Radiometric calibration of the NIRSpec instrument on the James Webb Space Telescope in the wavelength range from 0.7 µm to 5.0 µm

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1. Introduction

The James Webb Space Telescope (JWST) with its 6½-meter wide primary mirror is generally considered as the successor of the Hubble Space Telescope and the Spitzer Space Telescope. The JWST is an international collaboration between the NASA, the European Space Agency (ESA) and the Canadian Space Agency (CSA) and will be launched 2013 [1].
The scientific instrumentation of the JWST consists of four instruments of which one is the near-IR multiobject dispersive spectrograph (NIRSpec), operating in the wavelength range from 0.7 µm to 5 µm.
The NIRSpec instrument is foreseen to be calibrated on-ground at the Optical Ground Support Equipment by means of the Radiometric Calibration Spectral Source (RCSS) and in space by the NIRSpecs Internal Calibration Assembly [2].
The RCSS is designed as a very low photon flux, point-like radiation source, typically with photon fluxes in the range from 10^4 to 10^7 photons·µm^{-1}·s^{-1} in the wavelength range from 0.7 µm to 5 µm. It consists of a gold coated integrating sphere, several separately operable tungsten filament incandescent light sources with lead-glass bulbs, a 10 µm pinhole and a mirror-based optical imaging system. A schematic view of the RCSS is given in Fig. 1. The RCSS is intended to be operated under vacuum and under cryogenic conditions.

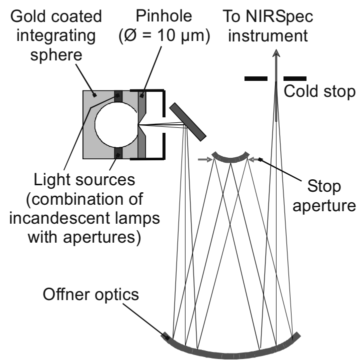

Figure 1: Schematic view of the Radiometric Calibration Spectral Source RCSS)

2. RCSS Calibration schemes

For the calibration of the photon flux emitted by the RCSS, traceable to the Spectral Radiance Primary Standard, the PTB has developed two new calibration schemes, specially adapted to the low photon fluxes delivered by the RCSS [3]. The calibration schemes depend on the calibration wavelength region and are divided into two spectral regions.
Scheme 1 comprises the wavelength interval from 0.7 µm to 1.7 µm and is performed at the Spectral Radiance Comparator Facility (SRCF) of the PTB [4]. As a consequence of the several orders of magnitude difference between the photon flux of the Spectral Radiance Primary Standard and the RCSS, the calibration had to be laid out as a two step procedure. A flow-chart of the calibration procedure is displayed in Fig. 2. In a first step, the spectral radiance of a transfer standard (integrating sphere or a variable temperature blackbody) is calibrated by comparison against the Spectral Radiance Primary Standard. The second step includes the calibration of

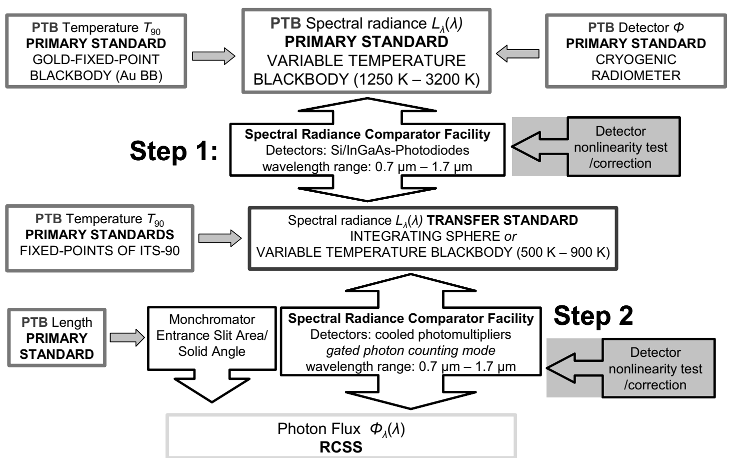

Figure 2: Calibration Scheme 1 for the traceable calibration of the RCSS in the wavelength range from 0.7 µm to 1.7 µm

