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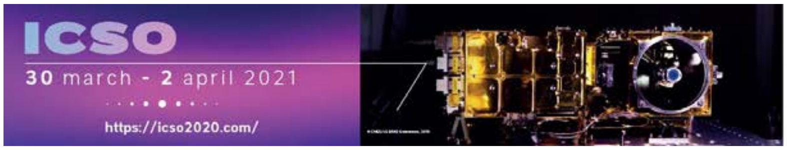

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The STAR-CC-OGSE system for pre-flight sensor calibration

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ABSTRACT

Reliable characterization and radiometric calibration of satellite sensors are critical to their optimal performance on-orbit. The uses of satellite sensor data, with their increased use in long-term environmental monitoring and climate studies mean that the performance and data quality provided by a single sensor can no longer be considered in isolation but needs to be considered as a part of the international Earth Observation (EO) infrastructure and referenced to common standard, the SI. The drive for improved performance, together with the desire for inter-operability between sensors creates increased demands on the pre-flight characterization and radiometric calibration of sensors.

Sensor pre-flight characterization and calibration facilities, or optical ground support equipment (OGSE) test sensor performance over a few broad categories including geometric performance/image quality together with spectral and radiometric calibration. The specific requirements of the sensor have historically created a drive for a bespoke OGSE. For large-scale multi-sensor series programs, a bespoke solution may remain the preferred solution. However, for single/few unit explorer missions, the expense & post-use redundancy of a bespoke OGSE system may be prohibitive.

NPL together with M Squared lasers has developed a universal OGSE facility, the Spectroscopically Tunable Absolute Radiometric calibration & characterization OGSE (STAR-CC-OGSE), a versatile facility for the radiometric calibration and characterization of satellite sensors. The system is provided fully characterized, calibrated and performance verified, with an easy to use software interface that allows fully automated remote operation

Keywords: Calibration, characterization, earth observation, satellite sensors, traceability, OGSE

1. INTRODUCTION

Earth observation system

Satellites have global coverage, therefore are invaluable for environmental and climate monitoring. Reliable data from earth observation (EO) satellites is crucial for global policy decision making. The quality of data from these satellites relies on the characterization and radiometric calibration of their sensors. To fully exploit the financial investment made into in-orbit hardware, there must be a robust understanding of the instrument’s performance and possible degradation mechanics.

The design of the majority of EO satellite missions have focused mainly on short term environmental monitoring, disaster management and civil defense objectives. However, there is a drive to use these assets for longer term climate applications. This necessitates the comparison and combination of data from past, present and future satellites, meaning satellite sensors should not be used in isolation but instead treated as part of the international EO infrastructure, with their uncertainties traceable to international standards, the SI. Figure 1 illustrates pasts, present and future ESA-developed EO missions [1], highlighting not just the number of EO satellites, but the breadth of applications and drivers. Biases will exist between sensors and only through robust calibration to a common standard (the SI) will the data be inter-comparable. Figure 1 shows just the ESA sensors, and the contribution of global space agencies only adds to the need for a common calibration standard.

Figure 1. Illustration depicting the past, present and future ESA EO satellites in orbit [1]. Credit: ESA

Pre-flight sensor characterization and calibration

It is critical to understand the behavior of the satellite instrument in all its operational modes before launch. Optical ground support equipment (OGSE) are used for sensor alignment, integration and testing (AIT) and characterization and calibration (C&C). Hyperspectral imagers need geometric characterization together with radiometric calibration and characterization. With performance metrics including:

Geometric characterization

- Field of view (FOV)
- Instrument line shape (ILS)
- Inter-band and intra-band co-registration
- Spatial response function
- Smile and tilt, keystone and tilt
- Spatial, spectral and temporal registration
- MTF, spatial sampling, dazzling

Radiometric calibration and characterization

- Radiometric calibration (absolute, relative intra-band/inter-band)
- Spectral calibration
- SNR
- Dynamic range
- Instrument spectral response function (ISRF)
- Linearity
- Polarization sensitivity

