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CONCEPT FOR IMPROVED RADIOMETRIC CALIBRATION OF RADIANCE SOURCES AT THE CHB FACILITY

P. Gege, J. Fries, P. Haschberger, K. Lenhard, P. Schötz, Ch. J. Schwarz, T. Schwarzmaier

DLR, Remote Sensing Technology Institute, Oberpfaffenhofen, D-82234 Wessling, Germany
Email: peter.gege@dlr.de, jochen.fries@dlr.de, peter.haschberger@dlr.de, karim.lenhard@dlr.de,
paul.schoetz@dlr.de, christian.schwarz@dlr.de, thomas.schwarzmaier@dlr.de

ABSTRACT

The Calibation Home Base (CHB) is a facility for the calibration of airborne imaging spectrometers such as APEX, ROSIS and in the future ARES, and for field spectrometers. Absolute radiometric calibration in the spectral range of 350–2500 nm is currently based on an integrating sphere whose spectral radiance was calibrated by the German National Metrology Institute PTB. However, a single radiance source cannot meet the requirements of a multitude of sensors, hence CHB operates several sources. In order to enable consistent calibration at CHB, a transfer radiometer based system will be used in the future. Detectors are much more stable than lamps, hence a well-designed system based on accurate detectors can reach much higher absolute accuracy of radiometric calibration than a lamp based set-up. The concept of this system, its hardware components and the expected accuracies are presented.

1. INTRODUCTION

The Calibration Home Base (CHB) is an optical laboratory of the German Aerospace Centre (DLR) in Oberpfaffenhofen for the calibration of airborne hyperspectral sensors and field spectrometers [1]. It is a unique facility in Europe for precise characterisation of the radiometric, geometric and spectral properties of bulky and heavy instruments up to 500 kg (including mechanical interface) in a wide spectral range from 380 nm to 14 µm.

Absolute radiometric calibration in the spectral range of 350–2500 nm is currently based on an integrating sphere which is illuminated from the interior by four lamps (see chapter 3.2). However, as the dimensions of the exit port are optimised for ROSIS, the port is too small to illuminate the complete field of view of sensors like APEX or ARES. As this example illustrates, a single radiance source cannot meet the requirements of a multitude of sensors. Thus CHB operates several sources. One of these is an integrating sphere that is too large to be transported to another laboratory for calibration (see chapter 3.3). In order to enable consistent calibration of all sources, a system is currently under development which will allow to perform absolute radiometric calibration of radiance sources directly at CHB. Since the system is based on the stability of detectors rather than lamps, improved accuracy is expected. This system is described here.

Traceability of spectral radiance to SI units will be ensured by calibrating the essential system components at the German National Metrology Institute PTB (Physikalisch-Technische Bundesanstalt). PTB is a world-wide leading metrology authority, in particular for radiometric calibration [2], as international comparisons demonstrate [3–5].

2. CALIBRATION CONCEPT

Radiometric calibration of radiance sources in the CHB will be based in the future on three hardware systems: a spectrometer system, a radiance standard, and a transfer radiometer. The concept is illustrated in Figure 1.

Individual hardware components are shown as blue boxes. Bold blue frames mark systems consisting of several components. Red text notes the physical quantity to be calibrated and the laboratory performing calibration. The sequence of procedures is shown in green. A detailed description of the hardware components and the processes is given in the following chapters.

3. RADIANCE SOURCES

3.1 Radiance Standard

3.1.1 Rationale

So far the small integrating sphere described in chapter 3.2 is used as reference for absolute radiometric measurements in the CHB, and the white panel described in section 3.5 as backup system. In the future