the RCSS against the calibrated transfer standard. Being a point-like source, the calibration of the RCSS against the large area transfer standard implies also the traceable measurement of geometry parameters: the solid angle and the area of the surface element used for calibration of the transfer standard. In both steps the non-linearity of the used detectors, i.e. Si and InGaAs photodiodes in step 1 and of the photomultipliers in step 2, is measured and used as a correction for the calibration. In the wavelength interval between 0.9 µm and 5 µm a second scheme, Scheme 2, is applied and the calibration is carried out at the Reduced Background Calibration Facility (RBCF) of the PTB [5]. Here, the RCCS is calibrated against a dedicated Vacuum Variable Low Temperature Blackbody (VLTBB). If the linear detection range of the comparison instrument, a vacuum FTIR spectrometer, is exceeded, the calibration of the RCSS will be performed in a two step procedure, similar to Scheme 1, via an integrating sphere as a transfer standard, as shown in the flow-chart diagram in Fig. 3.

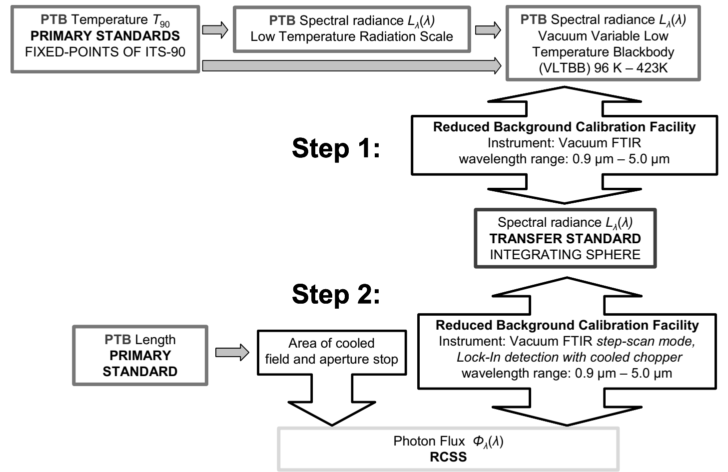

Figure 3: Calibration Scheme 2 for the traceable calibration of the RCSS in the wavelength range from 0.9 µm to 5 µm

3. Experimental setup

As the photon flux of the RCSS is about ten orders of magnitude lower than the Spectral Radiance Primary Standard, a significant improvement of the detector instrumentation, both for the Spectral Radiance Comparator Facility (SRCF, Fig. 4) and the Reduced Background Calibration Facility (RBCF, Fig. 5) was mandatory.

