

MERLIN – PFM Progress and related instrument performance according to the current AIT status

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ABSTRACT

The optical design for the MERLIN instrument ensures failure tolerant operation of a bi-static configuration and consists of a separate transmitter (TX) and receiver path (RX). Due to external constraints, the instrument needs to have a very compact design and has to rely on passive thermal control. The predicted performance of the Methane measurement accuracy, based on detailed analyses prior CDR, was presented at ICSO in 2018. Having advanced in the AIT, these predictions are updated based on optical performance measurements in the lab and compared to the previous analyses. All passive RX and TX optical components in the entire optical chain have been assembled into their structure elements of the PFM with excellent optical performance.

This presentation will concentrate mainly on the achieved optical performance test results for RX- and TX paths, and the resulting prediction of instrument in-flight performance. The achieved on-ground-WFE of the 50x-magnification-RX telescope is better than predicted from the tolerance analysis, which is remarkable for an off-axis parabola of F# 0.88x/0.93y as M1 RX. The DEA (Detection Assembly) contains a folding mirror, three lens packages and the detector. The challenge in the DEA integration was the axial alignment of the DFL (Detector Focusing Lens) with a F# of 0.64 to the detector, which has been achieved within 3 μm (given tolerance was 5 μm). The DEA environmental test campaign is completed now and the final as-built-performance test results will be presented.

Keywords: MERLIN instrument, bi-static DIAL, optical design, as-built test results and instrument performance

1. INTRODUCTION

The Methane Remote Sensing LIDAR Mission (MERLIN) is a joint French-German cooperation on the development, launch and operation of a climate gas monitoring satellite, executed by the French Space Agency CNES and the German DLR Space Agency. Airbus DS GmbH is the industrial Prime Contractor for the German contribution to Mission Phase C/D and builds the MERLIN Payload, which is the first realization of an IPDA (Integrated Path Differential Absorption) LIDAR for space in Europe.

The German contribution to the MERLIN mission is funded by the Federal Ministry of Research, Technology and Space.

MERLIN is focused on global measurements of the spatial and temporal gradients of atmospheric Methane (CH_4) with a precision and accuracy sufficient to determine Methane fluxes significantly better than with the current observation network [1], [2], [8]. Merlin is a LIDAR Instrument using the IPDA principle [3]. This instrument principle relies on the different absorption of the laser signal by atmospheric Methane at two laser wavelengths – on-line and off-line – both around 1645 nm, reflected by the Earth surface. The attenuation is strong at the on-line wavelength; the off-line “reference” wavelength is selected to be only marginally affected by Methane absorption. Being an active instrument with its own light source, the MERLIN LIDAR Instrument does not rely on sun illumination of the observed areas and therefore operates continuously over the orbit at day and night and even through thin cirrus cloud layers [4].

The paper presented here concentrates on the results of the current AIT and environmental test status and the instrument performance connected with it. The performance results will be compared with data based on the analysis presented in [5] and [9].

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2. MERLIN PAYLOAD OVERVIEW

The MERLIN instrument is compatible with the French MYRIADE Evolutions Platform. The satellite, with a total mass of 400 kg for platform and instrument together, is limiting the useable budgets. Because the MERLIN satellite was supposed to be launched as a secondary passenger together with other satellites only a limited envelope for the instrument was allowed. The main payload characteristics are summarized in Table 2-1.

Table 2-1: Main instrument characteristics

Parameter	Unit	Value
Online Wavelength vac	nm	1645.552
Offline Wavelength vac	nm	1645.846
Pulse Energy	mJ	9
Pulse Length	ns	20 - 30
Repetition Rate	Hz	2*20 (for double pulses)
Instrument Mass	kg	150
Instrument Power	W	150
Instrument Volume	mm ³	930 x 850 x 1300
Data Rate	Mbit/s	3.50
Data / Day	Gbit/day	300

The limitations of the envelope enforce a compact instrument design with an elegant arrangement of all subsystems (ref to Figure 2-1). In order to increase the compatibility with co-passengers, the satellite design shall be compatible for two SSO LTAN options of 6am or 6pm [5]. The operational temperature for different subsystems of the instrument can reach values between -20°C and +30°C, which can vary over time and can occur as local gradients on the structure.

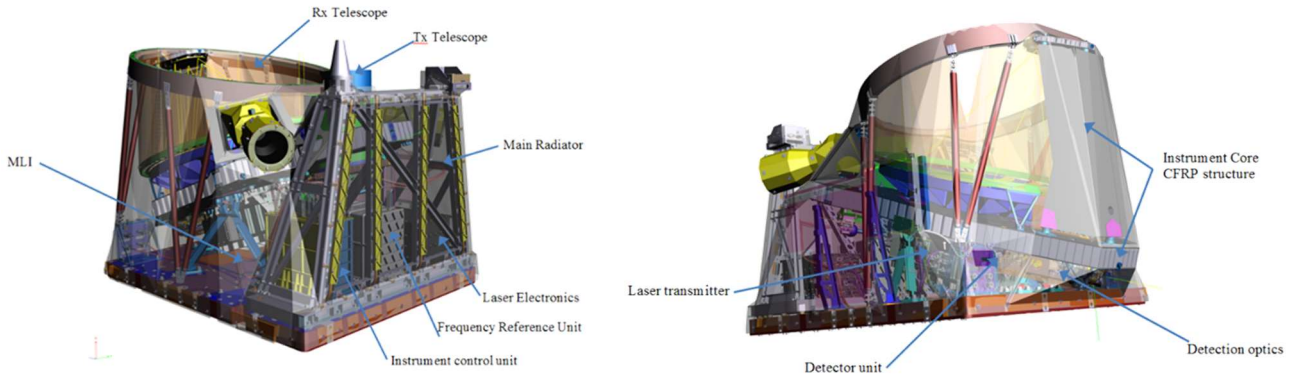


Figure 2-1 Perspective views on the Merlin Payload

The accommodation of the MERLIN payload compatible with the MYRIADE Evolutions platform is illustrated in the Figure 2-1. Similar to current LIDAR instruments (e.g. ATLID and DWL), the MERLIN instrument is a bi-static Lidar, which uses two separate telescopes for the transmission (TX) and reception (RX) of the laser pulses. Both telescopes are mounted on the same optical bench, which accommodates also the laser transmitter, the detection unit as well as two star-trackers for verification and control of the pointing. The main structural element of the payload is the optical bench, made of CFRP (Carbon Fiber Reinforced Polymer) and designed for maximum stiffness and lowest CTE (Coefficient of Thermal Expansion). Primary and secondary mirrors of both TX and RX telescopes are made of Zerodur. The aim of the optical bench is to ensure a proper operational alignment of the two telescopes with the star tracker, and to decouple thermally and thermo-elastically the payload from platform for greater stability.

3. PRESENTATION OF THE INSTRUMENT SUBSYSTEM DESIGN AND HARDWARE STATUS

MERLIN payload passed the CDR in 2020 and is now progressing in Phase D. The payload structural and thermal model (STM) was successfully assembled, integrated and tested in 2019. Further details of the instrument development status are shown by an overview of the current hardware and design status of the major subsystems in this chapter.

