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Next-generation white light source for on-board characterisation and monitoring

Ralph Snel[a], Niels Dijkhuizen[a], Luud van Riel[a], Gerard Otter[a], Geert Slegtenhorst[a], Dana Tomuta[b]
[a]TNO, Stieltjesweg 1, 2628 CK Delft, the Netherlands; [b]European Space Agency, Keplerlaan 1,
2200 AG Noordwijk, the Netherlands

ABSTRACT

In-orbit white light sources (WLS) have been used in many in-flight calibration units of optical space instruments. Usually, a QTH lamp (Quartz Tungsten Halogen, broad band light source) is used on board for in-flight characterisation and health checks of the instruments. The major issue of the QTH lamps used are their limited lifetime, reliability and recently their obsolescence and lack of suppliers. This study addresses these issues and looks for alternatives to replace in-orbit WLS as QTH with the best equivalents today available on the market.

The objective of the activity is to identify an alternative broad band (in-flight) WLS to replace and outperform the QTH. Here, alternative light sources are proposed, their concept and relevant use cases for their implementation are described. The study explores the feasibility of the alternatives proposed and establishes trade-off criteria based on use case requirements. Finally, the future potential usage of the alternative WLS and further steps for breadboard manufacturing, testing and space qualification are presented.

Preliminary requirements for the innovative WLS (iWLS) are collected, partly based on requirements of the imaging spectrometers OMI, SCIAMACHY, GOME-2, TROPOMI and Sentinel 5, and on typical use cases.

Typical use cases cover on-ground and in-orbit instrument characterisation and monitoring, in particular of detector properties such as electronic offset, electronic gain, noise properties, linearity, and pixel response non-uniformity (PRNU). Ideally, the iWLS can be used to transfer the radiometric calibration of the instrument from ground to orbit and monitor it for the entire mission duration.

We identify a list of alternatives for the on-board WLS. For a selection of alternatives, we perform a trade-off based – where available – on performance.

The trade-off addresses technology readiness level (TRL) for use on ground and space, market availability for use on ground and space, radiometric stability, radiometric level, spectral coverage, power usage, heat dissipation, mass, size and volume. In addition, the applicability of the sources to the required use cases is addressed in the trade-off: PRNU, pixel map, relative radiance, absolute radiance, non-linearity, on-ground usage, and potential new usages (extended functionality).

Light sources selected for the final trade-off are: Sun irradiance, Earth radiance, Moon irradiance, QTH lamp (for comparison), single narrowband LED, single white light LED, multiple narrowband LEDs, multiple white LEDs, and white laser.

The trade-off results in multiple narrowband LEDs as the optimal solution using scores of the aspects mentioned above and are presented in this paper. The QTH lamp and natural sources also rank high, confirming, as expected, the validity of the trade-off.

A conceptual breadboard implementation of a multiple narrowband LED source is finally proposed. An analytical approach for performance estimation is also presented in support of the proposed breadboard concept and compared to the required classical QTH WLS performance for Sentinel 5.

Keywords: white light source, LED, space optical instruments, on-board instrument calibration

1 INTRODUCTION

At TNO in the space instrument calibration group we have two overarching goals: *self-calibrating instruments*, and *calibration in a day*. This study on an innovative white light source for in-flight calibration, funded by ESA, aims to work towards the former goal, self-calibrating space instruments.

In orbit white light sources have been used in many in-flight calibration units of optical space instruments. Usually, a QTH lamp (broad band light source) is used on board for in-flight calibration and health checks of the instruments. The major issue of the QTH lamps used are their limited lifetime, reliability and recently their obsolescence and lack of suppliers. The current activity addresses these issues and looks for alternatives of replacing in-orbit white light sources as QTH with the best equivalents today available on the market.

The objective of the activity is to identify an alternative broad band white light (in-flight) source to replace the QTH and outperform its performance. In the activity, alternative light sources shall be proposed. Their concept and relevant use cases for their implementation shall be described. The activity will explore the feasibility of the alternatives proposed and establish trade-off criteria based on use cases requirements. The activity will finally present the future potential usage of the alternatives selected and further steps for breadboard manufacturing, testing and space qualification.

2 WLS USAGE AND REQUIREMENTS

White Light Sources have been and are being used in a number of imaging spectrometers and hyperspectral imagers, among which OMI [1]; SCIAMACHY [2]; GOME-2 [3]; TROPOMI [4], and will be used in Sentinel-5 [5]. From these applications the usage of a WLS were derived, also using the relevant requirement documents for these instruments ([6], [7], [8]): Pixel response non-uniformity (PRNU) characterisation; Detector response and non-linearity characterisation; Instrument/sub-system throughput monitoring; On-ground instrument health checks; Relative radiometric response calibration and monitoring, in particular spectral overlap regions where present in the instrument; Time variable properties of the instrument (example: Etalon of cooled detector, Filter cut-off of dichroic mirrors) monitoring.

In addition, in the TROPOMI instrument a broadband visible light LED is used to test its potency as a WLS replacement. In other missions narrowband LEDs are used to monitor sub-systems of instruments, e.g., detector properties or spectral channel throughput monitoring only.

In the typical use case, the WLS is used to characterise and monitor a subset of optical properties of the instrument (in-orbit and on ground).

2.1 WLS use cases in more detail

On-ground. During on-ground calibration the instrument will view a selection of on-ground calibration sources. In order to monitor potential changes of the instrument during the on-ground calibration period, regular monitoring measurements are done with the instrument internal sources, among which the WLS.

The calibration of the on-ground sources can in principle be transferred through the instrument to the on-board calibration sources. As the instrument is transferred from on-ground calibration conditions to in-flight operational conditions, the calibration assigned to the on-board sources can thus be transferred from ground to orbit. This assumes stability of the on-board calibration sources during this transfer (which is not the case for the radiance levels of a QTH, due to the difference of halogen convection in the lamp between 1 g and microgravity).

