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Spectral Emissivity of Surface Blackbody Calibrators

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Abstract The normal spectral emissivity of commercial infrared calibrators is compared with measurements of anodized aluminum samples and grooved aluminum surfaces coated with Pyromark. Measurements performed by FTIR spectroscopy in the wavelength interval from 2 to 20 μm and at temperatures between 5 and 550°C are presented with absolute uncertainties from 0.25% to 1% in spectral regions with sufficient signal and no significant atmospheric gas absorption. A large variation in emissivity with wavelength is observed for some surfaces, i.e., from 1% to 3% to more than 10%. The variation in emissivity using similar materials can be reduced to 0.5–1% by optimizing the coating process and the surface geometry. Results are discussed and an equation for calculation of the equivalent blackbody surface temperature from FTIR spectra is presented, including reflected ambient radiation. It is in most cases necessary to correct temperature calibration results for calibrators calibrated at 8–14 μm to obtain absolute accuracies of 0.1–1°C in other spectral regions depending on the temperature. Uncertainties are discussed and equations are given for the correction of measured radiation temperatures.

Keywords Blackbody · Calibration · Emissivity · FTIR · Infrared · Temperature

1 Introduction

Many blackbody calibrators marketed for the calibration of IR thermometers are designed with a simple cooled or heated surface, i.e., typically a painted or coated metal disk with a plane or grooved surface, to increase the effective emissivity. The

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design leads to compact and low-cost calibrators compared with cavity blackbodies and surface calibrators can be more easily designed with a large target size. A large target is advantageous for the calibration of modern low-cost infrared thermometers because it is difficult to obtain accurate results using cavity blackbodies with a 25 mm aperture or less. The emissivities of many commercial infrared flat-plate calibrators are specified as 0.95 or 1.00 in the datasheet, and the emissivity is usually not specified precisely, although it is one of the major components of the uncertainty budget. An apparent emissivity value of 0.95 or 1.00 is obtained by offsetting the actual surface temperature compared with the temperature reading of the instrument. Spectral emissivity measurements in our laboratory on various commercial blackbody surface calibrators show that most instruments perform well at 8–14 μm; however, emissivity changes with wavelength and temperature, and some products show large deviations due to aging of the coating or other changes in the optical properties of the surface. A 1–3% variation in emissivity with wavelength is seen for most surface infrared calibrators. Nevertheless, variations in emissivity from 1% to more than 10% have been observed for some instruments. Industrial users working at wavelengths shorter than the popular 8–14 μm region should consider these effects, e.g., calibration of line scanners, thermo cameras operating at 3–5 μm, and IR-sensors may be affected. Users of infrared surface calibrators may ask how the uncertainty in emissivity affects their temperature calibration, and it may be a hard question to answer in a simple way.

A Fourier transform infrared (FTIR) spectrometer is used in this work for accurate measurements of spectral radiance in the range from 2 to 20 μm by comparing blackbody surface calibrators to a high-quality reference blackbody of known temperature and emissivity. The measuring method and data analysis procedure used here are described in [1]. A comparison of emissivity results obtained using three different experimental setups is described in [2] for selected samples and coatings. The FTIR method and instrumentation are described briefly, and measurements are demonstrated at temperatures below ambient. The instrumentation and the method can be used for emissivity measurements below 0°C, e.g., as low as −80°C with an alcohol-cooled reference blackbody, but this would require purging the experimental setup to avoid condensation and ice formation and is beyond the scope of the current work.

2 Background and Theory

Planck's radiation law and a simple physical description of terms are essential to understand the processing of data and the correction of emissivity effects. The effect of a 1% error in emissivity on the radiance temperature is shown in Fig. 1 at five selected wavelengths [3], e.g., the temperature error at 400°C due to an emissivity of 0.99 instead of 1.00 is −1.26°C at 4 μm and −2.62°C at 10 μm. This leads to typical errors of 2.5–5°C for a low-cost infrared calibrator at 4 μm calibrated at 8–14 μm. The error pattern changes at temperatures below ambient, i.e., the temperature error at −20°C due to an emissivity of 0.99 instead of 1.00 is +2.04°C at 4 μm and +0.77°C at 10 μm. The emissivity effect on temperature is large compared with the accuracy of the temperature control system of most commercial infrared calibrators.