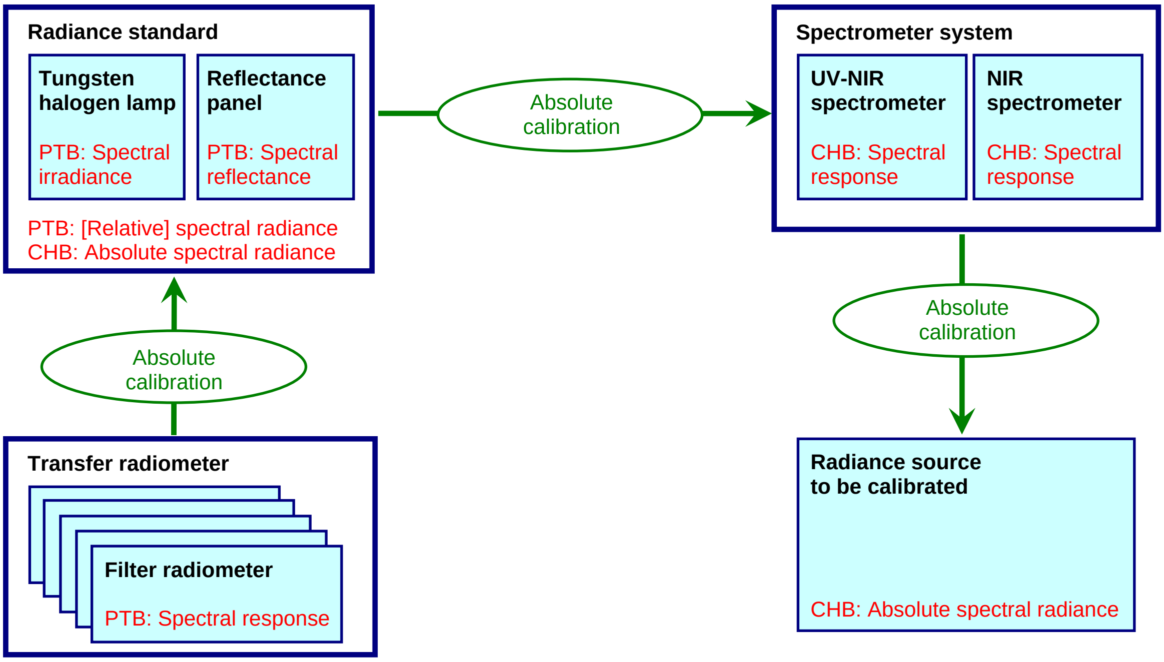

Figure 1. Concept for radiometric calibration of radiance sources in the CHB.

the reference source will be a combination of reflectance panel and FEL 1000 W lamp as described in 3.1.2. The reasons for the change are:

- Redundant calibration. In contrast to the sphere, the new source allows redundant calibration: additionally to the radiance of the complete system also lamp irradiance and panel reflectance will be calibrated. This redundancy allows to detect errors and will reduce calibration uncertainties.
- Size and shape. The reflectance panel has an area of 25 cm x 25 cm, while the exit port of the sphere is 20 cm x 4 cm. The increased size makes the new source more useful for sensors with large field of view, and the square shape allows to illuminate symmetrically the entrance aperture of sensors with circular field of view like field spectrometers and cameras.
- Flexible geometry. The reflectance panel is mounted at an inclination of 45°, while the sphere exit port is oriented horizontally. Thus the panel allows measurements for vertical sensor alignment like the sphere, but also for horizontal alignment.
- Flexible radiometry. Radiance sources of different intensity and spectral shape can be realised easily by exchanging the reflectance panel. Currently five alternate panels are available constituting five radiance sources (see chapter 3.4).
- Reduced complexity. The radiance reflected from a panel that is illuminated by a single lamp can be calculated easily, while the radiance emitted from the sphere is difficult to model since neither the coating nor the lamps can be characterised if the sphere is not disassembled. The sphere is frequently used in combination with filters; these reflect however some radiation back into the sphere, and the induced changes of sphere brightness are difficult to estimate. Modifications of the new source can be modeled easier, e.g. exchange of lamp or panel.
- Maintenance. Re-calibration of a radiance source is necessary when its spectral radiance differs significantly from that during calibration. The main cause for changes are the lamps. Since the new source uses a single lamp, while the old uses four, the probability of lamp failure is reduced and hence the interval of lamp exchange. Moreover, if a calibrated lamp is available as backup, there is no need to send the new source to PTB for calibration since the radiance of the source can be calculated. This eliminates periods of non-availability.

3.1.2 Components

The new radiance standard of CHB consists of two calibrated components: a tungsten-halogen lamp and a reflectance panel. These components are shown in Figure 2.

Figure 2: Tungsten-halogen lamp (left) and reflectance panel (right).

