IMPLEMENTATION OF A QUASI-OPTICAL FREE-SPACE S-PARAMETERS MEASUREMENT SYSTEM

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ABSTRACT

A quasi-optical (QO) free-space test bench, based on two dual reflector Compact Test Range (CTR) systems, has been developed to characterise the RF properties of materials and QO components used in mm-wave astronomical instrumentation. While this facility has been designed to operate for several spectral bandwidths, in the first instance measurements have been performed in the W-band (75-110 GHz). We present the modelled and measured performance of the test bench and the procedure for calibrating and measuring samples under test. First measured results of the field across a 10 cm quiet zone indicate a maximum intensity variation of -4.5 dB and a maximum phase variation of 7°. Measurements of the cross-polarisation indicate higher levels than were predicted. A free-space calibration method has been developed based on the use of 3 calibration standards (Thru-Reflect-Line). Initial measurements of the reflectivity and transmittance for a range of materials have been performed, allowing the deduction of the refractive index.

1. INTRODUCTION

Measuring the Cosmic Microwave Background (CMB) polarisation is a powerful tool for testing cosmological models. Several present and future projects aiming at measuring this polarisation are based on the use of cold detectors coupled to microwave waveguide components and quasi-optical (QO) components. Some of them will contain interference filters, dewar windows and lenses for instance. The signal from the B-mode CMB polarisation is predicted to be extremely faint. Therefore these instruments require highly sensitive detectors and receiver components with well-known and characterised systematic effects that they will inevitably introduce in the measured signal.

A test set-up has been constructed to accurately test the RF and optical properties of quasi-optical components that are being developed, and to study their systematic effects. Components such as interference filters, half-wave plates and polarisers are all under study. This test bench will also allow the RF characterisation of materials from which these quasi-optical components are constructed. For instance, the accurate modelling and performance prediction of the QO components that are being developed are highly sensitive to the refractive index of the material being used. For the same material, the refractive index could vary from one supplier to another.

In order to retrieve the most accurate performance, these measurements must be performed in a collimated beam, to disentangle systematic effects that might arise from an oblique incidence on the sample under test. Moreover, since the QO components will be used in instruments dedicated to the study of the CMB, it is vital that they are tested within a zone with low aberrations and a low cross-polarisation [1] and where the electro-magnetic field is well controlled and known (referred as the Quiet Zone).

The CMB is best studied in the frequency domain comprised between 40 to 300 GHz. While this range could be covered in principle, our test set-up has been optimised for W-band to be used with our Vector Network Analyser in order to reach a typical maximum cross-polarisation of -40 dB [2].

2. SYSTEM DESIGN AND MANUFACTURE

The optical design of the test set-up coupled to a Vector Network Analyser (Rohde & Schwarz ZVNA-40) is detailed in a previous article [1]. It is based on two dual reflector Compact Test Ranges (CTR), each comprising a parabolic and a hyperbolic mirror (Fig. 1). Each CTR has a VNA converter head located at its focus acting both as a receiver and emitter. For these tests, the converters are operating in the W-band (75 – 110 GHz). However the corrugated horns that have been used on the converter waveguide outputs only transmit above 82 GHz. The combination of the converter, horn and CTR is creating a collimated beam where the EM field is pseudo-planar where the samples under test can be located. This cylindrical Quiet Zone (QZ) region has low intensity and phase variations. The beam is then refocused on the horn aperture of the second VNA converter located at the focus of the second CTR. The mirrors have serrated edges in order to minimise the phase and amplitude variations across the QZ [1].