In-orbit. A WLS is used in-orbit to *characterise* instrument spectral features rapidly varying with wavelength such as detector etalon (caused by e.g., a protective silicon dioxide layer on the detector material)) and PRNU, and for relative detector electronic gain characterisation. The characterisation data are used for correction of instrument measurement data during on-ground processing.

Characterisation of (change of) spectral features is done by assuming spectral smoothness of the WLS. An appropriate polynomial is fitted to the detector (spatial and spectral) response to WLS illumination, following the low-frequency features of the instrument and the lamp. The measurements are then divided by the polynomial fit, removing the low-frequency features and leaving only high frequency features. The choice of polynomial will influence the turn-over frequency between “low” and “high”.

Relative detector electronic gain is applicable for OMI where gain switching was used during CCD read-out in order to better cover the expected dynamic range in the spectrum. WLS measurements at different gain settings are made. At a gain switch a jump in the spectrum will occur. Assuming spectral smoothness, the magnitude of the jump (i.e., the relative gain actor) can be determined from the smooth spectra adjacent to the jump. Alternatively, lamp reproducibility can be assumed and the ratio of measurements with and without gain switching will provide the relative electronic gain during switching.

Instrument monitoring. A WLS is used in-orbit to *monitor* charge transfer efficiency, detector pixel health, and for detector linearity checks. The monitoring data is only used for health monitoring and flagging data, it is not used for corrections of the data.

During Charge transfer Efficiency (CTE) monitoring, the efficiency of charge transfer through the CCD pixels is assessed. A known bright/dark transition will be smoothed out in the read-out direction due to a fraction of the charge lagging behind during a pixel charge transfer, resulting in a somewhat more blurred bright/dark transition than with perfect charge transfer. Long-term stability of the intrinsic sharpness of the bright/dark transition is assumed.

Detector pixel health is assessed by means of WLS measurements (effectively PRNU determination), where pixels exceeding pre-defined PRNU values are flagged as bad or dead.

Radiometric calibration. A special use case for a QTH WLS is applied in SCIAMACHY [9], [10]. The absolute radiometric calibration of the instrument as determined on-ground is transferred to the WLS, changes from ground to orbit are tracked using the WLS in combination with a correction for 1 g to microgravity, and ageing of the WLS during the mission is also modelled to maintain the absolute radiometric calibration.

2.2 Requirements on WLS

The WLS requirements of previous and current Earth observation hyperspectral imagers mentioned above can be summarised as follows:

- Wavelength range should cover that of the instrument. There is no need to cover a larger spectral range. Because of potential out-of-spectral-band stray light of the instrument, it is wise to limit the spectral range of the WLS to that of the instrument.
- Spectral shape should be smooth and should be reproducibly smooth. Any high frequency spectral features observed in the observations of the WLS should only be caused by the instrument and not by the WLS.
- Spectral radiance should somewhat match that of the atmosphere, or alternatively the WLS signal recorded at the detector pixels should result in a well-exposed spectrum when using exposure times that are similar to those used during nominal earth and sun observations. The goal is to have WLS measurement with a good SNR.
- Radiometric stability is required to be good over relatively short timescales, at least over the typical burn time of a single on-off cycle (typically 120 seconds). It would be valuable to have good reproducibility over multiple on-off cycles on timescales of months to years, though it is currently accepted that the WLS will slowly degrade. Predictable long-term degradation is preferred over erratic or discontinuous long-term degradation (the OMI QTH shows hysteresis depending on the halogen cycle and deposition versus recycling of tungsten on the quartz bulb inner surface).
- Illumination of the instrument using the WLS should match that observed when observing the earth or sun. This means that the etendue should be matched, the instrument pupil and field should be properly filled for all wavelengths. Ideally, the instrument pupil is uniformly illuminated, ensuring the same weighting of light paths through the instrument as is the case when viewing the earth.
- The WLS is used to monitor relatively slow instrument changes, typically on the timescale of weeks or slower. In special cases (after thermal instabilities of the instrument), changes on the timescale of days or even hours are expected and seen. Typically, a WLS is used on a daily basis to monitor the instrument. For the occasional periods after thermal instabilities, orbital instead of daily measurements would be beneficial. Together with the nominal and expected mission duration (which may be factors longer than the nominal mission duration) and the on-ground use of the WLS, this will give the minimum required number of WLS cycles, and together with the typical burn time, it will give the total burn time of the WLS. On-ground use of the WLS should not be forgotten in these budgets.
- As the WLS is used to monitor as much as possible of the instrument, it should be placed early in the optical chain. Optical components unique to the WLS optical path should ideally be stable in time, so that any changes observed over time can be ascribed to the instrument instead of the WLS unique optical path.
- The WLS should be compatible with use on-ground, subsequent transportation and launch, and use in orbit. This defines the environmental requirements of the WLS (shock and vibration, thermal, vacuum, radiation, EMC).

- The WLS availability, mass, volume, power consumption, heat dissipation, and cost should be reasonable for the intended application.

In historic missions, the WLS has sometimes been used beyond its intended purposes. Predictability of the WLS played an important role there, e.g., the link between radiances at wavelengths over the entire spectral range of the instrument by means of the black (or grey) body curve of a QTH. Likewise, heat-up times and stabilisation times were characterised and optimised.

Future use of QTH's in space instruments may become difficult. Since 1 September 2018 the EU has decided to stop halogen lamp production, the main reason being the energy savings when e.g., switching to LED. This has resulted in QTH producers not investing in or further supporting the production of these light sources. Next to that, QTH sources limited irradiance stability (hysteresis and ageing) and limited lifetime have been an issue in previous missions.