3.1 Laser transmitter

The design and development status of the MERLIN laser is described in detail in the article „Merlin Laser Platform – Optical Performance of the Laser Transmitter and Outlook for future Missions” of J. Ammersbach et al. [13], which is published in the same issue of these proceedings. Therefore, only a very brief summary of the design and hardware status of the laser is given below.

Laser optical bench – subcontracted to Fraunhofer Institute for Laser Technology (ILT)

On the top and bottom side of the laser optical bench (LASO) are the optical components that form the Nd:YAG master oscillator power amplifier (MOPA) and the subsequent optical parametric oscillator (OPO). The compliance of the concept has been validated before in air-borne LIDAR applications and ESA’s technology project FULAS [7].

The design makes use of specially developed key optical components for spaceborne lasers [7]. All mirrors, lenses and crystals – especially for the demanding components like Faraday isolator, Pockels cell, piezo actor and OPO crystal control heater – are soldered to their mounts avoiding any adhesives. These designs are inherited from the technology demonstrator FULAS.

LASO CDR was successfully passed May 2019. LASO EQM/PFM assembly, integration, and test have been completed in summer 2026.

Laser Housing – Airbus internal build item

The laser housing (LASH) is built as a pressurized and hermetically sealed housing with an isostatic mounting I/F for accommodation e.g. into an LIDAR instrument structure. The central frame of the housing provides several hermetical feedthroughs for electrical and optical connectors, thermal-hydraulic feedthroughs for the miniature loop heat pipes (LHP) and a beam exit window. Furthermore, two connectors for purging and pressurizing the housing before final sealing are implemented. The compliance of the concept has been validated before in ESA’s technology project FULAS and dedicated technology qualification activities.

Assembly, integration, and test of LASH EQM and FM have been successfully completed in 2024.

Laser electronics - subcontracted to von Hoerner&Sulger (vH&S)

The Laser Electronics (LAE) is the only electrical Interface (I/F) towards the Solid State Laser (LAS). It provides: control for oscillator cavity length matching to the Frequency Reference Unit (FRU) generated seed light, high power current pulses towards oscillator and amplifier pumping laser diodes, high voltage pulses to the Pockels cell, FRU input based control of the OPO cavity length, as well as thermal control of the two OPO crystals and the Loop heat pipe (LHP) cooled main heat sources on the Laser optical bench.

The LAE EM has been in use since 2019. The PFM will include some improvements thanks to the testing on laser assembly level using LASO EQM, FRU EM and LAE EM. Its delivery is expected in Q1/2027.

Frequency reference unit - subcontracted to SpaceTec GmbH (STI)

One part of the MERLIN laser system is the Frequency Reference Unit (FRU), which stabilizes the frequency of the pulsed laser relative to the absorption lines of methane at around 1645.55 nm with MHz accuracy. For the absolute reference of the online wavelength, a methane gas cell is flown within the unit. For relative frequency of the offline wavelength, a



Figure 3-1: Laser (LAS): Laser housing (LASH) with integrated optical bench (LASO).

Fizeau wedge with about 4.28 GHz free spectral range (FSR) is used, being part of a wavemeter. Low noise laser diode drivers have been developed and implemented in order to keep the laser frequency within the desired accuracy range. Also, the MERLIN master oscillator is seeded by the FRU with narrowband 1064 nm laser light.

The major functional and performance requirements of the FRU are: seeding of the 1064 nm master oscillator, absolute frequency referencing to the 1645.55 nm methane line and seeding of the OPO at the two wavelengths, λ_{on} and λ_{off} , spectroscopic measurement of every individual OPO laser pulse, providing a frequency knowledge better than 8 MHz for the online and 50 MHz for the offline frequency and control and stabilization of the instrument's OPO cavity length according to the performed measurements [10].

The FRU completed its Critical Design Review (CDR) in July 2018. Afterwards, the flight-design representative Engineering Model (EM) FRU was successfully tested and delivered to the instrument prime in 2019. The PFM will include some improvements thanks to the testing on laser assembly level using LASO EQM, FRU EM and LAE EM. Its delivery is expected in Q3/2026.

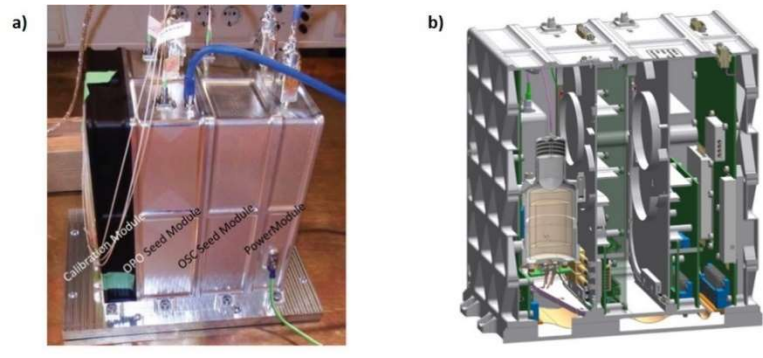


Figure 3-2: Design of the FRU overall system (EM at EMC test) (left), Cut-away view of the FRU assembly (right)

3.2 Internal calibration chain - subcontracted to SpaceTec GmbH (STI)

The Internal Calibration Chain (ICC) is used to provide fractions of the emitted laser beam to the Signal Chain, as well as the Frequency Reference Unit, in order to determine the following information: 1) Radiometric reference signal, 2) TX laser pulse time stamp and 3) TX laser pulse frequency.

Tasks (1) and (2) is assigned to the ICC path towards the SIC via two integrating spheres. Task (3) is assigned to the ICC fiber interface towards the FRU, which are schematically shown in the functional block diagram on Figure 4-1.

The dominating performance aspect of the ICC is the radiometric energy references for the IPDA. Here a huge effort was spent to meet the dynamic range of the signal chain and to minimize the systematic errors in this subsystem. Important elements to be addressed in order to achieve this systematic error free concept for the two wavelengths are error sources like coating variations, etalon effects and speckle statistics.

For the speckle topic a dedicated decorrelation mechanism is used to generate independent start conditions for the phase correlation of the two pulses. This mechanism is realized by a moving diffusor at the first scattering surface of the reference path.

The ICC completed its Critical Design Review (CDR) in June 2021. Afterwards, the Qualification Model (QM) ICC was successfully qualified and delivered to the instrument prime in 2022. The PFM ICC is planned for delivery in Q3/2026.

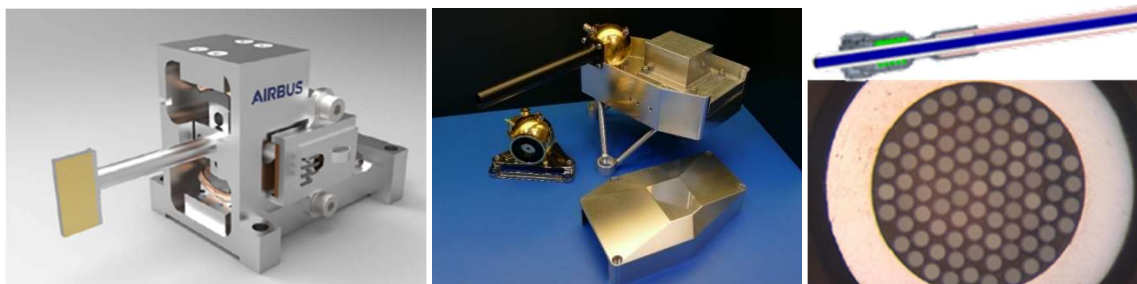


Figure 3-3: ICC HW status decorrelation mechanism (left), Integrating spheres (middle), Transfer fiber bundle (right)

3.3 Instrument control unit - Airbus internal build item

The Instrument Control Unit (ICU) with the included decorrelation mechanism (DCM) module of the Signal Chain (SIC), is the sole command interface between the platform and the instrument. It provides the command interface and the science data interface. The command interface will be used to receive commands and to send telemetry. The science data interface will be used to provide the measurement data and all ancillary data, which is required for the on-ground processing of the measurement data (e.g. timestamps, signal energy data, detector temperature, etc.).