- Straylight (spectral and spatial)

Traditionally OGSEs are built bespoke for a satellite mission. The requirements of the OGSE are driven by the requirements of the sensor, this includes elements like FOV, spectral extent and nominal radiance. For large scale sensors programs a bespoke solution will still be the preferred solution. However, for single/few and more agile sensor programs a bespoke OGSE can be unnecessarily costly in time and money. NPL have provided support into satellite sensor calibration over several decades, most recently suppling an OGSE with novel features for the EC Copernicus Sentinel-4 mission. However, it was clear that the needs of a great many current and proposed optical sensor could be met by a transportable, adaptable, re-usable, traceable and verified system with advantages including:

- a more time and financial cost-effective solution than a bespoke OGSE
- a state-of-the-art system which could evolve over time (instead of being mothballed post use),
- a system which provides SI traceability

Although a generic system, it can be adapted for specific customer requirements, including the provision of bespoke field mask for geometric characterization and adaption of the tunable laser source to the target spectral range.

2. STAR-CC-OGSE

STAR-CC-OGSE overview

The Spectroscopically Tunable Absolute Radiometric calibration and characterization OGSE (STAR-CC-OGSE or STAR) is a versatile facility for the geometric characterization and radiometric calibration and characterization of satellite sensors. Figure 2 shows (a) a 3D rendering of NPL's STAR system and (b) a photograph of the system taken during verification testing.

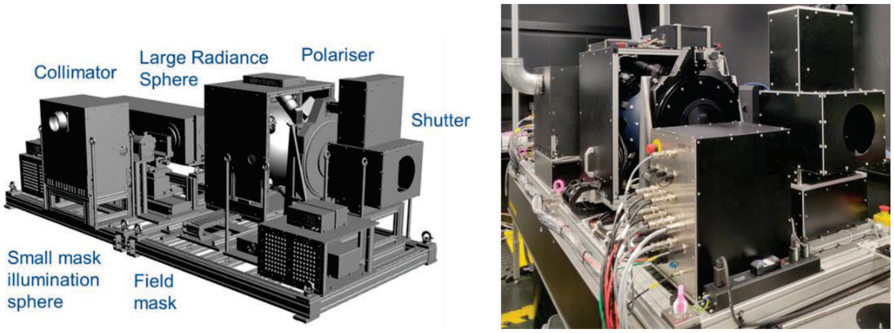

Figure 2. Images of NPL's STAR system. (a) CAD model rendering of STAR illustrating its subcomponents. (b) Photograph of STAR, recorded during verification testing

Geometric characterization

The geometric characterization is provided by an illuminated feature target at the focus of a collimator, allowing re-imaging of the feature patterns by the sensor under test. The 'small sphere' provides a spatially flat field illumination of the features of the field mask, illuminated by either internal QTH lamps for broadband illumination or tunable monochromatic laser illumination. The field mask is mounted on a stack of 3 linear stages for precise positional placement and feature interchange. Each feature can be positioned at the focus of the collimator to provide a collimated beam source for geometric optical testing and characterization.

Field mask

The field mask acts as an optical test card for the satellite sensor and is made bespoke for each customer. The mask feature shape, dimensions and orientation are driven by the sensor requirements and include geometric shapes such as slits, squares, pinholes etc. For example, a customer may want a slit to image an edge within a hyperspectral imager in order to characterize its response to a non-uniform scene, perhaps mimicking cloud coverage. On the other hand, a square may be projected on to the sensor to characterize the extent of optical distortions like barrel or pincushion induced by its imager optics. Each field mask is precision engineered and SI traceable via dimensional measurements at NPL, with typical uncertainties of ~ 1 µm (k=2). The field mask can be manufactured to include fibre feeds to provide a high intensity source for straylight characterization (Figure 3).

