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A Vacuum Infrared Standard Radiation Thermometer at the PTB

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Abstract A thermal infrared radiation thermometer was jointly developed by the Physikalisch-Technische Bundesanstalt and Raytek GmbH for temperature measurements from $-150°C$ to $170°C$ under vacuum. The radiation thermometer is a purpose-built instrument to be operated with the PTB reduced-background infrared calibration facility. The instrument is a stand-alone system with an airtight housing that allows operation inside a vacuum chamber, attached to a vacuum chamber, and in air. The radiation thermometer will serve to calibrate thermal radiation sources, i.e., blackbody radiators, by comparing their radiance temperature to that of a variable-temperature reference blackbody inside the reduced-background calibration facility. Furthermore, since it can be operated under vacuum and in air, the instrument also allows the water- and ammonia-heat-pipe reference blackbodies of the PTB low-temperature calibration facility operated in air to be compared with the variable-temperature blackbody operated under vacuum. Finally, provided that sufficient long-term stability is achieved, the instrument shall be used as a transfer radiation thermometer to carry and compare the temperature scale of PTB by means of radiation thermometry to remote-sensing calibration facilities outside PTB. The mechanical, optical, and electrical designs of the instrument are reported. Results of investigations on the temperature resolution, size-of-source effect, and the reference function are given. The heat-pipe blackbodies operating in air are compared to the variable-temperature blackbody operated under vacuum by using the vacuum radiation thermometer.

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1 Introduction

Thermal imagers and infrared radiometers used in remote sensing are usually calibrated in terms of radiance or radiance temperature by observing reference blackbody radiators under vacuum conditions. At the Physikalisch-Technische Bundesanstalt (PTB), a *r*educed-*b*ackground *c*alibration *f*acility (RBCF) [1–4] was constructed. The RBCF is intended for the calibration of cryogenic and near-ambient-temperature blackbodies and infrared detector systems under medium vacuum ($p < 10^{-2}$ Pa) or controlled atmosphere conditions and reduced-background radiation (liquid-nitrogen-cooled radiation shields). This facility will extend and complement the existing PTB low-temperature calibration facility based on heat-pipe reference blackbodies operated in air over a temperature range from −60°C to 962°C [4,5]. At the RBCF, calibration of blackbody radiators will be performed by comparison to a *v*ariable-*l*ow-*t*emperature reference *b*lack*b*ody (VLTBB) with a temperature range from −173°C to 177°C via a vacuum infrared radiation thermometer. For this purpose, the PTB and the Raytek GmbH jointly developed a *v*acuum *i*nfra*r*ed *s*tandard radiation *t*hermometer (VIRST).

VIRST is a stand-alone system with an airtight housing that allows three modes of operation: (a) inside a vacuum chamber—to compare blackbody radiators at the RBCF, (b) attached to a vacuum chamber—to allow operation at calibration facilities outside PTB, and (c) in air—to allow a comparison of blackbody radiators of the RBCF with the blackbodies of the PTB low-temperature calibration facility. The priority for the design of VIRST was to build a low-budget instrument with a simple and rigid mechanical and optical system that allows blackbody comparisons over a temperature range from −150°C to 170°C with good temperature resolution. Under the condition that sufficient long-term stability can be reached with the instrument, it may be used to carry and compare the temperature scale of PTB to other remote-sensing calibration facilities outside PTB. As a result, VIRST is a DC-operated radiation thermometer with a thermopile detector. It is based on a modified version of the Marathon M instrument (formerly called the BOTO instrument) of the Raytek GmbH with specially designed optics, electronics, and a vacuum housing. The results of an extensive investigation of this prototype instrument will allow further developments (e.g., change of type of detector, AC operation) to further enhance the performance of the instrument with the ultimate aim of covering the complete temperature range of the RBCF with a high-resolution radiation thermometer. The mechanical, optical, and electrical designs of the instrument and the results of its characterization are described. The heat-pipe blackbodies operating in air are compared with the variable-temperature blackbody under vacuum by using the vacuum radiation thermometer as a transfer standard.