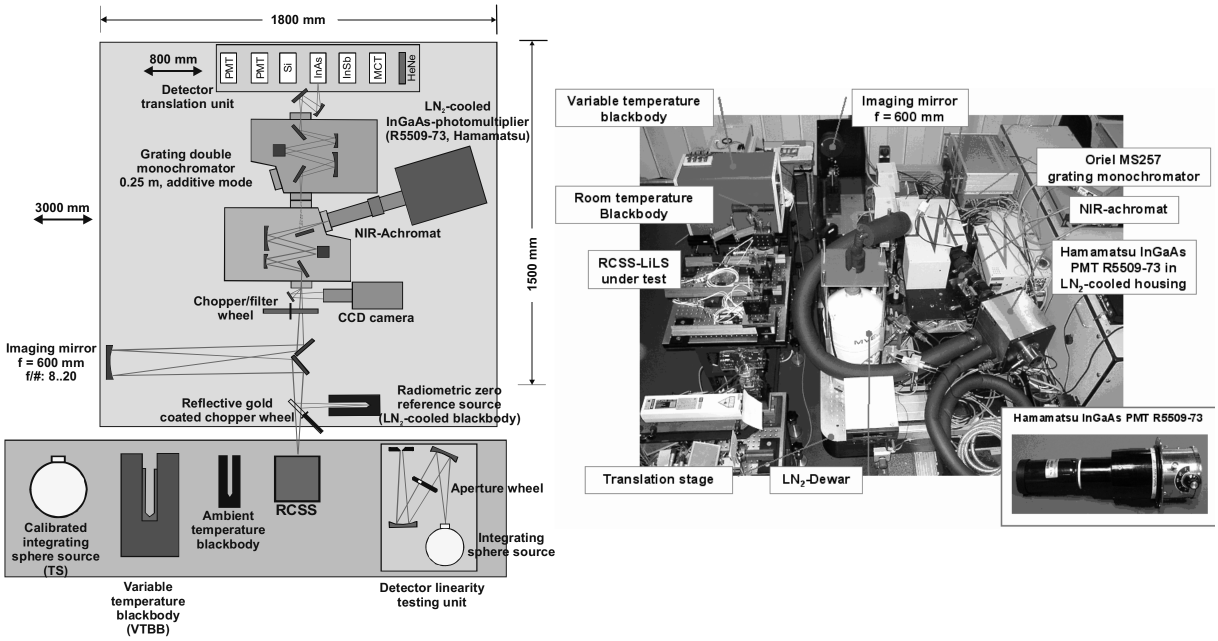

Figure 4: Schematic view and photography of the Spectral Radiance Comparator Facility (SRCF) of PTB, improved for the calibration of very low photon flux sources

A schematic view of the setup with the optical path and an image of the SRCF, used for the accomplishment of the calibration of the RCSS according to Scheme 1 are shown in Fig. 4. The radiating area of the RCSS or the transfer standard are imaged consecutively with an imaging ratio of 1:1 onto the entrance slit of the monochromator. Conditioned by the low photon flux to be measured, only the first monochromator of the double monochromator system is used. The exit slit of the monochromator is imaged by means of an NIR-achromat onto the detection system. The main improvement of the SRCF with respect to the calibration of very low photon flux sources, was the implementation of a set of cooled (-100 °C) photomultiplier tubes (PMT) as detectors. To cover the wavelength range from 0.7 µm to 1.7 µm, a trialkali-, an S1(Ag-O-Cs)- and an InGaAs-photocathode PMT are applied. Depending on the flux to be calibrated, the PMTs can be operated both in current and in counting mode. By measuring the ratio $Q_\lambda(\lambda)$ of the signals $I_\lambda(\lambda)$ of the RCSS respective the transfer standard, the spectral photon flux $\Phi_\lambda(\lambda)$ of the RCSS can be calculated according to

$$\Phi_{\lambda,\mathrm{RCSS}}(\lambda)=Q_\lambda(\lambda)\cdot L_{\lambda,\mathrm{TS}}(\lambda)\cdot A\cdot\Omega\cdot\tau=\frac{I_{\lambda,\mathrm{RCSS}}(\lambda)-I_{\lambda,\mathrm{RCSS,dark}}(\lambda)}{I_{\lambda,\mathrm{TS}}(\lambda)-I_{\lambda,\mathrm{TS,dark}}(\lambda)}\cdot L_{\lambda,\mathrm{TS}}(\lambda)\cdot A\cdot\Omega\cdot\tau,$$

where $L_{\lambda,\mathrm{TS}}(\lambda)$ denotes the spectral radiance of the transfer standard, A the area of the entrance slit of the monochromator, Ω the solid angle defined by the diameter and the focal length of the imaging mirror and τ the transmittance of the cryogenic vacuum chamber (see Fig. 7) the RCSS is accommodated in. A detailed description of the calibration procedure is given in Ref. [3] and [4].