3 A NEW WLS FOR USE IN FLIGHT

In this section we present a list of alternatives for the on-board white light source. For a selection of alternatives, we present a trade-off based – where available – on performance numbers.

We consider a light source to be conceptually composed of one or more of the following components: a *power source*, a *power converter*, resulting in an *intermediate spectrum*, a *spectral converter*, providing a *final spectrum*. For all light sources identified we describe the following aspects:

- Power source: the basic power source of the light source. We distinguish between: nuclear (e.g., by means of fusion in the Sun); electrical; chemical; relativistic electrons (for synchrotron); acoustic (for sonoluminescence); light (for long-lasting luminescence).
- Power converter, the process and object used to convert the energy to light (as intermediate or final spectrum): Sun (fusion); Resistor (electric current heating); Diode (electroluminescence); Magnetic field (synchrotron); Flame (oxidation); Plasma arc (electrodes + gas); Conductor, gas, or plasma (inductive heating); Transparent medium (Cherenkov effect); Transparent liquid (sonoluminescence); Phosphor (short-term luminescence; long-lasting luminescence; electron stimulated luminescence).
- Intermediate spectrum: if applicable, the intermediate spectrum as generated by the power converter: Monochromatic, a single wavelength (within the spectral resolution of the instrument), possibly outside of the spectral range of the instrument; Narrowband, covering only a small part of the spectral range of the instrument; Broadband, a continuous spectrum with relatively smooth spectral behaviour, possibly complemented with narrowband or monochromatic features (spikes); Black body Planck, a black body or grey body type of spectrum, with the spectral radiance described by an analytical function of wavelength and temperature; Fraunhofer, the spectrum as emitted by the Sun, i.e. a black body with superimposed absorption lines; Top of Atmosphere, a Fraunhofer spectrum multiplied with the Earth spectral reflectivity, the latter affected by the Earth surface (somewhat broadband spectral variation) and Earth atmosphere (high spectral frequency variation); Weighted Fraunhofer, A Fraunhofer spectrum multiplied with a spectrally smooth reflectivity, e.g. a man-made or natural diffuser (Moon); Synchrotron, a continuous spectrum with the spectral radiance described by an analytical function of wavelength and other parameters, somewhat similar to a black body spectrum but in general more powerful at shorter wavelengths; Cherenkov, a continuous spectrum with the spectral radiance described by a combination of an analytical function and optically transparent medium properties; Spectral comb, a spectrum composed of many monochromatic lines, spectrally spaced at well-defined positions or intervals.
- Spectral converter: process or object used to modify or mix the intermediate spectrum/spectra: Elastic scatterer, e.g., an on-board diffuser, used to mix light coming from multiple sources; Moon, an external diffuser with predictable wavelength-, illumination geometry-, and viewing geometry dependent (elastic) scattering properties; Earth / planets, an external diffuser with partially predictable wavelength-, illumination geometry-, and viewing geometry dependent scattering properties. Averaging over time, geolocation, wavelength and possibly other parameters will improve the predictability, as will detailed modelling of the atmospheric and surface conditions of the Earth scenes viewed, using external information; Black body, an object that absorbs the energy of the intermediate spectrum and (partially) converts it to a black body spectrum by heating up; Phosphor / quantum dots, a material specifically selected or designed to absorb (parts of) the intermediate spectrum and re-emit the energy at longer wavelengths over a broader spectral range; Doped YAG rod, similar properties as phosphor or quantum dots; Hot matter, a solid (e.g. graphite, tungsten, calcium oxide), liquid, gas or plasma (e.g. xenon) that

heats up by absorption of energy and emits a continuous spectrum. Depending on the wavelength dependent optical density (absorbance) of in particular translucent materials, the continuous spectrum may have spikes; Non-linear fibre, a photonic crystal fibre that exhibits non-linear optical effects, allowing frequency or wavelength conversion of monochromatic light.

- Final spectrum: the final spectrum as generated by the power converter or spectral converter, with the same options as described under the intermediate spectrum

In addition to the light source itself, data processing of the results can be done to improve the knowledge of the final spectrum. One example of this is the lunar irradiance model, that describes the lunar radiance integrated over the entire lunar disc as function of wavelength, solar illumination geometry (time-dependent), and viewing geometry (time-dependent and observer location-dependent). A more complex type of data processing is that of the Earth Top of Atmosphere, that contains the Earth surface albedo (geo-location dependent, seasonally dependent) and Earth atmosphere (time-dependent through clouds, aerosols, gases), both of which are wavelength- and geometry-dependent. Averaging over geo-location, time, wavelength, or other parameters may simplify the dependence on remaining parameters. However, this is beyond the scope of this activity.

For the trade-off of the sources, we use the following criteria:

- TRL level (low=1 to high=9 using the ESA description for TRL levels): TRL for either ambient conditions on-ground use, or TRL for in-flight use in a space instrument.
- Market availability (low=1 to high=10): The availability of the source and all its components, also considering future availability. Goal for in-flight: 20 years availability.
- Radiometric stability / knowledge (low=1 to high=10): Short term: during 2 minutes after source warm up time. Goal is 0.1% standard deviation over 2 minutes. Long term: Absolute knowledge over full mission after source warm up time. Goal is 0.1% absolute knowledge over the full mission.
- Radiometric level / knowledge (low=1 to high=10): Goal is earth radiance into the instrument pupil for all instrument spectral channels.
- Spectral coverage (low=1 to high=10): Goal is anything between 260 and 2600nm wavelength.
- Space compatibility (low=1 to high=10): Vacuum, thermal, radiation, microgravity compatibility.
- Power usage (high=1 to low=10):
- Heat dissipation (high=1 to low=10): Goal is 0 Watt.
- Mass / size / volume (high=1 to low=10): The physical properties of the source. Goal is <0.5kg / 150mmx150mmx150mm.