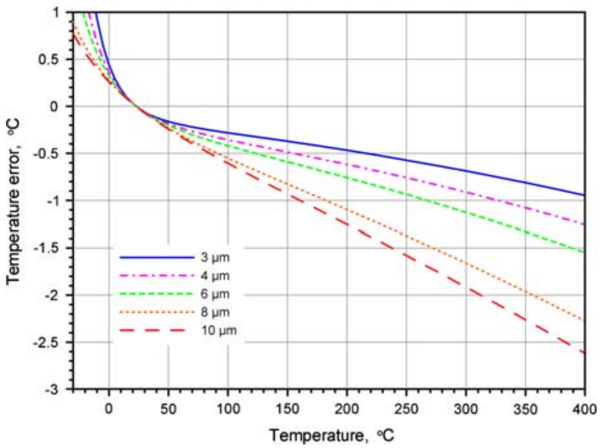


Fig. 1 Error in surface radiation temperature due to 1% error in emissivity. Ambient radiation at 23°C is reflected by the surface. BMC at our laboratory is presently 0.25% ($k = 2$)

The effect of reflected ambient radiation is included in Fig. 1, but at elevated temperatures the contribution from the reflected ambient radiation is small and the uncertainty in radiance temperature is related by Planck's law to uncertainty in emissivity by

$$\Delta T = \frac{\Delta\varepsilon}{\varepsilon} T^2 \frac{\lambda}{c_2} \tag{1}$$

where c_2 is the second radiation constant in Planck's law, as described later in Sect. 2.1, and the temperature (T) is in kelvin. Equation 1 states that the uncertainty in temperature (ΔT) depends linearly on the uncertainty in emissivity and the wavelength (λ). It is observed that raising the temperature by a factor of two requires that the error in emissivity be reduced by a factor of four to maintain the same temperature uncertainty from this source. Furthermore, Eq. 1 and Fig. 1 can be used to evaluate the size of source effects, i.e., if 1% of the field of view of an industrial infrared thermometer is not viewing the aperture of a blackbody during calibration, an error similar to the 1% error in emissivity is introduced.

2.1 Calculations

The subtraction method described in detail in [1] is applied in this work to eliminate thermal radiation from the spectrometer and to account for reflected ambient radiation. The set-point temperature or the reading from the temperature contact sensor is used as the reference surface temperature of the infrared calibrator in the following. Three measurements must be performed to calculate the spectral emissivity of the surface, i.e., a spectrum of the surface at the set point (S_r), another at ambient temperature

(S_{am}), and a spectrum of the reference blackbody (S_{bb}):

$$\begin{aligned} S_{\mathrm{r}}(\lambda) &= R(\lambda)\,\varepsilon(\lambda, T_{\mathrm{sp}})\,L(T_{\mathrm{sp}}, \lambda) + B(\lambda) \\ S_{\mathrm{am}}(\lambda) &= R(\lambda)\,L(T_{\mathrm{am}}, \lambda) + B(\lambda) \\ S_{\mathrm{bb}}(\lambda) &= R(\lambda)\,L(T_{\mathrm{bb}}, \lambda) + B(\lambda) \end{aligned} \tag{2}$$

where

$$L(T, \lambda) = \frac{2\pi c_1}{\lambda^5 \left(\mathrm{e}^{\frac{c_2}{\lambda T}} - 1\right)}; \quad \text{Planckian function} \tag{3}$$

$\varepsilon(\lambda, T_{\mathrm{sp}})$ is the surface emissivity of the calibrator surface at T_{sp}. $R(\lambda)$ is the response function of the entire system, and $B(\lambda)$ is thermal radiation from the background. The surface is compared at a given set point, T_{sp}, with a reference blackbody of known emissivity (e.g., 0.9996) and known temperature, T_{bb}, that may be close to T_{sp}, e.g., in a thermostated room at T_{am} (23 ± 2°C). The ratio of the two signals is $\varepsilon_{\mathrm{r}}(\lambda, T_{\mathrm{sp}})$. The apparent emissivity, $\varepsilon_{\mathrm{r}}(\lambda, T_{\mathrm{sp}})$, can be found from:

