The 2009 CEOS Comparison of IR Brightness Temperature Measurements in Support of Satellite Validation

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The measurement of the Earth's surface temperature is a critical product for meteorology and an essential parameter/indicator for climate monitoring. Satellites have been monitoring global surface temperature for some time, and have established sufficient consistency and accuracy between in-flight sensors to claim that it is of "climate quality". However, it is essential that such measurements are fully anchored to SI units and that there is a direct correlation with "true" surface/in-situ based measurements.

The most accurate of these surface-based measurements (used for Cal/Val) are derived from field deployed IR radiometers. These are in principle calibrated traceably to SI units, generally through a blackbody radiator. Such instrumentation is of varying design, operated by different teams in different parts of the globe. It is essential for the integrity of their use, to provide Cal/Val data for satellites both in-flight and to provide the link to future sensors, that any differences in the results obtained between them are understood. This knowledge allows any potential biases to be removed and not transferred to satellite sensors. This knowledge can only be determined through formal comparison, of the instrumentation, both in terms of its primary "lab based" calibration and its use in the field. If a fully traceable link to SI can also be established and demonstrated, this will ensure that the data will be robust and can claim its status as a "climate data record".

The "IR Cal/Val community" is well versed in the need and value of such comparisons having held highly successful exercises in Miami and at NPL in 2001 [1] and 2009 [2]. The overarching objective of these comparisons was "*To establish the "degree of equivalence" between surface based IR Cal/Val measurements made in support of satellite observations of the Earth's surface temperature and to establish their traceability to SI units through the participation of national standards laboratories".*

This objective was sub-divided into:

1) The evaluation of differences in IR radiometer primary calibrations (laboratory based), i.e.

   a. Comparison of reference standards used (blackbodies) and their traceability
   b. Comparison of the response of radiometers to common blackbody targets.

2) The evaluation of differences in radiometer responses when viewing a water surface target

3) The establishment of formal traceability for participant blackbodies and radiometers

This document provides a brief description of the activities of the most recent comparison/Workshop which took place in 2009. During the 2009 comparison, NPL acted as the pilot, supported by NIST and the Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami. NPL, the pilot, was responsible for inviting participants and for the analysis of data, following appropriate processing by individual participants. NPL, was the only organisation to have access and view all data from all participants. This data remained confidential to the participant and NPL at all times, until the publication of the draft report which showed the results of the comparison to participants.

Participants to the 2009 comparison included:

i. the STFC Rutherford Appleton Laboratory, Oxon, UK,
ii. the National Oceanography Centre, Southampton, UK,
iii. RSMAS, University of Miami, USA,
iv. the Institute for Meterology and Climate Research, Karlsruhe, Germany (KIT),
v. the Grupo de Observacion de la Tierra y la Atmosfera (GOTA), Spain,
vi. the Ocean Remote Sensing Institute, Ocean University of China, Qingdao, China,
vii. the Imaging Processing Laboratory (IPL), Universitat de Valencia, Spain and

viii. DLR, Remote Sensing Technology Institute, Germany.

All participants were asked to demonstrate independent traceability to SI of the instrumentation that they used, or make clear the route of traceability via another named laboratory. By their declared intention to participate in this key comparison, the participants accepted the general instructions and the technical protocols and committed themselves to follow the procedures strictly. Once the protocol and list of participants had been agreed, no change to the protocol or list of participants was made without prior agreement of all participants. The protocol covered a number of individual comparisons. Each comparison had its own specific characteristics but all comparisons, in principle, took the same form i.e. they observed a common entity. Where required, demonstrable traceability to SI was obtained through the participation of NIST and NPL as pilot.

The laboratory calibration comparison exercise consisted of two separate comparisons:

i. **Comparison of the participants' black bodies.** In this comparison, the black bodies provided by participants were compared relative to a reference blackbody using a well-characterised transfer standard radiometer. The transfer radiometers used was the NPL AMBER facility which set to measure the radiance temperature of the blackbodies for a wavelength of 10.1 µm and the NIST TXR infrared radiometer which is was set to operate on its 10 µm channel. The comparison was performed at three nominal temperatures: 283 K, 293 K and 303 K.
ii. **Comparison of the participants' radiometers (laboratory).** In this comparison all participant radiometers were compared to a reference blackbody calibrated traceable to SI. The reference black bodies used were the NPL variable temperature blackbody (VTBB) and the NIST Water bath blackbody (WBBB). Both reference blackbodies, were well-characterised, had high spectral emissivity and had an aperture sufficiently large to accommodate the field of view of all the participating radiometers. The reference black bodies were set to a fixed known temperature and then viewed by all radiometers. Measurements were performed at nominal temperatures of 278 K, 283 K, 293 K and 303 K, or a subset of these determined by time or other constraints.

