ESA STUDY CONTRACT REPORT

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ESA Contract No:	**SUBJECT:**	**CONTRACTOR:**
4000116263/15/NL/PS/gp	*High Dynamic Absolute Nanometric Optical Encoder technology assessment for space* DANOE C17 - Executive Summary Report	Micos Engineering GmbH (Switzerland)
***ESA CR ( ) No:** 4000116263/15/NL/PS/gp	**No. of Volumes:** - x - **This is Volume No:** - x -	**CONTRACTOR'S REFERENCE:** Doc. ID: M042RP19082703

ABSTRACT:

The objective of this activity was for the development and test of an Elegant Breadboard model of an Encoder that has been designed and developed under this contract using a baseline design from CSEM in Switzerland and that which was developed under the previous DANOE C16 by Micos Engineering GmbH.

The outcome of the DANOE C17 development phase was to reach a technology readiness level of TRL3 with respect to the DANOE Imager (E2V Ruby) and the electronics design design while establishing an Elegant Breadboard Model (EBB) to allow the demonstration of design adequacy and performance in representative environment for the mechanical structure to reach TRL5. The performance of the EBB was assessed based on a semi-commercial electronics developed by CSEM.

Part of the scope of the C17 development phase was to identify a design for the electronics for the DANOE Encoder to ensure that the performance can be achieved and the the operation of the encoder meets the requirements of future spacecraft applications.

Most notably, the electronics used in the EBB was an improvement from phase C16, but was based on semi-commercial electronics. As well, due to budgetary and scope constraints, it was possible to customize the semi-commercial electronics to the the representative imager, as the focus was to advance the thermomechanical design of the encoder to TRL5, while the electronics and imager maturity was goaled at TRL3 within the Statement of Work. Due to financial constraints, it was not possible to adapt the semi-commerical electronics a redesign activity would have been required.

There are elements of the performance that have not been verified and will need to be performed in the future. All other objectives were reached during the development.

Based on the constraints during the development phase C17 (workflow, budgets), the de-risking activities on imager were possible only on a very limited batch, and due to E2V management of their distributor the components delivered where from two batches, greatly reducing the representativeness of the available residual components. Nevertheless, the imager is qualified according to JESD JEDEC G47 and, a part of radiation verification and annealing can be performed at batch level. A more commercial approach can be undertaken, to qualify the overall encoder electronics is qualified as a single product but only after having achieved sufficient confidence and having undertaken de-risking on the critical components.

The encoder performance can only be assessed with the correct encoder architecture and with the finalized electronics.

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Title	**DANOE C17 - Executive Summary Report**
Project	**DANOE-C17** *High Dynamic Absolute Nanometric Optical Encoder technology assessment for space*
Business Doc Number	**M042RP19082703**
Date	**22.09.2020**
Issue / Revision	**01-00**
Document Type	**Report**

Prepared by	**[Name Surname] (Company Name)**
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DOCUMENT INFORMATION

Distribution List

Company	Name	Function
ESA ESTEC	Dr. Elena Cristina Paul	Technical Officer

Document Change Record

Filename: **M042RP19082703-01-00-DANOE C17 - Executive Summary Report**

Issue	Revision	Date	Change Description
01	00	22.09.2020	First Release.

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REFERENCES AND DEFINITIONS

Applicable Documents

[AD##]	Title	Doc. Ref. Name	Iss/Rev
[AD01]	Annex B of Contract 4000116263/15/NL/PS/gp	4000116263/15/NL/PS/gp	

Reference Documents

[RD##]	Title	Doc. Ref. Name	Iss/Rev
[RD01]	TN05 DANOE Imager requirement specifications, technology trade-off and selection.	M042TN1609	
[RD02]	Véronique Ferlet-Cavrois, "Electronic radiation hardening – Radiation Hardness Assurance and Technology Demonstration Activities" ESA / ESTEC, TEC-QEC, JUICE Instrument Workshop, 9-11 Nov. 2011, Darmstadt.		
[RD03]	Poivey, Christian, and John H. Day. "Radiation hardness assurance for space systems.", NASA GSFC (2002).		
[RD04]	Gubby, Robin, and John Evans. "Space environment effects and satellite design." Journal of atmospheric and solar-terrestrial physics 64.16 (2002): 1723-1733		
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[RD07]	Cabral,Boster "Mechanical Testing of Structural and Hybrid Epoxies",		14 May 2010
[RD08]	Nhamoinesu, Overrend "The Mechanical Performance of Adhesives for steel-glass composite façade system" Conference on architectural and structural applications of glass		
[RD09]	Sundvoid "Optical Adhesive Property Study"		1996
[RD10]	"Evaluation of Adhesive Materials used on the long duration exposure facility"	NASA Contractor Report 4646	March 1995
[RD11]	SenthilKumar, Kirankumar "Adhesives for optical components implementation Study"	Journal of Optics 41(2):81-88	
[RD12]	DANOE breadboard CDR and imager PSR minutes of the Meeting	M042MN16101202	01
[RD13]	Scotchweld 2216 B/A datasheet		
[RD14]	Dow Corning 93-500 datasheet		

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[RD##]	Title	Doc. Ref. Name	Iss/Rev
[RD15]	Rhodorsil 147/148 datasheet		
[RD16]	Solithane 113		
[RD17]	Friedman, J. H. (1984). A Variable Span Smoother. Tech. Rep. No. 5, Laboratory for Computational Statistics, Dept. of Statistics, Stanford Univ., California		
[RD18]	TN09 - DANOE Electronics Requirements Specification	M042RS17030802	02-00
[RD19]	DANOE-C17 Eccentricity Correction & Data Calibration Algorithms	M042RP16113002	00-02
[RD20]	EV76C661 Datasheet	1086A–IMAGE–04/12	04/12
[RD21]	Spacecraft discrete interfaces	ECSS-E-ST-50-14C	C
[RD22]	ProASIC3 Flash FPGA Family Datasheet		Rev. 5
[RD23]	TMP461-SP Datasheet	SBOS876A	Dec 2017
[RD24]	E2V EV76C661 "Ruby" Datasheet	1085A-IMAGE	
[RD25]	Single event effects in 0.18 µm CMOS image sensors	Proc. SPIE 99152Q (5 August 2016); doi: 10.1117/12.2235212	
[RD26]	E2V manufacturing line	21 March 2012	
[RD27]	8 bit mode application mode	E2V EOS_AN_027	
[RD28]	EV76C661 Product Specifications	SP 31S 207684	A
[RD29]	E2V Ruby publication **last**		
[RD30]	TN01 DANOE encoder design description		
[RD31]	TN05 Imager requirement specification, technology trade-offs and selection.	M042TN16091603	01-00
[RD32]	TN07 Imager Evaluation Test Plan		
[RD33]	Emma Martin - Space radiation induced dark current degradation in 5T pinned photodiode 0.18 µm CMOS image sensors	ESA CNES Final Presentation Days 5-6 June 2013	
[RD34]	TOWERJAZZ AND CMOSIS ANNOUNCE RAMP TO VOLUME PRODUCTION FOR CMOSIS' 12-MEGAPIXEL CMV12000	11 June 2013	
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[RD36]	Design and development of CMOS image sensors with TowerJazz	Workshop on CMOS Active Pixel Sensors for Particle Tracking (CPIX14, 15-17 Sept 2014)	
[RD37]	APSEL Deep n-well and Deep p-well CMOS sensor with ST and TowerJazz Technologies	Workshop on CMOS Active Pixel Sensors for Particle Tracking (CPIX14, 15-17 Sept 2014)	

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[RD38]	Developing and qualifying parts using third party libraries and manufacturing services	Cobham Gaisler AB ESCIES Document Library, March 2016	
[RD39]	Private email communication between E2V and Micos	31/05/2017	
[RD40]	Ruby Product Family Qualification Report (EV76C660-EV76C661)	NE 31S 208561/A	09/07/2012
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[RD43]	Test Procedures for the test on CMOS Image Sensor for Micos	ATN-TP-17-0035 TEST PROCEDURES v1	
[RD44]	Total Dose Steady-State Irradiation Test Method	ESA ESCC 22900	
[RD45]	Standard for characterization of image sensors and cameras	EMVA Standard 1288 Release 3.0	
[RD46]	1.3 Mpixels B&W and Color CMOS Image Sensor Datasheet	DSC_EV76C661	
[RD47]	Destructive Physical Analysis Results	2018901602-001	
[RD48]	DANOE imager PSR and EBB CDR minutes of the meeting	M042MN16101202	01-00
[RD49]	Radiation test CMV2000 and CMV4000 - Report	CMV2000-RT-V1	12/07/2011
[RD50]	Imaging Instruments for Ganymede Mission" G.A. Avanesov, R.V. Bessonov, B.S. Zhukov, A.A. Forsh Space Research Institute of the Russian Academy of Sciences		
[RD51]	CNES "Evaluation of CMV Image Sensor for space applications" 2014. From private communication from CMV		
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[RD53]	Caltech: "AAReST Detailed Design Review Mission Overview" Sept. 2014	AAReST DDR, 8 Sept. 2014	
[RD54]	Antti Näsilä: "Validation of Aalto-1 Spectral Imager technology to Space Environment" May. 2013, Aalto University	1 May 2013	
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[RD56]	C3D – An imaging radiation damage experiment on Ukube-1	The 4S Symposium 2014	
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[RD59]	"Space radiation induced dark current degradation in 5T pinned photodiode 0.18µm CMOS image sensors"		

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[RD62]	E2V Imaging and the cubesat revolution		22/04/2016
[RD63]	Tobias Schwarz "Prototyping of a start tracker for pico-satellites" University of Würzburg 2015		
[RD64]	E. F. Garcia "Development and Verification of the Electro-Optical and Software Modules of the Facet Nano Star Sensor"		
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[RD66]	Blommaert et al "CHIEM the development of a new compact hyperspectral imager"	The 4S symposium 2016	
[RD67]	ONERA « Validation of effective NIEL for High Energy Electrons in Silicon"	RI 2/23288 DESP	Feb. 2015
[RD68]	Radiation Induced Dose and Single Event Effects in Digital CMOS Image Sensors	IEEE Transactions On Nuclear Science, Vol. 61, No. 6, December 2014	
[RD69]	DANOE C17 - Final Report	M042RP19082702	1.0

