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## *Laser source electronics (LASE) for the infrared atmospheric sounder interferometer next generation (IASI-NG)*

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## Laser Source Electronics (LASE) for the Infrared Atmospheric Sounder Interferometer Next Generation (IASI-NG)

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### ABSTRACT

The MetOp-SG satellite program is an EUMETSAT/-ESA cooperation with the objective to obtain long-term collection of remotely sensed data of uniform quality for meteorology and climate monitoring state analysis and forecast. A series of three satellite pairs (MetOp-SG-A1, -A2 and -A3) are to be launched, ensuring continuity of data to beyond 2045.

The Infrared Atmospheric Sounder Interferometer Next Generation (IASI-NG), being developed by CNES, is one of the instruments on the MetOp-SG-A's. The IASI-NG is a Fourier Transform Infrared Spectrometer scanning the atmosphere to provide data for atmospheric gas characterisation.

Kongsberg Defence and Aerospace (KDA) has developed the LAsER Source Electronics (LASE) for the IASI-NG instrument. The LASE provides a wavelength-stabilized optical source to be injected into the IASI-NG with a wavelength stability within  $\pm 0.00015$  nm throughout the instrument lifetime. The wavelength is locked and controlled using a feedback-loop containing a gas cell filled with  $^{13}\text{C}_2\text{H}_2$ . The LASE shall in addition perform the conversion of the optical signal from the interferometer into analogue electrical signal which can be further processed. The lifetime includes 15.75 years of storage and 7.75 years in space.

The challenge of meeting the required Polarisation Extinction Ratio (PER) for a fiber optical system, as the one in LASE, is discussed.

**Keywords:** IASI-NG, MetOp-SG, laser, wavelength stability, RNE, PER, Polarisation

### 1. INTRODUCTION

The Laser Source Electronics (LASE) makes up part of the Laser Metrology chain of the Infrared Atmospheric Sounding Interferometer Next Generation (IASI-NG) instrument. The instrument will be mounted on the MetOp Second Generation (MetOp-SG-A) satellites. The IASI-NG instrument is a Fourier Transform Infrared Spectrometer scanning the atmosphere to provide meteorology data.

LASE is the Norwegian contribution to the IASI-NG. Kongsberg has so far designed, manufactured, tested and delivered an Elegant Bredbord model and the Engineering Qualification Model to Airbus DS. Manufacturing of the flight models, 3 units, has started. A Proof-of-Concept Demonstrator was established at KDA before start of the LASE contract.

The LASE (two per instrument, nominal and redundant) will be located under the IASI-NG instrument baseplate and will provide a wavelength-stabilized optical source to be injected in the Interferometer. It also performs the optical to analogue conversion of the interferometer outputs and transfers the electrical signals to the Laser Reception Electronics (LARE).

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## 1.1 Performance requirements

The main performance requirements for the laser part of the LASE:

- All requirements and functions shall be met in the temperature range [0 °C; 40 °C] at the Temperature Reference Point (TRP).
- The LASE output wavelength in vacuum shall be 1541 nm +/- 0.26 % (i.e., 1541 nm +/-4 nm).
- The wavelength shall be measured on ground and in vacuum with a relative accuracy better than  $10^{-8}$ .
- The long term (all life time) wavelength stability shall be better than  $10^{-7}$  (3 sigma).
- The random noise error on the wavelength (one sigma) shall be better than  $10^{-8}$  when estimated on the 5 kHz to 180 kHz bandwidth.
- The random noise error on the wavelength (one sigma) shall be better than  $2 \cdot 10^{-8}$  when estimated on the 1Hz to 5 kHz bandwidth
- The linear Laser polarization ratio shall be better than 15 dB at fiber end.
- The source shall be protected from retro-reflexion so that a retro-reflected power of -43 dB entering the output fiber remains compatible with the specified performances.

## 1.2 Architectural Design

Several alternatives exist for providing an on-board wavelength reference. One of the most common solutions is to use a molecular absorption cell (commonly referred to as a Gas Cell). A small tube containing a specific isotope of acetylene has absorption bands at certain precise wavelengths. The laser output power and wavelength are functions of temperature and input current. By utilizing a feedback loop that compares the laser wavelength with an absorption peak of the gas cell it is possible to correct for any drift of the laser. Gas cells are wavelength stable with respect to temperature and with respect to the mechanical environment.

The  $^{13}\text{C}_2\text{H}_2$  isotope of Acetylene has an absorption transition (P16) at  $\lambda = 1542.3837\text{nm}$ . This absorption line is used extensively within Wavelength Spectroscopy and so primary and secondary standard lasers are available against which the LASE may be calibrated. The P(16) line has good absorption and so a short single pass gas cell is possible reducing risk of optical misalignment, or internal etalon effects, which could upset the wavelength stability of the LASE.

Figure 1 shows the principle architecture of the LASE, which is based on the Pound Drever Hall (PDH) technique for wavelength locking [1]. The PDH circuit establishes a feedback loop that locks the DFB Laser output wavelength to the above-mentioned P16 line of Acetylene. The PDH circuit generates an error signal that is fed back to the current driver of the Laser.

The Laser Diode current is controlled by an FPGA using two identical external DACs that each has 12 bits resolution, one for coarse setting and one for fine setting.

The coarse DAC is used initially to turn on the laser by ramping the current up to the operating point defined in the Configuration Table stored in the LASE ROM. Then a temperature sweep is started, adjusting the laser temperature in 1 mK steps over a 1024 mK range. The absorption in the gas cell, the PDH error signal and the temperature are stored in the SRAM of the LASE at each step. In this way, a 13 GHz survey of the PDH loop is established. The temperature corresponding to midway between the minimum and the maximum PDH error is selected as a temporary temperature set point.

When the laser temperature has stabilized at the temporary set point, the fine DAC is used to perform a high-resolution scan across the absorption line, over a 600-800 MHz range, which establishes a basis for determining the laser drive current set point.

