

Development of a new generation of spaceborne blackbody calibration technology based on miniature fixed points

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Introduction

The global temperature changes by about 0.2 K per decade, which is roughly one-tenth of typical ENSO variations and one-fiftieth of weather-related changes. Natural inter-annual variations and measurement uncertainties can obscure long-term climate trends. Therefore, accumulating reliable climate data requires stable and precise instruments capable of long-term, accurate measurements. To achieve this, a highly stable climate detection system and an on-orbit high-precision radiometric standard calibration traceable to SI are essential. In the Chinese Space-based Radiometric Benchmark (CSRB) project, we developed a space temperature traceability technology using miniature fixed points (MFPs). By combining multiple microcells with reference materials and a blackbody radiation source, continuous self-calibration across all regions is achieved through phase transition characteristics under multi-physical field coupling, establishing a transfer link between fixed points, blackbodies, and remote sensors.

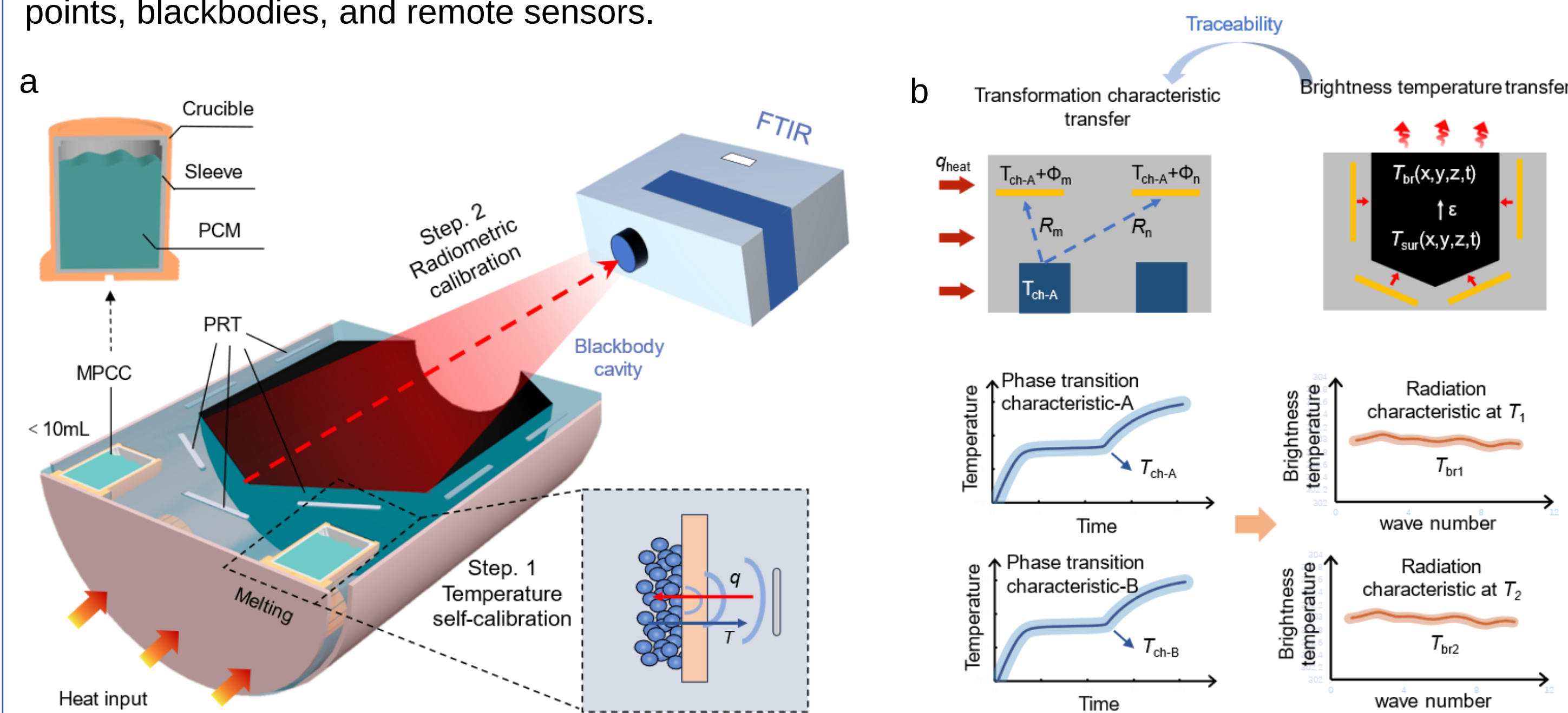


Fig. 1 Space temperature traceability method based on the MFP near-site transfer. a Schematic of space temperature traceability method. b Principle of space temperature transfer.

Spaceborne blackbody design

Based on the near-site transfer method, we have developed the latest generation of spaceborne blackbody with self-calibration function for the infrared hyperspectral atmospheric detector of FY-3 satellite (Fig. 4). The grating diameter is 115 mm, and the emissivity of the blackbody cavity is superior to 0.997. The blackbody carries four miniature fixed-point units in a groove at the bottom.