For the trade-off of the sources, we describe the following use-cases:

- PRNU (none=1 to all pixels=10): The ability to characterize PRNU (Pixel Response Non-Uniformity) of all spatial and spectral detector pixels using the full instrument spectral chains with this source. The usefulness of the source for PRNU determination depends on the $\delta I/\delta\lambda$ (derivative of source spectral (ir)radiance to wavelength) of the source, which should be small enough for the source to be useful. Instrument spectral instabilities will mix with the spectrum if the derivative is too large.
- Pixelmap (none=1 to all pixels=10): The ability to characterize good/bad pixels of all spatial and spectral detector pixels using the full instrument spectral chains with this source.
- Relative radiance (none=1 to all pixels=10): The ability to characterize relative radiance response of all spatial and spectral detector pixels using the full instrument spectral chains with this source.
- Absolute radiance (none=1 to all pixels=10): The ability to characterize absolute radiance response of all spatial and spectral detector pixels using the full instrument spectral chains with this source.
- Non-linearity (none=1 to all pixels=10): The ability to characterize non-linearity response of all spatial and spectral detector pixels using the full instrument spectral chains with this source.
- Ambient usage (none=1 to all=10): The ability to use the source for the characterisation measurements in ambient conditions.
- Potential new use (none=1 to a lot=10): The potential for new type of monitoring/characterisation measurements using this source with respect to QTH source.

3.1 List of sources

Sun irradiance. The sun is often used as calibration source for earth observation instruments via the sun port. The sun is nuclear fusion powered and the final spectrum is a Fraunhofer black body spectrum. The TRL of this source is 9 / 9 (ground / flight proven). The irradiance stability of the sun is low, as there are surface dynamic effects (like flares and spots) that give random and periodic variation to the irradiance level. The radiance level via the instrument sun diffuser is close to earth radiance by design. The diffuser is however susceptible to degradation. The spectral coverage is good, but for the use cases the Fraunhofer lines are hampering the data. The need for a sun port and diffusers on the instrument introduces additional mass and volume.

Power source	Nuclear
Power converter	Sun (Fusion)
Intermediate spectrum	-
Spectral converter	-
Final spectrum	Fraunhofer black body

The sun can be used very well for relative and absolute radiance characterisation.

Due to the Fraunhofer lines the sun is less useful for PRNU, pixel mapping and non-linearity.

Potential “new” application: Spectral calibration using Fraunhofer lines.

The spectral variability (stability) of the Sun is described extensively in literature, e.g. [11], [12]. The rotational variability of the solar spectrum ranges from about 0.5% at 280 nm to below 0.01% at long wavelengths (2600 nm). Variations are mainly caused by faculae and sunspots.

Earth radiance. Earth observation instruments measure the radiance level of the Earth nearly continuously. The data from the instrument and the knowledge of the Earth’s radiance can be used for monitoring of the instrument properties. The power source is nuclear, converted by the sun (fusion) to light (Fraunhofer black body). The light from the sun illuminates planet Earth with its atmosphere, generating a top of atmosphere final spectrum for the instrument to measure using its earth port. The spectral coverage is automatically good, but for monitoring hampered by Fraunhofer, Earth albedo, scattering, and atmospheric gas absorption lines. No additional mass or volume is needed for this source, just additional data processing.

Power source	Nuclear
Power converter	Sun (Fusion)
Intermediate spectrum	Fraunhofer black body
Spectral converter	Planet (Earth)
Final spectrum	Top of atmosphere

Potential “new” application: Just as for the sun, a limited spectral calibration can be performed using the Fraunhofer spectrum.

Moon radiance. The Moon has been used as in-flight calibration source on various instruments, among them GOME, GOME-2 and SCIAMACHY, as well as geostationary instruments.

Viewing the Moon with the instrument is possible if the Moon passes through the instrument field of view, as is the case with geostationary instruments imaging the whole Earth. With scan mirrors or agile platforms, the line of sight of the instrument can be directed towards the Moon.

Power source	Nuclear
Power converter	Sun (Fusion)
Intermediate spectrum	Fraunhofer black body
Spectral converter	Moon
Final spectrum	Weighted Fraunhofer

The spectral irradiance of the Moon has been characterised on-ground with traceability to SI by means of extensive lunar observations and correction for absorption of the atmosphere [13]. International collaboration on improving lunar models is ongoing and coordinated by GSICS (Global Space-based Inter-Calibration System, by the World Meteorological Organisation). One of the more recent publications combines timeseries of SCIAMACHY and GOME lunar measurements with lab measurements of lunar soil returned by the Apollo missions to improve lunar models and extend the lunar irradiance model from to 250 nm to 2500 nm, with a wavelength-dependent uncertainty on the order of 1% in the wavelength range between 500 and 1600 nm, and increasing outside of that range to about 5% [14].

As the Moon reflects the solar spectrum, the Fraunhofer lines in the latter will be present. This adds all the disadvantages of the solar spectrum to the lunar spectral irradiance. However, monitoring of the lunar albedo (which requires measurements of the solar irradiance) should allow comparison of the on-board diffuser and overall instrument performance with the lunar albedo, which is spectrally smooth and reproducible at the 10^{-8} level per year [15].

This source can be used for characterizing and monitoring the instrument.

Potential “new” application: Spectral calibration using Fraunhofer lines and polarisation calibration. Spatial straylight measurements are also possible using the moon.

QTH lamp. The QTH lamp is being used frequently as the standard source for in orbit monitoring and characterisation of the instrument properties. Production of QTH lamps has diminished over the last few years and is expected to stop completely in the near future. Electricity as the power source is used to heat up a resistor to a high temperature (3000 K). The output spectrum is very predictable because of its black body spectral output. The TRL is 9, flight proven. Radiance stability is very good on the short- and long term. Spectral coverage is high and radiance levels are low in the UV, but excellent in all other wavelengths (VIS a bit too high). Space compatibility is high, although QTL lamps exhibit a ground to orbit effect due to gravity change. Power usage is low (up to 5W needed) and heat dissipation is high, almost all power is converted to conductive and radiative heat.

