0(z)$  denotes the total Guoy phase. In order to get an in-phase image of the source  $\Delta p$  has to a multiple of  $2\pi$ . Assuming a circular symmetric field (m = 0) yields

$$u\pi = p\Phi_0(z) \tag{8}$$

trivially, if the relation 8 is satisfied for p = 1 then it is satisfied for all other modes too. For an entire optical system containing N focusing elements the Guoy phases have to be summed up according to

$$\Phi_0 = \sum_{q=0}^{N-1} \phi_0(w_q, d_{q,2}) - \sum_{q=0}^{N-1} \phi_0(w_q, -d_{q,1}) + \phi_0(w_N, d_N)$$
(9)

where  $w_q$  denotes the waist,  $d_{q,1}$  the positive distance and  $d_{q,2}$  the negative distance. In our example case  $\Phi_0$  is composed of four Guoy phase terms. Each of these terms corresponds either to a focusing or expanding part of the Gaussian Beam.



Figure 1: beam waist plot (left) and Guoy phase plot of the example case

In order to obtain a total Guoy phase of  $\pi$  the distance between the first mirror and the beam waist after it has to be varied. Equating (9) with  $\pi$  and solving for the distance  $d_{21}$  yields

$$d_{21} = \tan(\pi - \phi_0(w_1, d_1) - \phi_0(w_2, d_{22}) + \phi_0(w_3, d_{31})) \frac{\pi w_2^2}{\lambda}$$
(10)

A Guoy Phase conserving design can therefore be designed according to the following steps. First the field of the horn antenna has to be expanded in a series of Gauss-Laguerre Modes. The waist and the distance from the horn aperture was optimised for a maximum coupling into the lowest order mode. With this information equation (10) is solved. The mirror parameters for the first mirror is then computed using matrix optics. With this design approach at the output image plane a magnified version of the aperture field distribution is imaged yielding a gaussicity of about 98%. Furthermore the beam is distorted in one direction due to spatial aberation caused by the off-axis reflectors. In order to increase gaussicity the total Guoy phase with maximum coupling into a zero-order mode was considered as an optimisation parameter. Therefore the position of the best-coupled mode may vary with the total Guoy phase.

## 3 Analysis

In this section results of the numerical analysis using physical optics (GRASP) and Gaussian Beam Analysis are presented. The horn antenna has an aperture

radius of 1.77 mm and a flaring angle of  $4.95^{\circ}$ . This yields a best-coupled zeroorder mode with a waist of 1.0245 mm which is located 3.3361 mm from the horn aperture inside the horn. The coupling coefficient into the fundamental mode is 98.08%. In a second step the guoy phase for a maximal coupling into a fundamental gaussian beam at the image plane is computed. For a given value of the guoy phase the optics is computed using the scheme given earlier in the text. Redesigning the optics implies changing the distance between the mirrors and the mirror curvature, thus the amount of aberations changes as well. Then the field propagation is computed using physical optics with the software package GRASP. The field at the image plane is sampled in a rectangular grid. A schematic of the simulated optics is shown in figure 2. We observe that the optical setup is symmetrical along the y-axis of the coordinate system of the near-field data. Therefore we assume that the resulting fields are symmetric along this axis.



Figure 2: Schematic of the simulated optics, the model includes a feed horn, the optimized elliptical mirror and the common\_a mirror of the TELIS optics

For this field the waist and the position of the best-coupled fundamental mode is searched. The simulation shows that the waist of the best-coupled fundamental mode is 3.0968 mm. It is therefore slightly smaller than expected. The bestfit gaussian beam is located at 1.8 mm from the expected position. With this information the optics is redesigned for a 3.2/3.0968 = 1.033 times bigger image plane beam waist. Redesigning the optics for a size-corrected waist of 3.33056 mm and a total Guoy Phase of 1.179  $\pi$  yields a best-coupled waist of 3.2009 mm which is located at 1.6 from the image plane. The coupling coefficient for the zero-order mode is 98.18%. The sudden change of all parameters around  $\Phi_0 = 1.05\pi$  is possibly due to spatial aberations. Figure 4 and 5 show cuts through the simulated near-field amplitude pattern for several design of the optics resulting in a total Guoy phase shift of  $0.8\pi$  to  $1.3\pi$ . Figures 6 to 8 show phase and amplitude cuts for the optical configuration with a total Guoy phase shift of  $\pi$  and for the setup which yields the highest coupling value of a fundamental gaussian beam. The asymmetry in the y-plane arises from the aberations at the elliptical mirrors.