2 Design of the Instrument

2.1 Mechanical Layout

The mechanical layout of the instrument is shown in Fig. 1. VIRST is mounted in a portable cylindrical vacuum chamber with outer dimensions of 240 mm diameter and 500 mm length. A double-walled cylindrical pipe through which a temperature-controlled liquid circulates to provide a stable thermal environment for the complete instrument is concentrically located inside the outer vacuum chamber via Teflon rings. The outer chamber and the temperature-controlled pipe are thermally isolated by a vacuum space. The inner cylinder of the temperature-controlled pipe, which holds the optical and electrical components, is purged with temperature-controlled dry nitrogen to improve the isothermality and to avoid moisture and absorption inside the instrument. The front end of the inner cylinder is closed by an aspherical germanium lens that separates the purged inner cylinder from the isolation vacuum. All other optical and electrical components are mounted on a cardanic suspension inside the inner cylinder. This allows horizontal and vertical movements and tilting of the main parts of the instrument for alignment with manual feedthroughs placed on the rear panel of the vacuum chamber. A remote-controlled displacement of the field stop, transfer mirror,

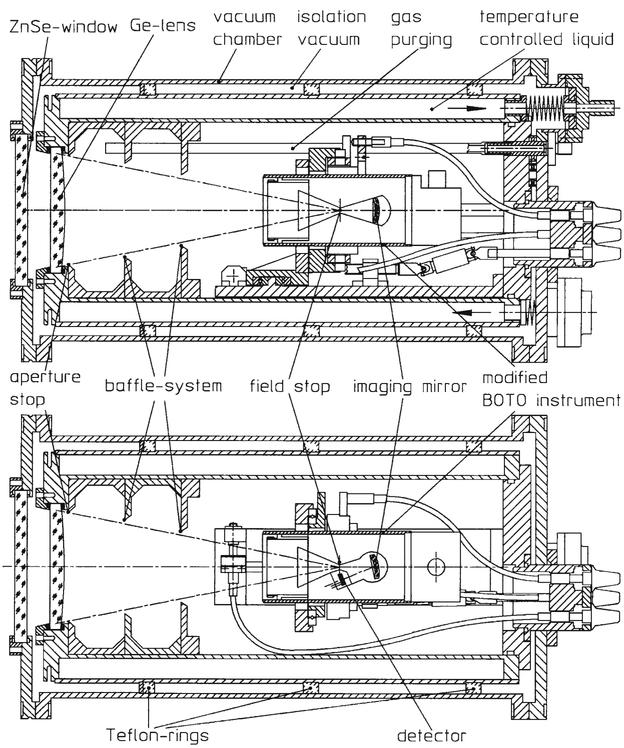

Fig. 1 Mechanical layout of VIRST

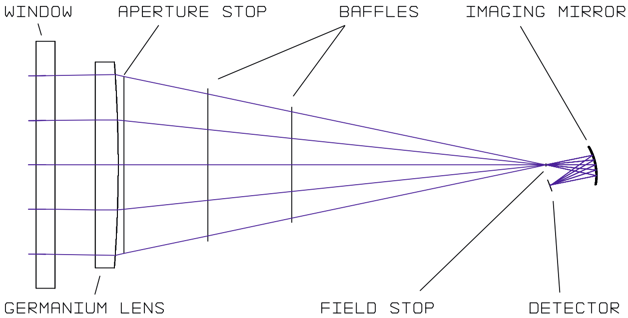

Fig. 2 Optical layout of VIRST

and detector as a whole along the optical axes allows focusing of the instrument over a measuring distance from 1710 mm to 3430 mm. Three thermometers and one humidity sensor are placed inside the inner cylinder. For operation in air, an antireflection-coated ZnSe window can be placed on the front panel of the outer chamber to separate the isolation vacuum from the air.