This scheme for obtaining the laser set-point is considered essential in order to make sure the system locks to the same absorption peak of the gas-cell each time it is started, despite of component ageing effects.

When the PDH loop is locked, neither laser drive current nor temperature are fixed; the drive current is adjusted to compensate for rapid, but small, wavelength deviations, while the temperature is adjusted to compensate for slow, but large, deviations.

Additionally, the LASE has a five channel programmable gain transimpedance amplifier with AVIM inputs. The amplifiers will be connect to the spectrometer outputs and converts the optical signals to electrical. Key performance parameters are low noise, high bandwidth, stable propagation time and low power consumption. A photodiode has been custom made and qualified for this amplifier.

Certain parameters of the LASE are also configurable from ground.

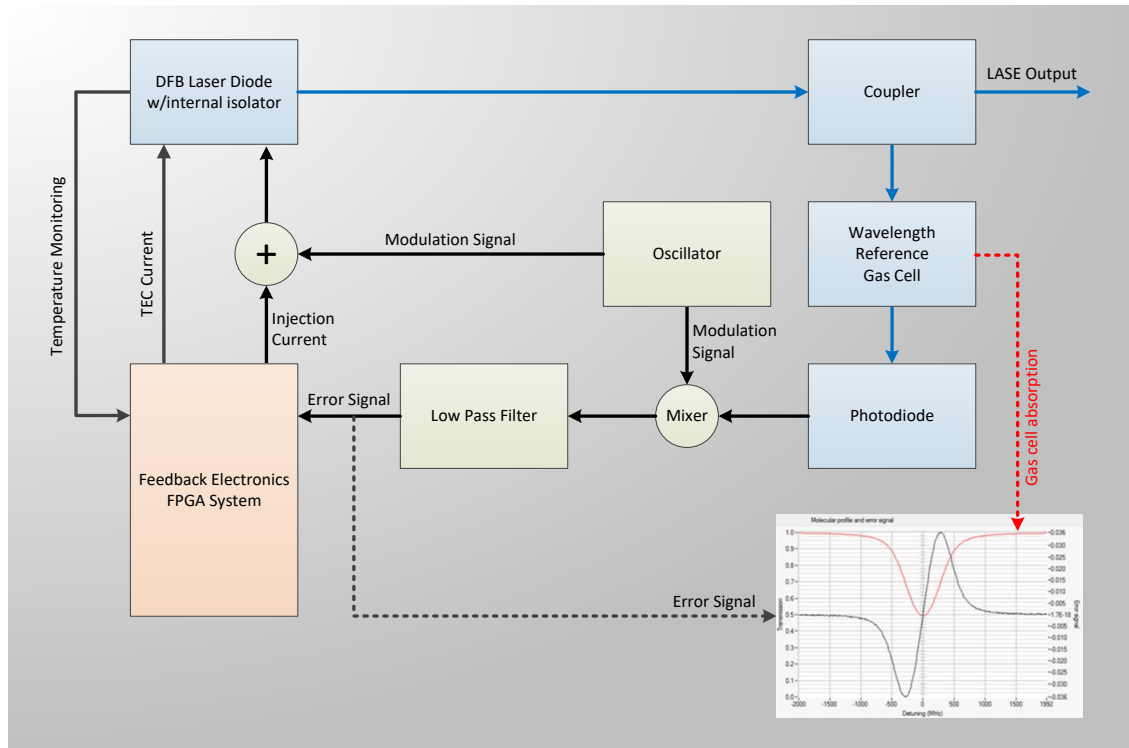


Figure 1 Principle architecture of the LASE

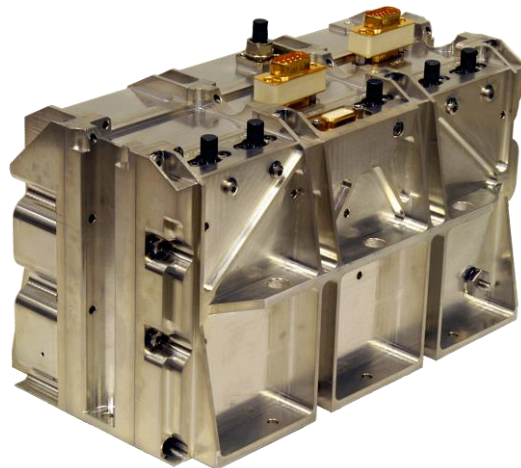


Figure 2 The Laser Source Electronics (LASE) unit (EQM).

The LASE development has followed the traditional approach for space.

### 1.3 Components qualification

For the LASE, the EEE components were either selected from the ESCC QPL or procured from suppliers being able to deliver space quality components. In case of the optical and electro optical components, it was necessary to run dedicated programs for component qualification. Figure 3 illustrates the procurement flow applied to:

- DFB laser
- Gas cell
- Fiber splitter
- Photodetectors
- Lenses

The evaluation phase, which is for risk reduction, focused on manufacturer evaluation, construction analyses and environmental testing. For each component category, several alternative components could be subjected to the evaluation test phase.

The qualification test campaigns were derived from [2].