Normative Documents

[ND##]	Title	Doc. Ref. Name	Iss/Rev
[ND01]	Generic procurement requirements for hybrids	ECSS-Q-ST-60-05	Rev 1
[ND02]	Requirements and guidelines for the Process Identification Document (PID)	ESCC 22700	Issue 2
[ND03]	Adoption Notice of ISO 16290, Space Systems Definition of the TRL and their criteria of assessments	ECSS-E-AS-11C	1/10/2014
[ND04]	Requirements for the capability approval of electronic component technologies for space applications	ESCC 24300	
[ND05]	Stress-Test-Driven Qualification Of Integrated Circuits	JEDEC JESD47	I.01
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[ND07]	Commercial EEE Components	ECSS-Q-ST-60-13C	
[ND08]	Moisture/reflow sensitivity classification for non hermetic solid state surface mount devices	IPC/JEDEC J-STD-020D.1	
[ND09]	ESD Sensitivity Testing Human Body Model (HBM)	JEDEC 22-A114	F

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[ND##]	Title	Doc. Ref. Name	Iss/Rev
[ND10]	Generic Specifications: Photosensitive Charge Coupled Devices and CMOS Imaging Sensors with hermetic and non-hermetic packages	ESCC 9020	2/2010

Acronyms and Abbreviations

Acronym	Description

Acronym	Description

Definitions

None

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1 OBJECTIVES AND DOCUMENT OUTLINE

1.1 PURPOSE

This document provides the Executive Summary to the Final Report [RD69] for the activities undertaken for the DANOE C17 activity under the ESA contract 4000116263/15/NL/PS/gp.

The objective of this activity was for the development and test of an Elegant Breadboard model of an Encoder that has been designed and developed under this contract using a baseline design from CSEM in Switzerland and that which was developed under the previous DANOE C16 by Micos Engineering GmbH.

1.2 SCOPE

This document presents the Executive Summary Report for the DANOE C17 activity which included the development of an Elegant Breadboard.

This report briefly addresses the activities performed during the various phases of the development and covers the following points:

- Assessment of Requirements
- Overview of Encoder Design
- FEM Analysis
- Flight Encoder Electronics
- Power Budget
- Imager Testing
- EBB Testing
- Future Development Plan

At the end of the report, there is a conclusion and summary for the activity.

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2 ASSESSMENT OF REQUIREMENTS

The requirements specified in [RD01] were reviewed at the start of the development and with the exception of one requirement, all were considered to be compliant.

The one requirement that was considered to be non-compliant was X-180 which is relevant for the power disipation of the encoder.

Although there are many other requirements that considered not relevant for the Elegant Breadboard development undertaken during this activity. Many of these are relevant for the electronics which will be part of a later development.

X-180	Encoder power consumption shall be < 1.25 W during normal operations. Maximum consumption as resulting from worse case environments shall be less than 2.4 W	This requirement could reveal to be challenging to be achived: - the candidate imagers datasheet provide depending on the model, between 200 mW and 600mW during operations.being two imagers required, the power consumption may be already 1.2 W for the two imagers (to be understood). - depending on the type of FPGA deployed, the power consumption may vary The preliminary design will confirm if the electronics design can allow this requirement as compliant.

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3 DESIGN CONSIDERATIONS

As this development was a follow-on from the DANOE C16 activities, which was for the development of an Optical Encoder, the main aim of this development was to continue this development and bring the TRL higher to level 5.

There are many patents on the optical layouts of Optical Encoders so much care had to be taken during the design phase not to infringe any of these.

To this end, a study of existing patents for optical encoders was undertaken to evaluate suitable optical layouts for this development without infringing any of these patents.

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4 OVERVIEW OF ENCODER DESIGN

4.1 CODE DISK

The Code Disk design was developed during the DANOE C16 activity so was taken over directly for this activity. The M7 design that was defined was developed in Float Glass, but it had been suggested that it would perform better as a Chrome disk to avoid barrel distortions. This was not undertaken as it would have added risk to the development. For this reason, the plate glass disk has been retained for this development.

The code disk has an external diameter 80 mm, the code diameter 62 mm to 78 mm. the mean radius is 35 mm. The pattern for this pre-existing code disk design has 1024 periods, that lead to an average period pattern of about 200 um. For this element the envisaged performances are as follows:

Input drivers:

- Code disk R_m 35 mm
- Pattern Period 200 um
- SNR drivers
  - Number of pixels Npix we assume an ROI of 360x360 pixels to allow ROI reassessment for static eccentricity correction.
  - Pixel full well capacity Nfull 13 ke- (imager driven) for candidate imagers
  - Nominal image contrast Cim 25% best knowledge from experience
  - Nominal image intensity lim 50% best knowledge from experience
  - The signal is estimated as $S = \mathrm{Npix} \cdot \mathrm{Nfull} \cdot \mathrm{Cim} \cdot \mathrm{I\_LED} * \mathrm{Texp}$
  - The shot noise limited SNR as $SNR = \frac{\mathrm{Cim}}{\sqrt{lim}} \sqrt{\mathrm{Npix} \cdot \mathrm{Nfull} \cdot \mathrm{I\_LED} * \mathrm{Texp}}$
  - LED intensity I_LED setup driven
  - Exposure time Texp setup driven

The achievable performance follows the formulation as follows:

- Pattern period Tpat influences precision p (and therefore resolution), repeatability r and the best uncalibrated uncertainty u performance in linear [nm] terms as follows:

$$p_{x,(1\sigma)} = \frac{Pattern\ Period}{SNR} = \frac{Pattern\ Period}{\frac{\mathrm{Cim}}{\sqrt{lim}}\sqrt{\mathrm{Npix}\cdot\mathrm{Nfull}\cdot\mathrm{I\_LED}*\mathrm{Texp}}};$$

$$r_{x,(1\sigma)} = 2p_{x,(1\sigma)}$$

$$u_{x,(1\sigma)} = \frac{Pattern\ Period}{400}$$

- Code disk radius R_m converts the metrological performance conversions in angular terms

$$p_{\theta,(1\sigma)} = \frac{p_{x,(1\sigma)}}{R\_m}$$

$$r_{\theta,(1\sigma)} = 2p_{\theta,(1\sigma)}$$

$$u_{\theta,(1\sigma)} = \frac{u_{x,(1\sigma)}}{R\_m}$$

For the current configuration,

- $p_{\theta,(1\sigma)} = 0.317$ µrad (requirement X-100: resolution 0.37 urad)
- $r_{\theta,(1\sigma)} = 0.634$ µrad
- $u_{\theta,(1\sigma)} = 15.3$ µrad $u_{\theta,(3\sigma)} = 44.1$ µrad (requirement X-110: calibrated 3s uncertainty 20 urad)

The above values provided by the CSEM performance model delivered during the DANOE C16 activity have been met verified by the testing executed.

The precision p drives the setting of the digital resolution in the bit conversion.

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The uncertainty u has to be considered as the best possible uncertainty attainable without dedicated calibration.

Whereas a narrowed period would allow for higher accuracy, a larger pattern period allows for simplification in terms of mounting tolerances. A code pattern of 200 µm allows approximately 1.6 mm of detector to code disk mounting max distance, whereas a pattern of 50 µm would impose approximately 0.1 mm for the same distance.

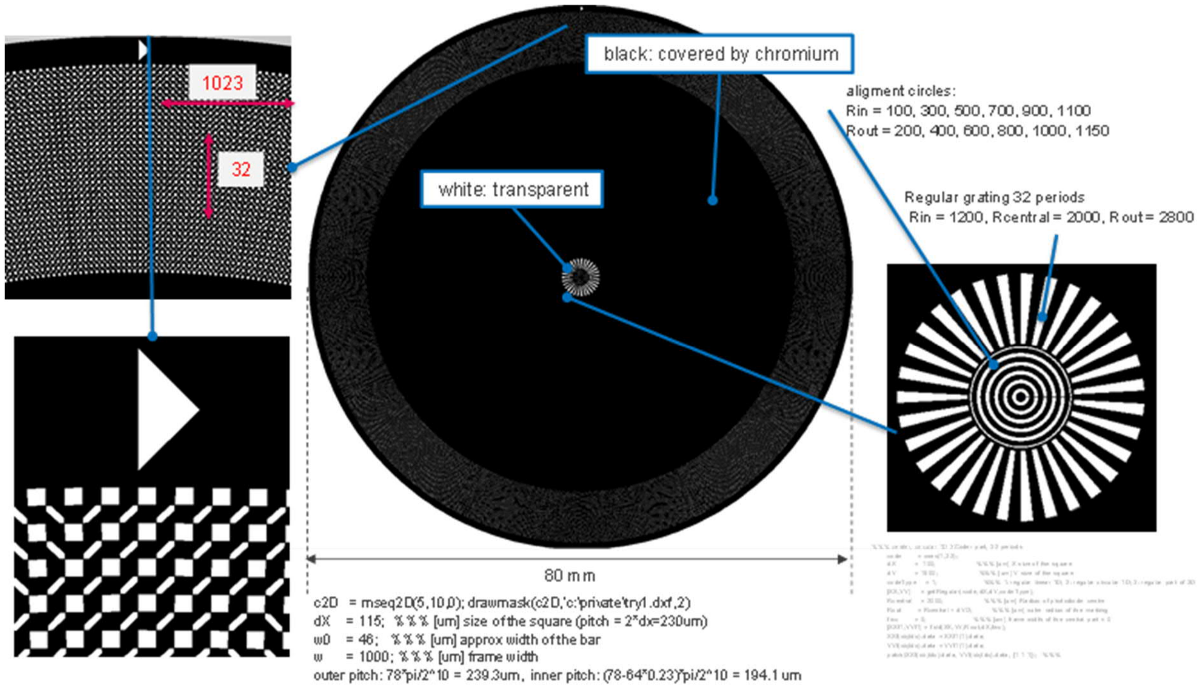

Figure 4-1: Code disk type M7. A nominal zero sign is manufactured on the code disk.