$$\begin{aligned} &\varepsilon_{\mathrm{r}}(\lambda, T_{\mathrm{sp}}) = \tfrac{S_{\mathrm{r}}(\lambda) - S_{\mathrm{am}}(\lambda)}{S_{\mathrm{bb}}(\lambda) - S_{\mathrm{am}}(\lambda)} = \tfrac{\varepsilon(\lambda, T_{\mathrm{sp}})(L(T_{\mathrm{sp}}) - L(T_{\mathrm{am}}))}{L(T_{\mathrm{bb}}) - L(T_{\mathrm{am}})} \\ &\text{or} \\ &\varepsilon(\lambda, T_{\mathrm{sp}}) = \varepsilon_{\mathrm{r}}(\lambda, T_{\mathrm{sp}}) \tfrac{L(T_{\mathrm{bb}}) - L(T_{\mathrm{am}})}{L(T_{\mathrm{sp}}) - L(T_{\mathrm{am}})} \end{aligned} \tag{4}$$

It should be noted that the constant $2\pi c_1$ in Eq. 3 disappears by division, and c_2 is set to 0.014388 m·K as defined by ITS-90. The set-point temperature or the reading of a calibrated contact sensor can be used as the reference surface temperature of the calibrator surface. The calibrator set-point temperature, T_{eq}, to obtain similar radiance as a blackbody at T_{bb} can be found from

$$1 = \varepsilon_{\mathrm{r}}(\lambda) \frac{L(T_{\mathrm{eq}}, \lambda) - L(T_{\mathrm{am}}, \lambda)}{L(T_{\mathrm{sp}}, \lambda) - L(T_{\mathrm{am}}, \lambda)} \tag{5}$$

Solving Eq. 5 above for temperatures above ambient gives

$$T_{\mathrm{eq}}(\lambda) = \frac{C_2}{\ln\left(1 + \frac{\varepsilon_{\mathrm{r}}(\lambda)}{e^{\frac{C_2}{\lambda T_{\mathrm{sp}}}} - 1} + \frac{1 - \varepsilon_{\mathrm{r}}(\lambda)}{e^{\frac{C_2}{\lambda T_{\mathrm{am}}}} - 1}\right)\lambda} \tag{6}$$

Equation 6 is useful for the correction of calibration results and to find the set-point value to obtain a certain radiance temperature.

Table 1 Instruments and samples characterized

Code	Surface	Remarks
O: #020901133	Plane surface, coated	Commercial calibrator, low cost
Sample TRIRAT[a]	Plane, black anodized Al	Material used for blackbody cavity
C: #130751	Structured, black anodized Al	Commercial calibrator, large area
P1: #0001[b]	40° grooves, Pyromark	Brush coated
P2: #0001[b,c]	40° grooves, Pyromark	Coated by brush and sprayed
P3: #0002[b,c]	40° grooves, Pyromark	Coated by brush and sprayed

[a] EU-project TRIRAT

[b] Pyromark 2500 on aluminum

[c] Blackbody calibrator, type R550, Risø National Laboratory

3 Measurements

We present the results for the three infrared surface calibrators and three samples, see Table 1.

3.1 Experimental Setup

The infrared calibrator surface is compared directly with a reference blackbody at a similar temperature. The set point of the infrared calibrator surface temperature may be raised slightly to obtain blackbody radiation similar to the reference blackbody in the spectral range of interest, e.g., from 8 to 14 µm. A water heat pipe blackbody was used as the reference blackbody in the temperature range from 50 to 250°C, a cavity blackbody integral to an electrically-heated stirred salt bath from 250 to 550°C and a blackbody cavity mounted in a thermostatted water bath at 5–50°C. Measurements were carried out with an FTIR spectrometer, Bomem Model MB155, placed on a rail in order to move the field of view of the spectrometer from the reference blackbody to the infrared surface calibrator or the heated sample. The optics can be adjusted to a spot size of 5–25 mm, and a 25 or 50 mm aperture can be used in front of the sources to minimize the size of source effects. The path between the FTIR spectrometer and the blackbodies was similar to minimize the influence of absorption from water vapor in the air. The spectral resolution was 8 cm^{-1} in all measurements, and the signals were typically averaged over 200–400 scans or approximately 3 min. All measurements were background corrected using a measurement at ambient temperature on an infrared calibrator surface with a set point of 23.0°C, or turned off, to eliminate errors due to thermal radiation from the FTIR spectrometer, reflected radiation from surfaces, etc. Details about the instrumentation and methods are described in [1].