The tungsten-halogen lamp [6] is of type 1000-W FEL (Gamma Scientific Model 5000-16C, serial number GS1032), which is widely used as an irradiance standard. An identical calibrated lamp is available as backup (serial number GS1033). The lamp is mounted in a lamp holder and powered by a highly stable power supply (Gamma Scientific Model 5000-2C). Lamp and lamp holder are installed inside a lamp housing, which is mounted on an optical bench. The reflectance panel (Labsphere SRT-99-100, serial number OD65B-7257) has a size of 25 cm x 25 cm. It is mounted at an angle of 45° on the bench, facing towards the opening of the lamp housing (Figure 3). The distance of 50 cm is measured accurately by mounting temporarily a lamp alignment jig instead of the lamp.

Figure 3: Set-up of the radiance standard.

Calibration of the radiance standard is currently traceable to the National Institute of Standards and Technology (NIST). Irradiance of the tungsten-halogen lamps was calibrated by Gamma Scientific on 16 October 2009 for the spectral range of 250–1100 nm in steps of 5 nm. Reflectance of the panel was calibrated by Labsphere on 24 August 2009 for the range of 250–2500 nm in 50 nm intervals. It is planned to repeat these measurements in 2010 at PTB for the range 350–2500 nm, and to calibrate additionally the radiance of the complete set-up at PTB. This redundancy will allow to identify and quantify potential errors and will thus reduce calibration uncertainties.

3.1.3 Absolute calibration

Since lamps are less stable than detectors, only the relative spectral radiance from the PTB calibration will be used, while the absolute scaling of the radiance spectrum will be determined at each usage by means of a transfer radiometer. This concept, which is summarised in Figure 1, makes calibration insensitive to changes of lamp intensity, errors in lamp–panel distance and wavelength-independent errors of panel reflectance e.g. due to BRDF effects.

3.2 Small integrating sphere

Absolute radiometric calibration of sensors at CHB is currently based on an integrating sphere which is illuminated from the interior by four QTH lamps [1]. The sphere (Figure 4) has a diameter of 50 cm and an exit port size of 20 cm x 4 cm. In November 2007 PTB calibrated the radiance spectrum in the spectral range of 350–2500 nm and characterised the homogeneity across the aperture. Long-term variations are so far monitored by measuring the radiance spectrum after warm-up using a ZEISS MCS 501 UV-NIR spectrometer in the range of 450–950 nm and comparing it with the initial measurement after calibration. The new concept (Figure 1) replaces the ZEISS spectrometer by a transfer radiometer, and it allows re-calibration of the spectral radiance at each usage of the sphere instead of monitoring only.

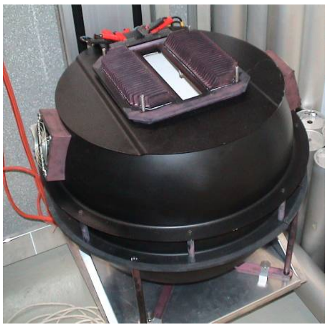

Figure 4: Small integrating sphere.

3.3 Large integrating sphere

A large integrating sphere (165 cm diameter, see Figure 5) is available at CHB for radiometric characterisation of instruments with a large field of view. It is illuminated from the interior by 18 stabilised lamps and provides homogeneous radiance for an area of 55 cm x 40 cm (variations <0.5 % rms). The radiant exitance can be changed from 57 to 1524 W m^{-2} in order to adjust brightness to instrument sensitivity and to measure detector linearity. A photodiode inside the sphere monitors intensity changes. The spectral radiance has been measured for 12 lamp combinations using a field spectrometer (ASD FieldSpec® FR [8]). However, the accuracy of spectrometer calibration is not known, hence uncertainty of the measurements is unknown, i.e. the spectra are not traceable to SI units. For this reason the sphere was used so far only for relative measurements [1]. It is planned to perform reliable absolute radiometric calibration using the concept shown in Figure 1.

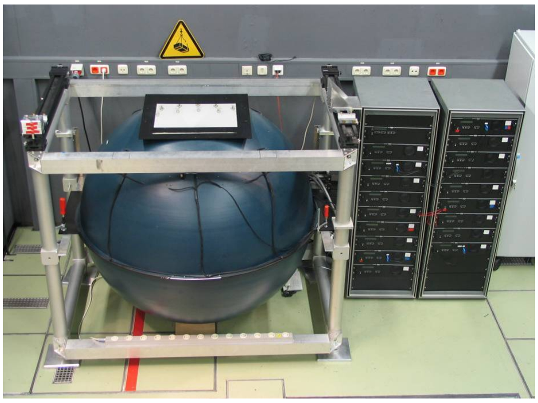

Figure 5: Large integrating sphere.

