ABSTRACT

Instruments for Earth observation working up to mm-wave frequencies mainly use Quasi-Optical Feed Systems (QOF) to illuminate the corresponding antenna reflector. The final design of the QOF for the Cloud Profiling Radar System (CPR) for the EarthCARE satellite is presented. Such a QOF subsystem achieves polarization and frequency tuning, as well as separation of transmit and receive channels. The RF design of the QOF has been established by MAAS and Thomas Keating (TK) as subcontractor of Astrium GmbH. The final contractor of QOF is NICT (National Institute of Information and Communications Technology in Japan) while the CPR instrument is under the responsibility of JAXA (Japan Aerospace Exploration Agency) and will be provided to ESA for the EarthCARE satellite.

The QOF structural design features a dimensionally stable carbon fibre sandwich structure consisting of several panels. The structure design is based on a lightweight and stiff optical bench like CFRP-Al sandwich which carries all quasi optical elements. Care is taken for a good thermal control and for protecting the structure from atomic oxygen degradation.

1. INTRODUCTION

The Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) is the sixth Earth Explorer mission of ESA’s Living Planet Program. The mission is developed in cooperation with JAXA, the Japanese Aerospace Exploration Agency, and Astrium GmbH, who is responsible for the satellite design, development and integration. The purpose of the mission is the understanding of the interactions between clouds and radiative and aerosol processes in order to provide more reliable climate predictions and better weather forecasts.

A central instrument of the EarthCARE satellite is the Cloud Profiling Radar (CPR), a 500 m range Doppler radar working at 94.05 GHz. The front end consists of a parabolic reflector of 2.5 m diameter, fed by a Quasi-Optical Feed (QOF) with integrated hyperbolic sub-reflector.

The QOF converts the linear polarized Tx and Rx waveguide signals into circular polarized transmit and receive beams, providing high isolation of the Tx and Rx channels, across the system bandwidth of 7 MHz. In particular, the QOF consists of planar mirrors, refocusing mirrors, a polarization grid and a Martin-Puplett interferometer. The design of the QOF is optimized in order to use the minimum number of components with minimized size, for quasi-optical good undistorted transmission.

1.1. Project Background

The basic electro-optical design of the QOF has been established between NICT and TK during the following pre-phases:
- 2002 - 2004: Phase A Study, basic design is adopted
- 2004 - 2005: Extended Phase A+, development
of a Breadboard Model with aluminium structure
JAXA suggested to NICT to place a contract with Astrium GmbH, Friedrichshafen to build the QOF in thermally stable lightweight technology.
- 2007 - 2008: Pre-Phase 1 for small study with Astrium for development of a CFRP structure
- Sept. 2008 - July 2009: Phase B up to PDR
- July 2009 - March 2011: Phase C up to CDR including the delivery of a Functional Model (FCM) with full qualification.

1.2. Model Philosophy
At CPR level a full EQM and PFM model philosophy has been established. The same model philosophy had been initially foreseen for QOF. However, due to schedule constraints an EQM could not be realised for QOF. Therefore the QOF model philosophy was adapted to the specific test needs at CPR level, which resulted in the following model philosophy:
- Breadboard Model (BBM), established during the pre-phases and used for verification of basic RF design
- Thermal Model (THM) thermally representative, made from aluminium and used for thermal qualification testing at CPR level
- Structural Model (SM), structurally representative and used for structural qualification testing at CPR level
- Functional Model (FCM), with flight representative structure and QO-components, not fully redundant and used for full qualification of QOF
- Proto-Flight Model (PFM), not yet contracted.

2. OVERALL REQUIREMENTS
Being part of the EarthCARE Cloud Profiling Radar the QOF shall accommodate the quasi-optical parts comprising
- the sub-reflector \{SR\},
- the Inatani-type Martin-Pupplett Diplexer \{FSP1 & FSP2\},
- the separation grid \{GRID\}
- the re-focussing mirror MD1 for Tx \{MD1-Tx\},
- the re-focussing mirror MD1 for Rx \{MD1-Rx\},
- the switching mirror units (SMUs, identical:1 for Tx and 1 for Rx) \{SMU-Tx & SMURx\},
- the 4 identical feed horns \{2 Tx & 2 Rx\}.