Power source	Electricity
Power converter	Resistor (Elec. Current heating)
Intermediate spectrum	
Spectral converter	
Final spectrum	Black body Planck

This source can be used for characterizing and monitoring the instrument.

Assuming a perfect black body of approximately 3000 K, the spectral stability of the QTH is coupled to the temperature of the black body or filament, and thus to the power source (excluding influence of the thermal environment of the lamp). Figure 1 shows the power source noise magnification factor as function of wavelength. E.g. a 1% increase in power supplied to the lamp will result in almost 5% increase in the UV and only 0.6% increase in the SWIR lamp output. The advantage of a black body is that fluctuations in one part of the spectrum are coupled to those at other wavelengths.

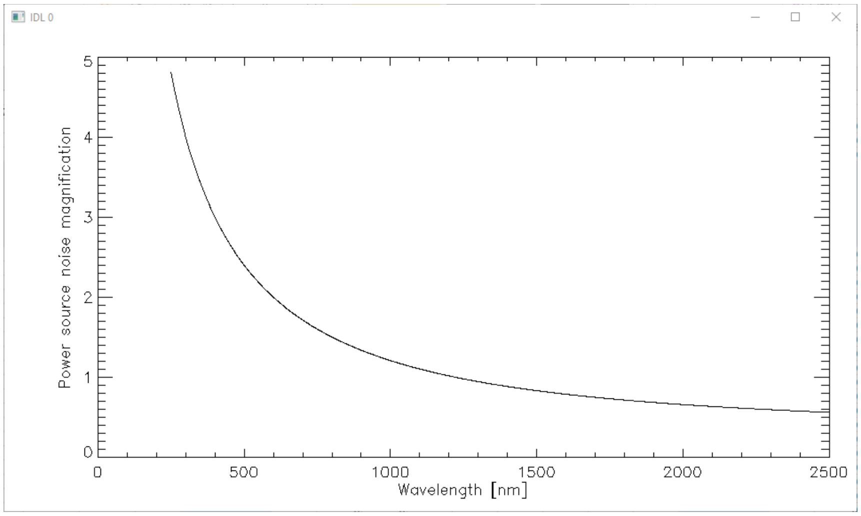

Figure 1. Spectral stability of a 3000 K perfect black body. The power source noise magnification is the factor with which fluctuations in the power applied to the lamp are multiplied

Single narrowband LED. Earth observation instruments have been using narrowband LEDs for detector monitoring for decades, which is still the standard source for this purpose. The power source is electricity, which is converted by a light emitting diode (through electroluminescence) to narrow band light (typically 10 to 20 nm FWHM bandwidth). The TRL is for some centre wavelengths 9 and for other wavelengths between TRL 1 and 8. Market availability is very high for ground applications, and average and growing for flight. Radiance stability is very good, although LEDs are sensitive to temperature and current fluctuations. The radiance levels of LEDs are excellent for a wide variety of LED central wavelengths, and average to low for others. Spectral coverage when implementing only a single LED is low, due to the narrow bandwidth per single LED. The power efficiency of a LED is high in most cases and the heat dissipation needs to be taken into account. The physical size and mass of a LED and its power supply is small.

Power source	Electricity
Power converter	Diode (Electroluminescence)
Intermediate spectrum	
Spectral converter	
Final spectrum	Narrowband

Using a single LED only a narrowband part of the spectral range of the instrument can be monitored and characterized.

New potential use: Linearity for the narrowband part of the detector.

Single white LED. Similar to the single narrowband LED, but with added phosphor (or quantum dots) for extended bandwidth. A phosphor is a substance that exhibits the phenomenon of luminescence; it emits light when exposed to some type of radiant energy. Typically, a narrowband UV LED is used to excite the phosphor. The emission spectrum of a single white LED has a bandwidth of a few 100nm. Space compatibility of the phosphor is to be investigated.

Power source	Electricity
Power converter	Diode (Electroluminescence)
Intermediate spectrum	Narrowband (UV)
Spectral converter	Phosphor / Quantum dots
Final spectrum	Broadband

Due to the extended wavelength range of this single white LED with respect to the single narrowband LED, monitoring of instrument properties is possible with coverage of a higher number of pixels.

Potential new use: Linearity using LED power control.

Multiple narrowband LEDs. Similar to the single narrowband LED, but then implementing an elastic scatterer to combine multiple narrowband LEDs to create a broadband spectrum.

Power source	Electricity
Power converter	Diode (Electroluminescence)
Intermediate spectrum	Narrowband + Narrowband + Narrowband + …
Spectral converter	Elastic scatterer
Final spectrum	Broadband

Due to the extended wavelength range of these combined narrowband LEDs, characterisation and monitoring of instrument properties is possible for the full instrument spatial and spectral range.

Potential new use: Spectral straylight by switching on and off individual single LED's; LEDs as (reference) detectors, redundant set could measure main set; Linearity with full LED power control.

Multiple white LEDs. Similar to the single white LED, but then implementing multiple phosphors with multiple excitation narrowband LEDs to create a broadband spectrum. Space compatibility of phosphor is to be investigated.

Power source	Electricity
Power converter	Diode (Electroluminescence)
Intermediate spectrum	Narrowband + Narrowband + Narrowband + …
Spectral converter	Phosphor(s)
Final spectrum	Broadband

Due to the extended wavelength range of these combined white LEDs, characterisation and monitoring of instrument properties is possible for potentially the full detector.