3.4 Colour Panel Set

Five radiance sources of significantly different spectral shape and intensity are realized by exchanging the reflectance panel of the radiance standard (Figure 3) by coloured reflectance panels with known reflectance. These sources will be used to determine calibration errors of spectrometers (see chapter 4.2).

3.5 White panel

A white reflectance panel in combination with a halogen lamp (see Figure 6) is currently used as backup system for the small integrating sphere. The panel is a Zenith Ultrawhite reflectance standard with a usable size of 18 cm x 18 cm. It is illuminated by a 800 Watt halogen lamp (General Electrics T4-4CL R7s-15) mounted in a reflector. The lamp is powered by a stable power supply (Toellner TOE 8871-200). PTB calibrated the spectral radiance of the system in November 2007 in the range of 350–2500 nm and characterised its homogeneity along the x- and y-axes.

4. SPECTROMETER SYSTEM

4.1 Components

A calibrated spectrometer system consisting of a UV-NIR and a NIR spectrometer will be used to measure the spectral radiance of the source. The quality of a measurement is described by two wavelength dependent parameters: spectral resolution and uncertainty. The first is a fixed instrument property, the second depends on instrument stability and calibration errors, which are mainly caused by stray light and detector non-linearity.

Figure 6: Set-up of the white panel.

Suitable spectrometers will be selected in the near future. Currently stability and calibration errors of the following instruments are being investigated:

- ZEISS MCS 501 spectrophotometer. Spectral range: 350–1000 nm; spectral sampling interval: 0.8 nm; spectral resolution: ~1.6 nm.
- ASD FieldSpec® FR [8]. Spectral range: 350–2500 nm; spectral sampling interval: 1.4–2.0 nm; spectral resolution: ~3–10 nm.
- SVC HR-1024 [9]. Spectral range: 350–2500 nm; spectral sampling interval: 1.5–3.8 nm; spectral resolution: ~3.5–9.5 nm.

Current baseline is to use the ZEISS as UV-NIR spectrometer due to its high spectral resolution, and either the ASD or the SVC as NIR spectrometer (the more accurate one). Since the NIR instrument covers also the spectral range of the UV-NIR instrument, the overlapping region can be used to determine measurement errors.

4.2 Calibration algorithm

Standard radiometric calibration assumes a linear relationship between dark current corrected signal C_i and radiance L_i for each spectral channel i. The ratio $r_i = C_i / L_i$ is the response of channel i. Calibration errors occur at the presence of stray light and non-linear effects, and if the response is not known with sufficient spectral or radiometric resolution. The instruments selected for the CHB spectrometer system will be characterised before their first operational usage, and the standard calibration algorithm will be modified to account for observed effects.

The influence of erroneous calibration is the larger the more the actual radiance spectrum differs from the light source which was used for radiometric calibration. Hence calibration errors will be determined using a number of radiance sources that differ spectrally and in intensity from the radiance standard. For this, the light sources described in chapter 3.4 will be used. The measurement errors will be determined as described in chapter 6 using the transfer radiometer. As long as significant errors are observed, instrument characterisation will be refined and the calibration algorithm improved.

4.3 Absolute calibration

Instrument instabilities are either caused by the optics or the detector. Optical components can become mis-aligned or contaminated. Fiber optic cables need careful handling, in particular if the fiber can be removed from the instrument like for the ZEISS and SVC spectrometers. Since the mount is usually not designed for accurate repositioning of the fiber after removal, altered geometry at the interface between fiber and spectrometer can cause significant transmission differences. For example, signal differences in the order of 10 % can be forced for the ZEISS by mounting the fiber in varying orientations. Fibers are an error source even for instruments with fixed fiber like the ASD: fiber flexure changes transmission in the order of a few percent [10]. Instability of detector response is mainly caused by temperature, thus it depends on the stability of detector temperature and on the detector material. The effect is wavelength dependent and can be large: [10, 11] report signal changes up to 10 % within 1 hour for spectrometers from type ASD FieldSpec® FR and GER 3700 (precursor of the SVC HR-1024). Nevertheless, even for the instable spectral regions repeatable measurements in the order of 1 % are feasible by recording frequently the dark current and using instrument-specific correction software [10].