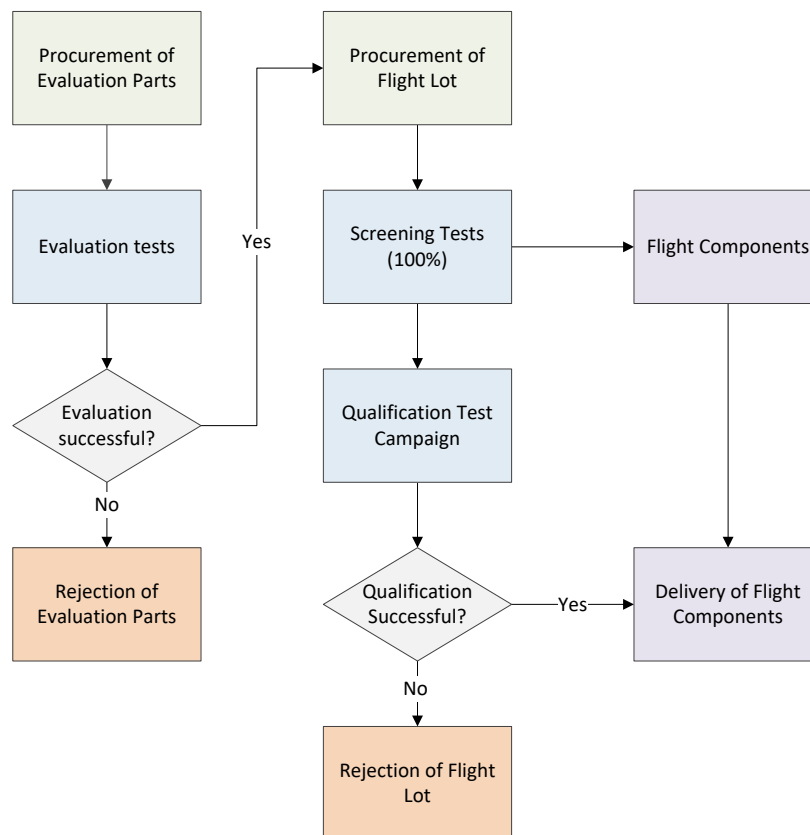
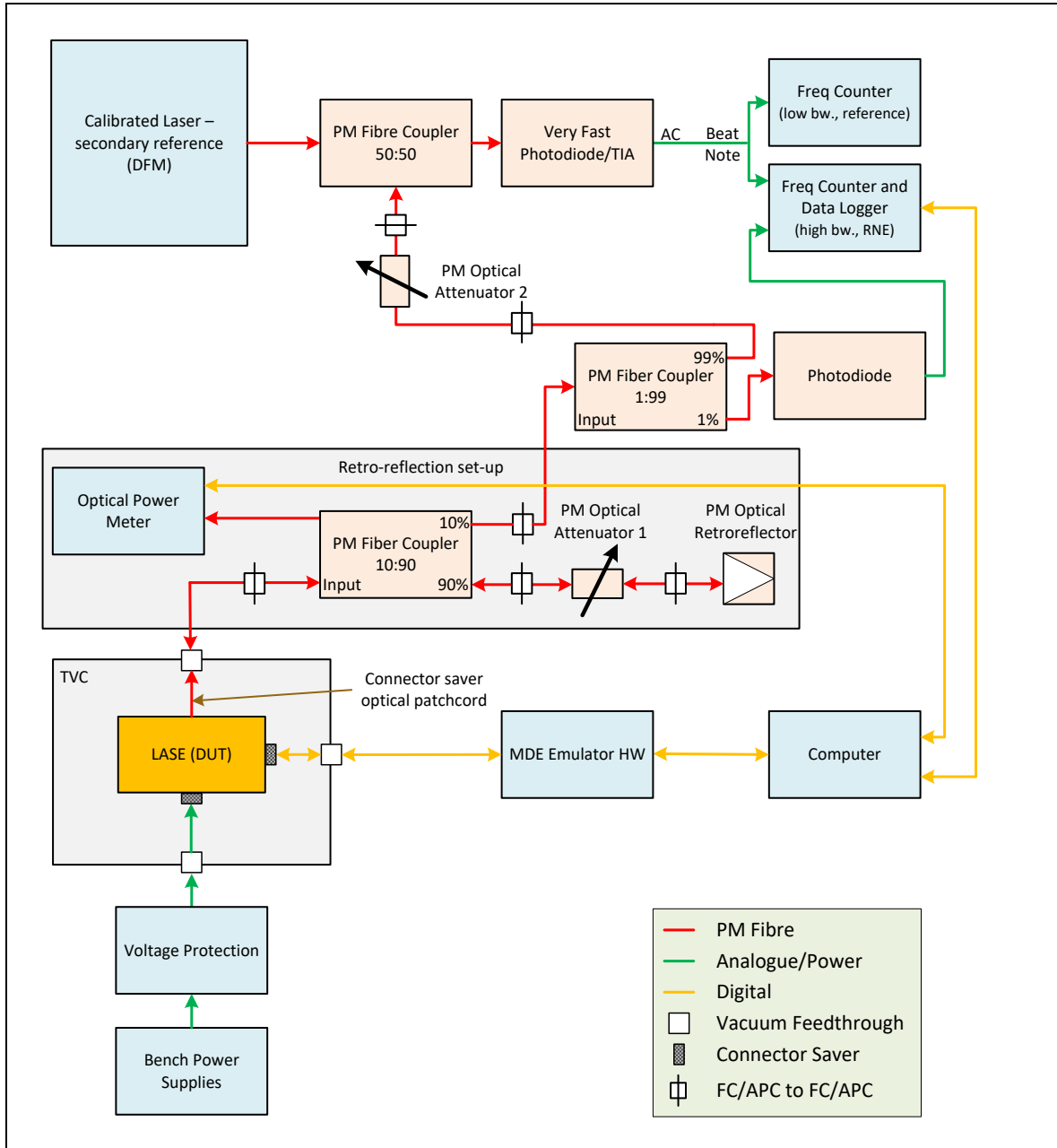


Figure 3 Component procurement flow.

## 2. LASE QUALIFICATION

Figure 4 shows the test set-up used during qualification of the LASE. The set-up was used for measurement of wavelength, wavelength stability, wavelength Random Noise Error (RNE), power variation and linewidth during Thermal Vacuum Testing, EMC testing and characterisation in ambient conditions.