The ICU makes use of recurring modules, with the exception of the SIC including the DCM, which is instrument specific.

The ICU EM was successfully assembled, integrated and tested prior to PL CDR. The ICU EM was also used for system level tests of the active pointing control (APC) scan unit and during the DEA alignment to operate the SIC. The fully calibrated FM was delivered Q1/2026 and was operated together with the SIC during the DEA campaign in Q2/2026 as well.



Figure 3-4: Merlin instrument control unit
ICU – PFM

3.4 Signal chain - Airbus internal build item (InGaAs-APD: Laser Components Detector Group, Inc.)

The SIC is in charge of acquiring the laser pulses during various stages. It consists of a focal plane incorporating an InGaAs-APD detector mounted in its housing (signal chain assembly = SICA), the analogue signal processing proximity electronics (signal chain unit = SICU) and the signal processing chain including the ADC, which is physically contained in the ICU (DCM module), as introduced above. There are two types of data products which need to be extracted from the measurement: the total absolute signal energy and the turnaround time (and thus the path length). Effectively, the ratio between transmitted (TX) and received (RX) signals, and online/offline are used for determination of the CH₄ mixing ratio. The main processing steps of the Signal Chain after are:

- Co-addition of the individual pixel values (within each sampling period “vertical”)
- Acquisition, time stamping, formatting of measurement data, configuration data, and ancillary data packages originating from the other sub-units
- Sorting of the data, coming from the different data sources, into the mission data stream and output of the data to the P/F Mass Memory.

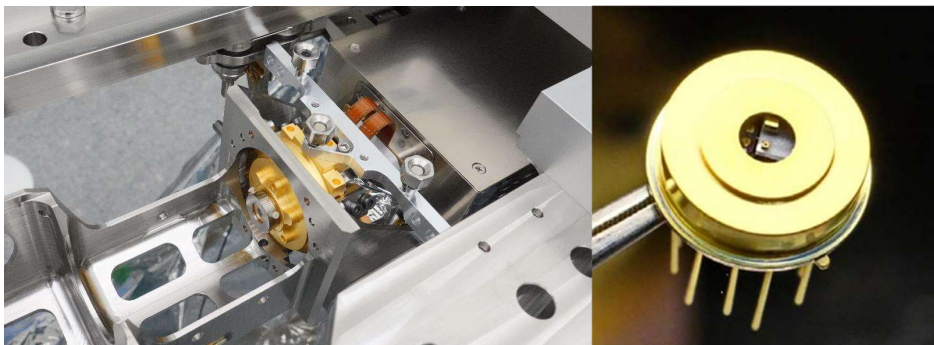


Figure 3-5: MERLIN SIC (SICA+SICU) FM mounted in DEA structure (left), SICD detector EM (right)

The radiometric resolution performance and the non-linearity calibration was confirmed with a selected combination of detector, front-end electronics and A/D converter EM. Subsequently, the qualification tests of the SIC QM were finalized in Q4 2024 and the calibration of the signal chain was concluded in Q1/2025. The SIC FM was integrated into the DEA in Q3/2025.

3.5 Optical subsystem - subcontracted to Safran Reosc

Safran Reosc has been selected as our subcontractor for all of the RX and TX telescope optics, including the lens packages. One supplier for all main components allowed us to find the best balanced solution for the RX and TX optics that ensures a good feasibility and an efficient manufacturing for all design aspects. Safran Reosc's critical design review (CDR) has been successfully passed in 2017. Qualification models (QM) of all optical elements of the TX and RX path were successfully manufactured and tested until 2021.

All of the RX- and TX telescope FM optics, including the lens packages have been successfully environmental tested at the premises of our subcontractor Safran Reosc. The large mirrors for RX and TX have been assembled at Safran Reosc on their individual CFRP baseplates, which were manufactured by Airbus and sent to Safran Reosc prior to mounting. All FM optics have been delivered to the instrument prime. The integration status of the optics at Airbus is described in detail in the following chapter.

4. CURRENT ASSEMBLY AND TEST STATUS OF THE MERLIN OPTICS

4.1 Overview on the Merlin Optics

On Figure 4-1 the functional optical block diagram of the MERLIN instrument is shown. From the laser box (LAS), a pulse pair with 300 μ s delay for on- and off-line wavelengths are emitted. The pulses pass through the internal calibration chain energy separation unit (ICCS), the APC unit and finally the transmitter telescope towards earth. A very small fraction of the outgoing laser pulses is extracted in the internal calibration chain (ICC) for the Frequency Reference Unit (FRU) and for the radiometric reference signal towards the Detection Assembly (DEA).

The receiver telescope consists of the two telescope mirrors RXOTP (M1), RXOTS (M2) and the ocular lens (OCL). The light coming from the M2 passes through a hole in the optical bench and is redirected by the folding mirror RXOTF, parallel to the rear side of the optical bench, but also out of the x-z plane for accommodation reasons. The detector focusing lens (DFL) images the incoming signal light backscattered from earth via the RX telescope and the incoming calibration light from the detection assembly calibration lens (DEAC) onto the detector.

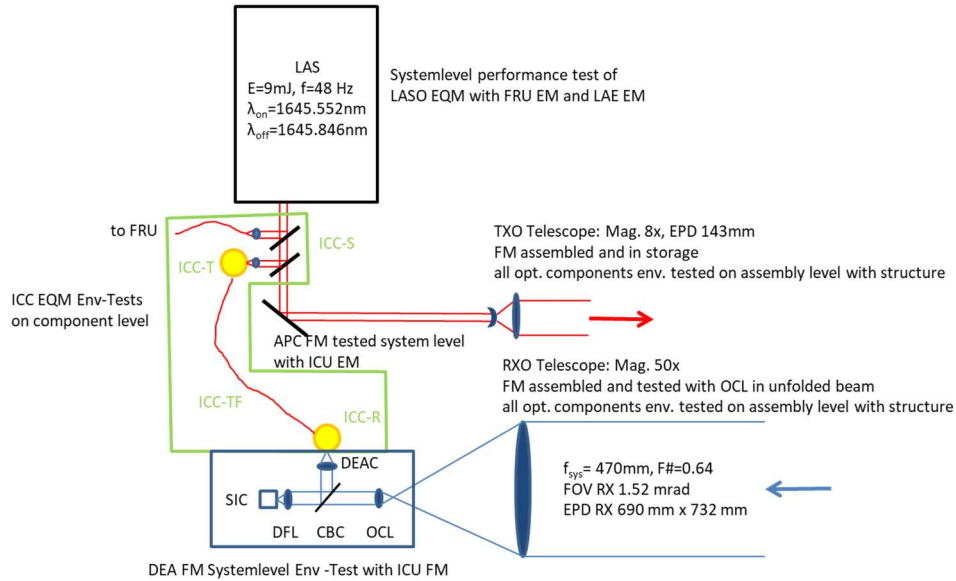


Figure 4-1: Function optical block diagram and status overview

The receiver telescope RX is an afocal design with a magnification of 50x (shown on Figure 4-2). A more detailed description about the optics design and its drivers can be found in [9]. The DFL also contains the narrow-band filter close behind the aperture stop (AS). This filter transmits the narrow window encompassing the two transmission wavelengths and suppresses all remaining detector sensitive light.