This disk was modified for the DANOE C17 development to have a central hole.

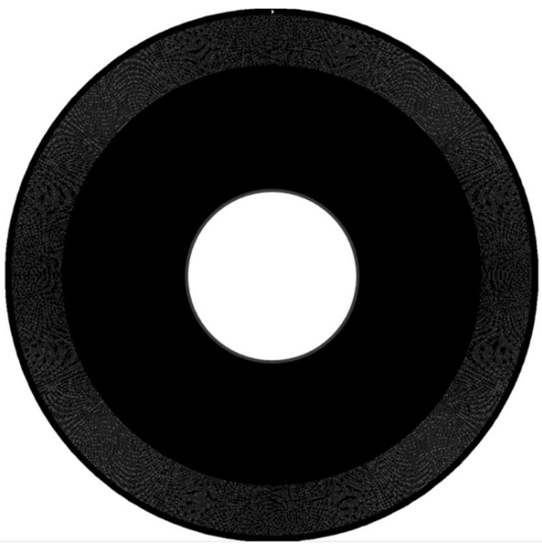

Figure 4-2: Code disk M7 modified with a hole for hollow shaft mounting.

4.2 OPTICAL CONFIGURATION

During this development, Micos implemented two different optical configurations in the EBB to investigate two different approaches for the optical configuration as a risk mitigation activity.

A first solution with a LED positioned closer to the center of the encoder

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- Main advantage: reduced envelope diameter based on the basic encoder building blocks, given the uncertainty on how large the electronics will develop
- Main drawback: no margin for a baffle limiting the optical beam, double crossing of the disk leading to increasing barrel distortion (valued negliglible for the current configuration) and slight loss of transparency, increased straylight

▪ A second solution (baseline) with a LED positioned to a larger distance from the center

- Main advantage: : baffle limiting the optical beam can be implemented, single crossing of the disk limiting the barrel distortion. Simplified light control.
- Main disadvantage: given the uncertainty on how large the electronics will develop, the proposed solution leads to a larger minimum size of the optical encoder.

The rationale for this double configuration is that systematic performance model able to predict the encoder performances based on the optical elements is not currently implemented. The performance assessment has been carried out mostly on an empirical approach based on testing of the configuration rather than in modelling of it.

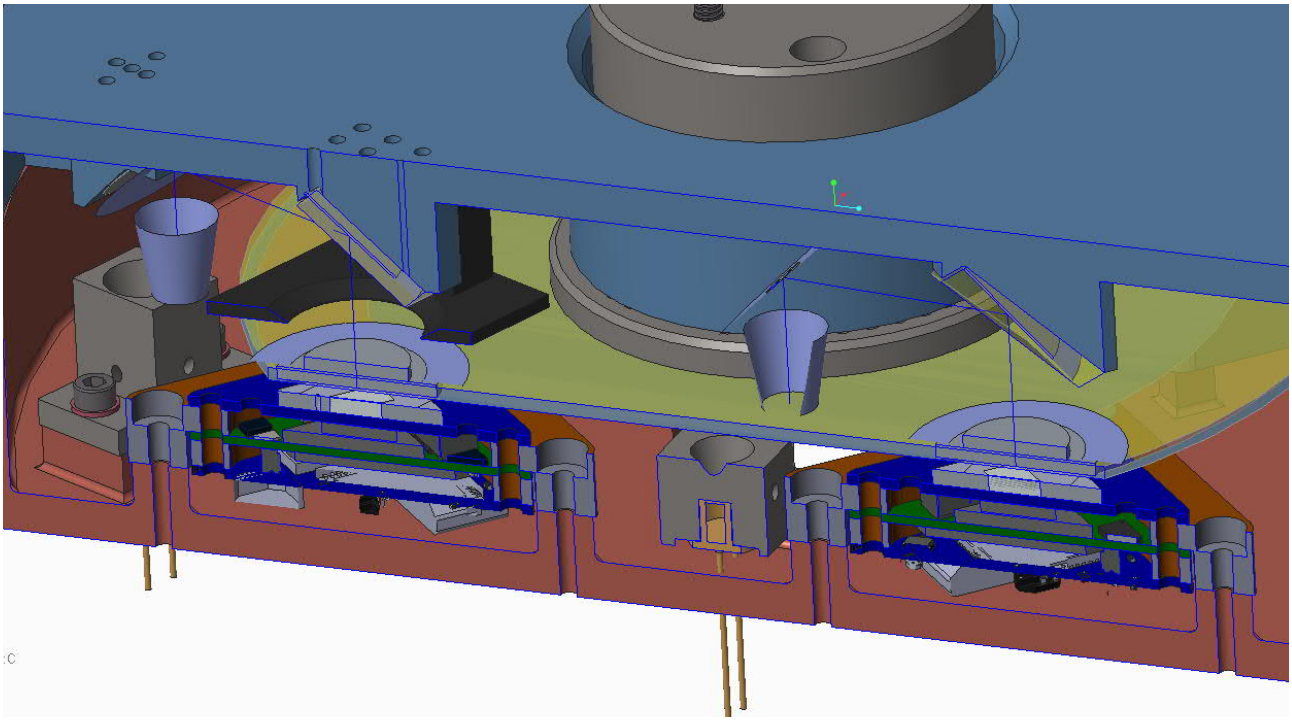

Figure 4-3: Representation of the two optical layouts. In the baseline layout, the LED is located outside of the code-disk footprint. In the second layout that is intended to be investigated, the LED is located beneath the codedisk, close to the shaft. This allows to have a more compact layout.

4.3 CODE DISK SHAFT SUBASSEMBLY

The Code Disk Shaft subassembly has been fully developed and represents the design of the subassembly in the final design.

The code disk subassembly is shown on Figure 4-4. The Code Disk is bonded to the Titanium 6Al4v Shaft using 3M Scotchweld 2216 B/A Grey. This adhesive was selected from a range of adhesives listed in the following:

- Scotchweld 2216 B/A [RD13]
- Dow Corning 93-500 [RD14]
- Rhodorsil 147/148 [RD15]
- Solithane 113 [RD16]

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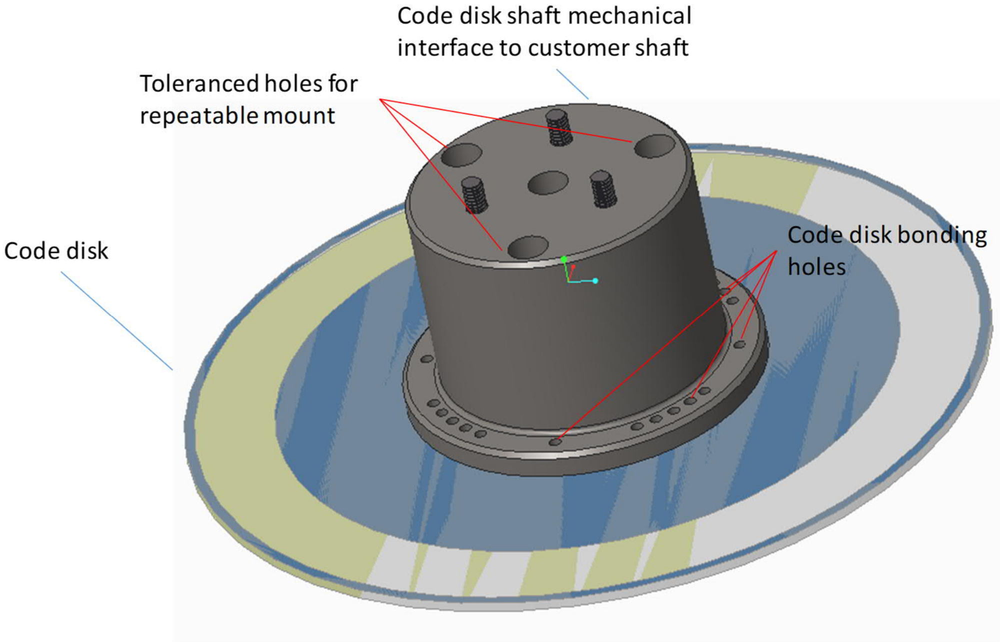

Figure 4-4: The code disk has 80 mm diameter.

A trade off of these adhesives was perfomed and the 3M Scotchweld 2216 B/A Grey was considered the better mechanical properties.

The bonding was performed using a specially prepared bonding jig which ensured repeatability of the bonding process. The shaft has been designed to allow for the bonding of the Code Disk to the Shaft.

A bonding jig was used to align and clamp the disk in place and to minimise the excentricity of the disk to the shaft.

4.4 IMAGER SELECTION

A requirements specification was prepared for the Imager procurement [RD01].

4.4.1 STATUS AFTER DANOE-C16 ACTIVITY

During the execution of the first DANOE-C16 work, it has been identified that in order to offer to the Agency and the community a product with the targeted restituted data rate, an high speed imager is required. The spaceCoder technology is treating the whole image sample of at least 256x256 pixels as 1 position sample. Commercial imagers are available, but apparently no suitable space qualified imager product exists. The initial specifications was a restituted data rate of 10 kHz, negotiable due to the technology limitations of products on the markets.

4.4.2 COMMERCIAL IMAGER OVERVIEW

The commercilally available imagers were reviewed and contact made with several potential suppliers.

The review of these commercially available imagers was based on the specifications required for the encoder functionality. High speed imager chips may have a small size of the imaging chip per-se but generally, in order to ensure high speed rate, the number of pins (~100ths) is rather large and imposes a rather large packaging.

The CMOS imaging sensors (CIS) do not suffer the charge transfer losses experienced by CCDs, however they are susceptible to SEU and latchup effects which are not a concern for CCDs [RD56].

Proton induced TID and D_d in CIS lead to dark current increase [RD51]:

- TID induces charge trapped and interface states

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- TID effects are reduced by using PPD, this way the SCR are recessed from oxide
- Displacement dose D_d induces bulk defects in silicon
  - Main issue in CIS using PPD is that this lead to hot pixels

4.4.3 IDENTIFICATION OF CANDIDATE IMAGERS

Following the review of the potential sensors, the following candidates were identified for further evaluation.