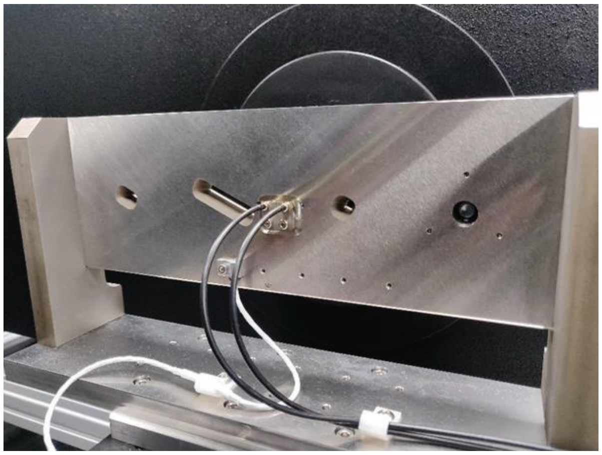

Figure 3. Photograph of the field mask manufactured for the first use of STAR-CC-OGSE. Here a high intensity fibre point source has been positioned at the focal point of the collimator.

The field mask is situated at the focus of a 1 meter focal length OAP-based collimator.

Radiometric calibration

The radiometric calibration is achieved via a large radiance sphere. This is mounted on a manual linear stage for easy translation between in and out of beam positions. The large sphere source is positioned in front of the collimator position, when in use, to allow a single sensor under-test mounting on a common beam for all testing to be possible without re-aligning the sensor to the OGSE. The integrating sphere has a 200 mm output aperture, illuminated by broadband radiation via multiple Quartz-Tungsten Halogen (QTH) lamps combined with a variable attenuator to provide a continuous range of radiance to its maximum. The radiance level is fully automated and user selectable via software control. The sphere can alternatively be illumined by tunable monochromatic laser illumination.

Polarization characterization

A broadband linear polarizer is mounted in a full 360deg automated mount in the common output path of the collimator and large sphere radiance source, to allow polarization characterization of the sensor under test. The polarizer is on a computer controlled linear stage to move between in beam and out-of-beam positions to allow automated characterization sequences to be performed.

A shutter also sits on the common output path to allow the source illumination to be extinguished without destabilizing the illumination sources.

Detector-based SI traceability

The radiometric SI-traceability is provided by a dedicated detector module. The module is designed to be mounted in the illumination beam near the sensor under test, to directly measure the radiance as viewed by the sensor, including the effects of any intervening windows or path absorption. The sensor is vacuum compatible, for use in TVAC environments.

The module consists of two broadband photodiode-based radiometers with a FoV of ±1.2 deg, calibrated traceable to the primary standard cryogenic radiometer at NPL. Figure 4 shows images of the detector module during calibration at NPL. The detector module also allows incident light to be coupled into a spectrometer. The spectrometer is calibrated using the tunable laser source and the radiance outputs of the photodiodes, allowing full spectral monitoring. This calibration is performed in-situ and repeatable at any time through the systems use, to ensure it remains accurate. The detector module will provide spectrally resolved accuracy of ~0.5 % (k=1) with better monochromatic accuracies.