2.2 Optical Layout

VIRST uses two-stage imaging of the radiation source onto the detector. The optical system layout is shown in Fig. 2. The 100 mm diameter germanium lens creates an image of the source in the plane of the field stop with a magnification of 0.1. The field stop is 1 mm in diameter and defines the field of view (FOV) of the instrument. The aperture of the system is defined by the first of the three optical baffles. A concave imaging mirror collects the radiation passing through the field stop and focuses it on the detector. This setup features a well-defined FOV with optimized use of the detector's sensitive area. Further advantages are the possibility to change the FOV without the need for another detector and improved stray-light reduction. A broadband filter directly in front of the detector serves as the detector window and limits the wavelength range of VIRST from 8 µm to 14 µm. The system is optimized for operation at 0°C instrument temperature, with an instrument temperature range from −20°C to 25°C. Germanium was selected as the lens material because of its low absorption in the desired wavelength range, its high index of refraction, and its mechanical properties. The lens separates the isolation vacuum from the inside of the chamber. Therefore, a minimum thickness of 10 mm is needed.

The design goal for the primary lens was to achieve an FOV of less than 10 mm at a distance of 2250 mm with a field stop of 1 mm diameter. Although germanium lenses have very small curvatures due to their high index of refraction, the spherical aberration is too high to achieve this goal with a single spherical lens. An aspheric lens was designed to solve this problem. One of the surfaces of an aspheric lens can be chosen to be a plane without degrading the image quality. For ease of vacuum sealing, the outer surface of the VIRST optics is a plane. Ray-tracing calculations show that the VIRST aspheric optics achieve an FOV of 9.8 mm at 99% energy level (without diffraction), and the spherical aberration is removed. Chromatic aberration, which cannot be corrected by single-element optics, dominates the image quality. Optimization could therefore be carried out without considering diffraction effects. The focal length is 206.75 mm at 8 μm and 207.05 mm at 14 μm. The lens is coated on both sides with a broadband antireflection coating. The reflection loss is less than 0.8% per surface from 8 μm to 11 μm and less than 2% at 13 μm.

The index of refraction of germanium changes rapidly with temperature. A change of only 5°C would cause the FOV to increase by 0.5 mm. To achieve the desired FOV over the full-operating instrument temperature range from −20°C to 25°C, refocusing is needed. A linear relationship between operating temperature and focus position was found. A 10°C temperature change can be fully compensated by 360 μm of field stop displacement along the optical axis. At lower temperatures, the focal length of the optics becomes larger. Therefore, the FOV after refocusing is slightly smaller at lower temperatures.

The germanium lens is also the vacuum window. With its central thickness of 12 mm, it will slightly bend if the VIRST vacuum chamber is evacuated. To estimate the effect of lens bending on the optical performance of VIRST, the amount of bending was calculated using a flat-window approximation [6]. With vacuum present, the center of the lens will be displaced by approximately 5 μm toward the outside of the instrument. This displacement is of the same order of magnitude as the manufacturing tolerances specified for the lens. The change of the optical performance was simulated, and the focus shift is the primary effect of the lens bending. Without refocusing, the FOV under vacuum will increase to 11 mm in diameter. After a shift of the field stop of 0.6 mm, the FOV diameter is 9.9 mm, which is slightly larger than the nominal value without vacuum. The design goal of 10 mm (99%) FOV is achieved even with lens bending, as long as diffraction is neglected. Furthermore, experimental investigations of the size-of-source effect showed that the effect of lens bending was overestimated (see Sect. 3.2).