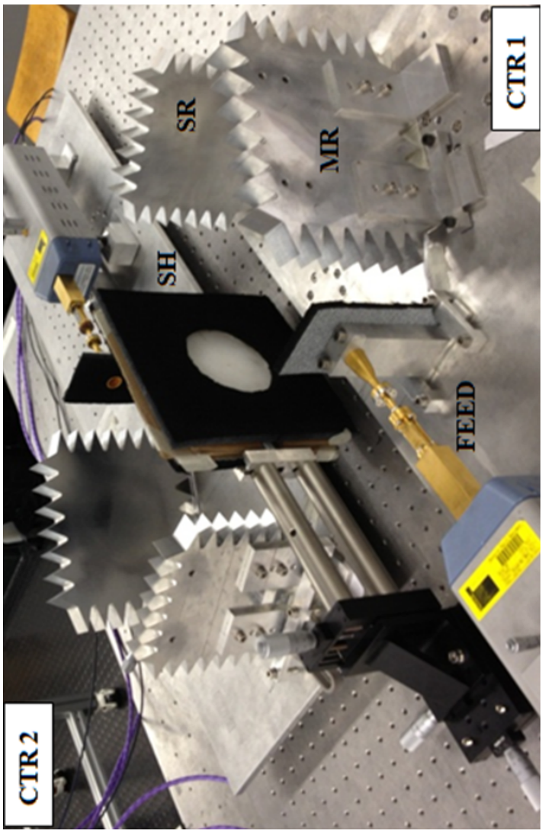


Figure 1. Test set-up. Each Compact Test Range (CTR) consists of a corrugated feed horn (Feed), a hyperbolic Sub-Reflector (SR) of size 17 cm and a parabolic Main-Reflector (MR) of 20 cm aperture, creating a central cylindrical Quiet Zone (QZ) region of 10 cm diameter, extending axially 5 cm towards each MR. Samples under test (SUT) are placed within this QZ, positioned such that the centre of the SUT lies coplanar to a reference plane, which is defined to be halfway between the two main reflectors. A Sample Holder (SH) secures an 11 cm diameter SUT and absorbs unwanted radiation from outside the QZ using a piece of RF absorber. The sample holder has been connected to a 3-axis positioning stage to allow accurate positioning.

3. ALIGNMENT

Each component has several degrees of freedom, making the alignment procedure difficult. To reduce the number of alignment parameters associated with the system, the feed horn is located in a fixed position. The reflectors (Main parabolic and Secondary hyperbolic) are positioned geometrically according to the CTR design parameters, with the feed horn acting as the point of origin. Each mirror is then roughly adjusted in order to maximise the signal between the emitter and the receiver. The CTR systems are then aligned independently to each other. A reflector is inserted in the QZ region and the Return Loss (RL) is optimised to be as close as possible to 0 dB (S parameter maximised close to 1) for each CTR individually by adjusting the position and tilt of the sub-reflector and the tilt of the main-reflector. Each component is repositioned in an iterative fashion until the optimum RL is reached.

The beam of each CTR is then investigated to ensure that it is at normal incidence to the QZ by scanning the phase across the reference plane using a 3D scanning system [3]. For these measurements the field probe consists of a circular to rectangular waveguide transition matched to free space and surrounded by absorber to eliminate reflections as shown in Fig. 2. Any misalignment would introduce a phase gradient over the scanned region. Adjusting the tilt of the main reflector accordingly can counteract this gradient. To achieve the optimal alignment the whole process is repeated iteratively, optimising the RL and correcting the phase gradient each time until no further improvement can be achieved.

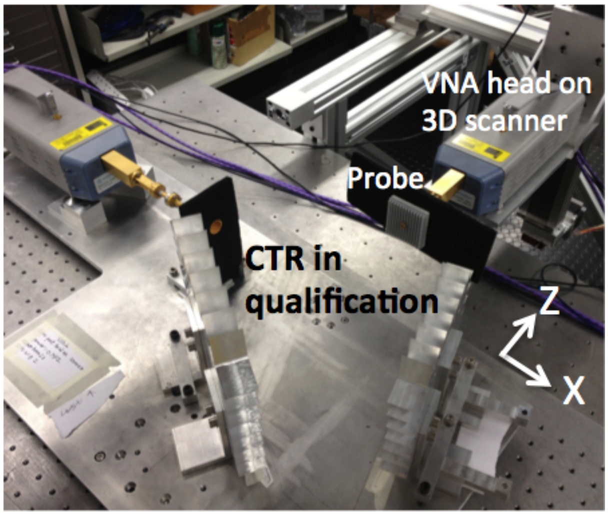


Figure 2. Image of the system configured to enable measurements of the QZ field in 3-dimensions using a circular to rectangular waveguide transition as the field probe.