**Figure 4 Set-up used during qualification of the LASE.**

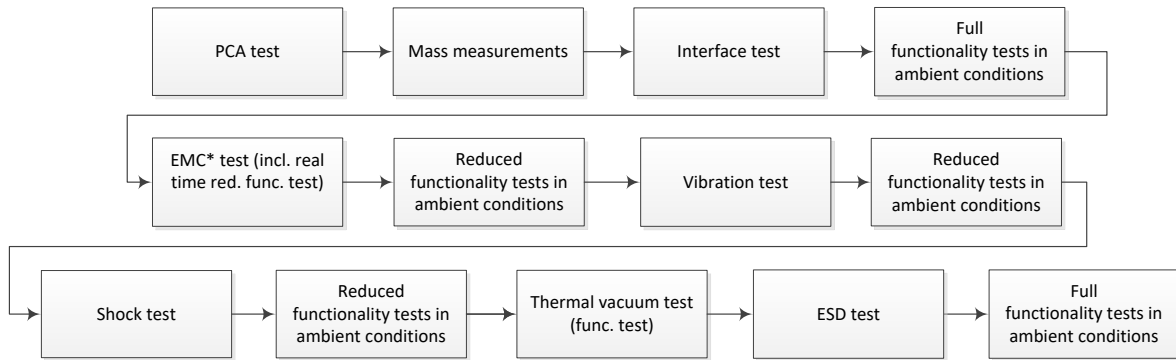
The LASE wavelength was determined by beating the optical output with the optical signal from a calibrated secondary reference laser manufactured by the Danish Fundamental Metrology (DFM). The two signals were combined using a fibre coupler and then injected onto a fast photodiode/TIA. The beat note from the photodiode was analysed using a fast frequency counter.

The required wavelength measurement accuracy of  $10^{-8}$  at 1542.383 nm corresponds to a frequency accuracy of  $\pm 1.94$  MHz.

The calibrated reference laser has a frequency of 194 369 569 385 kHz  $\pm$  10 kHz, which corresponds to a vacuum wavelength of 1542.383 712 37 nm  $\pm$  0.000 000 08 nm. The expanded uncertainty (95%) is given for a 1 second measurement. The calibration results (certificate no. LM1502) are traceable to one of the Danish primary standards for length.

Therefore, the jitter of the calibrated reference laser contributes only 0.5% to the measured beat note frequency difference at the frequency counter.

Figure 5 shows the qualification flow for the LASE, while some of the environmental test levels are given in the following tables.



**Figure 5 LASE Qualification flow chart.**

**Table 1 Qualification level, Sine vibration**

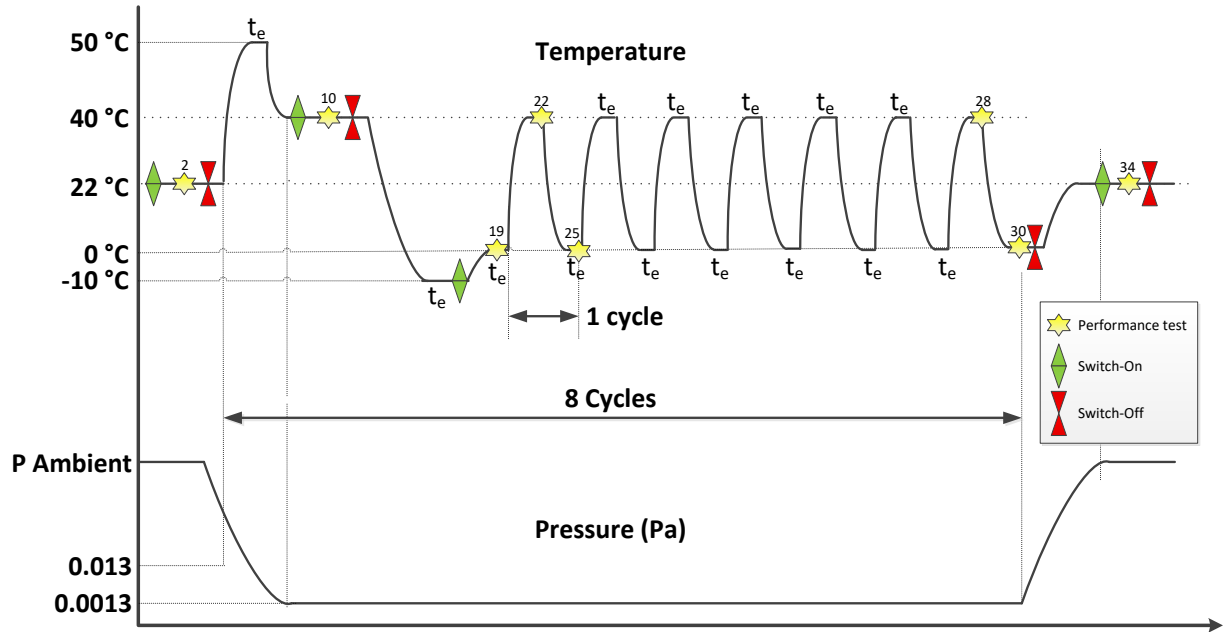
Frequency	Level
5 Hz to 27 Hz	10.4 mm amplitude
27 Hz to 110 Hz	30 g

**Table 2 Qualification level, Random vibration**

Frequency	X- and Y-axis	
20 Hz to 100 Hz	3 dB/oct	9.2 grms
100 Hz to 400 Hz	0.2 g <sup>2</sup> /Hz	
400 Hz to 2000 Hz	-20 dB/oct	
Frequency	Z-axis	
20 Hz to 100 Hz	6 dB/oct	12.5 grms
100 Hz to 400 Hz	0.4 g <sup>2</sup> /Hz	
400 Hz to 2000 Hz	-25 dB/oct	