2.3 Electronic Layout

The data acquisition system of VIRST consists of a two-stage amplifier and a low-noise Delta-Sigma analog-to-digital converter (ADC). The preamplifier (CS3001, Cirrus Logic Inc.) has an amplification of 181. Its input voltage noise density of $6\,\mathrm{nV}\cdot\mathrm{Hz}^{-1/2}$ is small compared to the thermal voltage noise of the thermopile detector, which is $25\,\mathrm{nV}\cdot\mathrm{Hz}^{-1/2}$. The amplified signal passes through a first-order RC low-pass filter with a time constant of 51.7 ms. This time constant matches the detector time constant. A secondary amplifier with a gain of two is used to add a constant offset voltage to the signal. This allows negative signals to be detected without the need for a negative reference voltage. The ADC (ADS1255, Texas Instruments) features an internal programmable gain that is set to eight. The signal is converted using a reference voltage of +5 V. The total voltage resolution of the data acquisition system is therefore $0.2\,\mathrm{nV}\cdot\mathrm{ADU}^{-1}$. A microcontroller initializes the ADC, collects the digital data, and handles the communication with the computer. The electronic resolution and the

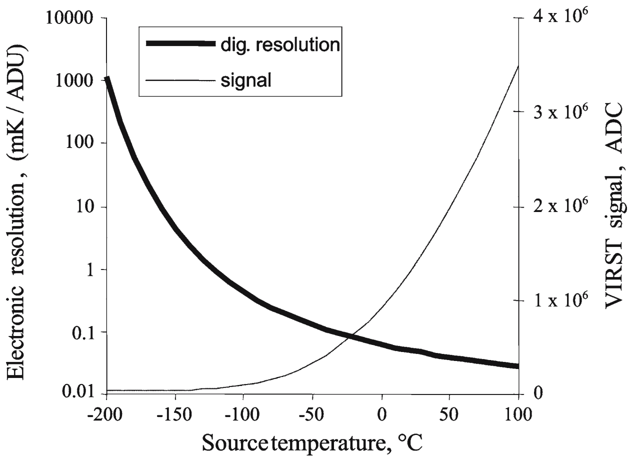

Fig. 3 Calculated electronic resolution and signal

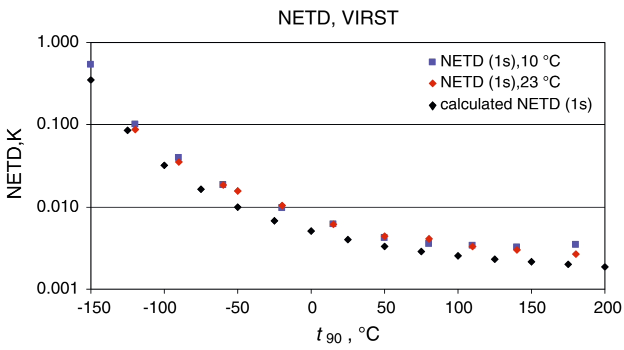

Fig. 4 Measured and calculated NETD of VIRST

signal of VIRST have been calculated (Fig. 3) assuming a detector responsivity of $122\,\mathrm{V \cdot W^{-1}}$.

3 Instrument Characterization

3.1 Temperature Resolution

The NETD of VIRST has been measured from $-150°C$ to 180°C for two different internal instrument temperatures (10°C and 23°C) with the VLTBB of the RBCF. In Fig. 4, the experimental results are compared with the calculated NETD assuming a specific detectivity D* of $4 \times 10^8\,\mathrm{cm \cdot Hz^{1/2} \cdot W^{-1}}$ for the VIRST detector, a Xe-filled thermopile from IPHT, Jena, Germany. The measured temperature resolution is in sufficient agreement with the design aim of VIRST (calculated data), and VIRST is well suited for temperature measurements down to $-120°C$. However, below $-60°C$, the integration time has to be increased to keep the temperature resolution below 20 mK.

3.2 Size-of-Source Effect

The quality of the optical system of radiation thermometers is expressed in terms of the size-of-source effect (SSE). If the source is larger than the FOV of the instrument, a small fraction of the radiation emitted outside the FOV enters the radiometer and causes a change of the reading. Root causes of this effect are aberrations of the optics, light scattering inside or outside the instrument, multiple reflections at different refracting surfaces, and diffraction. Ray aberrations are carefully minimized by the lens design. The influence of scattered light is reduced by the baffle system and the secondary imaging system. The lens and the window have high-performance antireflection coatings with average reflection losses less than 1% per surface. Therefore, the intensities of multiple-reflection images are at least 10,000 times smaller than the signal intensity. The major contribution to the size-of-source effect is diffraction at the system aperture.