Spectral emissivity curves are calculated from the calibrator temperature reading or a calibrated contact sensor inserted below the calibrator surface. Results can be reproduced with absolute errors less than 0.2% with sufficient care, i.e., stabilized instruments, short time between measurements, and well-defined field of view.

Fig. 2 Apparent emissivity of infrared calibrator with a plane, coated surface using the set-point temperature as reference. CO_2 and H_2O bands are present at 4.3 and 5–7 µm. Independent temperature calibration results are shown in Table 2

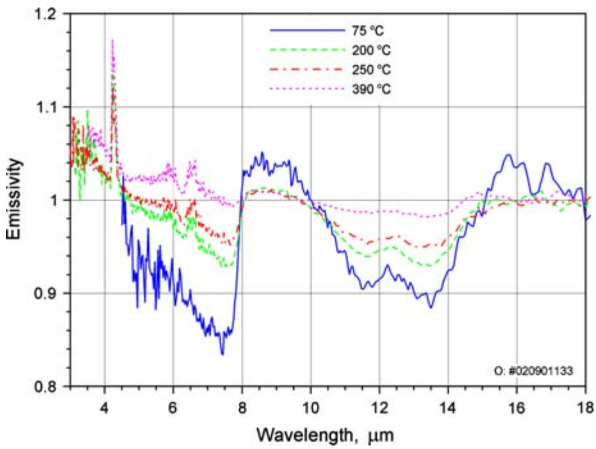


Table 2 Calibration results for infrared calibrator with plane coated surface (Fig. 2)

Display reading	1–1.6 µm[a]	3–5 µm[b]	8–14 µm[c]
75.0°C	–	74.8°C	74.9°C
200.0°C	–	201.3°C	198.9°C
250.0°C	254.4°C	252.6°C	–
390.0°C	395.9°C	394.5°C	389.5°C

[a] Mikron M190QS transfer standard

[b] Radiance PM IR camera

[c] Raytek Raynger ST

The emissivity setting of all IR thermometers has been set to 1.00

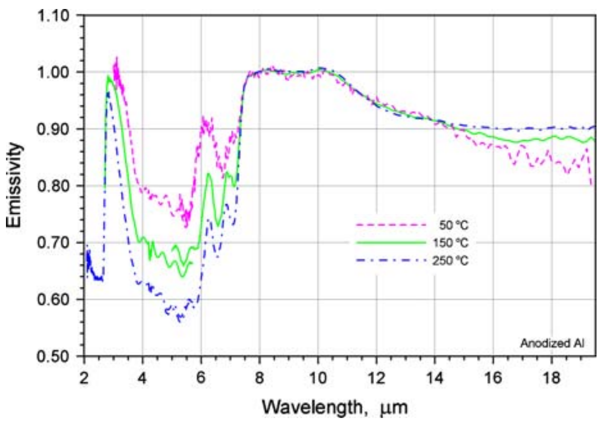


Fig. 3 Emissivity of black anodized aluminum sample with a plane surface as used for blackbody cavities. DTGS and InSb detectors have been used to cover the extended spectral range. Reference temperature was measured by a thermocouple

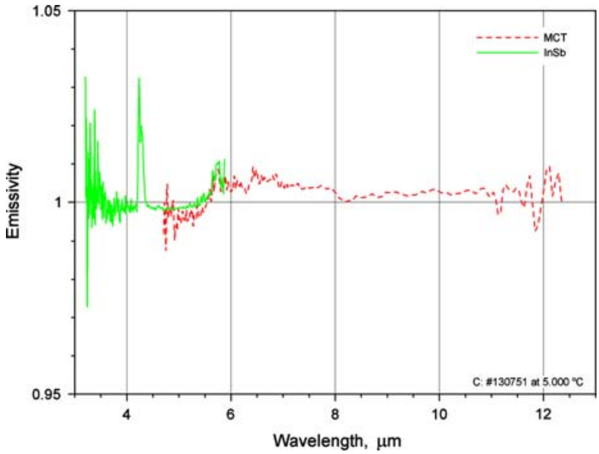
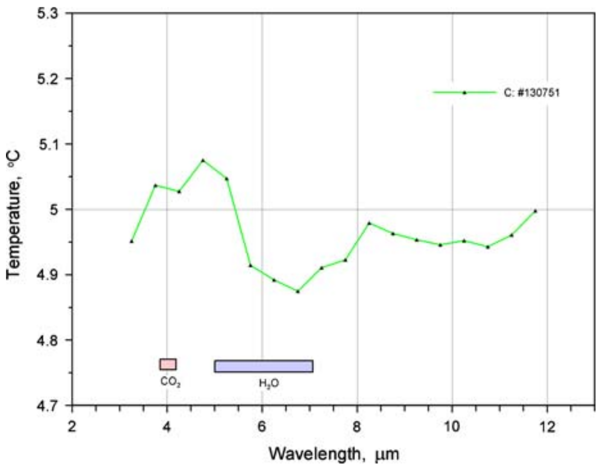