Potential new use: Linearity using LED power control; Limited spectral straylight monitoring when multiple phosphors are used.

White Laser (phosphor). Similar to the white LED, but then the phosphor excitation LED is replaced by a diode laser. This is done to decrease the illumination spot on the phosphor to create a bright spot. Typically being developed for automotive head lights.

Power source	Electricity
Power converter	Diode (Electroluminescence)
Intermediate spectrum	Monochromatic
Spectral converter	Phosphor
Final spectrum	Broadband

Due to the extended wavelength range of the phosphor, characterisation and monitoring of instrument properties is possible for only a part of the detector pixels.

Potential new use: Linearity using LED power control

YAG rod LEDs. Similar to the white LED, but then the phosphor layer is replaced by a (doped) YAG rod. This is done to combine multiple excitation LEDs to create a bright broadband emitting surface at the ends of the rod. Typically being developed for home use and automotive head lights.

Power source	Electricity
Power converter	Diode (Electroluminescence)
Intermediate spectrum	Narrowband + Narrowband + Narrowband + …
Spectral converter	(doped) YAG rod
Final spectrum	Broadband

Due to the extended wavelength range of the phosphor, characterisation and monitoring of instrument properties is possible for only a part of the detector pixels.

Potential new use: Linearity using LED power control

Laser driven plasma. The laser driven light source is commonly used source for on-ground calibration due to its high colour temperature (up to 6500K), high UV output and small spot size of typically a few 100 micrometres. Electricity is converted to monochromatic light by the diode laser. The laser light is focused into a high-pressure gas bulb (typically xenon bulb) to maintain a plasma. The plasma start-up is guided by electrodes. The final spectrum is broadband black body like with superimposed gas emission lines. The TRL is 9 for on ground and 1 for flight. Market availability is very high for on ground, but 1 for flight (development needed). Radiance stability on ground is excellent with a bulb life of more than 10000 hours. Radiance levels are very high and spectral coverage is excellent. Space compatibility needs work. Power usage and dissipation of this source is high (roughly 100W for the smallest source).

Power source	Electricity
Power converter	Diode (Electroluminescence)
Intermediate spectrum	Monochromatic
Spectral converter	Xenon bulb
Final spectrum	Broadband with atomic lines

Due to the excellent wavelength range and its high radiance stability, characterisation and monitoring of instrument properties is possible for all detector pixels, minus the xenon emission lines.

Potential new use: UV output is high, so better UV wavelength monitoring

Synchrotron (Microtron). High energy electrons, on the order of 100 MeV, emit synchrotron radiation (a form of Bremsstrahlung) when they are decelerated, accelerated, or deflected in a magnetic field. Synchrotrons are used as radiation sources, in particular for short-wave UV, X-ray and gamma radiation. In case only the UV part of the spectrum is needed, it suffices with lower electron energies than used for shorter wavelength radiation. E.g., PTB and NIST have access to synchrotron radiation sources for calibration purposes.

A smaller version of the synchrotron exists, usable only for electrons instead of any ion, known as a microtron. The dimensions of the microtron are much smaller than the synchrotron, on the order of one meter instead of tens to hundreds of meters, and even exist in portable versions. The main drawback of these types of sources as on-board calibration sources is the size, mass and power consumption.

Power source	High energy electrons
Power converter	Magnetic field
Intermediate spectrum	
Spectral converter	
Final spectrum	Synchrotron spectrum

Apart from its size and power consumption, synchrotron radiation sources seem quite ideal calibration sources, with well-defined spectral response and predictable radiance decay over time.

3.2 Source trade-off

The source trade-off was done by unweighted summation of the criteria scores for the source aspects and the source use cases. The scores were determined in a consistent way between the various sources, but it was in some cases difficult to properly quantify the score, mostly due to lack of firm numbers or performance details. For this reason, the QTH, Sun, Earth and Moon were also considered in the trade-off, to serve as reference for the scores attributed to new methods.

Table 1 shows the summary of the trade-off of the source aspects. The maximum number of points is 110, values above 80 points are marked in green. Table 2 shows the summary of source use cases. The maximum possible score is 70 points, values above 45 points are marked in green. Finally, Table 3 combines the totals of the previous two tables. The maximum for the combined scores is 180 points, those above 130 points are marked in green.

Table 1 Trade-off summary source aspects

Source	TRL ground / space	Market availability ground / space	Radiometric stability	Radiometric level	Spectral coverage	Space compatibility	Power usage	Heat dissipation	Mass / size/ volume /		Totals without weighting
Sun irradiance	9 / 9	10 / 10	5	7	10	10	10	10	5		95
Earth radiance	9 / 9	10 / 10	3	10	9	10	10	10	10		100
Moon radiance	9 / 9	10 / 10	4	9	10	10	10	10	10		101
QTH lamp	9 / 9	1	8	8	8	10	10	5	9		87
Single narrowband LED	9 / 8	10 / 7	9	10	3	8	10	6	10		90
Single white LED	9 / 4	10 / 4	9	10	6	1	10	6	10		79
Multiple narrowband LED	9 / 7	10 / 7	9	8	8	8	10	6	8		90
Multiple white LED	9 / 4	10 / 4	9	10	9	1	10	6	9		81
White laser	9 / 1	7 / 1	1	10	8	1	10	6	10		64
YAG rod LEDs	4 / 1	1 / 1	9	10	8	1	10	6	9		60
Laser driven plasma	9 / 1	9 / 1	9	7	10	1	1	1	5		54
Synchrotron	9 / 1	9 / 1	9	8	10	1	1	7	1		57