The allowable envelope is rather confined with a volume of about 650mm x 459mm x 460mm.

The maximum mass is specified not to exceed 25 kg with the QOF being fully equipped with all quasi optical elements, electronic box, harness and thermal hardware.

The minimum allowable natural eigenfrequency is 120 Hz. The quasi-static design loads are specified to 41g in X-axis (out-of-plane) and 30g in Y- and Z-axis (in-plane).

The QOF has to fulfil the stringent beam pointing requirements of less than 0.006 degrees (1 Sigma) in cross-track (RXCPR) direction and smaller than 0.006 degrees (1 Sigma) along-track (RYCPR).

3. STRUCTURAL DESIGN
3.1 Structural Design Concept
Driven by the challenging pointing requirements the structural design concept of the QOF reflects the classical optical bench principle with all irradiating and reflecting quasi-optical elements attached to one common mounting plane, the Single Wall Attachment Panel (SWA-Panel). Thus clear load paths are defined and the stability requirements can be met. The lay-out scheme is given in Figure 2 below.

![Figure 2: Lay-out scheme of the Quasi Optical Feed (QOF)](image-url)

For structural, thermal and mass reasons the structure of the QOF is built up as a sandwich design.
The QOF basically consists out of
- The Base Plate
- The SWA-Panel
- The Feed Horn Frame
- The Stiffening walls
- The Connection Angles
- The I/F-Brackets

The major structural components of the QOF are displayed in the following figure.
Guaranteeing the functionality of an optical bench the key element and main design feature of the QOF structure displays a single wall attachment concept (SWA). All Quasi Optical Parts (QOP’s) are mounted onto one stiff sandwich panel (SWA-Panel) which is providing a common, stiff and dimensionally stable mounting plane. This stable SWA-Panel is attached perpendicular to the Base Plate and supported by four Stiffener Walls. All sandwich panels are joined CFRP Connection Angles. On the opposite two additional optical feeds are inserted in a separate sandwich structure, called Feed Horn Frame. This stiff U-shaped structure is screwed to the SWA-Panel.

The SWA-Panel comprising ultra high modulus CFRP face sheets and a vented aluminium honeycomb core has an overall thickness of 30mm. The SWA-Panel provides hot spliced inserts and brackets for mounting of the QOP’s and feed horns. Before the bonding of the CFRP face sheets and the aluminium honeycomb, raw aluminium inserts (not finally machined), Alu block inserts and Feed Horn Brackets are placed in position and hot spliced into the aluminium core. For generating the precise mounting plane the interface surface with the hole pattern for all the QOP’s was machined with CNC accuracy after sandwich bonding. A cut out in the lower corner of the SWA-Panel provides sufficient clearance for harness routing and access to the E-box.

All QOP’s are mounted onto the SWA-Panel at three support points by screws. Lateral movement is suppressed by dowel pins.

The Base Plate, providing the interface between QOF and CPR, displays a sandwich panel with cut outs for some extended QOP’s. It contains inserts for mounting the E-Box and grounding rails. At the circumference the QOF displays six mounting brackets for bolting the QOF to the CPR components mounting surface. The six Titanium mounting brackets are located at the edges of the front, intermediate and rear stiffening sandwich walls. The mounting brackets provide through-holes of Ø 8.5 mm for accommodation of M8 fastening screws and have a supporting area with an outer diameter of Ø 16 mm. Two Ø 5 mm dowel pins are foreseen to guarantee the proper aligned position of the QOF on the CPR-interface plane.

3.2 Structural Performance

The design concept is transferred to a finite element model for the analysis according to FEM method. Due to the expected thermal gradients in the sandwich normal direction and for the detailing analysis of local effects for the stress and strength analysis of the concept it was decided to generate a FEM model with solid elements. The complete analysis model is shown in the following figure.