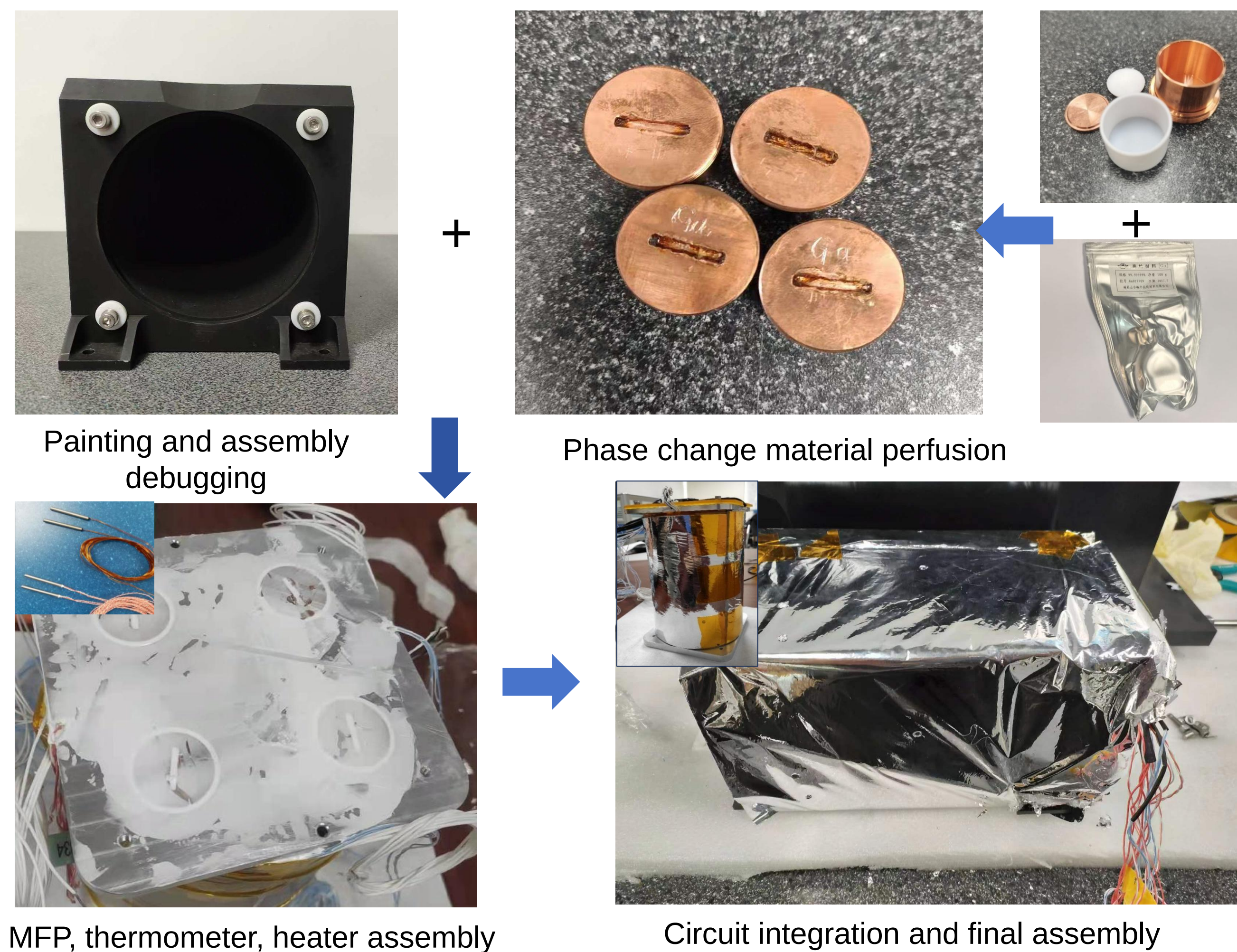


Fig. 4 spaceborne blackbody designed with self-calibration function for the infrared hyperspectral atmospheric detector of FY-3 satellite

Near-site transfer mechanism

Compared to traditional in-situ temperature calibration methods, achieving space temperature traceability requires accurately measuring blackbody radiation surface temperature. Thus, temperature sensors should be placed on the radiative surface rather than in phase-change media. Due to heating heat flow, external environment, and fixed point heat absorption during phase transition, the blackbody temperature exceeds miniature fixed point temperature. A theoretical model of multi-boundary thermal coupling is proposed, considering phase transition temperature and thermal conditions like heating power and ambient temperature. At steady-state, its characteristic temperature can be expressed as:

$$T_{cha} = T_{mel} + c_1 \Delta q_{heat} + c_2 \Delta T_{pla} + c_3 \Delta T_{amb} + c_4$$

where T_{mel} are the melting temperatures of PCM, T_{pla} and T_{amb} are the platform temperature and ambient temperature, respectively. c_1 , c_2 , c_3 , and c_4 are constants determined by the thermal resistance of the structure, and can be experimentally measured. c_4 tends to be equal to zero at the quasi-steady-state plateau.