To reduce the significant infrared background radiation in the RBCF, its detection system, an Infrared Fourier Transform Spectrometer (FTIR) is operated in step-scan mode. Furthermore, the radiation emitted by the sources is modulated with a high-reflective cooled chopper which faces also a radiometric zero source (LN_2 blackbody).

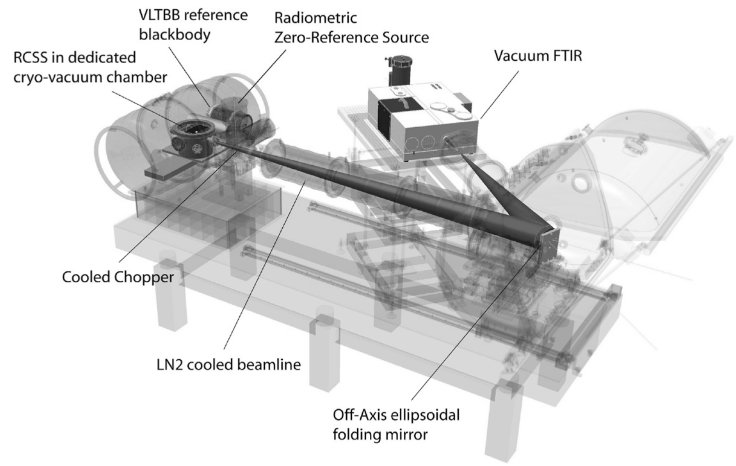

Figure 5: Schematic view of the dedicated cryogenic vacuum chamber and the beam path inside the Reduced Background Calibration Facility (RBCF)

Hereby the detection the of the very low signals with a Lock-In amplifier becomes possible. The interference pattern is measured stepwise: the detector signal is read out at every step from the Lock In amplifier and its processed signal is feed back into the interferometer electronics (Fig. 6). Simulations [3] showed that for the required detection of 10^7 photons / (µm·s) a chopper temperature of 130 °C, a chopper emissivity of 0.02 and a chopper temperature stability of 100 mK have to be maintained.

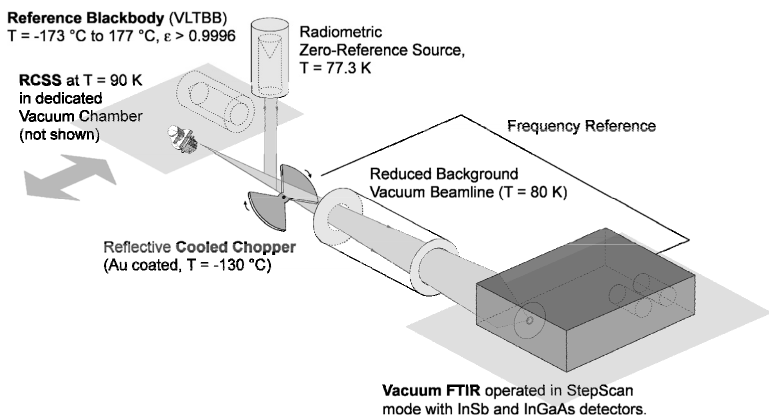

Figure 6: The functional scheme of the RBCF for the calibration of the RCSS. VLTBB and RCSS are positioned on the optical axis by a translation stage

Besides the mandatory improvement of the calibration facilities, for the calibration of the RCSS under vacuum at liquid nitrogen temperatures and to ensure simultaneously clean room conditions for space-borne instruments, a dedicated cryogenic vacuum chamber for the RCSS calibration has been designed and constructed by the PTB. A schematic of the chamber with the accommodated RCSS and an image of the partially opened chamber are shown in Fig. 7.