The calibration concept shown in Figure 1 was developed in order to minimize the influence of instrument instability. Subsequently to the measurement the spectrometers will be calibrated using the radiance standard described in chapter 3.1, and calibration of the radiance standard will be updated by means of the transfer radiometer described in chapter 5.

5. TRANSFER RADIOMETER

A transfer radiometer consisting of five filter radiometers will be used to improve absolute calibration of the radiance standard (see Figure 1) and to determine the absolute error of radiometric measurements of a radiance source (see Figure 9). Hence absolute accuracy of radiometric calibration in the CHB will be based in the future on the stability of the transfer radiometer. Until now it was based on the stability of the radiance of the small integrating sphere.

Highly stable filter radiometers with a large dynamic range of 8 decades have been developed by Gamma Scientific in cooperation with NIST for the purpose to perform SI traceable radiometric calibration at high accuracy. Figure 7 shows a photo of such a filter radiometer system, consisting of detector, amplifier and temperature controller [7].

Figure 7: Components of a filter radiometer [7]. The CHB radiometers have a baffle tube instead of a lens.

CHB will use a set of five filter radiometers from Gamma Scientific which covers the spectral range from 350–2500 nm. Preliminary response curves of these radiometers are shown in Figure 8. The actual spectral response of each filter radiometer will be determined at PTB.

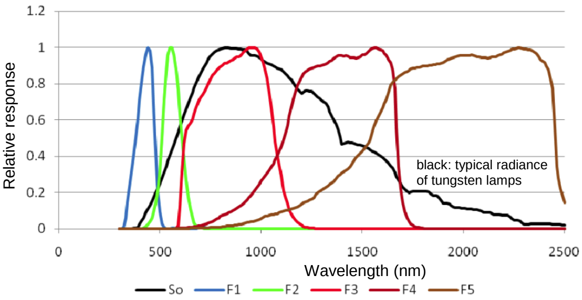

Figure 8: Relative response of the 5 filter radiometers; black: radiance spectrum of a tungsten-halogen lamp.

The filter radiometers F1, F2 and F3 use silicon detectors, F4 an InGaAs detector (range: 850–1700 nm), and F5 an Extended Range InGaAs detector (range: 850–2500 nm). F1, F2 and F3 have filters composed of ionically or colloidally colored optical glasses which are designed specifically for this application. F4 and F5 have no filters; their detectors have different spectral responsivities.