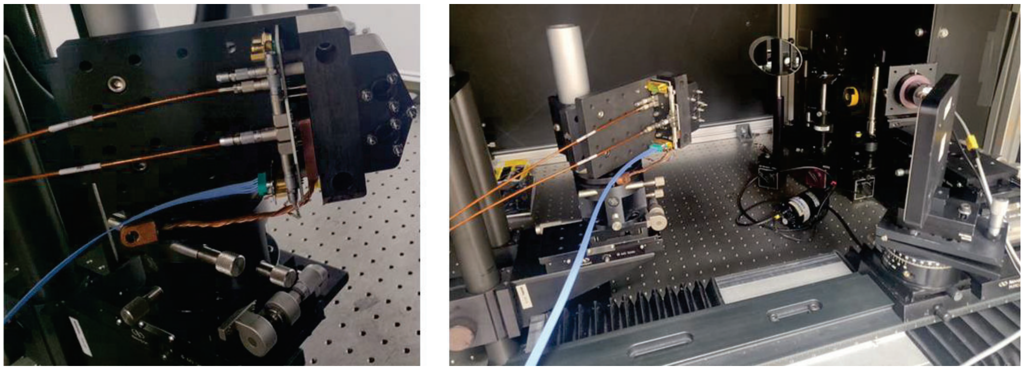

Figure 4. Images showing the features of the detector module (left) and the module being calibrated at one of NPLs facilities to establish traceability to the primary standard cryogenic radiometer at NPL (right).

It is possible to additionally provide an SI-traceable calibration of the large sphere source; however, this is not the intended SI-traceable route for the system and provides inferior accuracies at the entrance pupil of the sensor under test.

CW tunable laser System

M Squared laser (MSL) have provided a novel CW monochromatic source, continuously tuneability from 260 nm to 2700 nm. The laser is interchangeably fibre coupled to each integrating sphere and the field mask, with integrated interlock to allow safe and convenient use. Figure 5 shows MSL's laser system integrated with STAR. The building blocks of the system are their Equinox pump and Ti:Sapphire SolsTiS modules. A large range of wavelengths are achieved by adding difference frequency generation (DFG) and sum frequency generation modules (SFG). Through MSL's user interface the wavelength can be selected, and a range of parameter changed and monitored both locally and remotely. The system can be easily automated to step through customer-selected wavelengths across the full operation band as needed.

The ratio of laser power output at different wavelengths can be configured and optimized depending on the sensor's spectral requirements. Typical power tuning curves are shown in Figure 6. External attenuators have been installed at each laser output. These attenuators can be controlled remotely to vary the output power continuously and repeatably from zero to one hundred percent. This coarse and fine power control provides a versatile monochromatic radiance source.

The MSL CW system provides high optical powers (up to 2 W), a wide spectral range (260 nm – 2700 nm), small tuning steps (few pm) and narrow line widths (<0.1 pm). This allows for robust monochromatic radiance calibration, spectral response characterization and straylight characterization.

Temporal and spatial non-uniformity caused by laser speckle can contribute uncertainty to sensor characterization. Although speckle is an intrinsic feature of coherent light, STAR implements several solutions in conjunction to reduce the effects of laser speckle on output illumination uniformity.

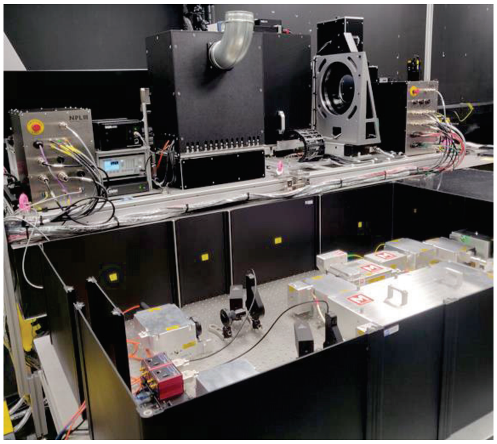

Figure 5. Image showing the MSL laser system (foreground) and NPL's STAR-CC-OGSE (background).