**Table 3 Qualification level, shock**

Frequency	Level
100 Hz	14 g
270 Hz	72 g
2000 Hz	204 g
10,000 Hz	144 g



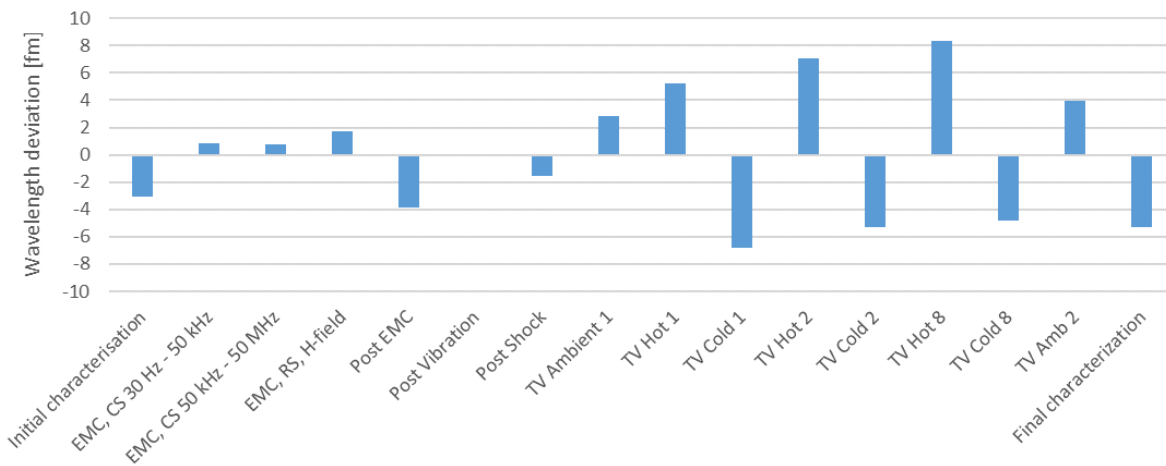
**Figure 6 Qualification Thermal Test Sequence.** The numbers corresponds to some of the tests presented in Figure 7: 2 = TV Ambient 1, 10 = TV Hot 1, 19 = TV Cold 1, 22 = TV Hot 2, 28 = TV Hot 8, 30 = TV Cold 8 and 34 = TV Ambient 2.  $t_e= 2$  hours dwell time.

### 3. TEST RESULTS

The following test results are obtained during qualification of the LASE.

#### 3.1 Wavelength stability

Short-term wavelength measurements at stable environmental conditions were performed repeatedly throughout the LASE qualification campaign. Figure 7 shows the results obtained at the various test events, which corresponds to a relative wavelength deviation of less than  $\sim 5.3 \cdot 10^{-9}$  (i.e. less than 8.1 fm). These tests were performed with a back reflection level of -43 dB using the set-up shown in Figure 4.