- CMOSIS CMV2000 due to the heritage studies on radiation hardening carried out by CMOSIS and CNES and its relatively high speed
- CMOSIS CMV300 (as it is based on the same libraries used by CMV2000, CMV 4000 etc, though it is manufactured in a different),
- E2V Jade due to the relatively large studies that adopted this sensor for space based applications
- E2V Sapphire and Ruby as E2V declares the possibility for a batch-based ESCC9020 screening process and its space worthiness.

4.4.4 IMAGER TRADE-OFF

Following an extensive trade-off using available data on the Radiation sensitivity of the Imagers, the E2V Ruby Imager was selected for the DANOE C17 development although the CMV 2000 scored slightly better. The reason for this was that Power is not of great concern; a maximum frame rate of about 140 Hz is considered satisfactory for the present and future applications; and the Radiation tolerance statements of E2V were convincing.

4.4.5 IMAGER TESTING

Despite ordering 25 Imagers and asking for all to have the same date code, Micos was sent two batches with different date codes.

15 Imagers were received with Datecode 1611 and 10 with Datecode 1534. These Imagers were tested by Alter as shown on Figure 4-5 .

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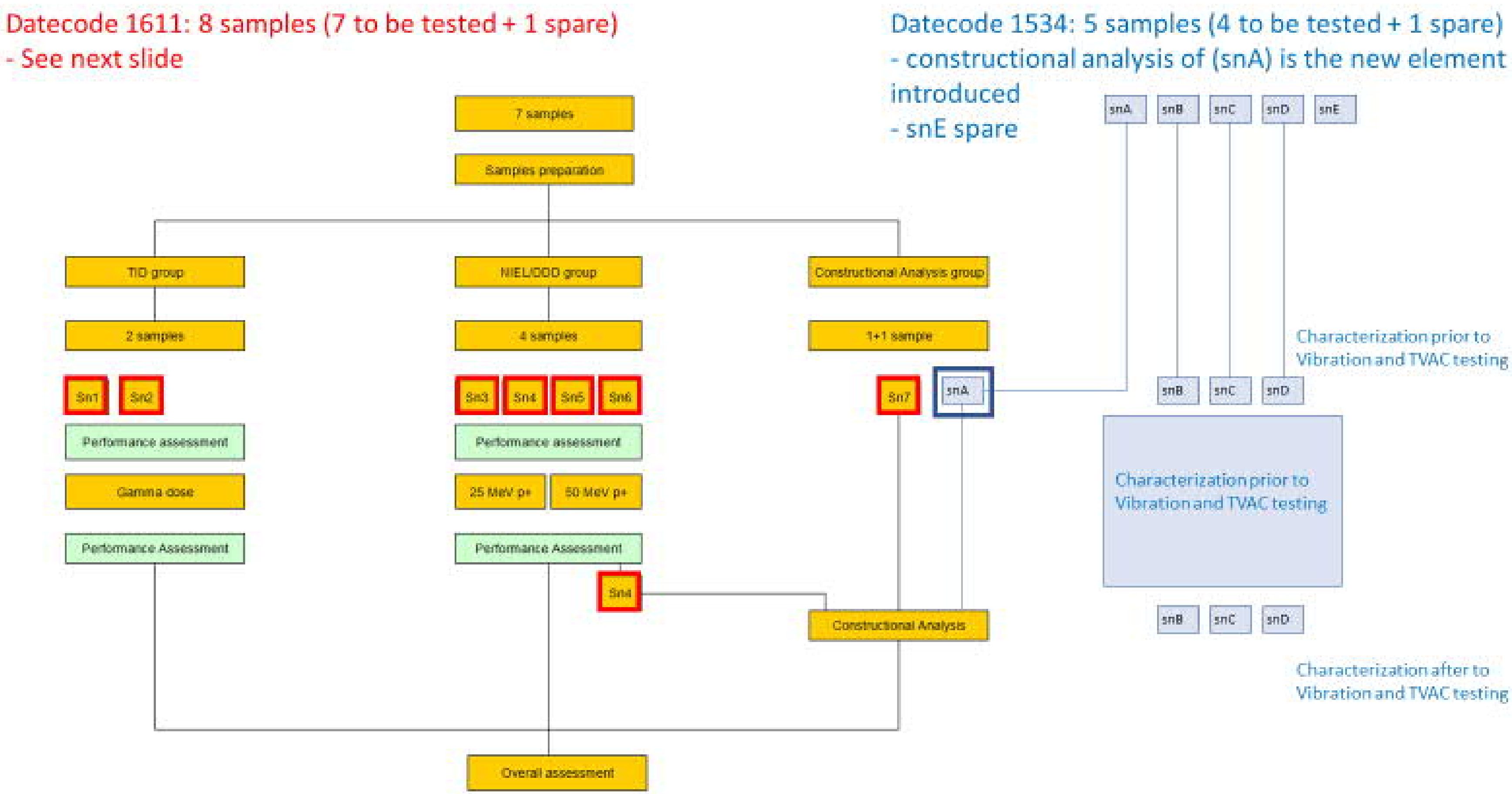

Figure 4-5: Imager Testing Plan

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4.5 DEFINITION OF THE LED

An LED is required to illuminate the Imager through the optical path of the encoder. The LED requirements are as follows:

1. To illuminate the detector area as uniformly as possible. In the setup,provided the angle to be covered as uniformly as possible is ±8°. The area used for the processing is smaller, but requires adjustment.
   This need is generally satisfied by LEDs characterized by a wide FWHM (45° to 50°) in order to have a rather good uniformity at over ±8° The drawback in having an LED with such a wide FWHM is the stray light control required
2. To illuminate the detector area with optical power in order to limit the integration time in the range of about 100-200 µs which leads to two opposing needs. The need for a LED characterized by a small FWHM (tendentially only covering the detector area) which is in contrast to the need covered in (1) above.
3. The need for an LED with relatively high nominal power to allow other nominal parameters to be tuned.
4. To have the position of the emitting source as stable within 10 µm over the temperature range of operations, to minimize geometric distorsion originated by the LED itself.

4.5.1 LED MOUNTING SOLUTION

A number of mounting solutions for the LED were investigated.

1. Mounted directly to the electronics PCB. In the present arrangement, this is not possible to implement due to the adoption of the VIP board that does not allow enough distance between the imager and the LED for the prescribed optical design.
2. Fixed by a two components mounting structure that holds the LED in position.
3. Bonded to the a single component.

Following a short review of the options, the third solution was adopted.

A small component that also operates as optical baffle holds the LED by means of four bonding connections of diameter 1.2 mm.

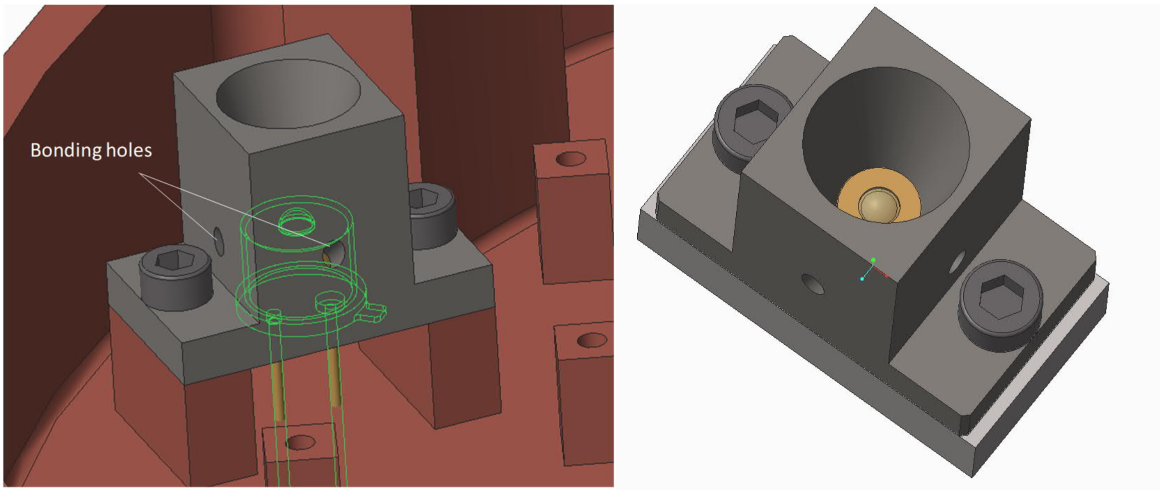

Figure 4-6: (right) the selected LED fixation solution to be bonded to a support that works also as baffle. (left) a dedicated bonding jig is required to bond the LED while holding it in position.

4.5.2 LED SELECTION

Following a trade off it was decided to use the Marktech Opto MTPS2085BSL1 and one Optoi LED during the test campaign in order to verify experimentally the best candidate imager.

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4.6 EBB ELECTRONICS DESCRIPTION

A special electronics was used for the control of the Encoder. This was based on the DANOE C16 development. These have been used for the DANOE C17 activity as no further development was foreseen at this stage.

The overall architecture of the system is shown on Figure 4-7. For one encoder configuration, two imaging elements are required in order to correctly retrieve the eccentricity of the encoder. In DANOE C16, commercial sensors from uEye were adopted, leading to a sampling rate of about 1 frame each 10 seconds. In order to improve the sampling rate and develop a breadboard allowing for operations aiming at being representative of real conditions, CSEM proposed to use the eye-on-chip system VIP (Vision In Package). The VIP is developed and produced by CSEM for experimentation and fast-prototyping purpose.