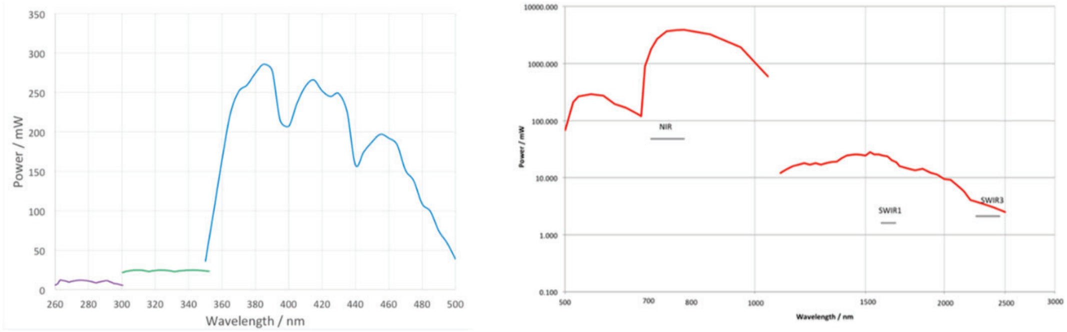

Figure 6. Typical power tuning curves of MSL laser system.

Environmental and transport properties

The entire STAR system is less than 500 kg and has been engineered to be easily transportable to customer sites. It can be craned and transported in two sections (Figure 7). The sections have repeatable inter-connection so that alignment is maintained after installation. Optical alignment infrastructure is included in the system to efficiently verify repeatable alignment after installation, through a combination of internally mounted alignment lasers and targets, see Figure 8.

The system also includes a pair of alignment cubes reference to the output optical beam direction to alignment to external references to <1 arcmin.

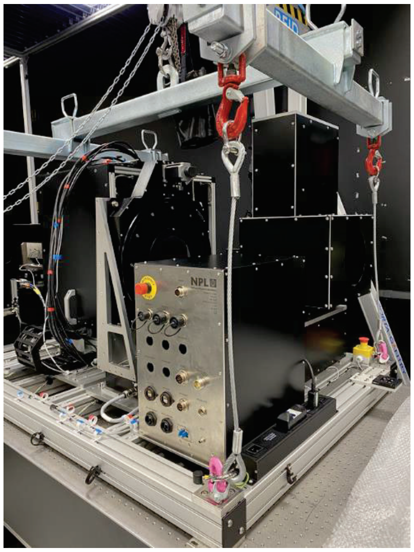

Figure 7. Picture showing a sub section of STAR being craned onto an optical table. The sub sections have repeatable interconnections for convenient re-alignment.

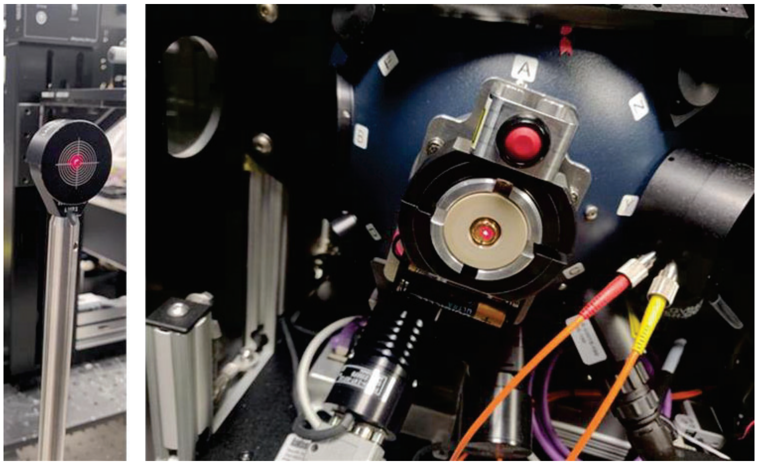

Figure 8. Pictures showing elements of STAR's internal alignment verification infrastructure.

The system is currently cleanroom compatible to ISO 6 standards but could be adapted to ISO 5 standards.

3. PERFORMANCE

STAR verification tests have been completed, including spatial and temporal uniformity, field mask alignment, polarizer alignment and polarizer beam deviation to name a few. Some examples of these test results are shown below.

Spatial uniformity

For example, the spatial uniformity of a mask slit feature in the geometric calibration system is shown in Figure 9. Here a 28 mm slit is at the collimator focus, illuminated by laser light at 765 nm. The P-V uniformity along the slit is shown to be well below 1%, with very low small-scale variation that includes all residual laser speckle effects.