The ultimate performance of every optical system is limited by diffraction at the aperture. For a circular aperture with radius A, the encircled energy of the diffraction-limited image of a point source at a distance D is given by [7]

$$I(\vec{r}) = 1 - J_0\left(\frac{2\pi A}{\lambda D}r\right)^2 - J_1\left(\frac{2\pi A}{\lambda D}r\right)^2$$

Here $\vec{r}$ is the coordinate vector in the image plane and λ is the wavelength. $J_0(x)$ and $J_1(x)$ are the Bessel functions of orders 0 and 1, respectively. The energy fraction outside a given radius r decreases in proportion to $1/r$. To collect 99% of the energy emitted by a point source, the detector has to be 20 times larger than the diameter of the first dark ring of the diffraction pattern. This shows that diffraction is the most important effect limiting the optical performance of VIRST. Since the blackbody radiator is an incoherent source, the total energy distribution and the size-of-source effect for a real extended radiator in the diffraction-limited monochromatic case can be obtained by two-dimensional integration of the intensity over the FOV.

Figure 5 compares the theoretical prediction with the measured SSE data. The calculation was done for a wavelength of 10.5 µm, assuming an ideal image of a 9.8 mm source. Measurements and calculations are normalized to a source diameter of 60 mm. Measurements were taken with the ZnSe window under vacuum and in air. The source temperature was 50°C, and the temperature of VIRST was 23°C. Differences for a source diameter of 10 mm are due to focus uncertainties. The measurements show that the optical performance of VIRST is very close to the diffraction limit.

The results in Fig. 5 show that the ZnSe window does not contribute significantly to the size-of-source effect and that SSE measurements under vacuum and in air give almost identical results. Evidently, the estimation of the defocusing due to the bending of the germanium lens was too pessimistic.

3.3 Reference Function

VIRST was calibrated at seven temperatures in the range from −20°C to 170°C with the ammonia- and water-heat-pipe blackbodies of the low-temperature calibration

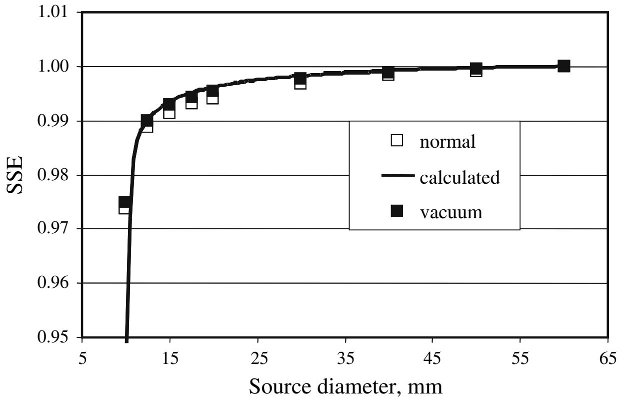

Fig. 5 Measured and calculated SSE of VIRST

facility [4,5] at a distance of 2250 mm. With this unusually long measurement distance in air, the dominating contribution to the uncertainty of the radiation temperature of the heat-pipe blackbodies (T_{HPBB}) at temperatures below 0°C and above 60°C is the correction of the atmospheric transmission in the broad spectral range of the radiation thermometer for a relative humidity of 46%. For example, at a radiation temperature of −20°C, this correction is −74 mK, and at 170°C, it is 144 mK. Half of this correction was included as an additional standard uncertainty to the uncertainty budget of the heat-pipe blackbodies as given in [4,5]. From the seven calibration points, the reference function of VIRST was determined according to the scheme described in [8], relying on Planck's formula. In addition to the scheme described in [8], which assumes a rectangular responsivity profile, the known relative spectral characteristics of the interference filter and the detector have been included. Also, in addition to [8], the radiation incident on the detector from the surrounding housing, the ZnSe window, and the Ge lens as a function of the measured instrument temperature and the derating of the thermopile as a function of the detector temperature have been included. With the resulting reference function, the deviation of all calibration temperatures (T_{90}) from the reference function (T_{Ref}) was determined and plotted in Fig. 6. All calibration temperatures agree within 40 mK with the resulting reference function of VIRST, well within the uncertainty of the heat-pipe blackbodies. The result confirms the good linearity and high temperature resolution of VIRST.