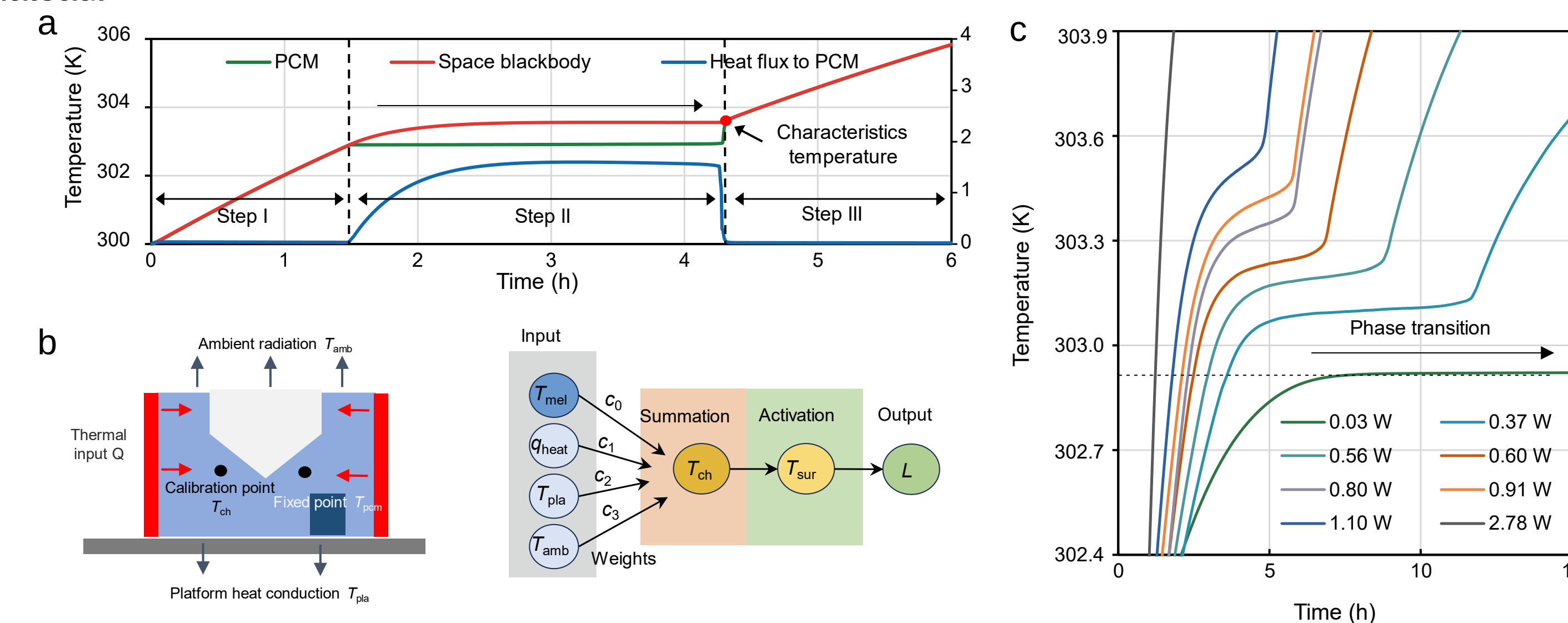


Fig. 2 Space temperature traceability method based on the MFP near-site transfer. a Schematic of space temperature traceability method. b Principle of space temperature transfer. c Phase transformation curves of spaceborne blackbody at the gallium point under different heating power increments.

Spatial replication and noise fluctuation

The FY-3 spaceborne blackbody was successfully launched in 2021. The spaceborne blackbody mounted on a constant temperature platform at about 283.3 K using insulated housing, was heated by an external source of 4.1 W to achieve faster calibration within approximately 3.1 hours. The phase transition curves and characteristic temperature statistics are illustrated in Fig. 5a and b. The blackbody demonstrates exceptional repeatability, with three consecutive measurements showing deviations of less than 9.1 mK and an average variation of 7.4 mK compared to ground-based tests. However, operational data revealed periodic fluctuations in the phase transition curves (Fig. 5c), synchronized with the orbital cycle. Further research will address the impact of external heat flow.