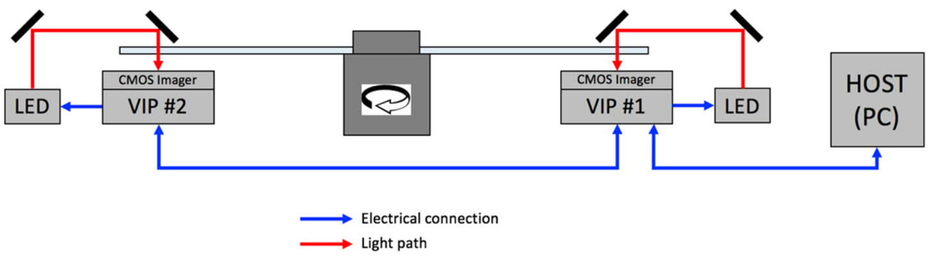

Figure 4-7 :: High level schematic of the encoder layout accounting for two VIP boards connected for communication and power supply.

The two VIP are connected together via a serial protocol. Two possible operation mode are possible:

- VIP provides the full frame of the code pattern. This mode provides a frame rate of about 10 fps, that is comparable to the commercial vision uEye adopted for the first DANOE C16. This is considered a debugging mode.
- VIP provides directly angular and radial position. This mode provides a data rate of about 60 Hz. This is considered the operational mode.

Hardware HDK

VIP-429

Figure 4-8 : Schematic of the layout accounting for the VIP, hosting the Aptina MT9V024 imaging sensor.

The VIP platform is composed of 3 stacked board comprising (from top to bottom at the right of Figure 4-8) the imager board, the processor board, the interface board. The VIP is based on the CMOS imager from Aptina (now ON Semi) MT9V024.

For each encoder configuration, the electronic architecture of the DANOE EBB will be based on the use of 2 VIP modules, each of which carrying an imager. An inter-VIP connection will provide synchronization signals, data exchange and power supply.

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4.7 ENCODER MECHANICAL DESIGN DESCRIPTION

The encoder housing is a 120 mm diameter shell in Ti6Al4V. the distance between bottom and top shell surfaces is 34 mm. Both these dimensions an be optimized but are driven by elements for the EBB design.

- The height of the encoder is driven by the following elements:
  - need to host the cabling between the different VIP board. Posts of 5 mm are accounted for this scope and could be possibly reduced when using a custom board
  - neet to accommodate a stack of two boards, the VIP imager and VIP daughterboard hosting the CPU. Depending on the possible implementation of the custom electronics, it would be possible to save between 1 and 3 mm.
  - need to accommodate the folding mirrors and sufficient distance for the optical path. This more complicated to reduce as the sensing principle requires a certain distance between imager and and the LED source.
- The outer diameter of the encoder is mostly driven by the need to accommodate the LED while hosting off-the-shelf electronics. The LED can be positioned as close as possible to the code disk in order to reduce the outer diameter.
  - If the LED could be hosted directly on the PCB structure of the custom electronics, possibly further saving in the diameter could be achieved.

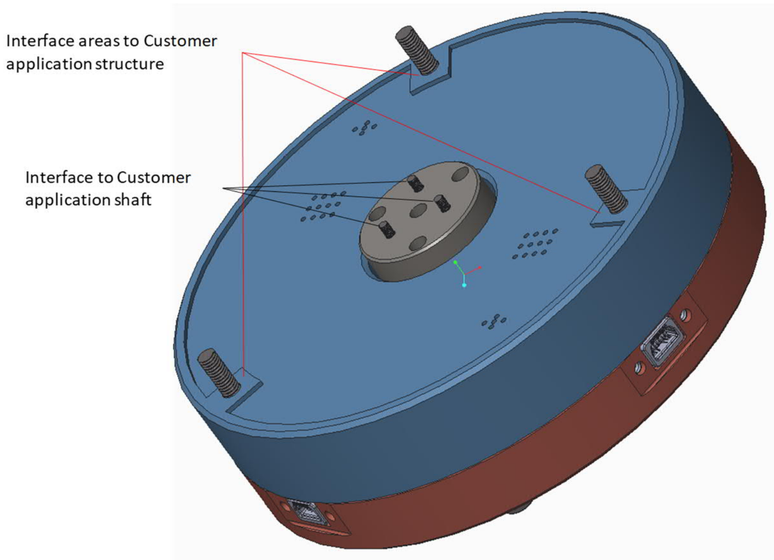

Figure 4-9 :DANOE EBB encoder outer envelope.

Although not an explicit requirement, ESA requested that a through shaft capability on the encoder was highly desireable. Nevertheless:

- for the purpose of the present EBB, a through shaft configuration is not considered as an advantage for setup simplicity as the goal was to test the optical configurations of the encoder with a representative mechanical structure)
- The code disk has currently an outer diameter of 80 mm and the through hole of the code disk has a diameter of 30 mm. the target is to provide an encoder with an outer diameter of ~100 mm once the electronics will be defined.
  - A through shaft configuration may be required to be implemented to allow feeding of cables through the shaft, and therefore drives the requirements on volume and diameter. The through shaft diameter might heavility depend on the specific application.

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- With this purpose, the dimension of the cable bundle is a driving requirement, as the current available diameter is about 20 mm.

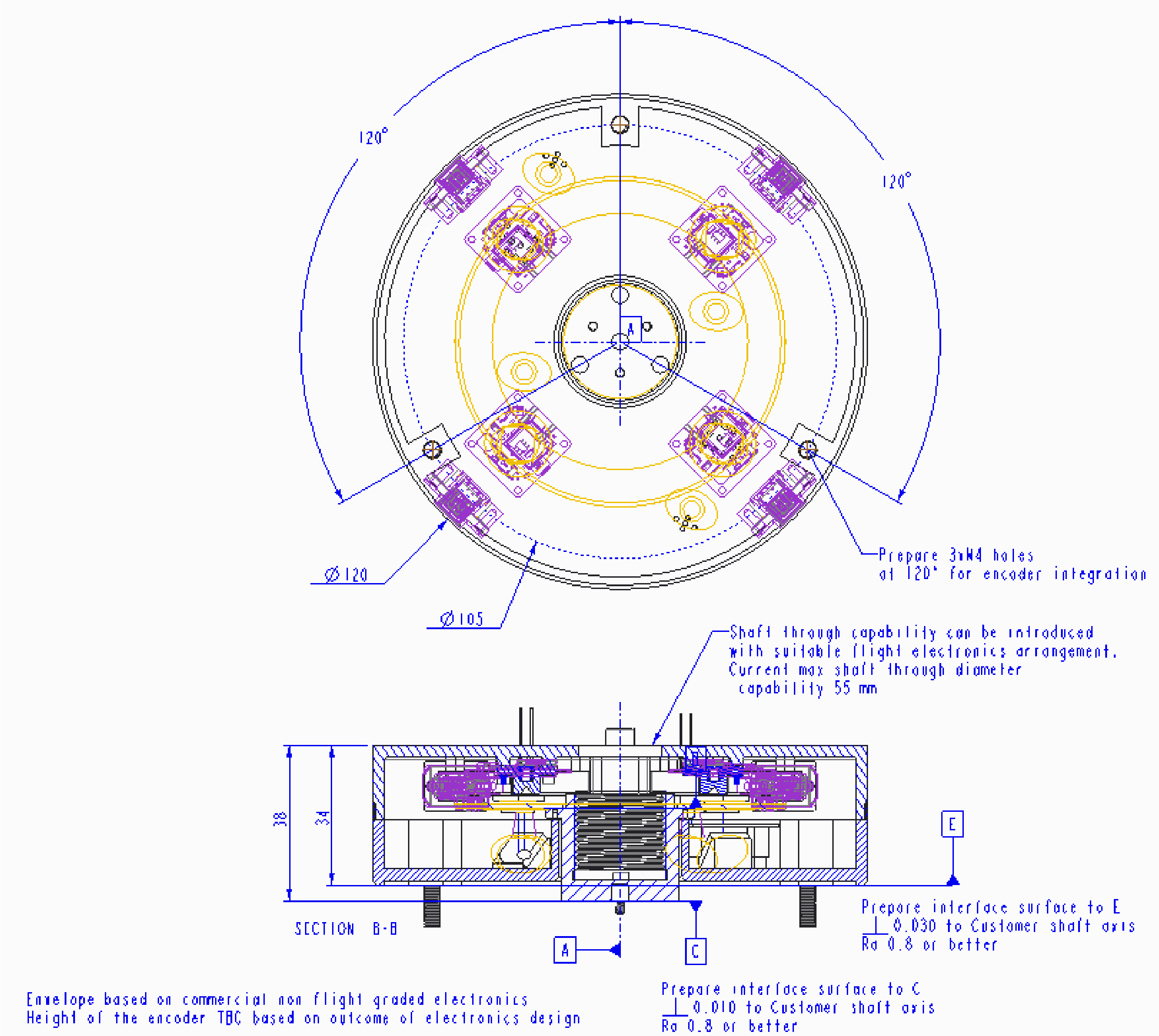

Figure 4-10 : main dimensions and interface for the integration of the encoder.

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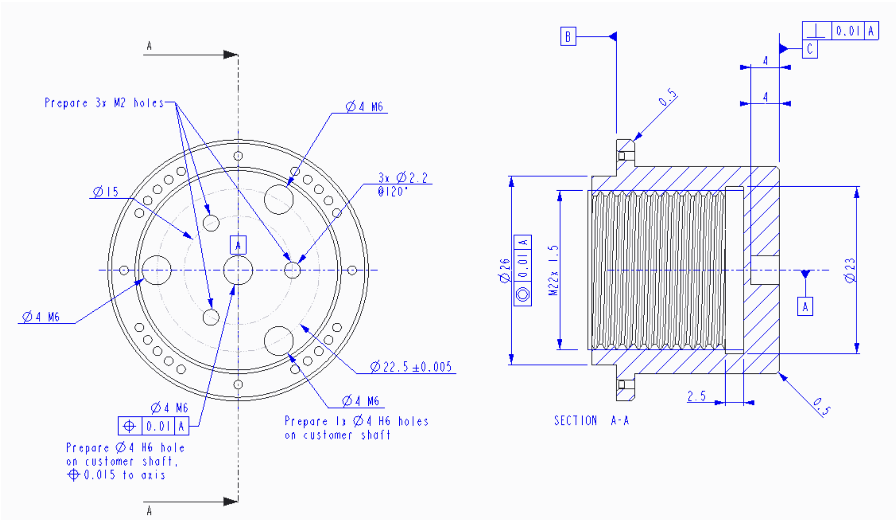

Figure 4-11 : encoder shaft interface to customer shaft.