3.4 Comparison of Heat-Pipe Blackbodies and VLTBB with VIRST

VIRST was used as a transfer instrument to compare the heat-pipe blackbodies with the VLTBB. Five months after the calibration with the heat-pipe blackbodies, VIRST was mounted inside the detector chamber of the RBCF for the measurement of the radiation temperatures of the VLTBB. To reduce the necessary SSE corrections for this comparison, the measurements in the RBCF were performed without reduced-background radiation, i.e., without LN_2 cooling of the RBCF, in a temperature range from

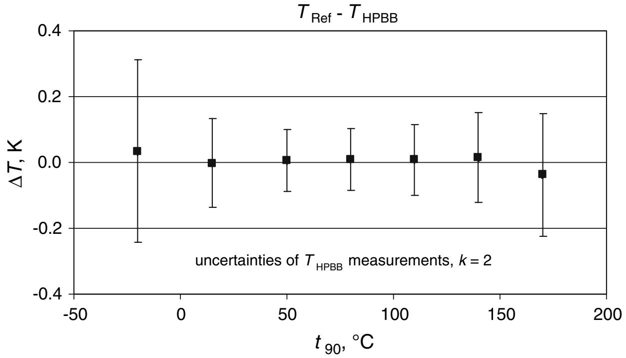

Fig. 6 Deviation of the calibration temperatures of the heat-pipe blackbodies (T_{HPBB}) from the reference function of VIRST (T_{Ref}) at T_{90} temperatures. The expanded uncertainty ($k = 2$) of T_{HPBB} is given. Correction of atmospheric absorption is the major uncertainty contribution

−120°C to 170°C of the VLTBB. The measured radiation temperatures of the VLTBB were corrected for the size-of-source effect (60 mm aperture diameter of the heat-pipe blackbodies and 20 mm aperture diameter of the VLTBB). Twenty percent of this correction was included as an additional standard uncertainty to the uncertainty budget of the VLTBB. At low temperatures, the uncertainty of the SSE correction is a significant contribution to the uncertainty budget (u(SSE) = 370 mK at −120°C). Furthermore, the limited instrument temperature stability of VIRST ($\Delta T_{\mathrm{VIRST}} = \pm 50\,\mathrm{mK}$) results in a significant uncertainty contribution to the uncertainty budget of the comparison at very low temperatures ($u(\Delta T_{\mathrm{VIRST}}) = 429\,\mathrm{mK}$ at −120°C). This uncertainty has also been included in the uncertainty budget of the VLTBB radiation temperatures. Finally, as we have insufficient experience with the long-term stability of VIRST as a transfer instrument, a possible drift of $33\,\mathrm{mK} \cdot \mathrm{month}^{-1}$ at 156.6°C has been added to the uncertainty budget of the VLTBB. This change in radiation temperature has been observed in long-term observations of the VLTBB at measurements near the indium fixed-point temperature.

The differences of the radiation temperatures between the VLTBB (T_{VLTBB}) and the heat-pipe blackbodies (T_{HPBB}) with respect to the reference function determined from the heat-pipe blackbody measurements (T_{Ref}) are given in Fig. 7. The radiation temperatures of the heat-pipe blackbodies and the VLTBB are in agreement within the combined uncertainties of the blackbodies from −20°C to 170°C. For temperatures below −20°C, the differences between T_{Ref} and T_{VLTBB} increase. In this temperature range, the reference function is extrapolated and a possible reason for this increase might be the unknown spectral transmission of the ZnSe window and the Ge lens. For both components, only integral transmission values are used in the reference function. Since the accurate consideration of all internal radiation contributions becomes more important at lower temperatures, it is necessary to measure and consider the spectral properties of these components in a future improved reference function.