Fig. 4 Emissivity of black anodized aluminum large area infrared calibrator with structured surface used at temperatures below ambient. CO_2 and minor H_2O band is present at 4.3 and 5–7 µm. MCT and InSb detectors have been used for sensitive measurements in the extended spectral range. Set-point temperature is used as the reference

Fig. 5 Set-point temperature, T_{eq}, to obtain similar radiance as a blackbody at 5.0°C as found from the data in Fig. 4



3.2 Results

An example of the measured emissivity for a commercial low-cost infrared calibrator is shown in Fig. 2. The temperature reading is used as the reference for calculating the apparent emissivity. Large variations in emissivity and a significant temperature effect are seen. Emissivity values over one are due to the fact that the actual surface temperature is adjusted to be higher than the temperature readout to obtain a radiance temperature close to the desired value for the 8–14 µm band, i.e., higher by more than 6°C at 390°C for the 1–1.6 µm band (Table 2). Temperature calibration results for three infrared thermometers with different bandpass filters are shown in Table 2. The infrared calibrator performs well for the 8–14 µm band.

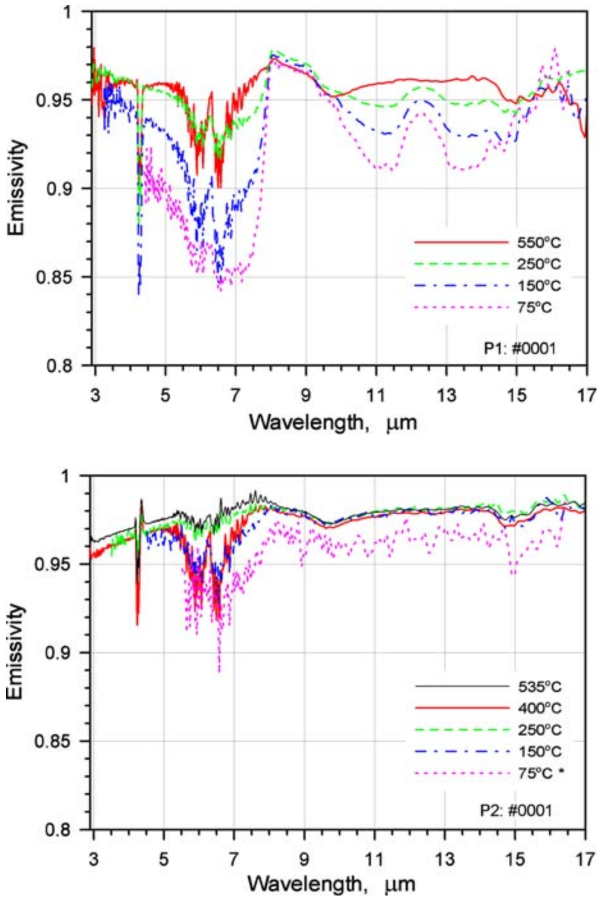


Fig. 6 Emissivity of grooved (40° V-groove) aluminum surface coated with Pyromark 2500 used for temperatures up to 550°C. Effect of the coating procedure is visible; coated by brush (upper plot) and coated by brush and sprayed (lower plot)

The increase in emissivity with temperature is a typical behavior for many painted surfaces, but the effect is significant when the coating thickness is too thin, and the absorption features of the coating can be seen in the emissivity curves (Fig. 2). Difficulties arise when using this unit to calibrate and test IR-scanners operating at several bands in the 3–14 μm range.