The bottom shell hosts the 4 VIP boards and the LEDs for the illumination. The connection to the data acquisition system is achieved by means of USB connections.

The top shell hosts the folding mirrors and a small baffle to limit the optical layout. The folding mirrors are implemented with commercial fused silica mirrors from QiopiQ and Edmund Optic. The mirrors are bonded by EC-2216 B/A. Bonding channels are derived on the top of the top shell..

The fixation to the customer structure is implemented by means of 3x M4 screws. In the EBB design, the screws are required to pass through the cover instead of the whole structure due to the limitations in space for arranging the electrical components.

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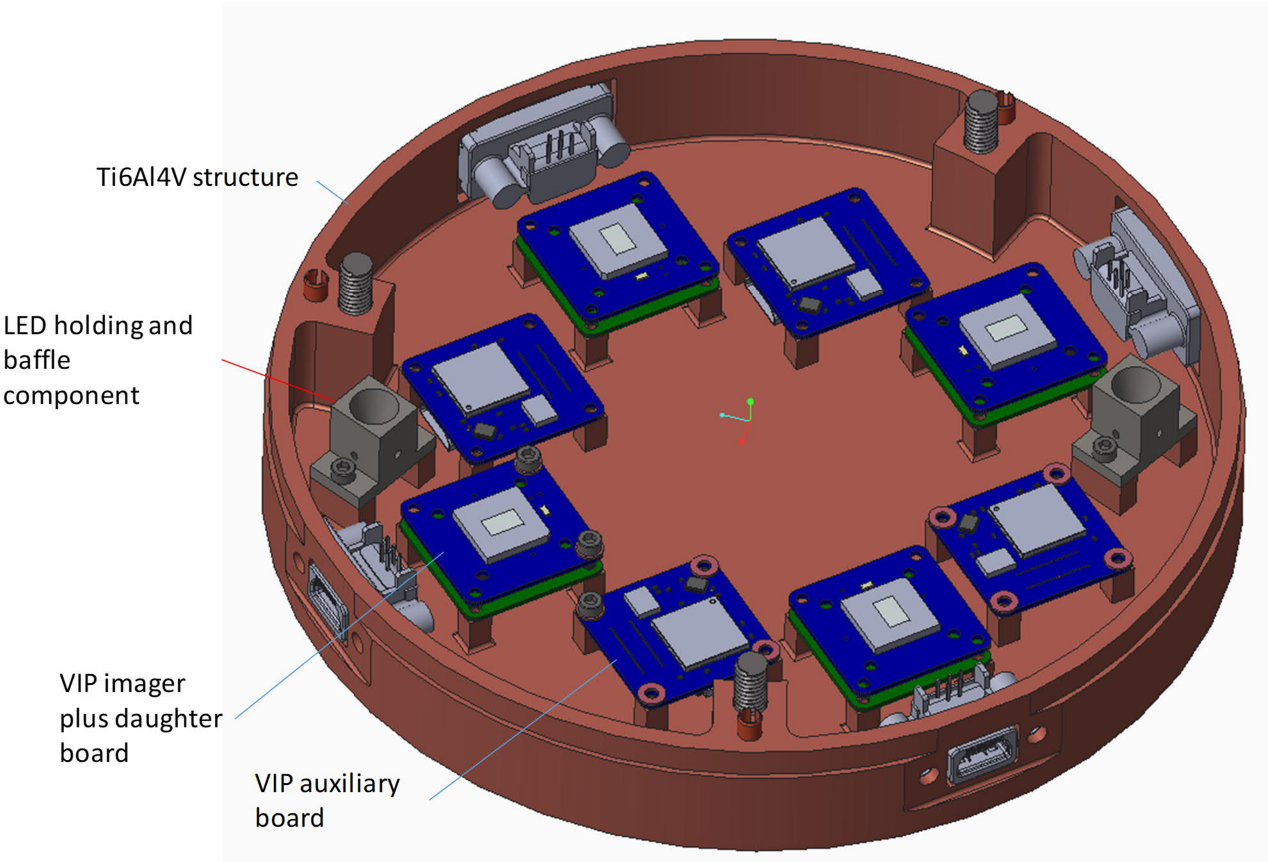

Figure 4-12 : encoder breadboard bottom shell.

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5 FINITE ELEMENT ANALYSIS

5.1 OVERVIEW

A finite element model was established for the EBB encoder which was used to analyse the structural and thermal performance of the DANOE encoder.

The model was subjected to the normal model checks to ensure that the model was suitable for the analysis that was to be performed.

These checks were all acceptable.

Analysis was performed to determine the following:

- Eigenfrequency Analysis with the critical element being the code disk
- Quasi-Static Loads analysis
- Thermo Elastic Load Cases:
- Survival
- Thermal Transient

5.2 RESULTS

The results from the eigenfrequency have shown that the critical eigenfrequency from the coder disk is higher than 1800Hz. The encoder itself will also have a very high eigenfrequency due to the way it is mounted.

For this reason, The quasi-static loads were taken as the dimensioning loads.

The problems seen in the fused silca mirrors and the glue are due to modelling anomalies. With a closer look at the actual stresses the levels in the fused silica do not exceed 7 MPa and also taking out the nodal concentrations at the edges of the glued areas, leads to far lower stress levels that do not lead to stress problems. This was demonstrated by testing.

5.3 CONCLUSION

The results from the analysis have shown that the encoder will easily survive the vibration loads, however due to the local CTE differences between the Glass mirrosrs and the Glues, issues could occur under the thermal environment.

Following a literature review, different glues were assessed and identified as potentially applicable to the model, the main design parameters being the CTE match with the interfacing components and their operating temperature ranges. The FEM verifications on the encoder and the code disk shaft assembly demonstrated all components would withstand the 65G quasi-static and the Survival Qualification Temperature cases (-30°C, +80°C, no power).

The glue was identified as critical independent of the type selected under the thermal load case but due to a limitation of data on the glue properties variation with temperature, a proper assessment of the integrity of the glue was undertaken during the thermal vacuum testing.

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6 FLIGHT ENCODER ELECTRONICS

Although the electronics for the EBB was taken from the DANOE C16 activity, the design of the Electronics for the Flight Model needed to established during this phase.

As an initial part of the development, a trade off was performed between Microcontrollers and FPGAs. Initially at the time of the trade off, FPGAs were prohibitively expensive to be implemented within an encoder so the initial design direction utilized a Microcontroller. However, as the design progressed, the team was made aware of a FPGA development that lead to a comparatively priced unit which had been qualified for space missions.

The design activity then turns about and instead of following the Microcontroller route, undertook to incorporate the FPGA in the design.

6.1 SELECTED COMPONENTS

The electronics includes the following components:

Component	Type
FPGA	Microsemi - RT3PE3000L-CG484B
CMOS Imaging Sensors	EV76C661ABT-EQTR
Infrared LEDs	Marktech Opto MTPS2085BSL1 Optoi LED
PSU	TBC
Temperature Sensor	TMP461-SP
Memory	EEPROM 3DEE2M08VS2154
RS-422 Interface	HS-26CLV32RH HS-26CLV31RH
Clock	QT188LP10S-240.000MHz

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6.2 ELECTRONICS BLOCK DIAGRAM

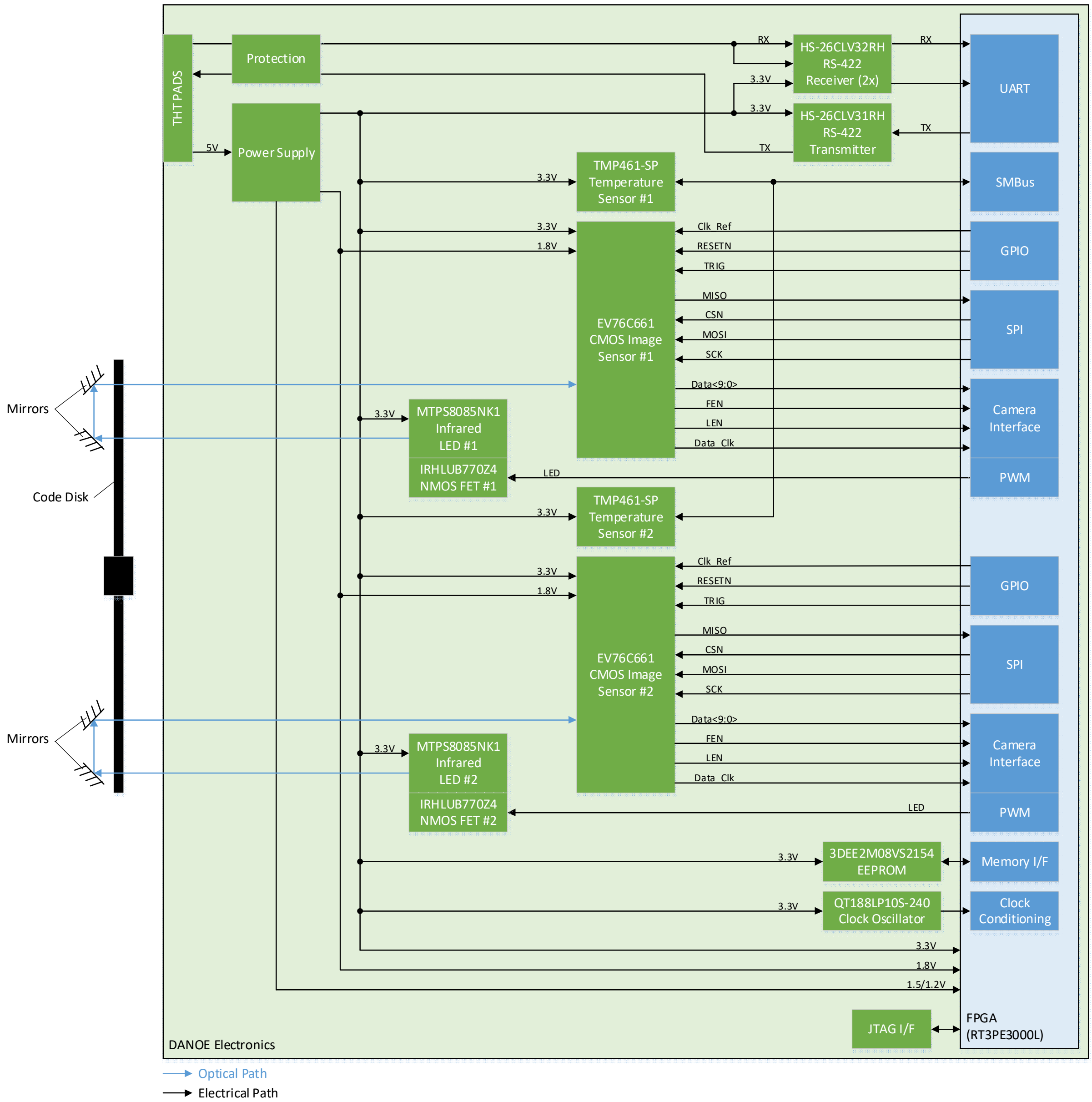

Figure 6-1: DANOE C17 Electronics Block Diagram
(Remark, the optical path is for showing the principle only)

6.3 MECHANICAL DESIGN OF ELECTRONICS

The electronics will be designed onto a PCB. This PCB fits into the allocated space of the provided encoder envelope. The final PCB outline, position of components and of the mounting holes etc. will be developed in once the encoder design has been finalized.