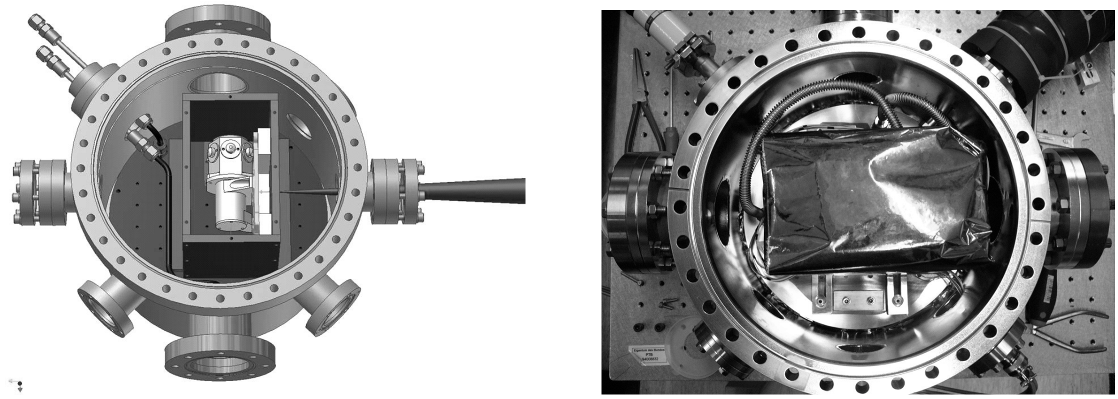

Figure 7: Schematic and image of the dedicated vacuum chamber for the calibration of the RCSS under vacuum at LN_2-temperatures**.**

The optical radiation of the RCSS is accessed through a wedged CaF_2 window, whose transmittance has been measured separately in the wavelength range from 0.6 µm to 5.2 µm. The cooling of the RCSS to cryogenic temperatures is achieved via a cooling plate inside the vacuum chamber by a regulated LN_2-flow, the temperature being monitored by four separately positioned temperature sensors. An intensive test campaign of the chamber with respect to the achievable vacuum and the cryogenic temperature stability revealed that at a vacuum of at least $3 \cdot 10^{-7}$ mbar the temperature can be maintained to 82 K ± 0.5 K for at least 48 hours. No restrictions are seen to extend this duration to several hundred hours.

4. Measurement results for the RCSS design

To verify and to optimize the opto-mechanical design and the parameters of operation of the RCSS with respect to the desired photon fluxes, systematic measurements of the photon flux at different design stages of the RCSS have been carried out at the SRCF.
The first approach was the measurement of the photon flux of the bare miniature tungsten filament lamps used as radiation sources in the RCSS at two different lamp currents (17 mA and 6.9 mA) in the wavelength range from 0.7 µm to 5 µm. As can be seen from the results depicted in Fig. 8, by using special lead glass bulb lamps, these lamps are capable of delivering photon fluxes up to a wavelength of at least 5 µm.

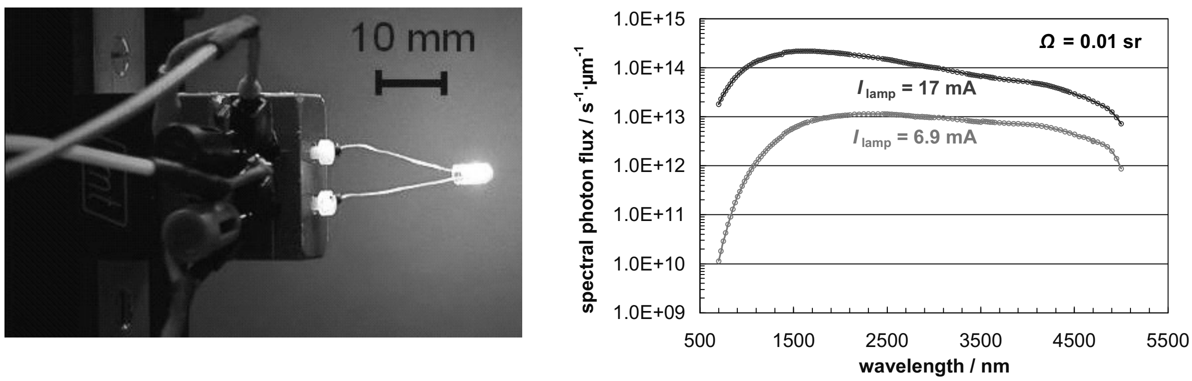

Figure 8: Miniature tungsten filament lamp used as radiation source in the RCSS and the measured spectral photon flux at two different lamp currents in the wavelength range from 0.7 µm to 5 µm