Once each CTR is aligned, both are assembled together and the signal between the two converters maximised. When the free-space S-parameter system is in place, a loss of less than 1dB between the two VNA converters is observed.

4. CALIBRATION

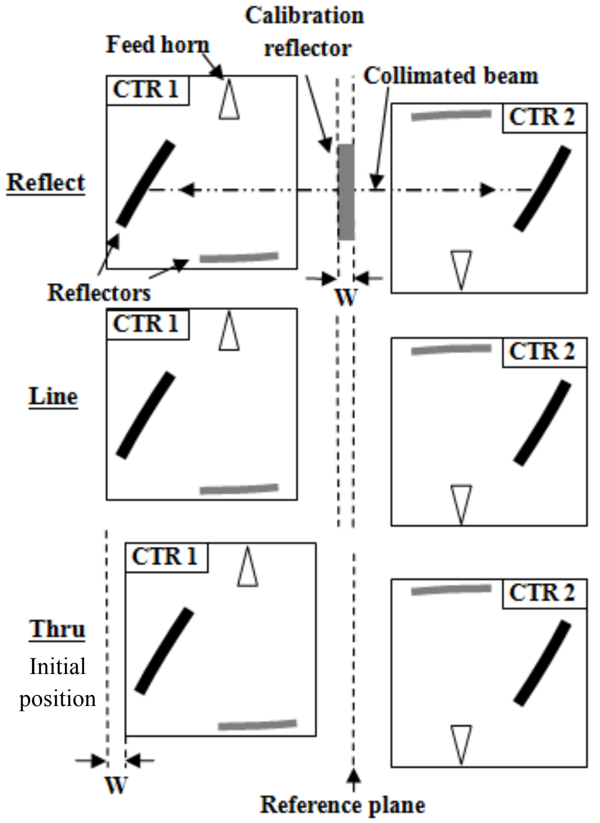


Figure 3. TRL calibration method of the set-up adapted from [5]. The initial position of the set-up is shown as the Thru standard, where the reference plane lies halfway between the two CTRs. The Reflect standard is taken by placing a calibration reflector of thickness W between the CTRs and moving CTR 1 back by a corresponding distance W. The Line standard is taken by removing the calibration reflector whilst keeping the separation distance between the two CTRs unchanged. The Thru standard is taken by moving CTR 1 back to its original position.

The set-up needs to be calibrated to remove systematic errors caused by transmission losses in the CTR components and the cables of the VNA. A well-established calibration method known as Thru-Reflect-Line [4] (TRL) is appropriate for this free-space set-up. This method requires the propagation distance between the two feed horns to be increased by a pre-determined precise amount when taking the Thru standard, therefore one CTR has been mounted on a micrometre controlled sliding platform. The TRL method is performed using the following procedure [5] (see Fig. 3):

1) Starting with the set-up initially in the Thru position, the Reflect standard is taken by placing a reflector of thickness W between the two CTRs, with one of the reflector faces aligned collinear to the reference plane, then moving CTR 1 back by a corresponding distance W.
2) The Line standard is obtained by removing the calibration reflector whilst keeping the separation distance between the two CTRs unchanged. The line length must satisfy: $10^\circ < k \cdot W < 170^\circ$ over the spectral band, where $k = 2\pi / \lambda$ and λ is the free-space wavelength. The restriction is to ensure that any phase ambiguity is avoided.
3) The Thru standard is taken by moving CTR 1 back to its initial position.