It is assumed that the PCB will be screwed onto the base element of the encoder titanium housing. To keep the PCB isolated from the housing, the mounting holes are not surrounded by a pad ring.

The LEDs are not assembled on the PCB itself to avoid thermal related distortion due to the thermal expansion of the PCB. To thermally decouple the LEDs from the PCB, it will be fixed on the titanium housing and contacted with an appropriate method (e.g. wire or rigid-flex PCB) to the PCB.

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Following image shows a rough outline of the PC with the big electronic components to estimate the needed PCB area.

6.4 THERMAL DESIGN OF ELECTRONICS

Currently there are no heatsinks and there is no active cooling inside of the encoder housing and there is no thermal contact between the PCB and the housing foreseen. Therefore radiation to the inside of the housing is the only thermal interface.

In the next development, it may be necessary to implement heatsinks in the design.

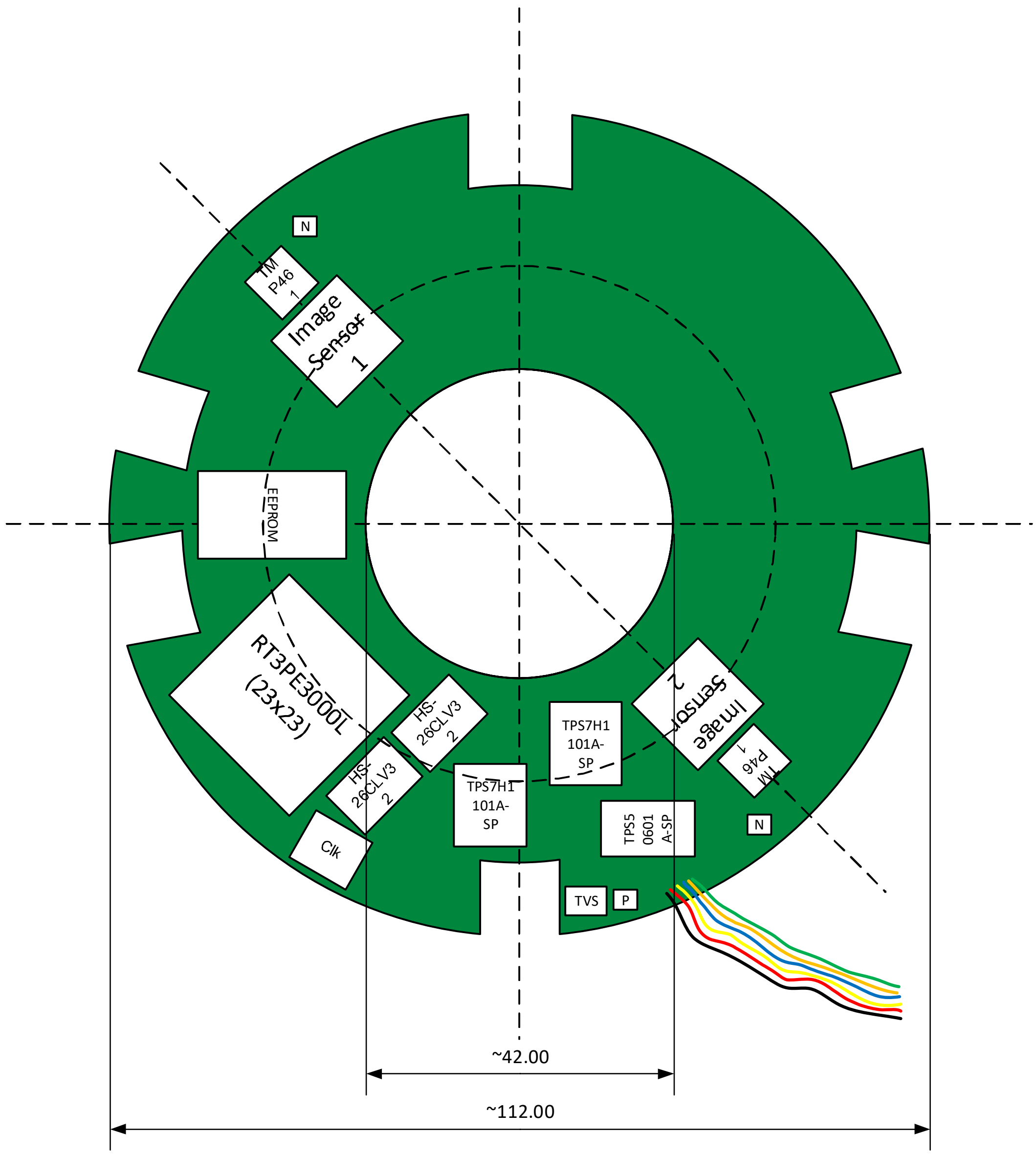

Figure 6-2: Mechanical Design (all dimensions in [mm])

7 POWER BUDGET

The requirement X-180 specifies the following:

Encoder power consumption shall be < 1.25 W typically. Maximum consumption as resulting from worse case environments shall be less than 2.4 W

The calculated performance is as follows:

	Min [mW]		Max [mW]	
LED	180 mW		250 mW	
Imager	500 mW	with margin, E2V Sapphire or Ruby	2100 mW	with margin. CMOSIS CMV300 or CMV2000
FPGA	500 mW	estimated	1000 mW	estimated
Total	**1180 mW**		**3150 mW**	

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8 IMAGER TESTING

The CMOS Imaging Sensors from E2V type EV76C661 were tested by ALTER Technology according to an agreed test plan.

8.1 EVALUATION TEST PLAN

The qualification approach for electronic components is normally more comprehensive that bthat undertaken under this activity. The reason for this is the scope that was defined and the finance available which did not allow for a comprehensive qualification of the Imaging Sensors.

The test activities that was performed on the E2V Ruby for this development are defined in Figure 8-1. The plan accounts for five main investigations: TID by means of gamma irradiation, TNID/NIEL/DDD effects by means of proton irradiation, constructional analysis, environmental testing and mechanical testing.

To cover this Micos identified a test plan to test the DANOE requirements with respect to burn in, vibration, thermal environment requirements and radiation for which there is a delta between the requirements expressed by the SoW and the qualification plan on which the commercialization of the E2V Ruby is based.

8.2 PERFORMANCE ASSESSMENT

At each performance assessment step, the imagers were monitored in terms of :

- Dark current
- Conversion factors
- Defect pixels

During the measurement, the imager temperature was controlled with 20°C ±2 °C

8.2.1 PERFORMED TESTS

The following testing was performed on the Imaging Sensors:

- Gamma Irradiation
- Proton Irradiation.
- Burn In
- Vibration tests
- Environmental tests

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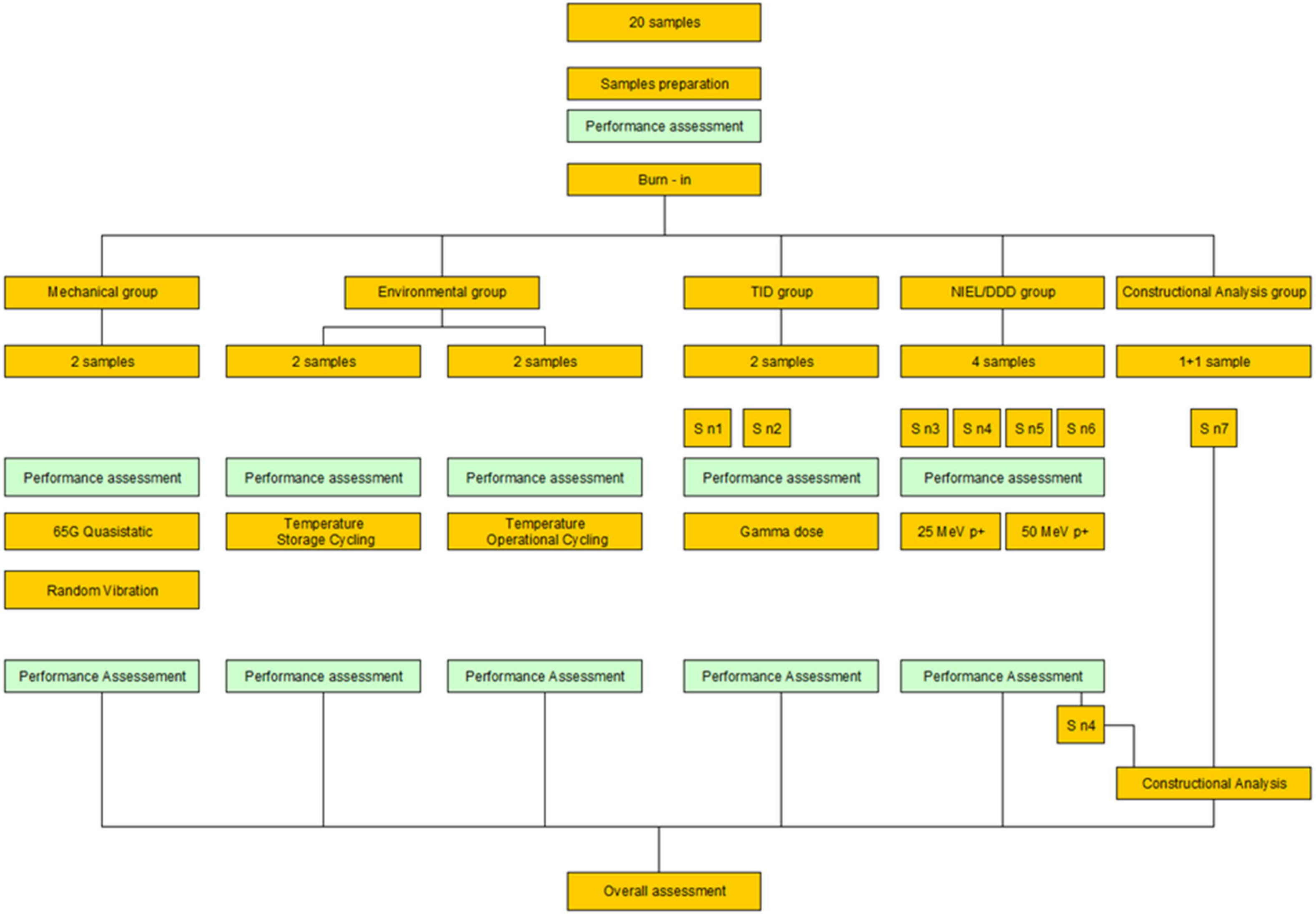