The next step was the radiometric investigation of lamp/housing/aperture combinations, the so-called lamp-in-light sources (LiLS). The LiLS consist of a pair (for redundancy reasons) of lamps, selected with respect to their electrical resistance, which are mounted into a gold coated, roughened housing of cylindrical shape.

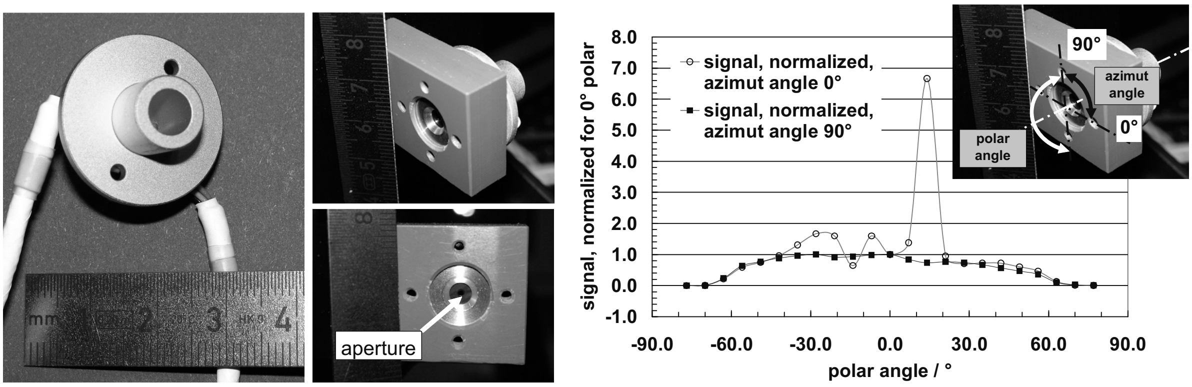

Figure 9: Lamp-in-light source (LiLS) of the RCSS without aperture (left), with a fitted 1 mm diameter aperture inside a mounting bracket (middle) and the corresponding relative angular distribution at the wavelength λ = 1.4 µm (right).

To control the photon flux, the LiLS can be equipped with apertures with selected diameters. A view of a RCSS LiLS with and without aperture is given in Fig. 9. The investigated LiLS configurations and parameters were:

- Measurement of the relative angular photon flux distribution for a LiLS with a 1 mm diameter aperture and a lamp current of 17 mA at λ=1.4 µm (Fig. 9).
- Measurement of the absolute photon flux of the LiLS in the wavelength range from 0.7 µm to 5 µm with four different lamp currents (7 mA, 12 mA, 15 mA and 17 mA) and an aperture with a fixed diameter of 1 mm (Fig. 10, left).
- Measurement of the absolute photon flux of the LiLS in the wavelength range from 0.9 µm to 1.6 µm with four different aperture diameters (10 µm, 50 µm, 100 µm and 500 µm) and a fixed lamp current of 17 mA (Fig. 10, right).