5. SYSTEM VERIFICATION

5.1 Simulation and measurement procedure

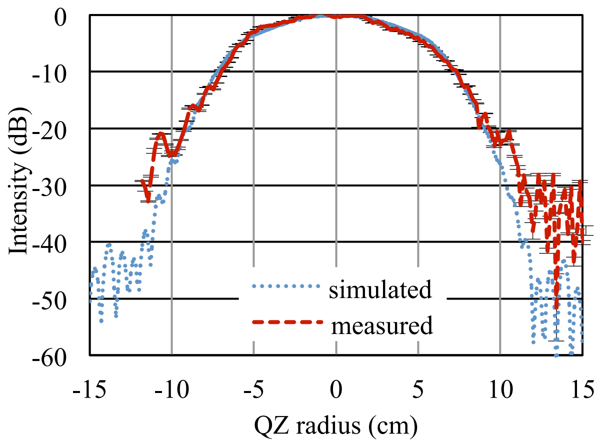
The free-space measurement system is modelled in GRASP [6]. Physical Optics (PO) calculations are conducted to simulate the properties of the RF field produced in the QZ. Further to simulation work conducted previously [1], the simulated far field radiation pattern of the corrugated feed horn is inputted as the radiation source instead of a simple linearly polarised Gaussian beam.

The intensity and phase of the field produced by the CTR system in the QZ region is sampled along the x-axis (as defined in Fig. 2) using the 3D scanning system described in section 3. In order to verify the performance of the system both GRASP simulations and the measured data are presented in the following two sections.

5.2 Intensity and phase measurements

As demonstrated in Fig. 4, the beam intensity observed across the QZ agrees well with the simulation over a 7.5 cm radius with increasing deviations from the model at larger radii. However, upon closer inspection over a 5 cm radius, deviations from the simulation in excess of 0.5 dB are observed. Over this 5 cm radius QZ, the intensities observed have a range of 4.5 dB; 1 dB larger than predicted using the GRASP model.

The general phase evolution over a 10 cm diameter QZ matches that of the model, however larger oscillations are observed over the plateau region as shown in Fig. 5. Deviations from the model are typically less than 5° and the maximum phase variation over this 10 cm QZ is 7°. Further agreement with the model is likely to be hindered by component inefficiencies such as in the VNA cables and imperfections on the reflector surfaces.



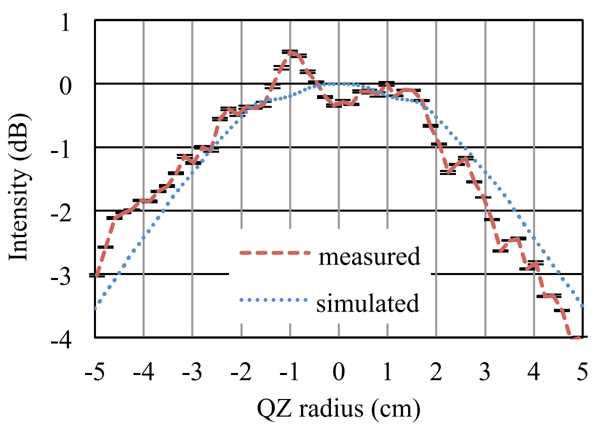


Figure 4. Comparison of the simulated field intensities across the QZ and the intensities measured using a circular to rectangular waveguide transition as a field probe. Data has been normalised using the maximum intensity of the model as the definition for the zero point. Top: comparison over a 30 cm diameter QZ. Bottom: comparison over a 10 cm diameter QZ.

5.3 Cross-polarisation measurements

It is predicted that the maximum cross-polarisation produced by the CTR system is in a diagonal cut through the QZ orientated at an angle of ϕ=45° to the test bench. In order to measure the field in this cut along the x-axis of the laboratory system, an additional waveguide was used, which rotated the beam pattern through an angle of 45°. The field could then be measured using the 3D scanning system.

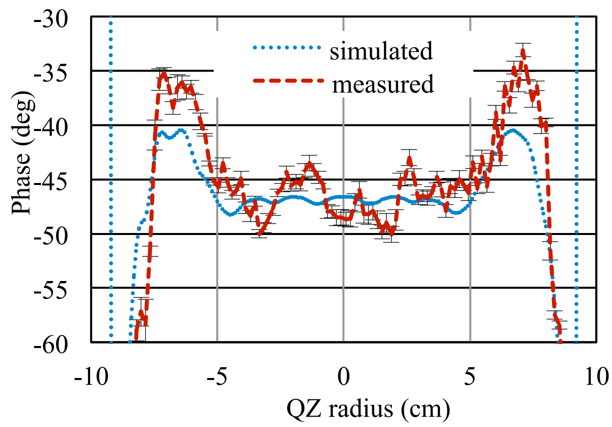


Figure 5. Comparison of the phase of the QZ field predicted by the GRASP simulation with the phase measured in the laboratory system over a 20 cm diameter QZ.

