A Novel Black Body for On-board Calibration

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Introduction

It is a basic requirement of space-borne infrared radiometers used as atmospheric sounders, sea surface temperature monitors, etc., that the data they produce are accurate for the whole mission lifetime, which may be many years. Typically, a major factor in achieving this is in flight re-calibration against an on-board black body. Such an on-board black body must have, as a minimum, a stable radiance, which ideally should be actively variable and calibrated (pre-flight) in terms of radiance and monitored in-flight.

The purpose of the TIFRI (Technology Innovations for Radiometer Instruments) project (supported by ESA contract no. 14328/00/NL/PA) is to design, build, test and radiometrically calibrate a new type of black body and its associated thermometry and electronics which, for a given mass and dimensions, has improved accuracy and long term stability or conversely for a given performance specification has lower mass and uses less power. Although the current instrument is a laboratory prototype, the choice of materials, processes and parts, the mechanical and electrical configurations and documentation are such that the transition to an instrument that is suitable for space flight, will be straightforward.

The TIFRI black body has been designed to have low mass, low operational power, high emissivity, and high accuracy as an infrared spectral radiance calibration source. It also has full active control of temperature, both above and below ambient, through the use of a peltier element, made possible because of the low mass.

For comparative purposes, we have chosen to design this prototype to meet the design goals (geometric and radiometric) of the HIRDLS (High Resolution Dynamics Limb Sounder) [1] atmospheric infrared radiometer, which was recently launched on the Aura mission. Similarly, all our performance targets are for an "end of life" (EOL) of 7 yrs.

Any black body can be considered as consisting of four major elements, see Figure 1. Each requires optimisation to meet the objectives of the TIFRI project and each is described briefly below.

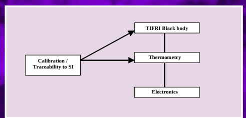


Figure 1: Schematic of the four major elements of the TIFRI project

Black Body

In order to produce a good radiance standard, a Planckian radiator of known temperature with an emissivity close to 1.000 is required. An ideal black body is one in which all the walls (back and sides) are at a uniform temperature so that the radiation escaping is fully characterised by the temperature of the small element of wall visible through the aperture as defined by the geometric viewing system used. In practice for real black bodies, this is difficult to achieve and made worse as the size of the exit aperture compared to the geometric size of the black body is increased.

The TIFRI black body design is based on a novel concept developed at NPL for the highest accuracy applications, [2, 3, 4]. This involves the creation of the effect of a large aspect ratio black body whilst only using a relatively simple black plate as the emitting source. The design principle underpinning this approach can be seen in Figure 2.

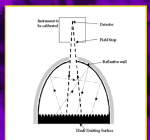


Figure 2: Reflective wall black body

A highly reflective hemisphere surrounds the black target. The instrument to be calibrated, through geometric considerations, can only view radiation originating from the black target. Since the internal walls of the hemisphere are highly reflective, via the reciprocity law, they have a very low emissivity. Thus radiation emitted by them and reflected from the black target makes an insignificant contribution to that emitted by the target due to its own temperature. Similarly, radiation emitted by the black target and incident on the walls will be reflected back onto the black target with little change to its spectral properties: i.e. it will still be Planckian and representative of the emissivity of the black target's surface temperature.

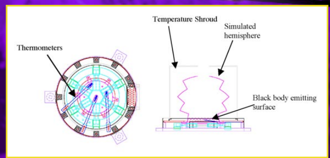
Advantages of this novel design include:

- low mass
- easier temperature control
- low power
- Faster temperature change

Simulated hemisphere reflective wall black body

Although the ideal hemisphere black body described above will give the performance required, its major limitation is that its physical size is still extremely large due to the need to position the walls of the hemisphere at a significant distance from the black emitting surface in order to get an appreciable gain in emissivity. However, NPL uses software based on Monte-Carlo simulations to design novel structures, which, by a careful selection of angles, can simulate the effect of a large hemisphere but in a more useful and compact size.

An example of such a design, the TIFRI black body, can be seen in Figure 3. This allows a relatively small black emitting surface to be used whilst gaining all the advantages of a large reflective hemisphere.



Schematic of the TIFRI black body design

Diamond turned reflective walls ("Sydney opera house" design)

TIFRI black body inside the temperature shroud

Figure 3: The TIFRI Black Body

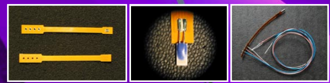
The TIFRI black body has an emissivity of >0.999, a mass of <300 g and a diameter of approximately 90 mm. (For comparison, the HIRDLS black body, which is a conventional black cavity, has a similar emissivity but a mass of ~700 g.)