Table 2 Trade-off summary source use cases

Source	PRNU	Pixel Map	Relative radiance	Absolute radiance	Non linearity	Ambient usage	New usage		Totals without weighting
Sun irradiance	3	6	8	9	5	1	8		40
Earth radiance	2	5	3	3	6	6	8		33
Moon radiance	2	3	9	8	8	1	9		40
QTH lamp	8	9	8	3	8	10	2		48
Single narrowband LED	3	3	5	5	5	10	5		36
Single white LED	5	5	7	7	7	10	6		47
Multiple narrowband LED	6	8	9	8	10	10	10		61
Multiple white LED	7	7	7	7	7	10	7		52
White laser	5	5	7	7	7	10	6		47
YAG rod LEDs	7	7	7	7	7	10	7		52
Laser driven plasma	6	6	9	8	5	10	6		50
Synchrotron	10	10	10	10	10	10	10		70

Table 3 Total scores of source aspects and source use cases combined

Source	Totals source aspects	Totals use cases		Total combined score
Sun irradiance	95	40		135
Earth radiance	100	33		133
Moon radiance	101	40		141
QTH lamp	87	48		135
Single narrowband LED	90	36		126
Single white LED	79	47		126
Multiple narrowband LED	90	61		151
Multiple white LED	81	52		133
White laser	64	47		111
YAG rod LEDs	60	52		112
Laser driven plasma	54	50		104
Synchrotron	57	70		127

The QTH, multiple narrowband LEDs and multiple white (phosphor) LEDS have all columns green.

As can be seen in the total combined score table, the currently used sources are scoring very well for monitoring of the instrument characteristics. For the iWLS replacing a QTH, a combination of multiple narrowband LEDs offers the best performance in this trade-off.

4 DRAFT IMPLEMENTATION

The iWLS based on multiple narrowband LEDs arose as the best option during the trade-off. Figure 2 shows a draft implementation of the proposed concept.

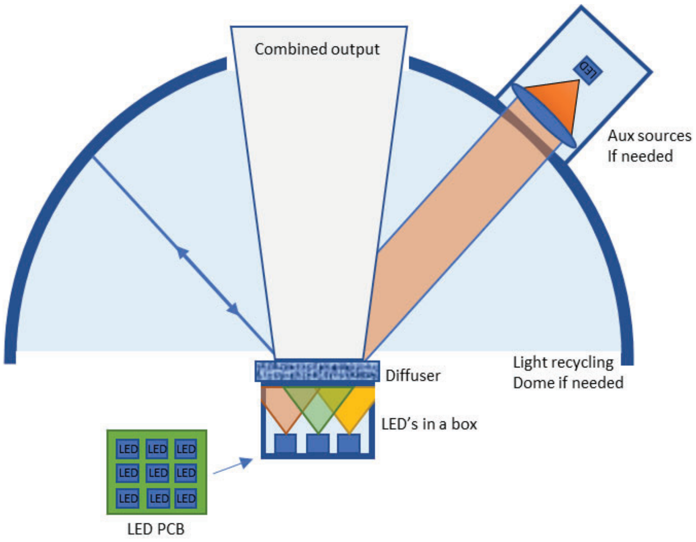

Figure 2 Draft implementation drawing of the multiple narrowband LEDs source

For the draft implementation a combination of different wavelength narrowband LEDs are soldered onto a printed circuit board (PCB). This PCB is then installed on the bottom side of a (reflective wall) box. The top side of the box is a transmission diffuser to combine and homogenize the light from the different LED's. A light recycling dome can be used to increase the radiance levels by a factor of 3 to 5, to smoothen out the BSDF of the diffuser and as a straylight baffle. Auxiliary sources (like laser diodes or fibre coupled sun) can be coupled into the system from outside the dome onto the diffuser. The diffuser is to be used directly in the instrument pupil. A reference detector (or the LEDs as detector) can also be easily added to the system.

The dome is roughly 150mm in diameter. The LED box is approximately 20x20x20mm.

4.1 Quantitative analysis for the Sentinel-5 use case

As an exercise to demonstrate the potential of the proposed iWLS, we design an implementation for Sentinel 5, used as a reference mission to calculate the performance of the iWLS. The Sentinel 5 calibration sub-assembly contains a QTH WLS, with specific performance requirements. The WLS is mainly used to derive the Pixel Response Non-Uniformity (PRNU) of the spectrometer detectors.

The wavelength ranges of the Sentinel 5 spectrometers are 270 nm to 310 nm for the UV1 spectrometer, 300 nm to 500 nm U2VIS spectrometer, 685 nm to 773 nm for the NIR spectrometer, 1590 nm to 1675 nm for the SWIR1 spectrometer, and 2305 nm to 2385 nm for the SWIR3 spectrometer.

The radiance levels the CAS is required to provide to the instrument are given in Table 4.

Table 4 Sentinel 5 CAS WLS radiance levels

Wavelength [nm]	Min [ph/(s.cm2.sr.nm)]
270	1.03104E+11
300	1.03104E+11
310	6.00920E+10
370	6.00920E+10
400	2.96142E+11
420	2.96142E+11
500	2.96142E+11
685	8.05152E+11
710	8.05152E+11
755	6.97856E+11
773	6.97856E+11
1590	7.36403E+11
1675	8.09917E+11
2305	1.45383E+12
2385	1.72864E+12

Other requirements for the WLS are: The WLS should not introduce spatial features with a similar frequency as the pixel size; The peak to peak output variations as a function of angle shall be smaller than 0.05% over every combination of XX° (with XX = 8.3 degrees for UVN and XX = 16.6 degrees for SWIR) in the FoV after a subtraction of a 2nd order polynomial; The number of on-off cycles are at least once daily, plus on-ground use, plus margin (factor 2); The total burn time is 120 seconds operation + appropriate warm-up/stabilisation time, per on-off cycle; The stability is better than 1% over 120 s (drift + higher frequency effects).

All of these requirements are expected to be fulfilled with the proposed design, but attention should be given to the power supply, current control and thermal control of the LEDs.