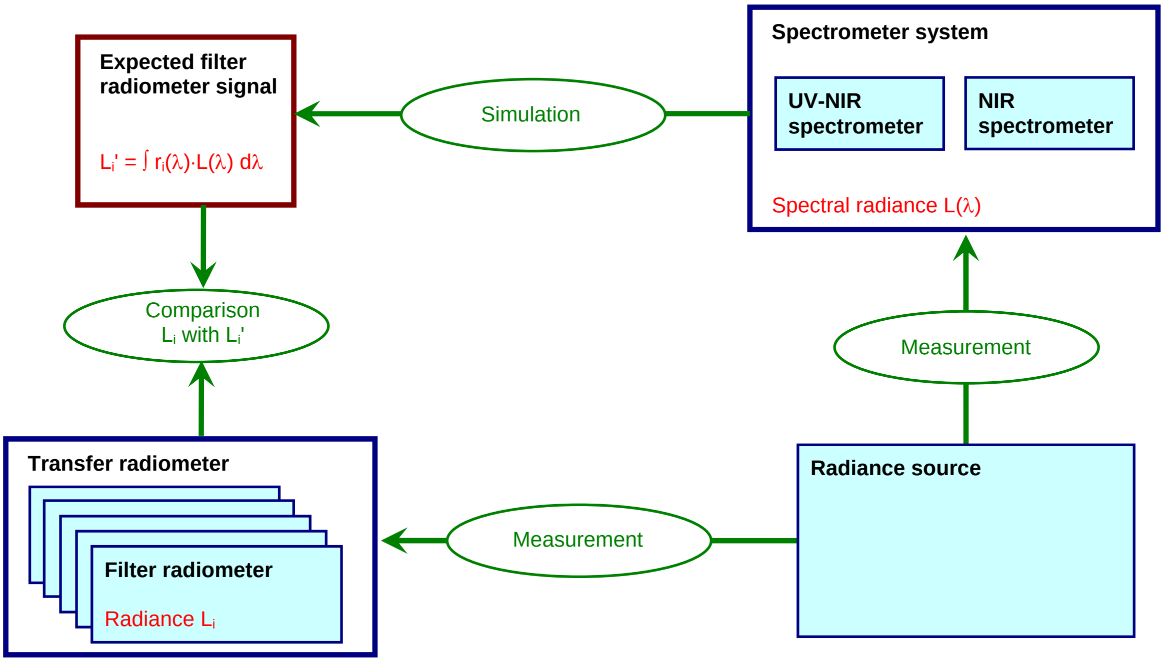

Figure 9: Concept for validation of a spectral radiance measurement.

The detector temperature is stabilized by means of a four-stage cooling system to <0.001°C during 1 hour; to reach such stability for the InGaAs based radiometers, a circulating water bath is used for F4 and F5. A field of view of 1° is realized by a special baffle tube (radiance adaptor) for each radiometer.

6. VALIDATION CONCEPT

The absolute error of radiance measurements will be determined by measuring the source subsequently to the spectrometer measurement using the transfer radiometer. The concept is illustrated in Figure 9.

The raw data of the spectrometer are converted to a radiance spectrum L(λ) using the actual spectral response functions of the spectrometers. Weighing of L(λ) with the spectral response functions $r_i(\lambda)$ of the individual filter radiometers yields expected signals of the transfer radiometer: $L_i' = \int r_i(\lambda) \cdot L(\lambda)\, d\lambda$. Comparison with the measured signals L_i provides five error values across the spectral range of 350–2500 nm.

The uncertainty of a radiance measurement in the CHB will be expressed by five values, each representing a spectral average corresponding to the reponse of a filter radiometer. The uncertainty measured with filter radiometer number i is the Root of Sum Squares of $(L_i'–L_i) / L_i$ and response uncertainty Δr_i.

7. EXPECTED ACCURACY

The accuracy of radiometric measurements in the CHB is currently based on the uncertainty of the small integrating sphere (see chapter 3.2). PTB certified an expanded uncertainty (k=2) of 1 % for the range of 390–1700 nm. Uncertainty increases towards shorter and longer wavelengths, reaching 22 % at 2500 nm. Stability is monitored in the range of 450–950 nm using a spectrometer; so far deviations up to ±3 % from the initial measurement are tolerated before re-calibration is performed. Hence uncertainty is currently 4 % in the range of 450–950 nm and not known below 450 nm and above 950 nm due to lack of monitoring possibilities.

The new concept is based on the stability of detectors, which is expected to be < 0.5 % for each filter radiometer. Furthermore, it uses redundant hardware components (more detectors than necessary, two spectrometers with large spectral overlap) and redundant calibration of the radiance standard (lamp and reflectance panel are calibrated additionally to the complete system). These redundancies allow to identify erroneous hardware components and to reduce the uncertainty of calibration.

Under these conditions a significant improvement of accuracy seems feasible compared to the current set-up. A cooperation agreement was negotiated with PTB in order to achieve state-of-the-art calibration accuracy. The goal is to characterise spectral radiance of sources in the CHB at an expanded uncertainty (k=2) of 3 % for the range of 350–1700 nm until end 2010, and 5 % for the range of 1700–2500 nm until 2012. Such accuracy of the long-wave range is currently not feasible even at PTB.

8. SUMMARY

A detector based system will be established at CHB for the absolute radiometric calibration of radiance sources in the spectral range of 350–2500 nm. It will consist of the following components:

- Radiance standard: Lamp based system as source for relative calibration.
- Transfer radiometer: Five stable filter radiometers for absolute calibration.
- Spectrometer system: Two spectrometers for performing the measurement. These instruments define the spectral resolution of the calibrated radiance spectrum.

The system shall be ready for operation at the end of 2010 and reach state-of-the-art accuracy in 2012.

9. ACKNOWLEDGEMENT

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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.

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