The transmitter telescope consists of the primary TXOTP (M1) and secondary TXOTS (M2) transmitter mirrors, an optical cover window (TXOW), and an active pointing control mirror (APC). The TXOW is required for contamination protection and the APC is necessary for active in orbit co-alignment between the RX and TX beams. The APC mirror is the only active pointing correction element for the optical performance, which ensures an optimal co-alignment between RX and TX footprints on ground. Two wedged glass plates from the ICCS, mounted to the laser box, are used for out-coupling laser light into monitoring paths of the internal calibration chain ICC.

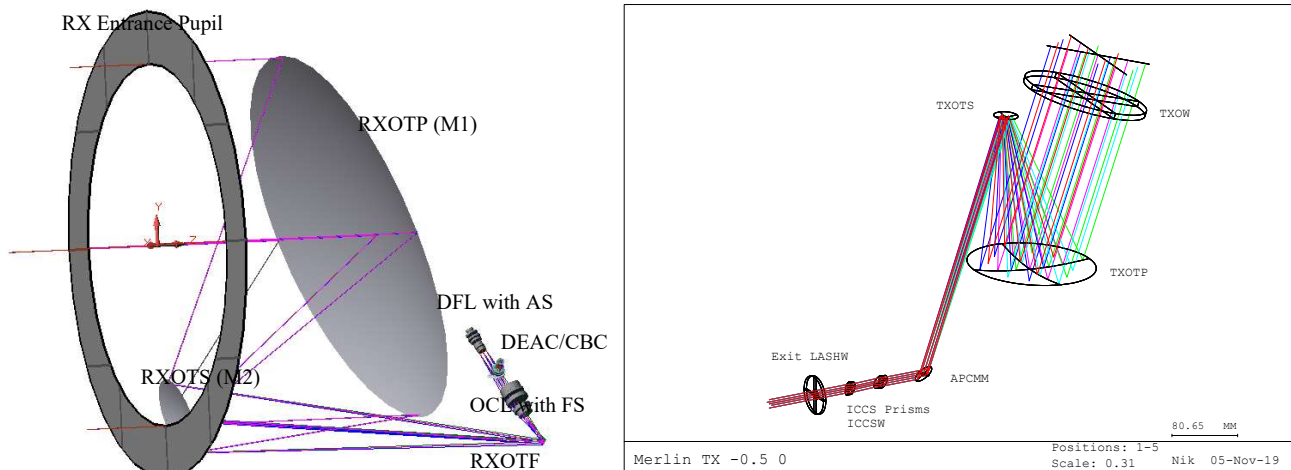


Figure 4-2: Overview of the RX path (left) and TX path (right)

4.2 Test of RX telescope

At Airbus the RX telescope has been assembled with M1 and M2 (see Figure 4-3 left side) and tested together with the OCL in unfolded configuration (without folding mirror RXOTF) across the entire FoV of $\pm 0.0435^\circ$ as shown on (Figure 4-3 right side). Because the OCL has been achromatized, this chain was verified at the alignment wavelength 635 nm. A wavefront sensor for the field scan is located in the exit pupil of the RX telescope. At this position in the system level configuration (as shown on Figure 4-2) with the later fully integrated DEA on the RXOB, the DFL aperture stop is located.



Figure 4-3: Merlin RX with integrated structure and M2 mirror (left) and with OCL in unfolded test configuration (right)

The wavefront error within the whole RX FOV is almost equally distributed at the expected performance 228 nm rms for the center field, between 213 and 298 nm rms for the off-axis fields and around 240 nm rms for the on-axis fields. This is a very good result, because the M2 position with respect to the fast M1 parabola with F# 0.88x/0.93y is the second highest sensitive tolerance within the RX path, which has been met after integration within 5 μm for decenter and focus. The entire

RX FOV is by a factor of 3 oversized to the used detector FOV, leaving sufficient margin for the Ground-to-Orbit (GTO) and in-orbit stability contributors on spot size and pointing.

4.3 DEA integration and environmental tests

The detection chain assembly (DEA) comprises the DEAC/CBC, DFL and the detector SICD with the SIC, which includes also the front-end electronics for the detector. The OCL belongs functionally to the RX telescope. Therefore, the OCL was tested together with the RX telescope mirrors. Optical and functional testing of the DEA has been performed via the chain DEAC/CBC, DFL and SIC at the Merlin operational wavelength. All these elements together with the OCL and the folding mirror RXOTF are mounted in the DEAM. For operation of the SIC and readout of the detector signals, the SIC was connected to the instrument ICU (either EM or FM).

The DFL with its F# of 0.64 to the detector in the focal plane is the tolerance with the highest sensitivity of the Merlin optics. For on-ground, the focus alignment shall be within $\pm 5 \mu\text{m}$ axially and after the environmental tests within $-10 \mu\text{m}$ to $+5 \mu\text{m}$. This corresponds to a spot size of about $10 \mu\text{m}$ in order to achieve a good instrument performance. In [5] a parametrical instrument performance analysis was performed for the detector axial focus cases of ± 5 , ± 8 and $\pm 12 \mu\text{m}$. The DFL was characterized, through-focus and entire RX FOV. At the focus position the DFL has a diffraction limited performance within the FOV. The narrow band filter blocks all other wavelengths except the Merlin ones. Therefore, a special wavefront sensor for the Merlin wavelength around 1645.7 nm was used.

The WFE data and the respective PSF were measured during the DFL characterization on Figure 4-4. The slopes from a knife-edge cut through the measured PSFs have been calculated (Figure 4-5 right), which was later the alignment criterion for the position of the detector within the DFL focal plane.

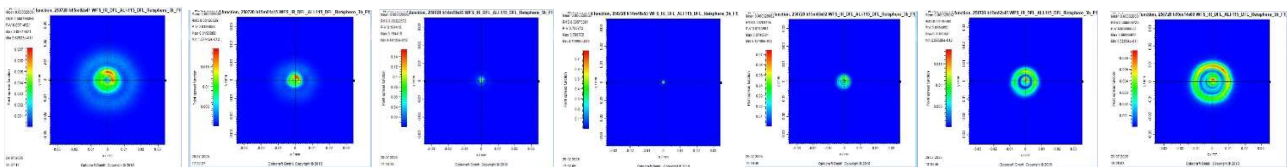


Figure 4-4: Measured Trough-Focus-PSF for DFL center field between -15 and $+15 \mu\text{m}$ with $5 \mu\text{m}$ steps

Using the hexapods for the DFL alignment and the knife-edge scans with a very high scan accuracy of $< 1 \mu\text{m}$, the DFL was integrated with respect to the SICD within $2 \mu\text{m}$ axially and $3 \mu\text{m}$ laterally. The wavefront sensor for the DFL alignment is used as a collimated light source for the angular knife-edge scan of the signal path.