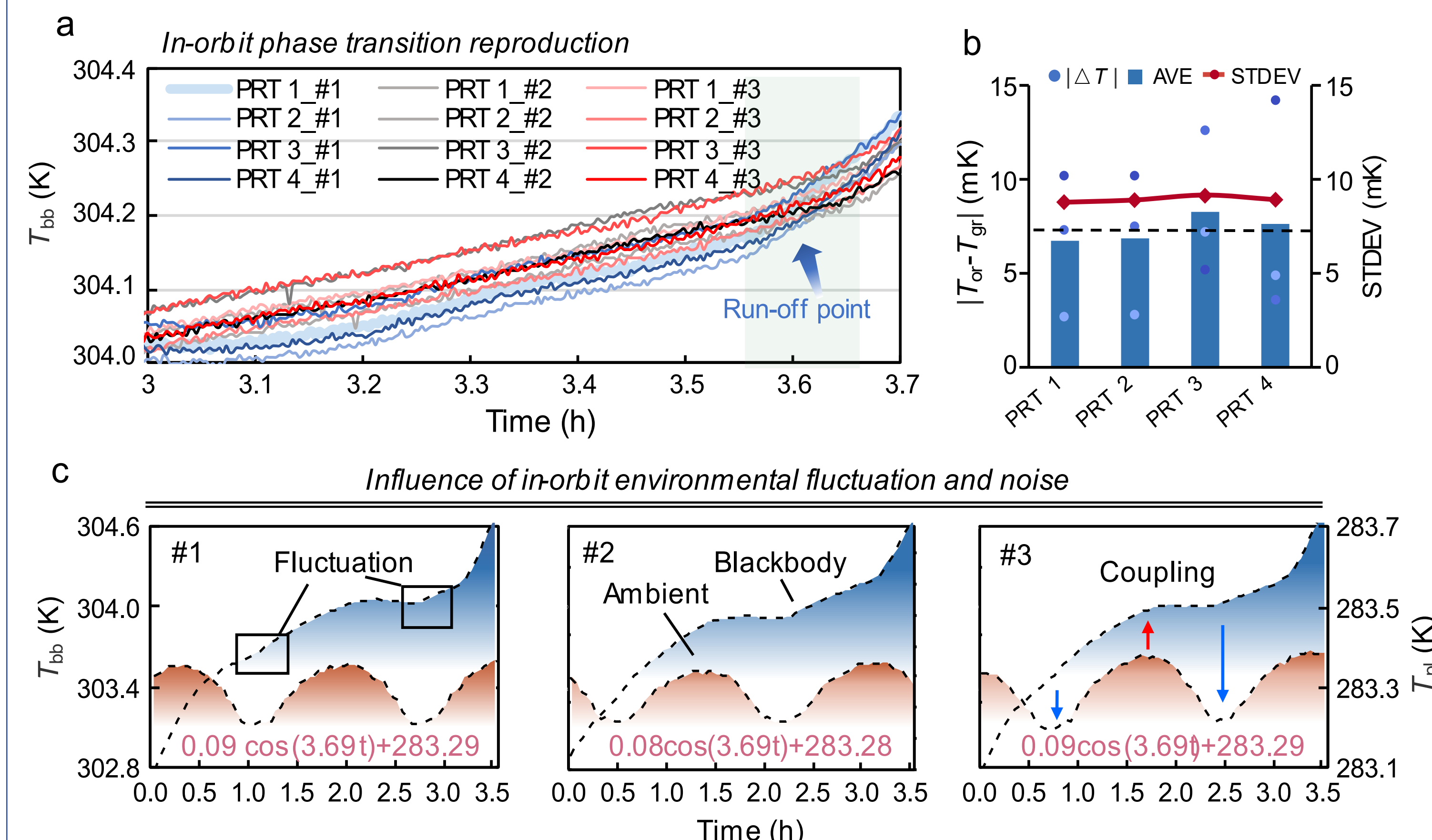


Fig. 5 Spatial replication and noise fluctuation. a In-orbit reproducible results. b Characteristic temperature statistics of in-orbit. c Phase transition curves versus experimental platform

Traceability link

Based on the above mechanisms, two traceability links and corresponding implementation methods were proposed for different on-orbit calibration scenarios. The space benchmark traceability link is based on the ITS-90 international temperature scale definition, where the reference temperature at which the Hg, Ga, and H₂O reference points undergo precise phase transitions at low power is used. The temperature values are transmitted from the PRT and blackbody radiation source to the infrared sensor. This method can be directly traced to the SI. A more convenient onboard blackbody calibration link involves determining the characteristic temperature under the given working conditions by a platinum resistance thermometer traceable to national standards (ground-based). The PRT is interpolated and calibrated to obtain the precise temperature of the blackbody radiation source, depending on the good reproducibility of the mean free path (MFP), and then the value is transmitted to the infrared sensor. Compared to the previous method, this method can use a higher input heat source to achieve a shorter phase change/calibration cycle. It is worth noting that in this case, the characteristic temperature is used as a weight after precise measurement, rather than as a defining value.