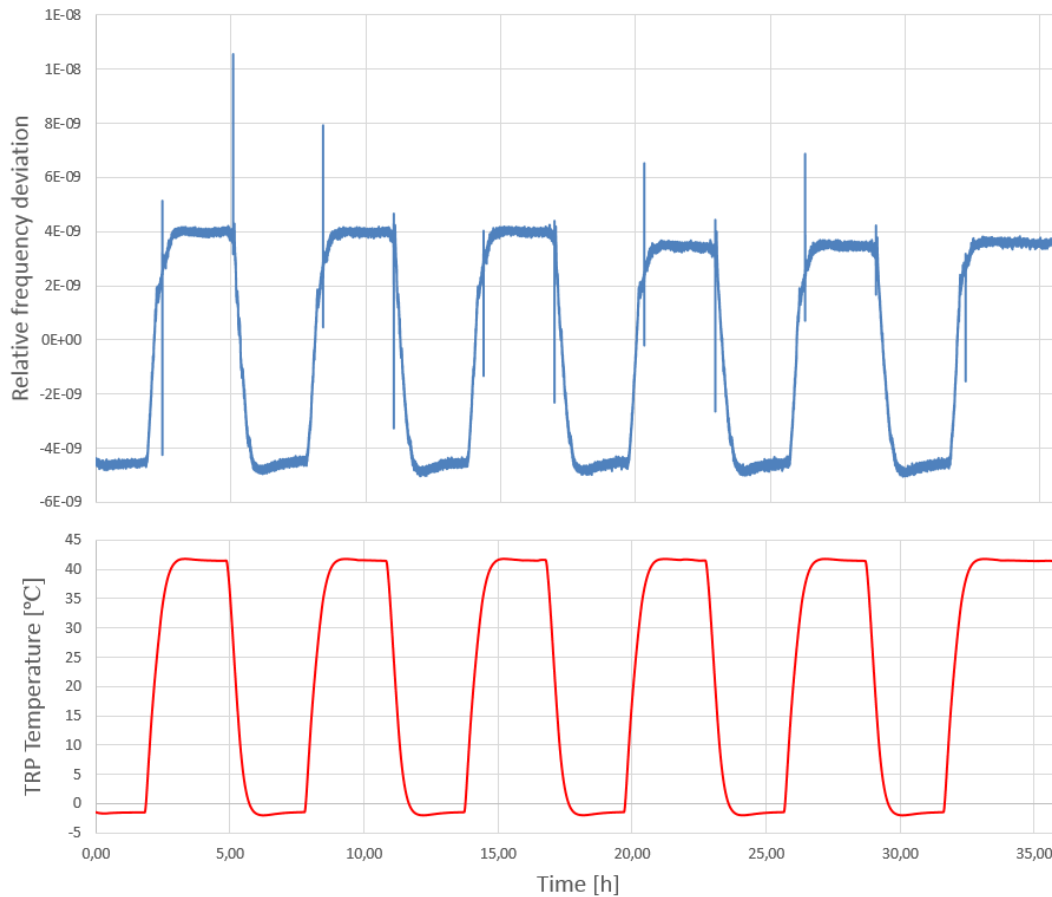


**Figure 7 Deviation of short term wavelength measurements relative to the average of all wavelength measurements.**

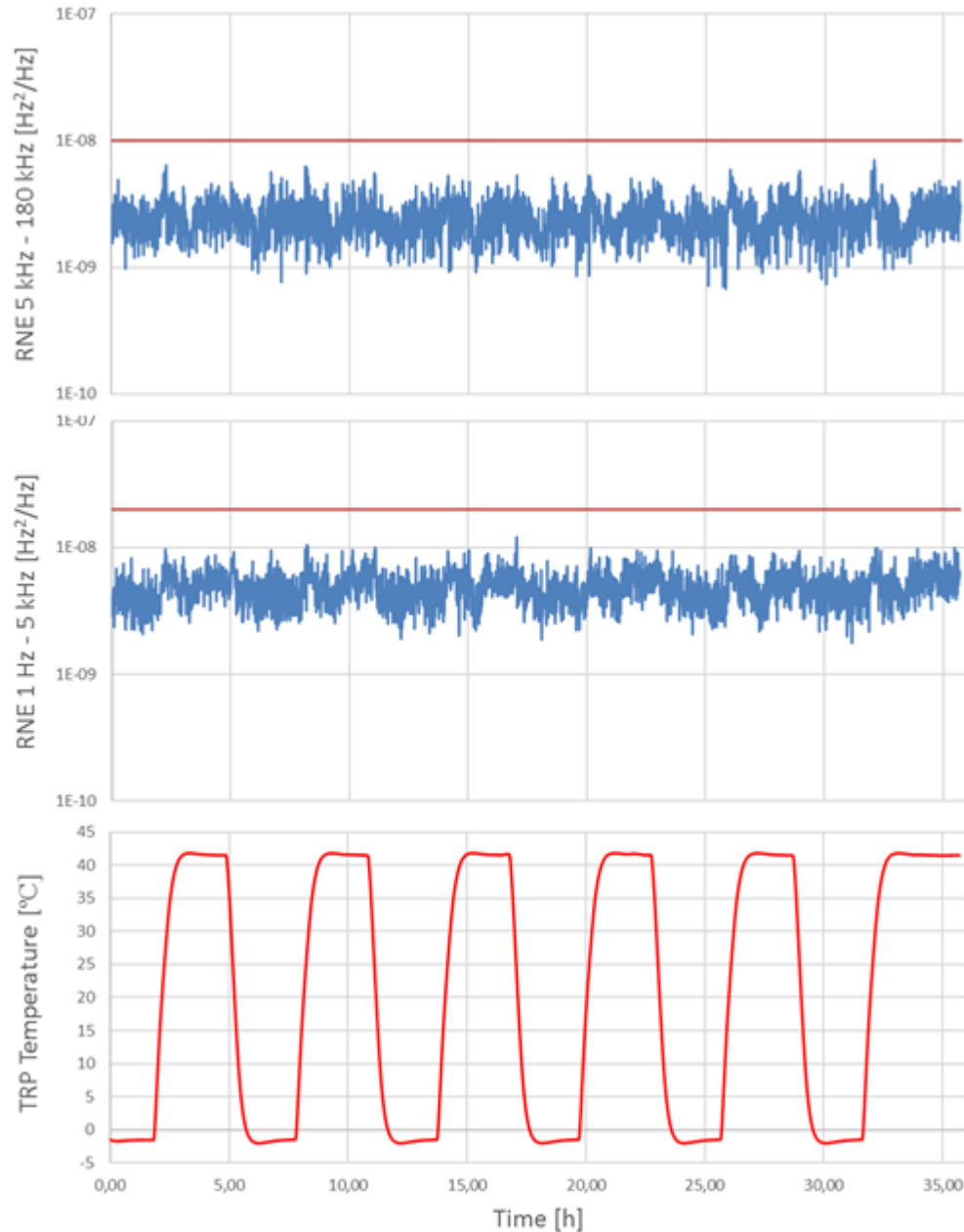


The LASE wavelength was also monitored during thermal cycling between 0°C and +40°C. Figure 8 shows the measured frequency deviation and the TRP temperature versus time. The frequency anomalies occurring at TRP temperatures of approximately 33°C were due to effects occurring when the laser modulation frequency becomes exactly 10x the FPGA oscillator frequency. Even though the frequency stability requirement is met throughout the thermal cycling, measures have been implemented in order to reduce this frequency anomaly for the flight models.

Figure 9 shows the wavelength RNE measured during thermal cycling. In both frequency bands, the RNE is below the requirements indicated by the red horizontal line in each plot.



**Figure 8 Wavelength stability measured during temperature cycling in thermal vacuum chamber.**



**Figure 9** Wavelength Random Noise Error (RNE) measurements performed during thermal cycling.

### 3.2 Polarization

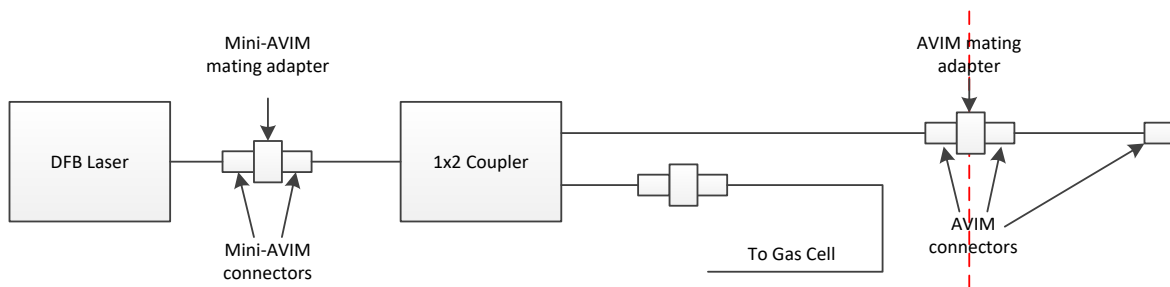
Predicting the Polarization Extinction Ratio (PER) of a system comprising several fiber optical sections and components is difficult and often an underestimated task.