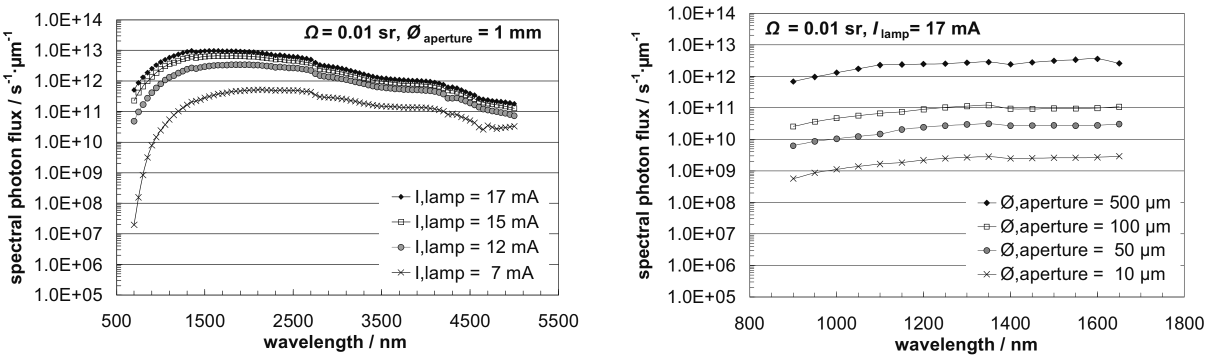

Figure 10: Spectral photon flux of the LiLS for two configurations: as a function of four different lamp currents (7 mA, 12 mA, 15 mA and 17 mA, left) and as a function of four different applied aperture diameters (10 µm, 50 µm, 100 µm and 500 µm, right)

A further step in the measurements performed for the design of the RCSS, is the determination of the spectral photon flux of the Breadboard Sphere (BB-sphere), which is a fully functional test model of the RCSS. Similar to the schematic view of the RCSS shown in Fig. 1, it consists of a roughened gold coated integrating sphere with two illumination ports where the LiLS are flanged as light sources. The exit port is made up of a mounting assembly with a 10 µm diameter pinhole, representing the desired point-like source. An overview of the BB-sphere setup is given in Fig. 11 (left).
The spectral photon flux of the BB-sphere was measured in the wavelength range from 0.7 µm to 1.6 µm as a function of the aperture diameter of the LiLS (Fig. 11, right). Three setups were investigated: no aperture, 3 mm diameter aperture and a 2 mm aperture. For the measurement, the BB-sphere was illuminated by one lamp of one LiLS only, whilst the other lamp of the LiLS and the second LiLS were not used. The lamp current was kept constant at 17 mA.

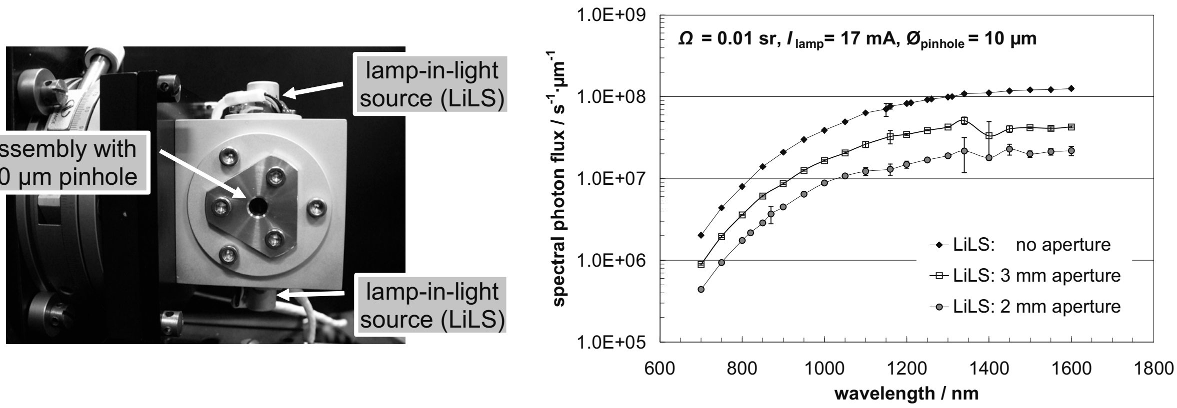

Figure 11: The Breadboard Sphere (BB-sphere) as the functional test model for the design of the RCSS and the measured spectral photon flux for three different LiLS-aperture configurations.

Note: References to commercial products are provided for identification purposes only and constitute neither endorsement nor representation that the item identified is the best available for the stated purpose.

References

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