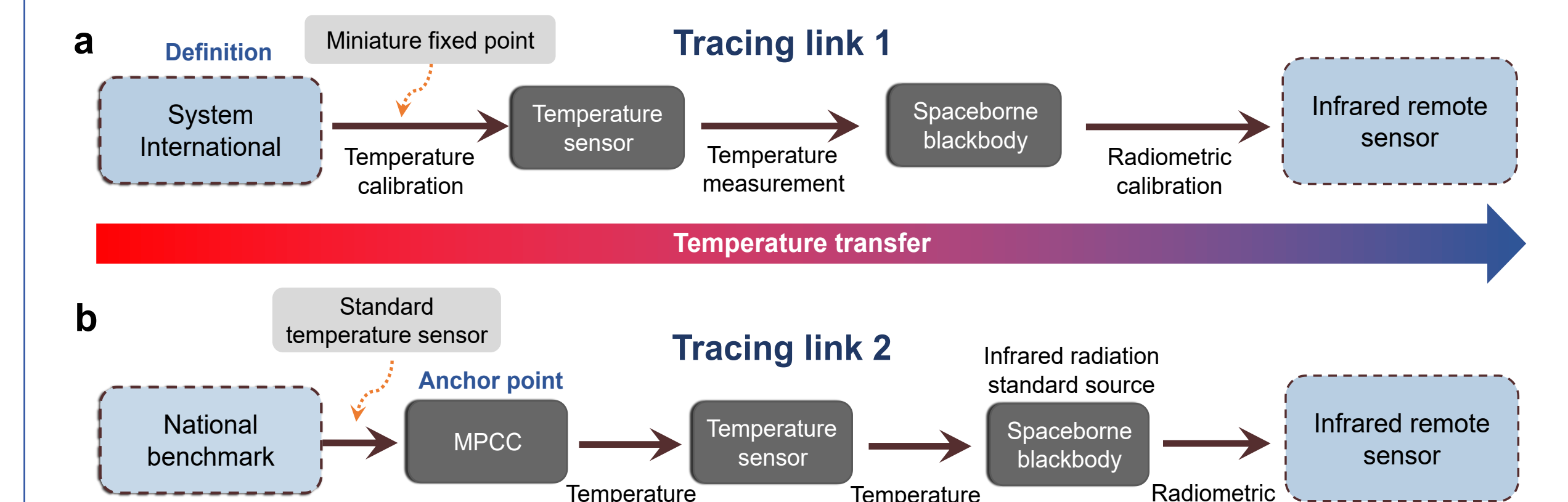


Fig. 3 Traceability link and calibration method. a Space benchmark traceability link. b Convenient spaceborne blackbody calibration link.

Conclusion

In summary, we demonstrated the latest generation of spaceborne blackbody calibration technology based on MFPs. A small amount (<10 mL) of reference material was integrated into the blackbody radiation source as an absolute temperature reference. The spatial metric of the radiation source temperature parameter was achieved by reproducing the known characteristic temperature during the fixed-point phase transition. In our study, the traceability principle was highlighted. The near-site transfer mechanism under multiphysics field coupling was determined by numerical and experimental methods, and the spaceborne blackbody calibration method traceable to SI was proposed. The reliable characteristic temperature depended on the solid thermodynamic transfer properties with the thermodynamic stability of the solid-liquid phase state. Finally, in-orbit experiments successfully demonstrated the feasibility of the technique, with statistics showing typical consistent behaviour. This research, as the core technology of the Chinese Space-based Radiometric Benchmark, addresses the key problem of high quantification of infrared remote sensing load and responds to the requirements of the World Meteorological Organization (WMO) for the observation accuracy and stability of climate monitoring system. In the future, this technology can provide important technical support and reference for the new generation of in-orbit radiometric calibration, which is anticipated to become the benchmark for infrared observations in space.

References

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