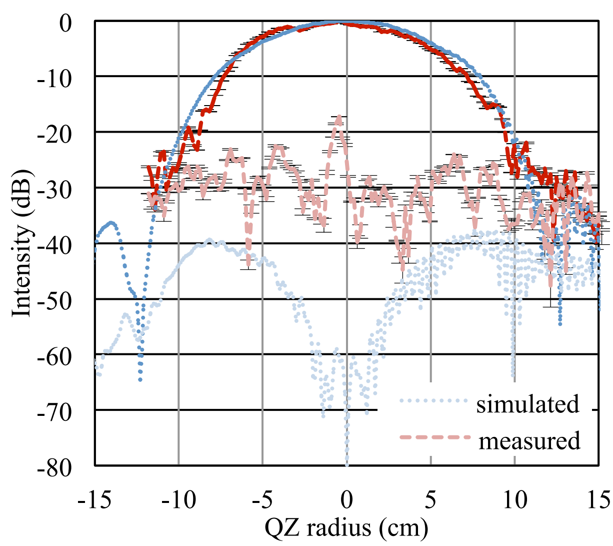


Figure 6. Measurements of the co-polarised intensity and cross-polarisation of the QZ field over a 30 cm diameter scan compared with the model prediction. Data is normalised so that the maximum intensity of the co-polarised field in the model is at zero.

Fig. 6 shows that the diagonal co-polarised intensity exhibits larger deviations from the model when compared with Fig. 4 (ϕ=0°), particularly at radii greater than 5 cm. The measured cross-polarisation is also significantly higher than predicted across the entire 30 cm diameter scan zone. Most noticeable is the lack of a dip near zero. It is expected that this high cross-polarisation can be in part attributed to the field probe used for data collection and part to the manufacture error of the corrugated horn.

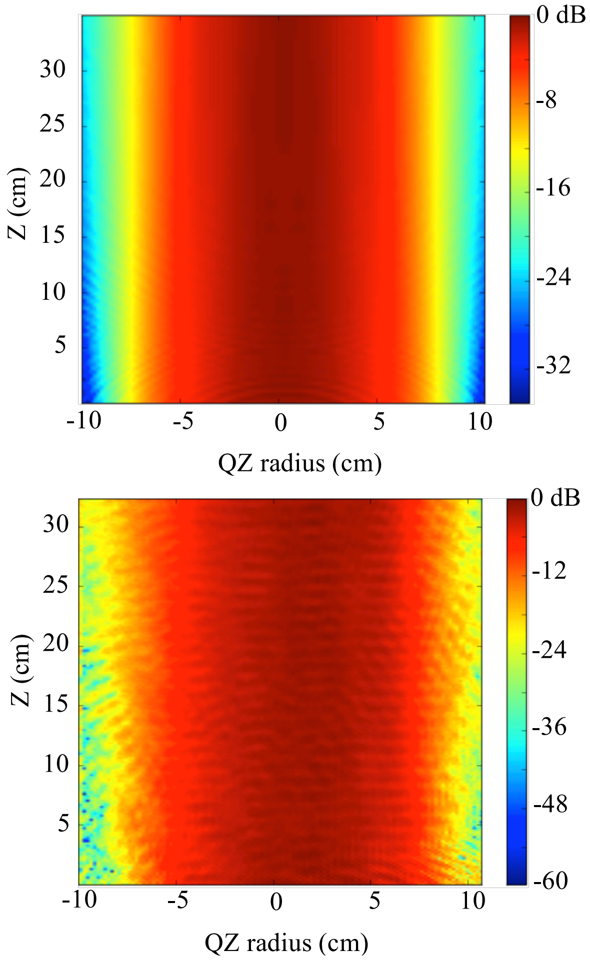


Figure 7: Top: Beam evolution predicted from the GRASP model. Bottom: Evolution of the beam measured from the CTR system using a circular to rectangular waveguide transition as a field probe.