Black anodized aluminum is used for cavity blackbodies as well as for surface calibrators. The behavior of this sample is opposite to that of most coated surfaces, i.e., the emissivity decreases by increasing temperature (Fig. 3), which is confirmed by other measurements [4]. Anodized aluminum, no matter the visible color, will perform best at low temperature and for the 8–14 μm band. An extended range of emissivity curves in Fig. 3 was obtained using a DTGS detector at long wavelengths and the far more sensitive InSb detector in the 2–6 μm range. The actual optical properties

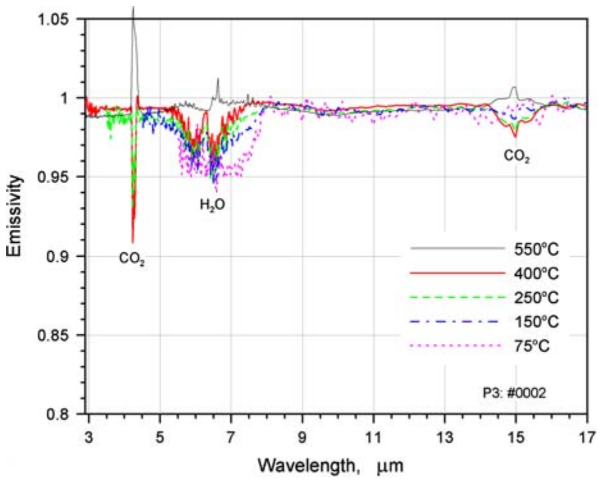


Fig. 7 Emissivity of grooved (40° V-groove) aluminum surface coated with Pyromark 2500 used for temperatures up to 550°C. Coating and heat cure procedure results in high emissivity with minor variations with temperature and wavelength. Disturbances from CO_2 and H_2O bands are visible at 4.3, 14.9, and 5.5–7.5 μm

of anodized aluminum depend on the process factors, i.e., higher emissivity may be obtained in the 2–8 μm range than the one measured in Fig. 3.

Anodized aluminum is used for many large area infrared calibrators and a flat emissivity curve is seen for some products, especially at low temperatures. An emissivity measurement flat within ±0.005 at 5.0°C is shown in Fig. 4, and a radiance temperature of ±0.1°C can be obtained in the spectral region from 3 to 12 μm without any corrections (Fig. 5). Measurements performed with the MCT detector should be measured at low signal levels and should be compared with a blackbody at a similar radiation temperature to reduce possible errors due to detector non-linearity. The noise in measurements at the low temperature may be reduced by using a spectroradiometer instead of the FTIR or by decreasing the spectral resolution from 8 to 16 cm^{-1}. The signal level is low for temperatures close to ambient, i.e., the signal will increase thus lowering the surface temperature.

We have used aluminum coated with Pyromark 2500 for some years. The emissivity can be increased using a grooved surface, but the coating and heat curing process is not trivial as results indicate in (Fig. 6) for a surface coated by brush and a combination of brush and spray. It is simply difficult to control the layer thickness, which is essential. The coating thickness will be largest at the bottom of grooves when a brush is used and at the top of the grooves with a spray process. Higher emissivity and a flatter curve are gained by combining the brush and spray processes.

The best result obtained so far for temperatures up to 550°C is shown in Fig. 7.

4 Conclusion

FTIR spectral emissivity measurements for infrared calibrators and samples have been presented. A large variation in emissivity is seen for some instruments used for the calibration of infrared thermometers. Users must be careful when they use infrared surface calibrators outside the popular 8–14 µm range unless the emissivity properties of the instrument have been specified or have been verified by calibration.

Emissivity measurements are traceable and can be performed accredited through the use of high quality reference blackbodies and measurement procedures similar to the calibration of infrared thermometers. The FTIR spectrometer can be seen as a multi-wavelength pyrometer and uncertainties should consider instrument stability, size of source effects (FOV), linearity of detector, SNR, etc. Best measurement capability (BMC) in our laboratory is 0.25% on emissivity, but this requires great care during measurements. The uncertainty of measurements can be lowered in the future, but this would require better control of the FOV and improved instrument stability.

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