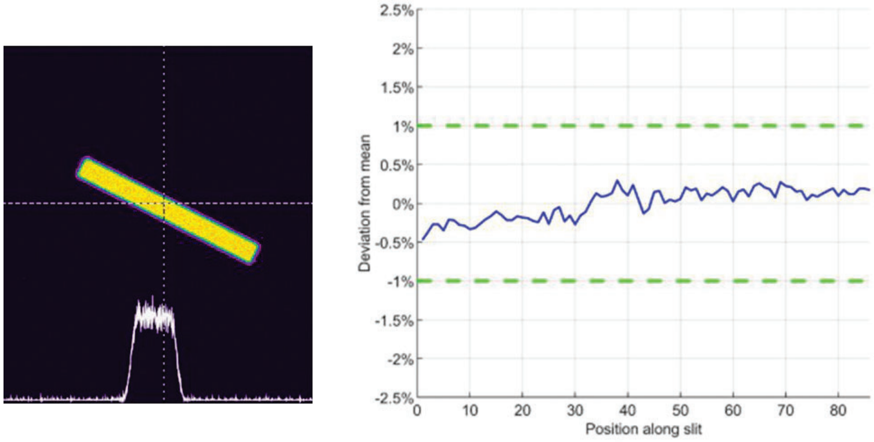

Figure 9. Results of spatial uniformity test of the field mask slit feature. Beam profile of the monochromatic source through the slit (left). Graph showing fluctuations from the mean (in peak to valley) along the slit feature.

Polarizer rotational beam deviation

The beam divergence under the action of the rotating polarizer was tested and found to be <10 µrad over the polarizer's full rotation (Figure 10). The spot CoM P-V variation is about 1 pixel in the image.

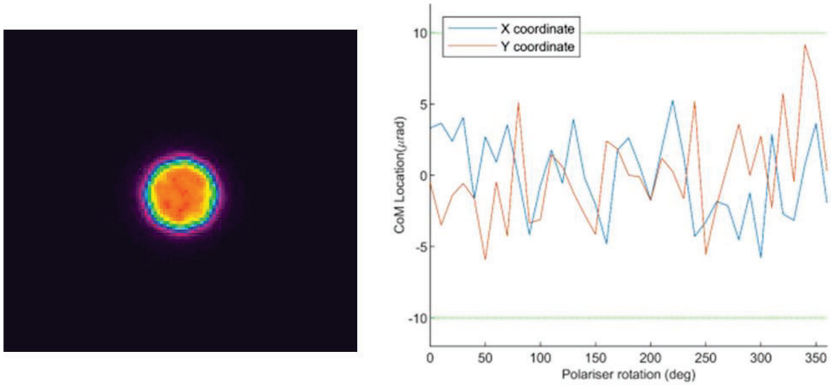

Figure 10. Polarizer beam deviation testing. Beam profile of the field mask high intensity fiber source (left). Graph of center of mass calculations as a function of polarizer rotation.

High intensity source radiance

The high intensity monochromatic source at the field mask is used for straylight characterization, Figure 11 shows the radiance levels that can be achieved at several wavelengths in the NIR (blue asterisks) in the order of 10^{19} to 10^{21} ph.s^{-1}.m^{-2}.sr^{-1}.

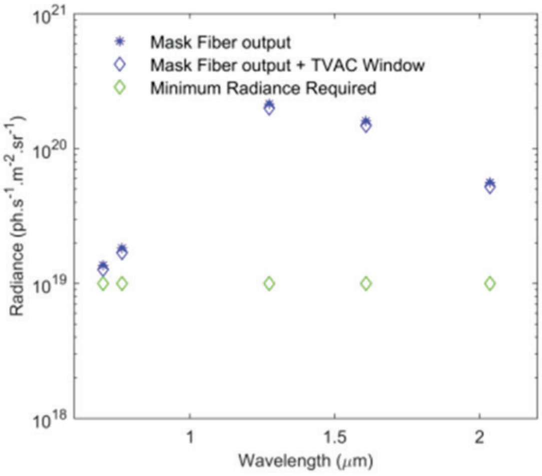

Figure 11. Radiance values produced by multiple wavelengths from the high intensity field mask source.