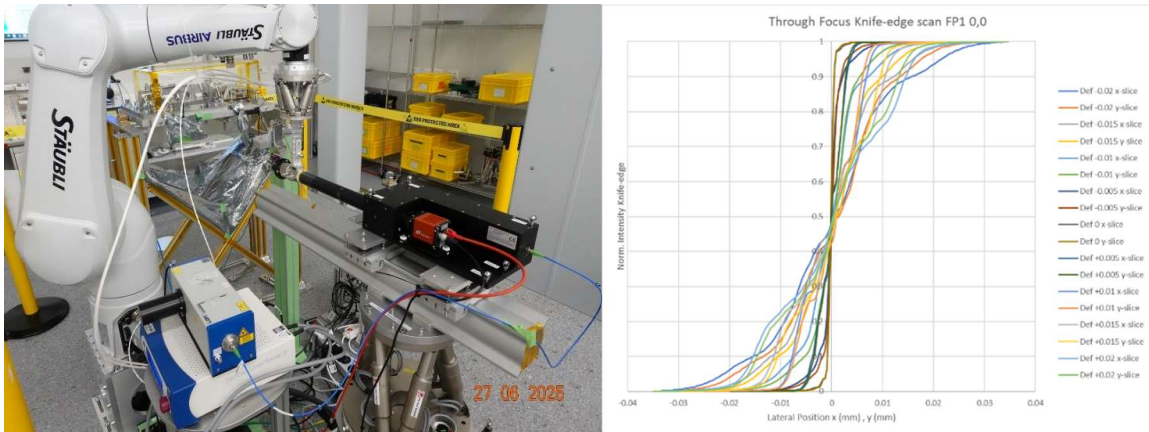


Figure 4-5: DFL characterization setup (left) and calculated knife-edge slopes from PSF measurements (right)

After integration of the DEAC/CBC to the DEAM structure, the knife-edge scan can be performed as well as lateral scan along the focal plane of the DEAC from the calibration path. The light of the WFS for that scan is focused into the DEAC by a F#-matched OGSE lens (as shown on Figure 4-6).

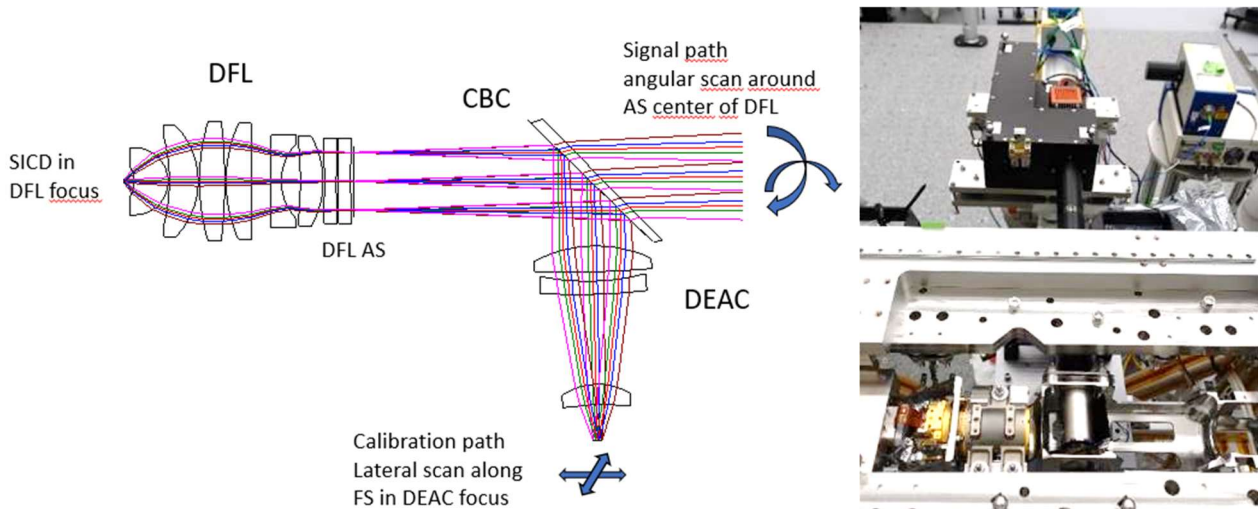


Figure 4-6: Knife-edge scan setup – layout (left) and lateral scan from DEAC focus (right)

A typical linear knife-edge scan along the DEAC focus in x- and y-direction is shown on Figure 4-7 (left side). The ripple of the detector response curve is caused by the granularity of the detector material. With the a precise 2D x-y raster scan it is possible to measure the local distribution of the quantum efficiency across the whole detector surface, shown on Figure 4-7, (right side). The Airy spot size in the DFL focus is about 3-4 μm , which has been sampled with 2 μm step size across the detector surface. This precise scan with the hexapod reveals a convex shape and a drop of the quantum efficiency towards the rim of the detector.

Since a local quantum efficiency distribution is relevant for the instrument performance, this effect is included in the radiometric systematic error (RSE) calculation. This effect was not known in the analysis from 2018 [5] and the quantum efficiency was assumed to be homogenous across the detector surface. Homogeneity measurements of the detector response were performed in 2022 with different OGSE focusing lenses for sampling the detector surface. In the RSE analysis performed in [11] an etalon effect between the InGaAs-layer surfaces for low NA focusing lenses had been observed. Increasing the AOI of the illumination this etalon effect reduces drastically. Measurements have been performed in [11] with AOI up to $\pm 30.3^\circ$ and linear stages with sampling steps above 10 μm . Now, having the DFL FM which delivers an AOI of $\pm 52.7^\circ$ onto the SICD FM and sampling step sizes with the hexapod motion possible in the sub- μm range, the local variations of the quantum efficiency were measured now with a much higher spatially resolved accuracy.