Figure 10 shows the basic optical configuration of the LASE, including the external 1m fibre at which end the Polarization Extinction Ratio (PER) shall be measured. The red, broken, line represents the wall of the LASE enclosure. AVIM and Mini-AVIM are fiber optic connectors manufactured by Diamond SA.

The parameters influencing the LASE PER are:

1. The PER at the DFB laser output fiber

2. Rotational misalignment between mated fibres, which occurs in the adapter between the laser diode and the coupler and in the adapter between the coupler and the external fiber. Each of these matings have three contributions to the misalignment:
  - a. Misalignment between the polarisation axis of the input fiber and the key of the optical connector.
  - b. Mechanical tolerances between the two connectors when mounted in the mating adapter.
  - c. Misalignment between the polarisation axis of the output fiber and the key of the optical connector.
3. Internal polarisation effects in the fiber optical coupler.
4. Phase shift between the two fundamental fiber modes:
  - a. Fiber lengths
  - b. Temperature
  - c. Refractive index
  - d. Fiber birefringence
  - e. Wavelength
  - f. Mechanical stress



**Figure 10 Basic Optical Configuration**

Table 4 lists the characteristics of the components affecting the system PER. Additionally, the PM fibre sections contributes significantly to the system PER through the temperature and stress dependence of the fibre birefringence that shifts the angle of polarisation of the light. In this way, the temperature can compensate for the misalignment of fibre polarisation axis at fibre junctions and result in extremely high PER values for certain temperature intervals. At other temperatures, the system will reach minimum PER values.

**Table 4 Component characteristics affecting the LASE PER.**

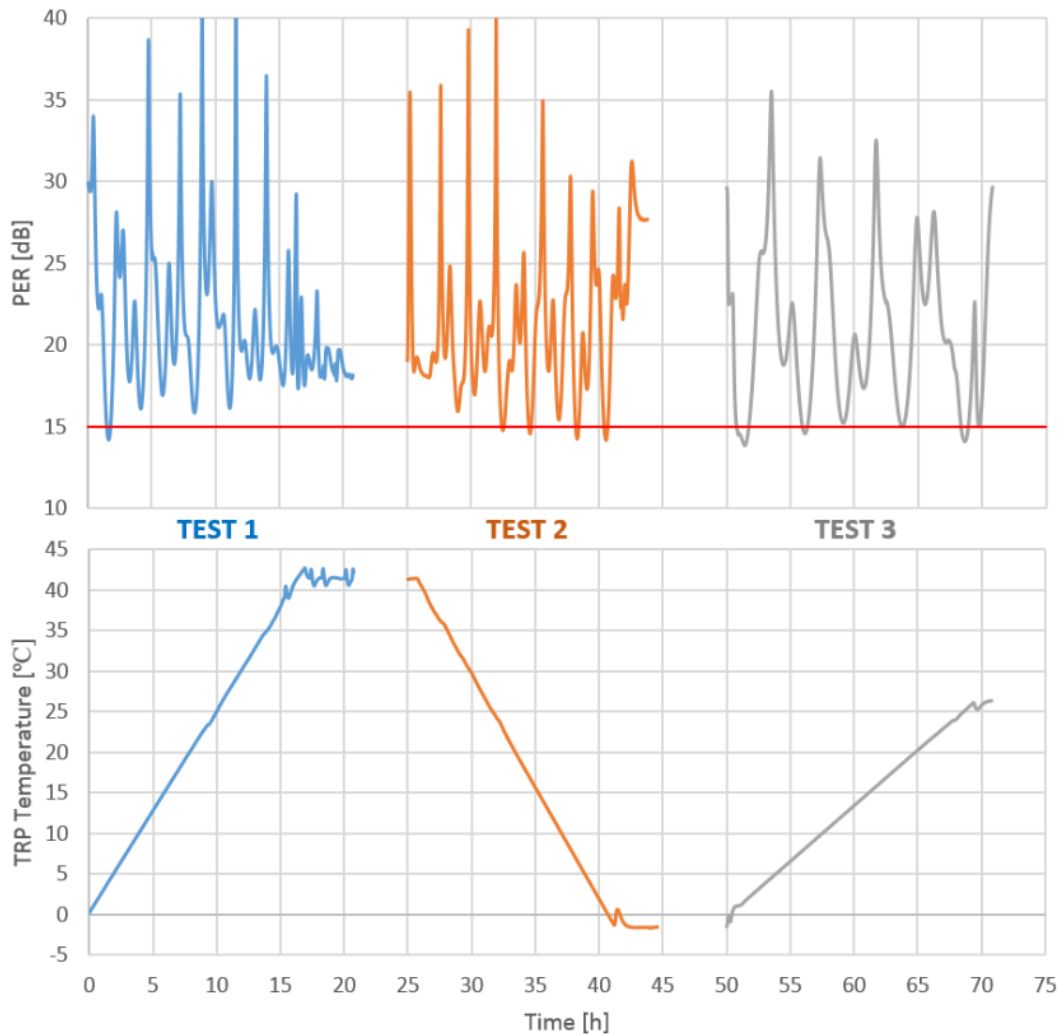
Item	PER [dB]	Angle [deg]	Comment
DFB Laser	26.6	$\pm 2.7^*$	Worst case, based on data for components selected for flight
Mini AVIM Connector, Passive alignment		$\pm 2.0$	Data from [3]
Mini-AVIM Connector, Active alignment		$\pm 0.8$	Data from [3]
AVIM Connector, Active alignment		$\pm 0.8$	Data from [3]
Mini-AVIM mating adapter		$\pm 1.4$	Data from [4]
AVIM mating adapter		$\pm 5$	Data from [4]
Optical Splitter	22	$\pm 4.5^*$	Worst case, based on data for components selected for flight

\*Angle calculated from the PER value.