Figure 3: power coupling, best-fit waist and best-fit distance plotted against  $\Phi_0$ 



Figure 4: field distribution at the image plane along the x-axis plotted against  $\Phi_0$ 



Figure 5: field distribution at the image plane along the y-axis plotted against  $\Phi_0$ 



Figure 6: phase plot at the image plane for the highest coupling (left) and  $\Phi_0 = 1$  (right)



Figure 7: amplitude plot at the image plane for the highest coupling (left) and  $\Phi_0 = 1$  (right)



Figure 8: x- and y-plane amplitude plots for the corrected waist

# 4 Summary

An in-depth analysis of a two mirror optical system has been carried out. Is has been demonstrated that the total Guoy phase remarkably affects the radiation pattern. Furthermore the beam quality can be slightly improved using the optimisation scheme presented.

# Test of the Telis coupling optics

### P. Fuerholz

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#### Abstract

This document decribes tests of the coupling optics used for the Telis nearfield antenna measurements. Measurement results in terms of a gaussian fit are presented.

# 1 Optics Design Summary

The aim of the coupling optics is to generate a gaussian beam with a waist of 5.2477mm. This is achieved with a combination of a corrugated horn antenna and an elliptical mirror. Special care has been taken upon the relative phases of the Gauss-Laguerre modes. This yields an offset elliptical mirror with the following parameters

$R_1$	$0.078~\mathrm{m}$
$R_2$	$0.448 \mathrm{m}$
$d_1$	$0.077~\mathrm{m}$
$d_2$	$0.357 \mathrm{m}$

Feeding is done with a corrugated horn antenna with an aperture radius of 1.77 mm and an opening angle of  $4.95^{\circ}$ . The optics is mounted on an aluminium plate with a thickness of 15mm. A second plane mirror is used to redirect the beam through the aluminium plate. The distance from the feed aperture to the elliptic mirror along the central optical axis is 0.077 m, the distance from the elliptic mirror to the plane mirror is 0.186 m. The beam is located at 0.031m above the plate. Therefore we expect the output waist to be localised at 0.125 m away from the plate.

# 2 Measurement Setup

The performance of the coupling optics was tested using planar nearfield measurements. For signal generation and detection a modified ABmm system with an ESA2 extension and an addition Lock-In Amplifier was used. The scanning has been done using a Owis 2D planar scanner with a scanning resolution of 1/160 mm. As a probe a corrugated horn antenna with an aperture radius of 1mm and a length of 14 mm was used. The distance between the coupling optics plate and the probe aperture was 14.5cm. Figure 1 shows a schematic of the setup used. The wiring of the Abmm modules is documented in the following tables



Figure 1: schematic of the measurement setup used for the test of the coupling optics

#### ABmm ESA2 PLL

Voltmeter	to Yellow DMM5000 voltmeter
Gunn	to ESA2 Gunn (on coupling optics)
Ref Input	to output F on ABmm internal synth
Mixer	to DC output at extension mixer of ESA2
Beat	to spectrum analyzer

### ABmm ESA1 PLL

Gunn A	to ESA1 Gunn (on probe optics)
Ref Input	to Stanford Synth (with doubler)
Mixer MU	to DC output at extension mixer of ESA1

#### ABmm vector analyzer back

Internal Synth Trig	to Ref on YIG PLL
Internal Synth 10.74 MHz out	to 10.74 MHz in on 10.488 kHz ADC $$
Internal Synth 10 MHz out	to 10 MHz in on outer downconverter
Internal Synth D1 CH1	to in D1 on outer downconverter
YIG PLL pll	to YIG pll
YIG PLL beat	to YIG beat
10.488 kHz ADC 10.488 kHz Trig	to Ref In on Lock-in
outer downconverter out 10.48 kHz	to input A on Lock-in
outer downconverter In IF	to ESA2 preamplifier output
ABmm YIG source (on front)	to power splitter and isolator
	and then to RF inputs of extension mixers

#### **GPIB** connection

The stanford synthesizer, the owis stepping motors and the Lock-In amplifier need to be connected to the GPIB card installed on the pc (National Instruments card).