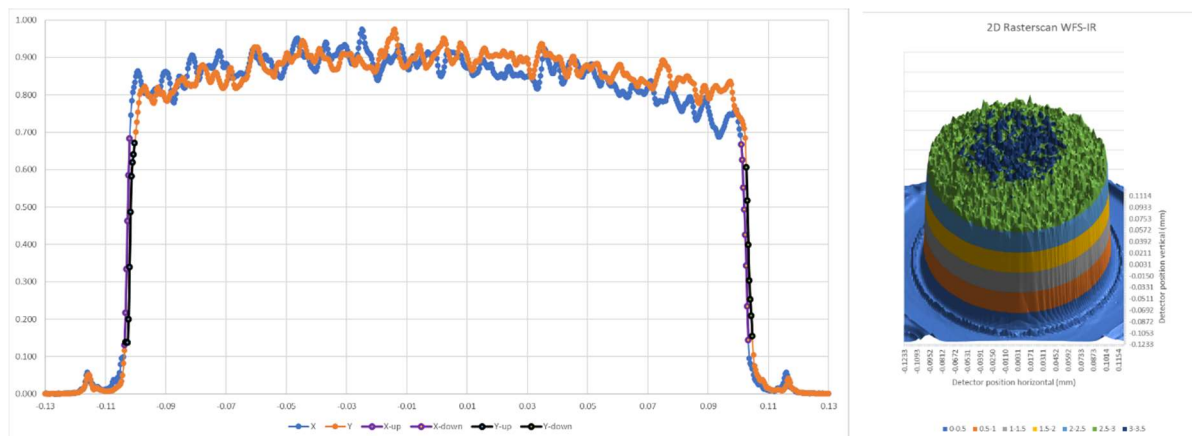


Figure 4-7: Normalized detector response function in relation to lateral position x, y (left), 2D raster scan, isometric view (right)

The detector has an internal double path absorption for increasing the quantum efficiency. At the very high AOI, the double pass absorption is partially “clipped” and the QE is reduced to single path absorption towards the rim of the detector. This

effect causes the curved shape of the normalized response function and a drop down from 1 at the maximum to 0.7 on the rim of the detector, as shown on Figure 4-7.

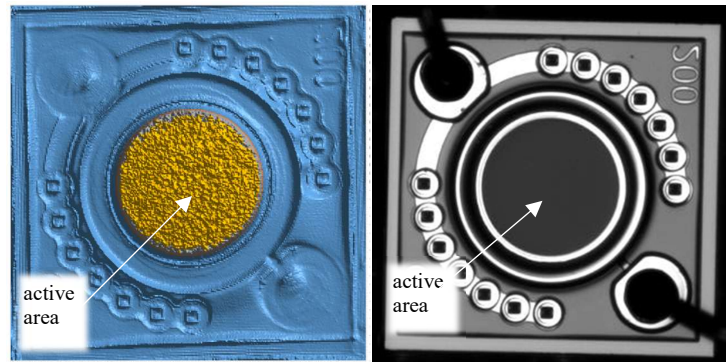


Figure 4-8: 2D-raster scan of the detector responsivity (left), photograph of the detector (right) and surrounding area

Extending the $2\mu\text{m}$ -raster scan across the detector up to an area of $500\mu\text{m} \times 500\mu\text{m}$, the structures around the $210\mu\text{m}$ detector chip become also visible, see Figure 4-8 left side. This can be explained by scattering on the surfaces around the detector and back reflection from the inner walls of the housing onto the photo sensitive area. A microscopic photograph of the detector on Figure 4-8 right side is shown for comparison to the response function from the 2D raster scan. This very fine raster scan is also used for a cleanliness check of the detector, because a particle above $0.5\mu\text{m}$ would cause a local drop of the detector response, which would be deeper than the normal granularity and curved shape. No particles on the detector surface have been found so far.

The OCL and the RXOTF have been integrated into the DEAM according to the coordinates prior to the DEA environmental tests. The DEA on the vibration setup and in the thermal vacuum chamber wrapped with MLI, is shown on Figure 4-9.

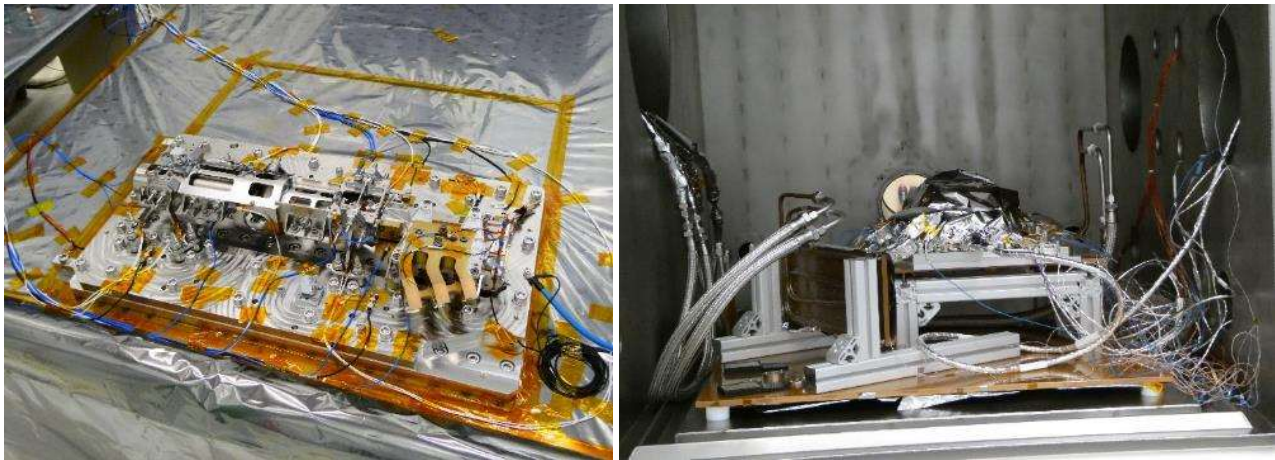


Figure 4-9: DEA on the shaker (left side) and in the thermal-vacuum chamber (right side)

A coordinate measurement and the knife-edge test via DEAC/CBC and DFL was performed after each environmental test. In the thermal-vacuum chamber the SIC was also functional tested at the operational temperatures with success. After both environmental tests, the final position of DFL wrt. SICD has been met within $3\mu\text{m}$ laterally and $1\mu\text{m}$ axially. This is an outstanding result for a lens with $F\# 0.64$, keeping the focal position stable on the detector with this high accuracy.

4.4 TX path test results

The TX telescope was aligned with a WFS at 635 nm. An adapter telescope behind the WFS ensures an aperture clear diameter of 143 mm at the M1 TX. The WFE at center field in optimal position of M2 TX is 108 nm rms, which is almost identical with the WFE of M1 TX alone with WFE of 101 nm rms (spec value 110 nm rms).

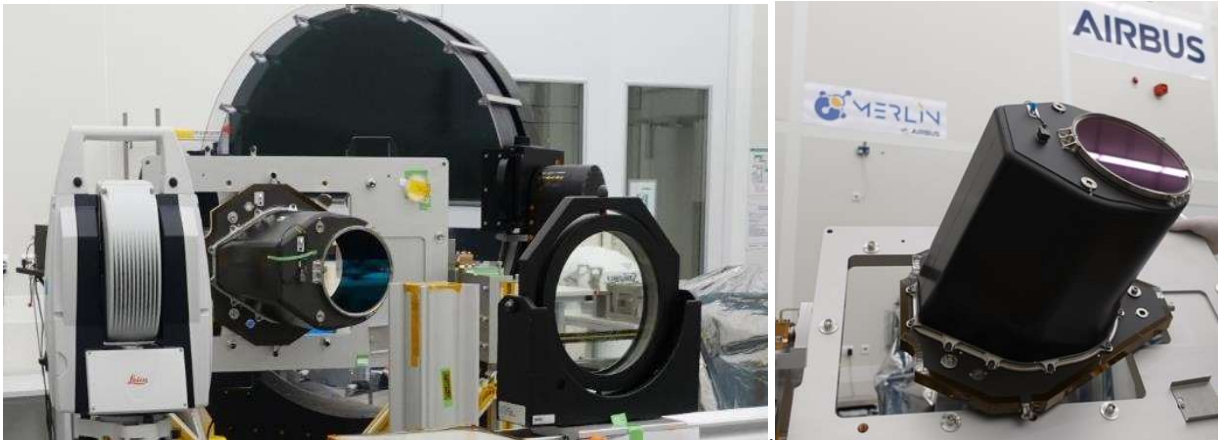


Figure 4-10: Setup for field scan of the fully integrated TX telescope

The fully integrated TX-Telescope with housing and cover window TXOW has been tested with a field scan of $\pm 0.5^\circ$ with the WFS on the hexapod in order to simulate the pointing angle scan generated by the APC. The integrated TX telescope shows diffraction limited performance with a WFE of 0.035-0.055 λ rms over the entire FOV at the operational wavelength of Merlin.