Figure 11 shows the measured PER, with the LASE in thermal vacuum chamber, during three temperature sweeps:

1. TRP temperature raised from 0 °C to +40 °C in approximately 15 hours, i.e.  $\approx 2.67$  °C/hour
2. TRP temperature decreased from +40 °C to 0 °C in approximately 15 hours, i.e.  $\approx -2.67$  °C/hour
3. TRP temperature increased from 0 °C to +25 °C in approximately 20 hours, i.e.  $\approx 1.25$  °C/hour

As can be seen, the three temperature responses differ. In case of the slow temperature change ( $+1.25$  °C/hour), PER values below the 15 dB limit are found at TRP temperatures in the range 1.05 °C to 2.07 °C and 7.86 °C to 8.37 °C. For the faster temperature change ( $+2.67$  °C/hour), violation of the 15 dB limit occurs in the range 3.99 °C to 4.74 °C.



**Figure 11 Polarisation Extinction Ratio (PER) measured with LASE in thermal vacuum chamber and temperature swept. The lower chart shows the corresponding TRP temperature.**

In case of the LASE, tested here, there will be states where the LASE PER falls below the 15 dB limit. The occurrence of these events depends upon the temperature and the temperature distribution of the fiber optic components inside the LASE. Most likely, the minimum PER will not be significantly less than the minimum value measured during temperature cycling; 13.86 dB during the  $+1.25$  °C/hour test from 0 °C to +25 °C.

Calculating the PER using only the extreme values given in Table 4, the result is 9.75 dB. This situation, with all parameters at their worst value, is however not likely. The angular misalignments of the connectors will have an

unknown distribution. A model for calculating the PER of the LASE has been established. Here, component characteristics are selected from Table 4 and the phase shifts of the fiber sections are adjusted to a worst-case situation. Initially, it is assumed that the component characteristics of Table 4 corresponds to  $3\sigma$  normal distributions. Then, it is assumed that the component characteristics are uniformly distributed. Figure 12 shows the simulated probability of obtaining a system PER of less than X dB using this model. Contributions from the laser and the splitter are fixed at their worst-case values. The blue curve of Figure 12 represents uniform distributions, while the red curve represents normal distribution with boundaries equal to  $3\cdot\sigma$ .

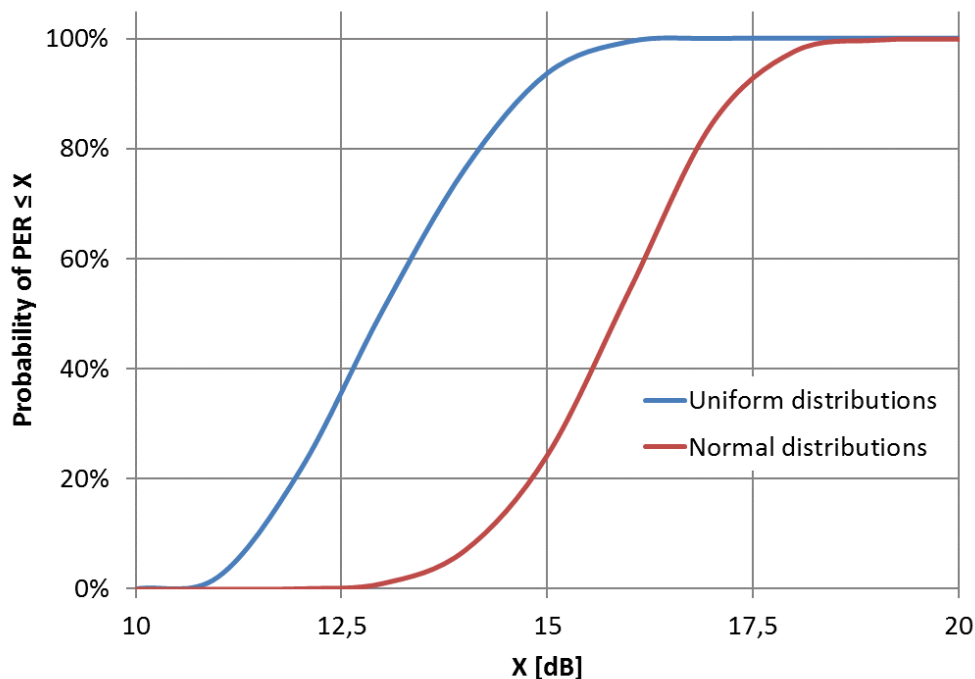
With uniform distribution of angular misalignments, the probability of obtaining a system with PER < 15 dB is 93.8 %. In the case of normal distributions, the probability is 25.3 %.

In order to improve the resulting PER, KDA foresee a process of matching parts prior to integration in the LASE. The matching process will comprise:

1. Assembly of a test system including the parts shown in Figure 10 (except the parts associated with the gas cell). Fiber coiling must be as realistic as possible.
2. The test system will be placed in a temperature chamber enabling a temperature sweep from above the dewpoint to 40 °C.
3. Run the temperature sweep while monitoring the system PER.

If the PER requirement is met by the test system in the whole temperature range, the system parts will be allocated to one future system. If not, the test has to be repeated with a different combination of parts.

Fusion splicing of fibers is expected to give better performance with respect to PER than the connectorized junctions. The lack of space qualified processes made this alternative not feasible.



**Figure 12 Simulation results showing probability of PER  $\leq$  X dB. The blue curve represents uniform distribution of component deviations, while the red curve represents normal distribution of components deviations.**

#### 4. SUMMARY

In this paper, we presented the LASE, the wavelength stabilized laser source to be implemented in the metrology system of IASI-NG. Results from the qualification campaign show that the wavelength stability requirement is met in the relevant temperature range and environmental definitions.

At some temperatures, the PER was not met with the EQM. Measures to improve the PER for the flight models have been discussed.

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- [2] ESCC No.23200, "Validation and Lot Acceptance Testing Guidelines for Laser Diode".
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