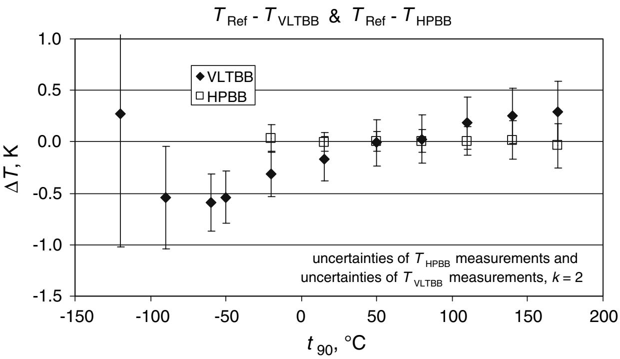

Fig. 7 Deviation of the radiation temperatures of the VLTBB (T_{VLTBB}) and the heat-pipe blackbodies (T_{HPBB}) from the reference function of VIRST (T_{Ref}) at T_{90} temperatures

4 Conclusion

A vacuum infrared standard radiation thermometer has been developed for the temperature range from −150°C to 170°C for operation with the PTB reduced-background calibration facility. The temperature resolution and size-of-source effect of the instrument are in accordance with the design goals, and the instrument fulfills the requirements for the calibration of temperature radiators by comparison to a variable-temperature reference blackbody. A comparison of the radiation temperatures of the heat-pipe blackbodies of PTB operating in an ambient atmosphere with the VLTBB under vacuum in a temperature range from −120°C to 170°C was presented. Further investigations (i.e., long-term stability, improved modeling of the reference function) and technical improvements are planned in order to use VIRST to transfer the International Temperature Scale by means of radiation thermometry under vacuum from PTB to customers.

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References

1. J. Hollandt, B. Gutschwager, T. Jankowski, R. Gärtner, in *Proceedings TEMPERATUR 2006*, ed. by J. Hollandt, S. Rudtsch, *Physikalisch-Technische Bundesanstalt, Braunschweig und Berlin, Germany, 2006*, pp. 71–79, ISBN 3-9805741-7-2
2. C. Monte, B. Gutschwager, S.P. Morozova, J. Hollandt, Radiation thermometry and emissivity measurement under vacuum at the PTB, in *Proceedings of TEMPMEKO 2007* (accepted to be published in *Int. J. Thermophys.*)
3. S.P. Morozova, N.A. Parfentiev, B.E. Lisianskiy, V.I. Sapritskiy, N.L. Dovgilov, U.A. Melenevsky, B. Gutschwager, C. Monte, J. Hollandt, in *Proceedings of TEMPMEKO 2007*, Int. J. Thermophys., DOI: 10.1007/s10765-007-0355-z
4. J. Hollandt, R. Friedrich, B. Gutschwager, D.R. Taubert, J. Hartmann, High Temp. – High Press. **35/36**, 379 (2003/2004)

5. J. Fischer, in *Proceedings of TEMPMEKO '99, 7th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by J.F. Dubbeldam, M.J. de Groot (Edauw Johannissen bv, Delft, 1999), pp. 27–34
6. W.L. Wolfe, G.J. Zissis (eds.), *The Infrared Handbook* (Office of Naval Research, Arlington, Virginia, 1993), Chap. 7.6
7. M. Born, E. Wolf, *Principles of Optics* (Pergamon Press, New York 1980), Chap.8.5.2, p. 395
8. B. Gutschwager, J. Fischer, in *Proceedings of TEMPMEKO '99, 7th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by J.F. Dubbeldam, M.J. de Groot (Edauw Johannissen BV, Delft, 1999), pp. 567–572