5. MERLIN INSTRUMENT PERFORMANCE

5.1 Input Data - Imaging performance with on-ground as-built data and GTO load cases

The on-ground performance of the RX path was calculated with the results from the RX OCL unfolded and the DEA. The WFE on-ground as-built for the whole RX path is 0.142 λ rms for the center field up to 0.19 λ rms for the outer off-axis field point at 1645.7 nm, which is much better than predicted with 0.34 λ rms from the tolerance analysis. The tolerance for the DFL-SICD distance was nominal $\pm 5 \mu\text{m}$. The fact, that the detector is located now within 1 μm , is the reason for the excellent on-ground performance.

The calculation of the RX path performance for GTO and in-orbit stability, the concept with the sensitivity load cases as described in [5] was used again, but with an updated data base after in-situ-WFE measurements in the TVac chamber on the mirror coating samples for the RX M1 and M2. The unit-load cases established from the Safran-Reosc-team for the deformations on the mirrors due to gravity, baseplate/mirror CTE mismatch, flexure/mirror CTE mismatch, air-to-vacuum stress in the coating etc. have been used again and scaled according to the environmental conditions vacuum and temperatures for hot case (HC) and cold case (CC). The image quality for all lens packages has been measured successfully at Safran-Reosc at their operational max and min temperatures in vacuum.

The mirror temperatures are expected to be for M1 around 13°C and 6°C for M2 in the HC. For the CC case the temperatures can drop down to -1°C for M1 and -8°C for M2. These are the upper and lower limits within the operational temperatures after GTO and in orbit may occur. The temperature spread is not the orbital variation, but also covers the two different orbit options, LTAN 6 am and 6 pm for which the instrument was designed.

The parametrical load cases for the structure deformations in [5] have been replaced by the values from the STM environmental test campaign 2019 at Airbus.

For both load cases, the RX resulting spot sizes are between 16 and 17 μm rms over the full RX FOV. Compared to the parametric analyses in [5], the as-built values for the RX path are a mix between all 3 parametric cases, which have been created for the two most sensitive tolerances DFL-SICD and M1-M2. The detector position has been met perfectly below the load case 1 nominal, the M1-M2 position is between the parametric stability cases 2 and 3. So, the RX spot sizes in orbit are well within the expected values from the analyses presented in [5].

The same approach has been applied to the TX path. The performance criterion here is the TX spot size on-ground, which shall be between 80-120 m for 90% encircled energy. Starting with the laser divergence

and pointing for the on- and off line from the LASO FM results, the as-built WFE of the TX telescope, overlaid with the GTO and in-orbit WFE contributions for the HC and CC for the TX telescope, the APC mirror and the other TX parts. On Figure 5-1(right) the spot size on-ground for the on-line is shown with Gaussian distribution of a diameter of 96 m (x) and 105 m (y) at 90% energy. The corresponding sizes for the off-line are 107 m (x) and 117 m (y). Both are separated by 1.1 m due to the pointing difference. This slightly elliptical shape and the pointing difference of about 1.1 m remain also for the other scan angles within the full FOV of the TX-path. For the instrument performance calculation, the TX Gaussian beam profile is convoluted by the intrinsic RX spots within the illuminated TX FOV (resulting from the laser divergence).

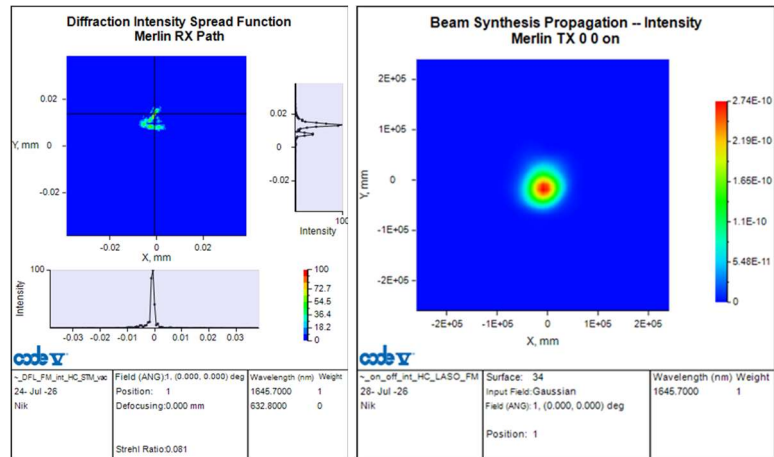


Figure 5-1: RX PSF on detector with WFE 0.5λ rms (left), TX spot size on-ground with WFE 0.036λ rms (right)

Pointing and Spot size

For the imaging of the illuminated ground spots, the following parameter were used in order to cover the three pointing cases, as shown on Figure 5-2. The red circles refer to the TX path, the blue to the RX path.

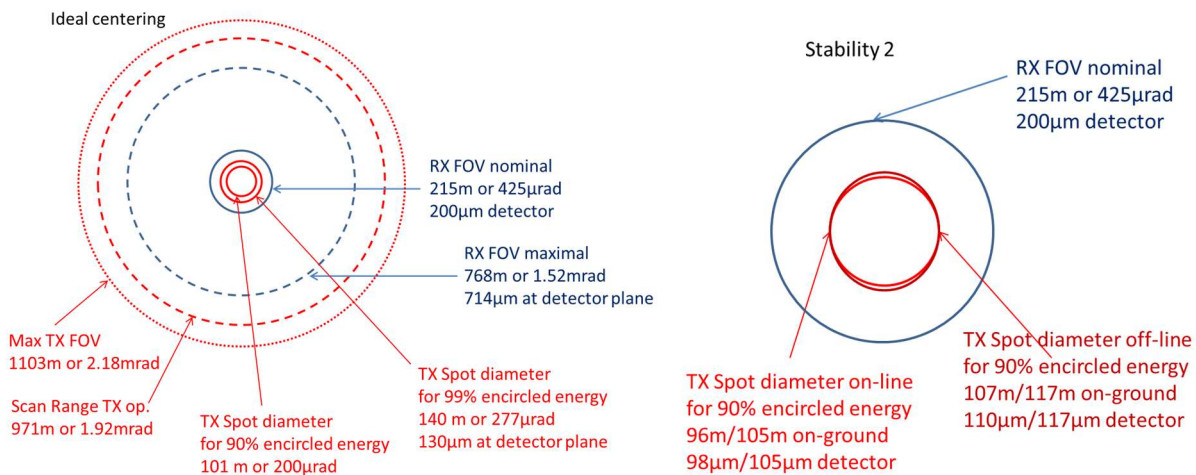


Figure 5-2: Merlin spot size relations projected on-ground and with detail on detector for stability 2

The maximal TX FOV (large red dotted circle) is given by the $\pm 0.5^\circ$ field scan which is possible to address by the APC mirror. The budget for manufacturing/alignment reduces the maximum TX FOV by a static offset. Within the remaining

operational TX scan range (smaller red dashed circle) dynamic corrections for GTO and long-term drift effects for the TX spot (solid red circles) can be performed. The RX path has a maximal FOV (large blue dashed circle) where the nominal RX FOV of the detector (solid blue circle) can be located with almost similar image quality. This covers all effects from manufacturing/alignment and stability 1 allocations for GTO and in-orbit long-term pointing drifts. The oversizing by a factor of 3 for the RX FOV guarantees a high tolerance of the optical performance against internal variation of the alignment parameters and simplifies the co-alignment of the bi-static system.