The detailing of the FEM model includes detailed models for the instruments, CFRP doublers, inserts and connection layers, as shown in the next figure.
For the dynamic performance of the design concept the dynamic behaviour is analysed. The boundary conditions are derived from the fixation concept with six interface positions. For a conservative approach the translational degrees of freedom (DoFs) were fixed. In Table 1 the main global natural modes ($m_{\text{eff}} \geq 10\%$) are summarized with the corresponding effective mass fraction.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Freq [Hz]</th>
<th>TX [%]</th>
<th>TY [%]</th>
<th>TZ [%]</th>
<th>RX [%]</th>
<th>RY [%]</th>
<th>RZ [%]</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>158.4</td>
<td>0.20</td>
<td>0.00</td>
<td>18.37</td>
<td>7.74</td>
<td>2.52</td>
<td>0.14</td>
<td>1st structural mode</td>
</tr>
<tr>
<td>8</td>
<td>238.4</td>
<td>9.41</td>
<td>10.36</td>
<td>0.01</td>
<td>12.31</td>
<td>6.87</td>
<td>32.68</td>
<td>2nd structural mode</td>
</tr>
<tr>
<td>22</td>
<td>389.1</td>
<td>10.60</td>
<td>12.94</td>
<td>4.64</td>
<td>8.87</td>
<td>2.31</td>
<td>0.41</td>
<td>3rd structural mode</td>
</tr>
</tbody>
</table>

Table 1: Dynamic performance of the QOF

For the functionality of the concept the analysis should state that the minimum Eigen frequency is above 120 Hz. The defined concept will fulfil the stiffness performance. In the following figures the mode shapes of the global z- and y-axis direction frequency are presented. The red outlining will show the un-deformed structure. The deformed structural is plotted in combination with the fringe results of the magnitude deflection.

The design concept has to withstand static load cases of 30 g in all axis directions. Derived from the 1g acceleration loading in each co-ordinate axis direction the maximum stress state was analysed by combining the single base accelerations to the defined load combinations. In the following table the stress level per base load case and the maximum stress for the worst case combination is given for all used isotropic materials with corresponding minimum margin of safety value for the worst case load combination.

Table 2 below shows the maximum static and the margins of safety for the isotropic materials, whereas Table 3 displays the single layer/matrix stress for the 1g load cases and the maximum layer/matrix stress for the composite materials.
The static requirements for the concept are fulfilled. The following figures show for a selected load case the stress situation in the CFRP panels and in the instruments.

**Figure 9: Layer stress for 1g load case in CFRP panels**

**Figure 10: Von Mises equivalent stress in quasi-optical components**

The structural stability performance of the QOF is defined by the thermal load cases. The following operational temperature cases are identified as the critical load cases:

- maximum temperature on feed horn frame (hot case)
- minimum temperature on single wall and top cover (cold case)
- maximum gradients on single wall and top cover (gradient case)

As an example the following figure provides the temperature distribution for the hot case in centigrade. For a better visualisation a part of the top cover is removed.

**Figure 11: temperature distribution for Hot Case**

The performance of the module is given by the stability of the mirror centre points and antenna focal points. For the selected worst case in orbit operational load cases the translational and rotational deformation is presented in the next table. The analysed values for the in-orbit stability are below the allowable values.

**Table 4: Thermal distortion for worst case in-orbit conditions**

### 4. THERMAL DESIGN

#### 4.1 General Overview

The QOF thermal design is driven by different considerations such as the material used, the Spacecraft mission and interfaces and the low Earth Orbit
The operational temperature of the structure being made of carbon fibre sandwiches and parts including inserts and different glues, is ranging from -65°C to +85°C.

In order to reduce the impact of the QOF on the CPR thermal design, different MLI (Multi-Layer Insulation) blankets made of Aluminised Kapton layers are placed around QOF. To protect QOF from the external environment temperature variations, a MLI with a Germanium coated Kapton external layer is placed above the interface between QOF and CPR. An active thermal control system using thermostats and heaters is used to maintain the temperature sensible electronic equipments above their minimal non-operational and operational temperature specifications.