Thermometry

Introduction

One of the objectives of the TIFRI project was to improve the sensing and measurement of temperature in black bodies and to seek alternative lower cost/lower mass options with potentially greater robustness than thermometers currently used in space. Seven models of IPRTs (Industrial Platinum Resistance Thermometers) from five different manufacturers were procured. Their strengths and weaknesses were assessed in the context of the goal to produce an overall system uncertainty of 10 mK at EOL of 7 yrs, which implies that the sensors should be reliable to 5 mK, at least over the central part of the range 200 K to 400 K.

Five examples of each model were repeatedly cycled, alternately to 130 °C and then - 75 °C to identify any hysterisis effects. Measurements were made of the resistances at the triple point of water (Rtp) after each temperature excursion, to test the stability of the sensors. In conclusion, the Heraeus Model M-FX 420 sensors (a thin film device) were identified as the best performers for the requirements of the TIFRI project. Eight of these sensors were then prepared for installation into the black body. This entailed connecting them to specially designed flexible printed circuit boards ('flexleads'); see Figure 4.



"Flexleads" *IPRT mounted on "Flexlead"* *"Flexlead" & IPRT assembly*

Figure 4: PRT and "flexlead" assembly

All eight sensors were subjected to preliminary cycling tests and Figure 5 shows the results of these. From these results, the best five sensors (probes 2, 3, 6, 7, 8) were chosen for calibration.

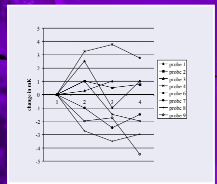


Figure 5: Results of the cycling tests for 8 M-FX 420 sensors mounted on 'flexleads'

Calibration of PRT's

The calibration procedure followed conventional NPL practice. Five temperatures, following the sequence 0.01 °C, 130 °C, 50 °C, 0.01 °C, - 40 °C, - 75 °C and 0.01 °C were used. The calibration sequence was carried out twice and is directly traceable to the NPL realisation of the International Temperature Scale of 1990, ITS-90.

Taking into account the measurement uncertainties and the repeatability of the two sets of calibrations, the overall uncertainty in the combined calibrations is estimated to be ± 2 mK at the triple point of water, and ± 5 mK at all other points (values at $k = 2$, giving 95% confidence).

These results and uncertainties are within the objectives set for the sensors for the TIFRI project. Finally, the best three examples were selected for installation in the black body, (as shown in Figure 3).

Temperature measurement performance goals

The following performance goals have been selected for the TIFRI temperature measurement electronics and are thought likely to meet or slightly exceed the requirements of the majority of Earth Observation radiometers for the next few years. Figure 6, shows an example of the electronics.

- 1 mK resolution and 5 mK accuracy from 200 K to 400 K under all operating conditions and for a mission duration of 7 years.
- The use of low frequency AC (rather than DC) can very effectively eliminate errors due to thermoelectric and other offsets. In addition, the AC technique also allows significantly better noise performance to be achieved compared with simple DC comparator techniques.
- Mass is clearly a major concern for any space instrument. The goal for the electronics unit is to demonstrate that a (nonredundant) flight unit could be built with a mass < 1 kg.
- Power is a further major concern. This is highly dependent on the black body heater/cooler and the operational environment. The following goals are proposed: 1 W without any heating/cooling and 10 W maximum (for short periods) with heating/cooling.

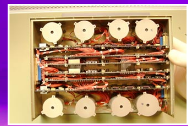


Figure 6: Example of TIFRI electronics

The HIRDLS design is a considerable improvement on its DC predecessors and the TIFRI design improves on HIRDLS in a number of ways as summarized in Table 1.

Parameter	HIRDLS	TIFRI
Resolution	2.5 mK (≈ 5 mohm, 17 bits)	1 mK (≈ 375 mohm, 19 bits)
EOL accuracy	200 mK (estimated)	5 mK (estimated)
PRT Rtp	500 ohm	100 ohm
PRT power (at 330K)	618 mW	31 mW
Reference resistor configuration	Single reference resistor	Three reference resistors
PRT cabling requirements	Requires special PRT cables	Quadrature compensation allows long capacitative PRT cables
PRT self-heating correction	Not possible: fixed PRT current	Possible: PRT current can set to x √2 by command
Power = 1.84 W	Power = 1.84 W (w/o black body heater)	Power = 1 W (estimated) (w/o black body heater)
Mass	Mass = 2230 g (dual unit)	Mass = 1000 g (estimated, single unit)

Table 1: Comparison of TIFRI and HIRDLS temperature measurement electronics

To date, most temperature measurement electronics for on-board black body calibrators for space flight have used some form of DC circuit incorporating an analogue-to-digital converter (ADC). Such a system is easiest to implement for PRTs having relatively high values of Rtp (e.g. 500 ohms), which tend to suffer more from thermal hysteresis effects than those having lower values, and is subject to thermoelectic effects due to temperature gradients across the circuit, offset drifts of op-amps, etc., and long-term changes in the ADC's voltage reference and internal resistive divider chain.

