ACCURATE RF MATERIAL CHARACTERISATION USING SCATTERING MEASUREMENTS FROM QUASI-OPTICAL BENCH

Executive Summary

R Appleby

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ESA STUDY CONTRACT REPORT

No ESA Study Contract Report will be accepted unless this sheet is inserted at the beginning of each volume of the Report.

<table>
<tr><td>ESA Contract No:

4000116424/16/NL/AF/eg</td><td>SUBJECT:

ACCURATE RF MATERIAL CHARACTERISATION USING SCATTERING MEASUREMENTS FROM QUASI-OPTICAL BENCH</td><td>CONTRACTOR:

Roger Appleby MMW Consulting</td></tr>
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ABSTRACT:

The European Space Agency (ESA) has developed a facility to determine the reflection and transmission coefficient of materials from 50 – 750 GHz. For smooth materials these coefficient's are used to extract the permittivity and permeability and for rough materials scattering can be measured and the surface parameters determined. This facility currently consists of a quasi-optical bench and Vector Network Analyser which utilizes frequency extenders and corrugated horns.

Following integration at ESTEC the scatterometer has undergone a continuous development program. This stems from the fact that nothing like it had ever been made before and never has such a system been exposed to such detailed testing and analysis. The result is an instrument that is among the best in the world for measuring reflection and transmission coefficients, permittivity, permeability and scattering.

The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.

Names of authors: Dr. R Appleby

<table>
<tr><td>** NAME OF ESA STUDY MANAGER:

Elena Saenz

DIV: Electromagnetics & Space Environments Division

DIRECTORATE: TEC-EFA</td><td>** ESA BUDGET HEADING:</td></tr>
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* Sections to be completed by ESA

** Information to be provided by ESA Study Manager

ADMINISTRATION PAGE

Customer	
Project	ACCURATE RF MATERIAL CHARACTERISATION USING SCATTERING MEASUREMENTS FROM QUASI-OPTICAL BENCH – Executive Summary
Organisation	ESA
Customer Contact	Elena Saenz
Contract Number	4000116424

Authors	
Prof Roger Appleby	
Company	R Appleby MMW Consulting
60 Churchill Drive Malvern Link Worcs WR14 1DJ	Tel: 01886 832883 Mob: 07775905591 Email: applebyroger@yahoo.co.uk

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EXECUTIVE SUMMARY

Following a feasibility study[1] contract No 4000116424 was let to R Appleby MMW Consulting with subcontractors Thomas Keating Ltd., TICRA and Pixel Analytics Ltd. And work started in 2016 to build the scatterometer. Thomas Keating led on the mechanical design and fabrication, TICRA on modelling, Pixel Analytics on the software with Roger Appleby MMW being the prime contractor and also the technical lead. This executive summary describes the project in three phases design, manufacture and testing.

DESIGN

A literature survey was conducted, and a database of 377 papers and other resources is available in the data pack. This body of knowledge along with work done in the feasibility study was combined with the ESA requirements to produce the Consolidated Requirements Document(D1). Preliminary Design work was then carried out on the scatterometer to evaluate several concepts including the baseline concept from the feasibility study and a short list produced.

1. **Baseline Design (Quasi-optic free space system)**
2. NRL arch with ZBD
3. **Quasi Optic resonator**
4. Unbalanced bridge
5. TDS system

A systems Design Review was held on an improved version of the Baseline concept. This concept is based on two base plates separated by 500mm and the optical components are mounted on both plates. Light propagates from the lower plate to the upper plate by a periscope which can rotate around the sample mounted on the bottom base plate. As the periscope rotates scattering is measured. This method allows the VNA frequency extender heads to remain stationary which is a major benefit for high frequency measurements.

TICRA used GRASP[2] to simulate the RF performance of the selected concept and this analysis enabled informed trade-offs to be made. A design was produced

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[1]ESA THz Sample Measurements, Impact of scattering, Final Report, 2013, Contract No 4000105412.

[2] https://www.ticra.com/software/grasp/

which followed the same optical path on the top and bottom base plates giving some symmetry. The mirrors in the periscope were changed from ellipsoids to paraboloids and the optical layout had excellent coupling loss, good cross polar performance and good beam quality in both reflection and transmission and was accepted at the Preliminary Design Review.

The software architecture was defined [D5] and the User interface prototyped. MATLAB was selected for the software with a built in user manual[D6] in the form of a help system.