### 4.2 Environmental Constraints

The fact that QOF is placed partially externally to the S/C and the function itself of the instrument has a key impact on the thermal design:

First of all, the QOF is obviously exposed to the CPR main Reflector (one component of the QOF is the sub-reflector of CPR). In a special constellation between Sun and Spacecraft orbit position, the solar beam illuminating the CPR Main Reflector can be reflected and focused on the QOF Sub Reflector for a few minutes. This amount of solar energy in such a short time increases the temperatures of the sub-reflector dramatically. A part of this energy is then reflected to the internal QOF components leading also there to a quick increase of the temperatures. Therefore, the components surfaces have been designed as being diffusive to reduce the solar energy concentration. A radiator made of secondary surface mirror (SSM) tapes is also foreseen on the top cover to reject heat to space and to protect the top cover and QOF from the concentrated solar beam.

The position of CPR on the S/C, placed in flight direction leads for such low Earth Orbits to a strong exposure to Atomic Oxygen (ATOX). Carbon being very sensitive to ATOX, special materials and design solutions are chosen to protect the structure, either by controlling the erosion of the materials used like the SSM foils, chosen with an adequate Teflon thickness for example, or by using ATOX resistant materials like Germanium coated Kapton. Indeed, the overall internal structure is covered with two layers of Germanium coated Kapton placed one on each over for redundancy (the Germanian layer being very sensitive to micro cracks). Other materials like VDA (Vapour Deposited Aluminium) Kapton could have been used but they have less favourable optical properties in terms of thermal control of QOF.

Externally, the MLI filling the gap between QOF and the CPR +X radiator has also a Germanium Coated Kapton external layer for the same reasons.

### 4.3 Thermal Design Description

Considering the two main constraints explained above, additional standard constraints for such equipments have to be considered for the establishment of the thermal design: reduction of the gradients for pointing accuracy, internal dissipations due to RF losses in operation, materials temperature limits, sub-systems operational and non-operational temperatures, reduction of the impact on the CPR thermal design.

This leads to the choice of low CTE materials like INVAR for the optical components or low CTE carbon fibre materials for the structure.

The internally dissipated heat is rejected through the top cover via a radiator made of SSM tapes. QOF and CPR are insulated via internal MLI blankets placed all around QOF and a VDA Kapton SLI between the QOF base plate and the CPR Mounting Plate.

Concerning the active thermal control, the operational part of it is driven by the QOF Electronic Box (QOFE) and aims at maintaining the QOFE and the Power Monitor Diodes above their operational temperature limits. A survival heater circuit, which power is directly provided by CPR aims at maintaining the QOFE and Power Monitor Diodes Temperatures above their minimal non-operational limits.

### 4.4 Temperature Ranges

The following table gives an overview of the temperatures reached by the QOF parts during the entire mission life (i.e. not only during operation):

<table>
<thead>
<tr>
<th>All temperatures in °C</th>
<th>Minimal Design Temperatures</th>
<th>Maximal Design Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panels, Structure parts</td>
<td>-60</td>
<td>75</td>
</tr>
<tr>
<td>Top Cover, Radiator</td>
<td>-80</td>
<td>115</td>
</tr>
<tr>
<td>QOF-Electronic Box</td>
<td>-30</td>
<td>70</td>
</tr>
<tr>
<td>Sub Reflector</td>
<td>-60</td>
<td>115</td>
</tr>
<tr>
<td>Quasi-Optical Components</td>
<td>-60</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 2: The temperature range of the QOF

### 5. MANUFACTURING & ASSEMBLING

#### 5.1 Raw Part Production

All CFRP laminates for the QOF sandwich parts have been made by fibre tow placement. Starting with a dry roving of high modulus carbon-fibre, the roving tow is impregnated with the right amount of epoxy resin in the impregnation stage of the placement machine and then placed track-by track and layer for layer onto the
mould plate with CNC accuracy. The laminates were cured and post-cured in an autoclave. The cleats and stiffening angles are made of carbon fabric/epoxy by hand lay-up and are autoclave cured. All panel face sheets were trimmed to size and cut-outs and holes for inserts were CNC-milled before sandwich bonding.