5.4 Beam evolution

In order to further test the alignment of this measurement system, further field scans were conducted at increasing distances from the main-reflector along the z-axis. Fig. 7 illustrates how the QZ beam evolves along the z-axis. Both model simulations and the laboratory measurements are shown. The measured field exhibits ripples associated with the performances of the feed pattern and diffraction effects [1]. Artefacts in the outer beam region are also observed due to reflections from the edge of the sub- reflector.

6. COMPONENT CHARACTERISATION

6.1 RF properties of materials

A useful parameter when describing a dielectric is its permittivity (or refractive index). The knowledge of a material's refractive index is important as it describes how the material will interact with an external electric field and will be crucial to model the RF properties of the QO components that we are developing.

When a SUT is placed in the set-up, the resulting S-parameter, corresponding to reflections, has a series of troughs at specific frequencies due to destructive interference within the sample, as shown in Fig. 8.

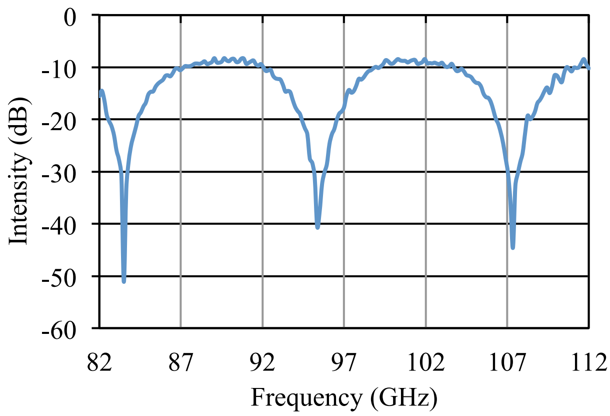


Figure 8. Illustration of the measured pattern in reflected power due to destructive interference within a 2.8 mm thick sample of Ultra-High-Molecular-Weight-Polyethylene (UHMWPE).

The position of the troughs is given by Eq. 1.

$$\alpha \frac{\lambda_0}{2n} = d \qquad (1)$$

where α is an unknown integer corresponding to the number of half-wavelengths in the sample, λ_0 is the free-space wavelength, n is the refractive index of the sample and d is the sample thickness. Using an initial guess for the refractive index that is close to its true value, the integer, α, can be found for the first trough in the series. For each consecutive trough the value of α simply increases by 1.

Samples of 8.3mm thick Ultra-High-Molecular-Weight Polyethylene (UHMWPE) and 2.8 mm thick Polypropylene (PP) were both characterised using an initial guess for the refractive index of 1.5. The results are shown in Table 1 and 2 respectively. The two main sources of error are identified to be due to inhomogeneities in the sample thickness and sample positioning errors during the characterisation process. The later error can be determined by repeating the procedure multiple times to determine a statistical error. For each result only the most dominant error has been quoted, and this varied between individual measurements.

Table 1. Measurements of the refractive index of Ultra-High-Molecular-Weight Polyethylene.

Frequency (GHz)	Refractive index
≈83.5	1.518±0.002
≈95.5	1.517±0.001
≈107.5	1.5178±0.0007

Table 2. Measurements of the refractive index of Polypropylene.

Frequency (GHz)	Refractive index
≈108.0	1.506±0.001

7. CONCLUSION

In this paper, the alignment techniques and TRL calibration for the CTR system operating in the W-band have been discussed. In addition, the QZ field has been measured and it has been compared against a model created in GRASP. The measured field characteristics exhibit a maximum intensity variation of 4.5 dB and maximum phase variation of 7° over a 10 cm diameter QZ. Measurements of the cross-polarisation indicate higher levels than were predicted however further work needs to be done in this area in terms of limiting the effects of the field probe on these measurements. First measurements of materials have also been conducted in the system. The refractive index of UHMWPE and PP was extracted from the s-parameters to be 1.517±0.001 at 95.5 GHz and 1.506±0.001 at 108 GHz respectively. Improvements of this system need to be performed in order to limit the standing waves created by reflections of the SUTs, which can impact their measured RF performance. The use of the time domain gating function of the VNA can limit their effects. Another solution would be to perform an average across the spectral bandwidth.

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