Figure 8-1: The evaluation test plan for the E2V Ruby imager

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8.3 SUMMARY OF TESTING

There were 13 image sensors received from MICOS for testing. The total project consists of total ionize dose test with gamma radiation, total non-ionizing dose (displacement damage) with proton radiation at 25 MeV and 50 MeV, thermal cycling tests, vibration tests, and constructional analysis. All tests were conducted according to the Test Procedures. After initial characterization it was found that some imagers showed strange behavior of the dark signal and strange response to the light. Short summary of each test is given below.

Thermal cycling

Three sensors have been tested by means of thermal cycling in unbiased condition (50 cycles) and biased condition (50 cycles). Full electro-optical measurements were performed after each thermal cycling experiment and the results were also presented. There were no major changes in the performance parameters.

Vibration test

Three sensors have been tested by means of three types of vibration tests: sine (sweep) vibration, sine burst, and random vibration in X, Y, and Z axes. All profiles were within 3dB tolerances. Full electro-optical measurements were performed after each thermal cycling experiment and the results were also presented. A deterioration of the responsivity, quantum efficiency and saturation capacity were found. The other parameters showed no straight tendency towards improvement or deterioration.

TID test

Two biased sensors have been tested by means of gamma radiation at CNA. The sensors were monitored during the irradiation and the supply voltages and currents were recorded and showed in this report. All intermediate measurements and full electro-optical measurements were performed, and the results were also presented. It was found that the most sensitive parameters to the radiation were dark current and DSNU. The obtained results are in line with the published data for image sensors, but some thermal effects have affected the results after annealing at 65°C. From the results for the sensor 1 it can be concluded that some changes in the sensor led to partial malfunction and the sensor does not respond correctly to the illumination.

TNID test

Four unbiased sensors have been tested by means of proton radiation at UCL. All intermediate measurements and full electro-optical measurements were performed, and the results were also presented. It was found that the most sensitive parameters to the radiation were dark current, DSNU, full well capacity and dynamic range. The obtained results are in line with the published data for image sensors.

Constructional Analysis

All three samples passed the CA test successfully.

The summary of the results form the Imager Tests are shown on Table 8-1.

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Test	No of Imagers tested	Result	Comments
External Visual Inspection	3	Pass	
Radiographic Inspection	3	Pass	
Seal Test	3	Pass	
Internal Visual Inspection	3	Pass	
Scanning Electron Microscope Inspection	3	Pass	
Bond Pull Test	3	Pass	
Glassivation Layer Integrity Test	3	Pass	
Die Shear Test	3	Pass	
Incoming Inspection		Pass	
Thermal Cycling	3	Pass[1]	[1] Changes in Dark Current noted in some imagers.
Vibration Test	3	Pass[2]	[2] Some deterioration of the responsivity, quantum efficiency and saturation capacity noted
Total Ionizing Dose Test	2	Pass[3]	[3] Deterioration has to be assessed to evaluate the impact on performance. Radiation deterioration was as expected . The Pass Criteria used needs to be reassessed.
	2	Partial Fail[4]	[4] Some anomalies were noted after annealing at 65°C. Sensitive parameters are the Dark Current and DSNU. Partial Malfunction of one imager noted
Total Non Ionizing Dose Test	4	Pass[5]	[5] Dark Current Increase noted. Significant deterioration of all parameters
Constructional Analysis	3	Pass	

Table 8-1: Summary of Imager Test Results

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9 EBB TESTING

9.1 OVERVIEW

The EBB was subjected to the following testing:

- Pre-testing of the EBB
  - Code-disc centering and gluing
  - Integration
  - Eccentricity
  - Performance:
  - Calibration
  - Wide-and narrow angle LEDs
  - Impact of exposure time of imager
- Environmental testing:
  - Vibration testing
  - Shock testing
  - TVAC testing
- Post-testing of the EBB
  - Stability before/after environmental testing
  - Static Zero-check stability
  - Summary of achievable EBB performance, including radiation testing

9.1.1 SUMMARY

The environmental testing effort of the Danoe EBB optical encoder passed successfully vibration, shock and thermal testing. In addition, the imagers of the Danoe EBB encoder passed also radiation testing successfully. The Danoe EBB performance was validated for two different LED systems, reflecting a wide- and narrow angle LED configuration. In addition, different exposure times and processing tactics were validated concerning their impact on the residual angular encoder error

The Danoe EBB configuration with highest angular performance comes with a residual angular error of 1σ = 8µrad over a limited angular rotation range of +-15˚. The configuration involves a narrow angle LED (Marktech MTPS8085NK1, view angle 24°), an exposure time of 40 µs and post-processing using the sin1+2+3+4 modes and preselected higher order sin waves, originated from the code-disc pattern and the encoder geometry. The low exposure time of the narrow angle LED allows high-speed angle acquisition. A reduction in the exposure time was found to degrade the residual angular error performance. Further improvements in the residual are expected by applying an advanced calibration and eccentricity correction on the raw data. Improvements of 60% in mean eccentricity value and 20% in standard deviation seem possible.

The wide-angle LEDs for the Danoe EBB shows a similar residual angular error of 1σ = 8-10 µrad to the narrow angle LED type. However, the wide-angle LED system comes with a benefit in residual error which remains quite constant over a full angular turn of 360deg (instead of the +-15˚ for the narrow angle LEDs). The result shows benefits for the wide-angle LED, when acquisition speed is not important.

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10 FUTURE DEVELOPMENT PLAN UP TO FLIGHT MODEL

For any future development of DANOE, the development of an electronics based on the selected imager shall be undertaken to validate the performances attainable with the selected E2V Ruby imager.

The other most critical and required action is to progress the development of the space compliant electronics aiming at the verification and qualification of the electronics design.

This will follow the standard qualification process and will include the production and test of an Electrical Model to verify its performance and then either an EQM or a QM to undertake the qualification of the electronics under the environmental test conditions that simulate the launch and operational environments.

The testing on the electronics will also include radiation testing as electronic components are particularly susceptible to TID and TNID environments.

Finally, once the electronics has been designed for an Electrical Model, it may be possible to optimize the dimensions of the encoder to make it slightly smaller then the current configuration, once real interfacing needs are available. Additionally, depending on the particular mission that is selected for the demonstration flight, a through hole may have to be added to the design to allow for the passage of an electrical harness though the encoder. As indicated at the beginning of the document, a customer survey involving RUAG, Airbus and TAS (but only covering some of their needs) indicated that most of the needs are related to hollow shaft encoder that allow to manage cable routing in the size of 5 to 10 cm in diameter within the shaft. Upon implementation of the EQM or QM design, mission based envelope and ICD requirements would be required to allow the development of a need-driven configuration.

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11 CONCLUSION AND SUMMARY

The outcome of the DANOE C17 development phase was to reach a technology readiness level of TRL3 with respect to the DANOE Imager (E2V Ruby) and the electronics design design while establishing an Elegant Breadboard Model (EBB) to allow the demonstration of design adequacy and performance in representative environment for the mechanical structure to reach TRL5. The performance of the EBB was assessed based on electronics developed by CSEM.

Part of the scope of the C17 development phase was to identify a design for the electronics for the DANOE Encoder to ensure that the performance can be achieved and the the operation of the encoder meets the requirements of future spacecraft applications.

Most notably, the electronics used in the EBB was an improvement from phase C16. As well, due to budgetary and scope constraints, it was possible to customize the electronics to the the representative imager, as the focus was to advance the thermomechanical design of the encoder to TRL5, while the electronics and imager maturity was goaled at TRL3 within the Statement of Work. Due to financial constraints, it was not possible to adapt the electronics a redesign activity would have been required.

There are elements of the performance that have not been verified and will need to be performed in the future.

All other objectives were reached during the development.

Based on the constraints during the development phase C17 (workflow, budgets), the de-risking activities on imager were possible only on a very limited batch, and due to E2V management of their distributor the components delivered where from two batches, greatly reducing the representativeness of the available residual components. Nevertheless, the imager is qualified according to JESD JEDEC G47 and, a part of radiation verification and annealing can be performed at batch level. A more commercial approach can be undertaken, to qualify the overall encoder electronics is qualified as a single product but only after having achieved sufficient confidence and having undertaken de-risking on the critical components.

The encoder performance can only be assessed with the correct encoder architecture and with the finalized electronics.

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