5.2 SWA-Panel Production

The SWA-Panel displays a 30 mm thick sandwich comprising a vented Al-honeycomb, two 2 mm face sheets and 36 hot spliced inserts which are the interface points for the quasi-optical components. The figures below show on the left side the honeycomb core with the already spliced inserts and on the right side a ready milled face sheet prior to sandwich bonding.

![Figure 12: SWA-Panel core (left) and face sheet (right)](image)

Sandwich bonding was performed at room temperature in order to avoid any additional stress build-up caused by cool down. The mechanical interfaces for the feedhorns and the other quasi-optical components were machined directly after sandwich bonding in order to benefit from free accessibility.

5.3 Feedhorn Frame Production

The Feedhorn Frame comprises three panels, the Center Panel which supports both primary feedhorns and the adjacent Front and Rear panels which. The 30mm Center Panel sandwich is connected by prefabricated and glued CFRP-angles with the Front Panel and Rear Panel, both being 20mm CFRP sandwich panels. Front and Rear Panel both carry block-inserts for precisely bolting the Feedhorn Frame to the SWA-Panel. Dowel pins are used for securing the precise position. The respective interface planes of the feedhorn frame panels were machined to the required tolerances before assembling the frame.

An assembling and aligning tool jig was used to guarantee the precise alignment of the opposite feedhorns in Feedhorn Frame and SWA-Panel during bonding assembly. The alignment measurements were performed with a 3D-coordinate machine and the panels were connected by glued CFRP angles after correct alignment was established and confirmed.

5.3 QOF CFRP Structure Assembly

The structure assembly work started with the mounting of the Baseplate on the assembly-jig. All further assembly steps were supported by utilizing a 3D-coordinate measurement device for position measurements and adjustments. The SWA-Panel was placed and fixed in its final position by adhesive bonding of CFRP-angles. In the next major step the six interface brackets were added. This was followed by the positioning and fixation of the front and rear walls and the stiffening webs. Then were all these sandwich elements connected with glued CFRP-angles. Final assembly work comprised local doubler bonding, attaching the cover, electrical grounding etc..

![Figure 13: Feedhorn Frame during assembly](image)

![Figure 14: QOF CFRP Structure during assembly work](image)

The final assembled CFRP structure is shown below.

![Figure 15: QOF CFRP Structure Assembly](image)
5.4 Final Integration

At the time this paper is written the final integration of the QOF is running at Astrium GmbH, Friedrichshafen and shall be completed begin of September 2010. The final integration comprises

- the installation of the electrical harness for the control and power supply of the switching mirror units, power monitoring signal, temperature sensors and grounding.
- the shimming and mounting of the mirrors, grids, SMU’s and feedhorns
- the installation of Germanium coated Kapton foils as ATOX-protection
- the integration of the Quasi Optical Feed Electronic box
- the integration of electrical thermal hardware and multi layer insulation blankets

6. VERIFICATION TESTING

The verification testing of the QOF-FCM is planned to follow the test sequence as:

- 3D-control of all interfaces
- Initial RF-performance measurements
- Vibration test
- Shock test
- Thermal cycling in vacuum/ thermal balance test
- Final RF-performance measurements

7. CONCLUDING REMARKS

A structural design for a Quasi-Optical Feed system for EarthCARE CPR instrument has been established in CFRP / Al-sandwich technology which meets the stringent requirements basically for

- Accommodation of quasi-optical components
- Specified RF-beam width
- High thermal stability
- Small envelope within CPR
- Low mass.

The static and dynamic performance of QOF has been verified by structural and thermal analyses up to now. The fully qualification testing is planned to follow in autumn 2010.

8. ACKNOWLEDGEMENTS

The development of such a challenging structure like the QOF is always an interaction between a large number of players. The authors would like to acknowledge

- the expert support for the development of the quasi optical design provided by our colleagues at Thomas Keating Ltd,