Usage

The first use of STAR will be used to calibrate and characterize the CNES/UKSA MicroCarb satellite [2]. The MicroCarb satellite will be used to monitor the concertation of carbon dioxide in the atmosphere and quantify sources and sinks on a global scale. The low levels of uncertainty provided by STAR's calibration and characterizations will mean greater confidence in the greenhouse gas source measurements from the sensor and ultimately better confidence in global policy and climate change action.

4. CONCLUSIONS

Robust and reliable measurements from EO satellite sensors are critical for confidence in global policy and climate action. Pre-flight calibration and characterization are a crucial element in assessing sensor performance against application requirements. Traditionally, optical ground support equipment (OGSE) has been built bespoke for each satellite sensor. In many cases, a completely bespoke system is not necessary and thus a more general system is both time and cost effective.

STAR-CC-OGSE is a versatile facility for the geometric characterization, radiometric characterization and radiometric calibration of satellite sensors. Although reusable, the system can be easily adapted to customer needs. The system is easily transportable and clean room compatible. NPL's SI traceability combined with M squared lasers tunable monochromatic source provides a novel means for detector based radiometric calibration along with a host of characterizations opportunities.

REFERENCES

[1] The European Space Agency, “ESA-DEVELOPED EARTH OBSERVATION MISSIONS” 19 January 2021, https://www.esa.int/ESA_Multimedia/Images/2019/05/ESA-developed_Earth_observation_missions (20 February 2021).

[2] CNES (Centre National Détudes Spatiales), “Microcarb” 17 August 2018, https://microcarb.cnes.fr/en/MICROCARB/index.htm (20 February 2021).

5. SPECIFICATIONS

Radiometric	
Monochromatic spectral range	260 nm to 2700 nm.
Broadband spectral range	250 nm to 2500 nm (eqv. to 3000K blackbody). Can be extended into UV
Monochromatic typical radiance	Max. 0.5 $W.m^{-2}.sr^{-1}$ (@800nm)
Broadband typical radiance	Max. 2000 $W.m^{-2}.sr^{-1}.nm^{-1}$ (@1200nm)
Radiance spatial uniformity	Typically <0.15% PV (application dependant)
Radiance temporal uniformity	Mono (0.2% PV), BB (0.02% rms)
Monochromatic source line width	<0.1 pm
Monochromatic source tuning step size	~few pm
Monochromatic source wavelength calibration	<0.2 pm (PV)
Calibrated TVAC-compatible radiance monitor	<0.5% (k=1) [TBC]
Collimator focal length & F/#	1000 mm & F/5
Polarization	
Contrast ratio	$>1:10^4$
Rotation extent, resolution & accuracy	>360°, <0.1°, <0.2°
Physical	
Physical size	2.6m (L) x 1.2m (W) x 1.0m (H)
Mass	<500 Kg
Transport	Crane-able & transported in sections
Beam diameter	200 mm
Field mask features	Slit, squares, MTF, high intensity point source. Bespoke for customer needs
Field mask rotation stage	±5°
Cleanliness	ISO6 (external surfaces compliant to ISO5)
Shutter response time	< 5 seconds
Operations	Completely remote controlled, interfaced to customer control systems.
Data management	Customer-tailored data interfacing system.
Environmental (operations)	Temp: 18°C ± 2°C, Pressure: 900 hPa -1084 hPa, humidity: 40 %rh – 70 %rh
Environmental (transport/storage)	Temp: 0°C - 40°C, Pressure: 900 hPa -1084 hPa, humidity: 40 %rh – 70 %rh
Compliance	CE & ROHS