The budgets for spot sizes and pointing have three contributors:

1. Manufacturing and Alignment (known from the as-built values on-ground)
2. Stability 1 for GTO and long-term drifts with APC correction (known from the load cases HC and CC with the updated unit load cases and the structure deformations from STM results)
3. Stability 2 short-term drifts between 2 calibration cycles without APC correction (mainly affected by the on-off pointing from the laser test results and offset to detector center)

Only the pointing contribution of stability 2 is relevant for the Merlin instrument performance. Monitoring of the pointing contributors to manufacturing/alignment and stability 1 is necessary in order not to exceed the scan range of the APC.

5.2 Instrument Performance Calculation

The Merlin LIDAR shall measure the so-called Differential Atmospheric Optical Depth (DAOD) of CH₄ with a Radiometric Systematic Error (RSE) of 0.13%. The mission overview and the description of the system architecture is given [12].

From the performance model the optical system requirements for the co-alignment (pointing), spot size on-ground and transmission have been derived. The as-built performance for the RX and TX path was calculated to fulfil these requirements together with the other constraints given by the environmental conditions as described in chapter 5. The allocation to the budgets for manufacturing/alignment, GTO effects and stability in orbit for the structure and the optical subsystems have been derived from the global tolerance analyses during the design phase and are now replaced by the as-built values for the calculation of the instrument performance.

The performance model of the Merlin instrument was updated in order to implement also the slightly elliptical Gaussian beam profile of the TX spots and the spatial inhomogeneity of the detector response, which contributes to stability 2.

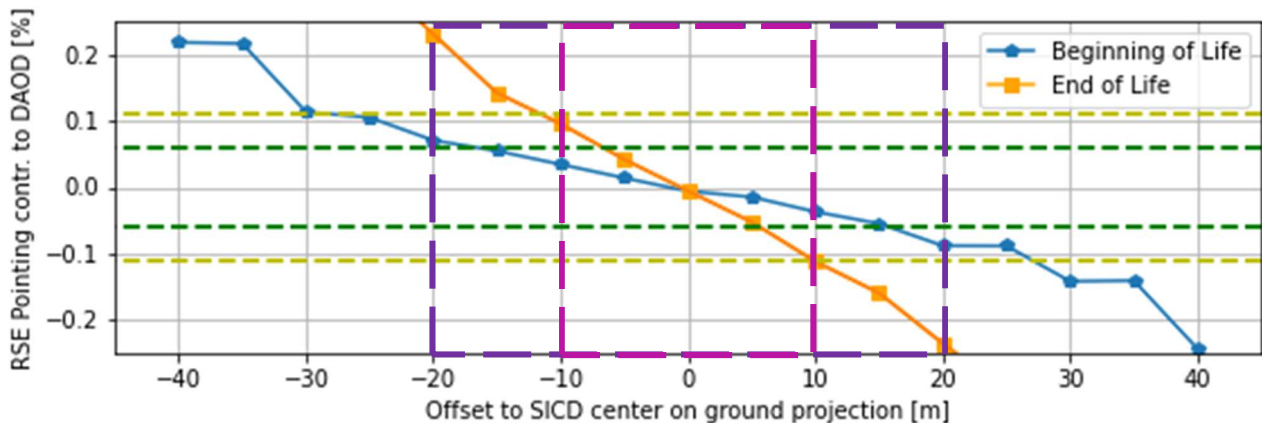


Figure 5-3: Pointing induced RSE contribution to the DAOD

Figure 5-3 depicts the result for the RSE caused by the beam and pointing properties of the light field passing TX, ground and RX depending on the offset, that the light has compared to the projected centre of the SICD on ground. The performance budget allocated initially $\pm 0.06\%$ of the DAOD to the RSE pointing contribution (green dashed lines). After evaluation of the other contributions of this budget the compliance to the mission RSE requirement of 0.13% on DAOD

can be met with an increased contribution of $\pm 0.11\%$, shown with the yellow dashed line. The RSE is evaluated for two different cases of the on-line to off-line co-alignment. First, the Begin-of-Life (BOL) performance, depicted with blue points, assumes a co-alignment of 20 μrad between on-line and off-line beams. The orange squares represent the End-of-Life (EOL) case with 60 μrad pointing offset.

In nominal operational mode the APC mirror will be used to keep the co-aligned beams within a ± 20 m offset to the projected SICD centre on ground. With the BOL performance the RSE is comfortably within the relaxed allocated budget.

The assumed worst case EOL performance exceeds this range. During the full performance APC calibration sequence the systematic on-off pointing can be measured with an accuracy of better 10 μrad and the case of a not covered performance case a payload mitigation approach will be used. In order to state fully compliant to the allocated relaxed budget, the APC might need to be activated more frequently in the EOL phase of the mission to keep the beam pointing closer to the SICD centre. The detection limit of the center position was simulated to be better than 2.5 m, which allows with a more frequent repetition calibration (up to every second orbit for pole scans) an accuracy of better than ± 10 m. In such a mode the RSE, even at worst case offset, the BOL performance could stay in the initially stated allocation of $\pm 0.06\%$.

6. CONCLUSION

The MERLIN instrument status and performance presented here has proven, that the robust optical design was aligned and tested successfully for the RX path with its two most sensitive tolerances. The TX path as-built performance is based on the test results of the fully integrated TX telescope, the APC and the LASO FM. With the demonstrated "as-built performance values" of the MERLIN payload, the most critical requirement of the mission can be met. The goal value for the payload level RSE on the DAOD of 0.09% (Spec:0.13%) is feasible with the optical performance on spot size and pointing as well as the performance relevant effects like the local variation of the detector quantum efficiency. This effect was discovered during the DFL to detector alignment by a high resolution 2D raster scan with unprecedented accuracy.

7. ACKNOWLEDEMENT

The authors would like to thank the whole MERLIN project team at DLR Space Agency, DLR Institute of Atmospheric Physics, DLR Remote Sensing Institute, CNES, Airbus DS, Fraunhofer ILT, Safran Reosc, SpaceTech, Laser Components Detector Group Inc., von Hoerner & Sulger, CGI and Holota Optics for their continuous support and their fruitful cooperation in this challenging project. The German contribution to the MERLIN mission is funded by the Federal Ministry of Research, Technology and Space under DLR contract 50 EP 1601.

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