To fulfil the wavelength range requirement and radiance levels, multiple LEDs need to be selected:

1) 270 to 400nm: 13 LEDs with 10nm FWHM each 10nm step centre wavelength.
2) 400 to 800nm, two options:
    a) 1 or 2 White light LED with Phosphor (radiation hardness would need to be tested)

   b) 20 LEDs with 20nm FWHM on average and 20nm step centre wavelength.
3) 1590 to 1675nm: 1 LED 150nm FWHM or multiple if more power needed.
4) 2305 to 2385nm: 1 LED 220nm FWHM or multiple if more power needed.

These LEDs are currently commercially available, though space qualification is likely missing. We approximate the LEDs in a box in combination with the hemispherical reflector (dome) by an integrating sphere of the size of the box. We assume the spectral reflectivity of the box, diffuser, and dome to be equal at $\rho(\lambda)$ as function of wavelength λ.

The port opening of the dome is transferred to the effective port opening of the box, as any photons exiting the transmission diffuser are reflected back to the diffuser either by the box walls or the dome. We calculate the effective port fraction f of the integrating sphere as the port fraction of the dome: $f = \frac{A_e}{A_d}$, where A_e is the area of the exit port of the dome, and $A_d = 4\pi r_d^2$ is the area of a 4π steradian dome with radius r_d.

Since we directly view the diffuser of the box, we need to calculate the radiance of the LED box using the area of the box, $A_b = 2(L_bW_b + L_bH_b + H_bW_b)$, where L_b, H_b, and W_b are the length, height, and width of the LED box, respectively. The dome sphere surface radiance then becomes

$$L_d = \frac{\Phi_\mathrm{i}(\lambda)}{\pi A_b} * \frac{\rho(\lambda)}{1 - \rho(\lambda)(1-f)}$$

$\Phi_i(\lambda)$ is the sum of the input spectral irradiances of all the LEDs in the box.

4.2 Radiance levels using the draft implementation

We assume for simplicity's sake a spectral distribution of the LEDs that is described by a Gaussian with centroid and width as given by the LED specification. The optical output power of the LED is equal to the integral of the spectral distribution.

Simulating the radiance spectrum of the iWLS, using a dome opening of 60 by 5 mm and aluminium coatings to calculate $\rho(\lambda)$, we get the result shown in Figure 3. The asterisks connected by the black line show the requirement for Sentinel 5 WLS, the black curves show the combined contribution of the individual narrowband LEDs, and the blue curve shows the predicted output if a 5 W QTH were to be used instead of the LEDs.

The SWIR-3 LED is slightly too faint in this calculation but inserting three 2350 nm LEDs in the box would mitigate this. The maximum power of the LEDs can be tuned down to better match the requirement.

For reference, the same calculation with a 5W QTH at 3000 K filament temperature is shown in Figure 3. The QTH in this configuration has too low output in the UV, and more than 2 orders of magnitude more output than required in the NIR and SWIR.

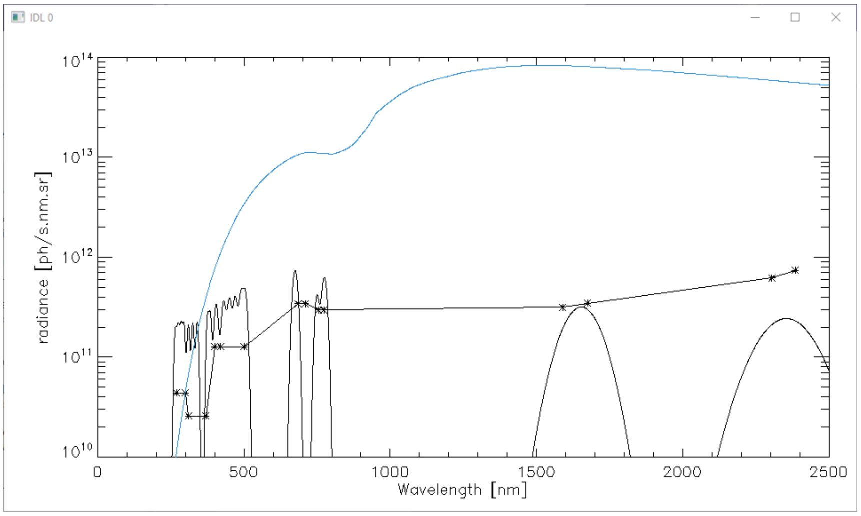

Figure 3. Simulated LED box + dome radiance (black curve) and requirement values (asterisks), with the addition of a 5 W QTH at 3000K (blue curve).

5 DISCUSSION AND CONCLUSION

A trade-off was made between a varying types of white light sources that could potentially replace incandescent quartz tungsten halogen lamps in the calibration units of satellite instruments. In the trade-off both existing methods as a few quite far-fetched methods were taken along, in order to have a broad coverage and see if unexpected insights show up. In the end, the best candidate to replace the QTH lamp was found to be a suitably chosen combination of narrowband LED sources. The output of the LEDs is combined and homogenised by means of reflective surfaces and a transmission diffuser and is shown on paper to be (almost) compliant to the requirements for the WLS of the hyperspectral imaging instrument Sentinel 5, using commercially available LEDs. The Sentinel 5 calibration sub-assembly is equipped with QTH lamps which will not be replaced by any other type of WLS, but future instruments may find it increasingly more difficult to find suitable space-qualified QTH lamps, as the main lamp manufacturers are evolving away from QTH lamps and will likely not serve the tiny market for satellite instruments.

A draft implementation of the LED-based WLS is proposed, and currently a proof-of-principle demonstrator is under construction at TNO, supporting the goal of the space instrument calibration group to work towards self-calibrating space instruments. This demonstrator will pave the way for a space-qualifiable breadboard of a LED-based WLS.

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