#### 2.1 Heterodyne setup

The measurement frequency is 625 GHz. The extension Gunns were locked at the 7th harmonic of the internal YIG Oscillator. The the measured signal was the 7th harmonic of the Gunn signal. Therefore the YIG were operated at 12.755 GHz, the Gunns at 89.28 GHz. The IF signal at the input of the outer downconverter is at 59 MHz(not exact), therefore the stanford synthesizer was tuned to 20.78 MHz (not exact).

# 3 Pattern prediction using GRASP

The optics including feed, elliptical mirror and planar mirror has been modelled using GRASP. The simulation includes the feed horn, the elliptical mirror and a plane mirror to redirect the beam. Figure 2 shows a drawing of the simulated optics. The cuts along which the field values are computed are shows in the lower left part in light blue. For the coordinate systems the x-axis is drawn in red, the y-axis in green and the z-axis in dark blue. The nomeclature used later in the text refers to the coordinate system in the lower left corner. The simulation plane has been chosen to be exactly the same as the measurement plane in order to do the closest possible comparison. For the simulated nearfield data the beam parameters of a best-fit gaussian beam was computed. This yields

horizontal waist	4.410  mm
vertical waist	4.381 mm
waist location	11.66 cm away from the plate
rotation around vertical axis	$0.021^{\circ}$
rotation around horizontal axis	-0.010°
gaussicity	99.10%



Figure 2: drawing of the GRASP model used for pattern prediction

# 4 Measurement Results

The scanning area was  $8 \times 8$  cm, the size of the nearfield image in pixel is  $256 \times 256$ . The coupling optics was slightly rotated around the y-axis to avoid standing waves inside the optics. To check the gaussian parameters of the measured field distribution a fundamental gaussian was fitted to the data yielding

horizontal waist	$4.436 \mathrm{~mm}$
vertical waist	$4.054 \mathrm{~mm}$
waist location	12.6 cm away from the plate
rotation around vertical axis	-0.518°
rotation around horizontal axis	$0.312^{\circ}$
gaussicity	97.66%

In this measurement setup a background signal with an amplitude at -30dB below the signal maximum was present. This background signal also varies in time therefore corrections for this measurement error needs to be made. This was done by averaging several vertical cuts (along the y-axis) away from the main beam. The vector taken then represents the overall field drifts for the background signal of the system. As a second step for each horizontal line (along the x-axis) the corresponding value of the correction vector was subtracted.

The measured data was also compared to computer predicted performance of the coupling optics (fig. 3). The measured pattern looks slightly bumpier than the simulated pattern. The main cause of this are stading waves between the coupling optics and the probe. This conclusion results from additional measurement which were taken at two different planes separated by  $\lambda/4$  (fig. 5). The initial distance along the propagation axis was chosen in such a way that constructive interference between the one-way signal and the standing wave occurs at the signal maximum.



Figure 3: amplitude pattern of the measured coupling optics



Figure 4: phase pattern of the measured coupling optics



Figure 5: comparison of the experimental data to simulations done using physical optics, cuts through the signal maximum



Figure 6: comparison of the experimental data to simulations done using physical optics, coutours of the amplitude pattern [dB],red: theory, blue: experiment



Figure 7: average of two measurement taken at two planes separated by  $\lambda/4$ , theoretical values for comparison



Figure 8: comparison of the average of two measurement taken at two planes separated by  $\lambda/4$  and the non-averaged data taken from the 2D measurement

# 5 Conclusion

A first test of the Telis coupling optics has been made. The analysis shows that no major design errors have been made. With this test both the measurement setup and the coupling optics itself has been tested. For the measurement setup we see that long-term drifts occur, however the data can be corrected easily. The dynamic range is around 70dB. The gaussicity of the measured beam is very close to the expected gaussicity, which is around 98%. The waist size of the fitted gaussian beam is slightly narrower than the specifications for both the simulation and the measurement. This is due to phase slippage of the higherorder Gauss-Laguerre modes. The asymmetry of the beam widths in x and y occurring in the measurement may be caused by standing wave effect and by alignment errors. The standing waves between the antenna under test and the probe results in a bumpy field pattern.