The simulated RF performance, mechanical design, software architecture and Test Plan were reviewed at the Detailed Design Review and it was agreed to commit to manufacture. Additional work was identified at the review and Contract Change Notice (CCN) 1 submitted which included, an improved sample holder, modifications to periscope, additional grids, compiled version of software, grid sensors, laser cut rough reference samples for 400 GHz and additional simulation.

MANUFACTURE

The mechanics of the scatterometer were manufactured along with the upgrades identified in CCN 1 and 2. CCN2 consisted of rotating the sample holder to provide a fixed reference surface for mounting samples.

The software defining the PNA interface proved particularly demanding and . help from Keysight was required to proceed. The software was tested during Factory Acceptance Tests and shown to be functioning correctly including all motion control, grid sensors and user interface in the form of a GUI. The PNA was tested with a mock interface as the real instrument was only available at ESTEC. The user manual was updated as necessary after the Factory Acceptance Tests.

Following the Factory Acceptance Review it was agreed that the system could be shipped to ESTEC for Integration.

TESTING

Integration gave rise to several mechanical problems including, a distorted lower baseplate, an unstable periscope translation stage, an offset the axis of rotation of the redirection mirror from that of the sample, instability of the sample holder and poor sample mounting. All these problems were overcome prior to acceptance testing apart for the offset of the rotation axis which required a redesign which was done under CCN3. There were also some emergent requirements during testing which included:

1. Calibration at all angles
2. Time gating of calibrated data
3. Uncertainty analysis and reporting of results
4. New methods for transmission measurements at normal incidence
5. Modifications to the GUI to facilitate a better workflow
6. Cross Polar calibration by VV
7. Coupling coefficient correction

All these requirements have now been addressed and the functions incorporated into the software.

As mechanical and software problems were resolved comparison to simulated data provided a means of identifying errors in the amplitude and phase of reference samples such as silica. This led to the realisation that introducing the sample at the focus with a large solid angle effectively displaces the beam altering the coupling in transmission. To overcome this problem the coupling coefficients were determined for a range of typical displacements in each frequency band and this data used to correct the measurements. A model of the system was produced by ESA based on equations from Goldsmith[3] which accurately described the RF performance. This model is known as the Gaussian model and was implemented as part of CCN3.

An uncertainty tool was developed to provide uncertainty analysis for measured data. The results are shown below at the focus for a 15.062 mm thick piece of silica. Many more results are available in the test report.

	92.5 GHz	**625 GHz**
Dielectric constant	3.805 ± 0.05	3.813 ± 0.05
Tan δ	$3.28^{*} \times 10^{-4} \pm 1.5 \times 10^{-3}$	$2.5 \times 10^{-3} \pm 1.0 \times 10^{-3}$

The test report concluded that the scatterometer was compliant with all but two of the requirements. The first was that the incidence and scattering angles covered were slightly reduced due to leakage and the second was the correction

[3] P. Goldsmith, *Quasioptical Systems.* : IEEE Press, 1998.

of S parameters for scattered energy which whilst done at one frequency has not been applied in earnest to correct S paraments in a controlled way.

The Test review Board was completed noting that the accuracy achieved whilst good was limited by the standing waves and coupling in the system.

Following the Test Review board CCN3 was implemented to provide a smaller solid angle and a larger beam waist at the sample. This was achieved by adding extra mirrors on the top and bottom base plates and modifying the periscope. Greatly reducing the impact of the coupling coefficients and giving a further increase in accuracy. Various changes to the software were also made including the implementation of the Gaussian model and making use of the optimizers available in SciPy[4].

Further testing following CCN3 confirmed that these changes were implemented successfully. The large beam waist gave excellent results at 75-110 GHz but the 500-750 GHz corrugated horn was incorrectly positioned due to the horn holder which requires a redesign. Although wrongly positioned good results were obtained in transmission but the results in reflection were poor due to spill over.

CONCLUSION

The scatterometer has required a continuous development program following integration at ESTEC. This partially stems from the fact that nothing like it had ever been made before and never has such a system been exposed to such detailed testing and analysis. The result is an instrument that is among the best in the world for measuring reflection and transmission coefficients, permittivity, permeability and scattering.

There are further improvements that could be made and could benefit future campaigns which include automating grid rotation to switch from vertical to horizontal polarization, and sample rotation for scattering measurements, propagating uncertainty through the time gating process, continuing to develop reference samples and inter-laboratory comparisons, accurately measuring sample position for reflection coefficient measurement and developing the modelling.

[4] https://www.scipy.org/