Conceptually, the temperature measurement electronics is an AC voltage comparator or bridge, which uses novel, miniature inductive voltage dividers (IVDs), the balance point of which represents the ratio of a reference resistor and a PRT. It is inherently immune to thermoelectic effects and offset drifts of op-amps. In addition, it is very suitable for use with PRTs having relatively low values of Rtp (e.g. 100 ohms) which tend to suffer less from thermal hysteresis than those having higher values.

A major factor in the development of the AC voltage comparator for space flight applications is the reduction of the mass of the instrument, also vibration, shock and reliability requirements make the use of mercury wetted relays. In addition, operation in vacuum and the space radiation environment had to be considered.

Inductive voltage dividers

The ratio transformer and the IVDs are multi-core devices, [5, 6, 7]. The cores are small (< 3 cm OD, typically a few x 10 g mass), high permeability, "clock spring" types.

The main advantages of such devices are as follows:

- The ability to be 'bootstrapped' so that they can present extremely high impedances.
- The ability to substantially correct errors due to the magnetising and core loss currents which has the effect of making them very close approximations to an ideal transformer or voltage divider.
- Voltage division without the introduction of transformer Johnson (thermal) noise.
- Extremely stable voltage division.

In addition, techniques to minimize the effects of vibration on the IVDs, particularly during launch, and to magnetically screen the devices have been developed. The construction of the ratio transformer is shown in Figure 7.

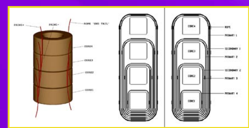


Figure 7: Construction of the ratio transformers

Peltier cooler/heater

Peltier devices are fitted to the base of the black body and can be commanded to heat or cool the black body to a specific temperature. An analogue PI heater control circuit is used to control the temperature. Temperature excursions of at least ±30 K from ambient (depending on conditions) with stabilities of better than 50 mK are possible. The power requirement is very dependent on the operating conditions but is expected to average <1 W.

Calibration Performance

Fundamental to the use of black bodies as calibration sources (as opposed to simply monitors of drift) is a knowledge and traceability to SI of its spectral radiance. Conventionally this has been carried out through the use of calibrated contact thermometers and a model/measurement of the spectral emissivity of the black body. This approach can be subject to many sources of error for large aperture black bodies, which include:

- Contact thermometer not measuring temperature of emitting surface
- Not operating in same conditions as calibration.
- Emissivity calculations can be prone to error for complex shapes
- Black coatings may not be uniform
- Anisotropy of temperature of BB not sampled by thermometers.

Therefore a final phase of the TIFRI project is to correlate the black body radiance as determined by contact thermometry with that of the more fundamental direct measurement of spectral radiance. This will be done using the NPL AMBER (Absolute Measurement of Black body Emitted Radiance) facility, [8]. As the title states, this measures the emitted radiance in a defined spectral band, using a radiometrically calibrated filter radiometer, rather than by calculation and thermometry. The facility obtains its traceability to the SI directly through radiometric standards in the form of a cryogenic radiometer (Figure 8), rather than through the ITS-90.

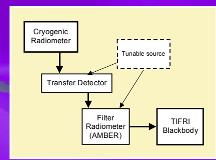


Figure 8: Traceability to SI through the Cryogenic Radiometer

The AMBER facility will be used to look at the performance of the TIFRI black body in both air and vacuum conditions. In addition, since the use of the AMBER facility itself is novel in concept, the performance of this technique will also be investigated and demonstrated through comparison of its use to measure other fixed-point black bodies, e.g. gallium freezing point (reference point of ITS-90). In this way, it can demonstrate the accuracy and convenience of its use for calibrating large area infrared spectral radiance sources and the ultimate traceability of the spectral radiance to SI units.

The AMBER facility should be able to achieve an absolute accuracy, directly traceable to radiance standards and not thermal, of around 25 mK at temperatures of 300 K and a resolution of around 1 mK

Conclusion

The innovations comprising the TIFRI black body offer a new alternative for the in-flight calibration of thermal infrared instruments. It offers low mass, low power with superior radiometric performance than conventional systems. The design concepts are easily transportable to any instrument requirement and similar versions have been developed for terrestrial applications where similar benefits can be found.

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Acknowledgements

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