Laboratory measurements of participants' blackbodies consisted of:

i. The transfer radiometers used to view the participants blackbodies were calibrated traceable to NPL and NIST primary scales prior to use. The NPL AMBER radiometer was used for the laboratory measurements at NPL, while the NIST TXR radiometer was used for the laboratory measurements at the University of Miami.
ii. The transfer radiometers were mounted so that they can be easily aligned to be coaxial to the participant blackbodies. Care was taken to avoid significant reflections or emissions from the transfer radiometer into the black body under test.
iii. Participants set their blackbodies to the nominal temperature specified by the pilot and indicated to the pilot when the blackbodies had reached equilibrium.
iv. Participants provided to the pilot the brightness temperature of their blackbody, together with the associated uncertainty, at different times during the measurement period. This allowed drifts in the brightness temperature of the blackbodies to be accounted for.
v. The operators of the transfer radiometers recorded the readings of their radiometers continuously during the 10 minute period over which each blackbody was being monitored. The operators of the transfer radiometers also recorded the identity of the participant and the information supplied by the participant.
vi. Data were given to the Pilot on a form provided.
vii. The process was repeated for each of the three nominal temperatures.
viii. The sequence was then be repeated for all temperatures to assess reproducibility.

Laboratory measurements of participants' radiometers consisted of:

i. The reference blackbodies used to be viewed by the participants' radiometers were calibrated traceable to NPL and NIST primary scales prior to use.
ii. Each participant radiometer was mounted so that it could be easily aligned to the reference black body.
iii. The reference blackbody was set to one of the nominal temperatures specified in the protocol. (NB, this was not necessarily the exact temperature, so as to ensure "blindness" to participants).
iv. Each participant radiometer was aligned to view the reference blackbody and when they are ready, make at least ten measurements of the brightness temperature of the blackbody over the 10 minute monitoring period. This information was recorded and unless it needed further processing, provided to the pilot as the results of the measurement.
v. The pilot recorded the actual temperature of the reference blackbody and any drift, which could have occurred during the time period of each participant's measurements, together with the results from the participant.
vi. The above process was repeated for all four blackbody temperatures specified in the protocol.
vii. Data were given to the Pilot on the form provided.

The evaluation of differences in radiometer responses when viewing a sea surface target consisted of:

i. Each participant radiometer mounted on the RSMAS pier and aligned to view the area of the sea indicated by the pilot. This target location was be chosen to allow comparisons to be made at a range of view angles.
ii. The "clock" of each participant was synchronised to that of UTC.
iii. Following an indication from the pilot, each participant started measuring the temperature of the target and recorded its viewed brightness temperature (Water and Sky as correction) at time intervals to suit each radiometer. The effective time of each observation was clearly indicated in the data given to the pilot.
iv. Measurements were also taken during night-time under unattended operation.
v. The host (RSMAS) collected measurements of meteorological data, time stamped during this process.
vi. After completing the above measurement sequence, participants carried out the necessary post processing e.g. sky brightness correction etc before they submitted the final results to the pilot, which included processed Water Surface Temperature (WST) values.
vii. The results were not be discussed with any participant other than the pilot until the pilot gave permission.

The 2009 Workshop took place in two stages, at two locations, at NPL and at the at the Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami, in order to allow maximum participation and to enable the traceability chain to be established to both NPL and NIST. NPL provided traceability to SI units during the laboratory comparisons in Europe while NIST provided traceability to SI units during the laboratory measurements at RSMAS. During the entire Workshop, NPL acted as the pilot laboratory but was supported by NIST and RSMAS who were acting as hosts during measurements in the USA.

Stage 1 took place at NPL in April 2009 and involved laboratory measurements of participants' blackbodies calibrated using the NPL reference transfer radiometer (AMBER). The performance of four blackbodies of four participants was evaluated during this part of the Workshop. Figure 1 shows the AMBER radiometer measuring the radiance temperature of the participants' blackbodies during the 2009 Workshop at NPL. Laboratory measurements of participants' radiometers using the NPL Variable Temperature Blackbody were also performed during this part of the Workshop. The performance of 8 radiometers operating on 24 measurement channels was compared during Stage 1. Figure 2 shows the ISAR radiometer monitoring the temperature of the NPL reference blackbody during the 2009 Workshop.

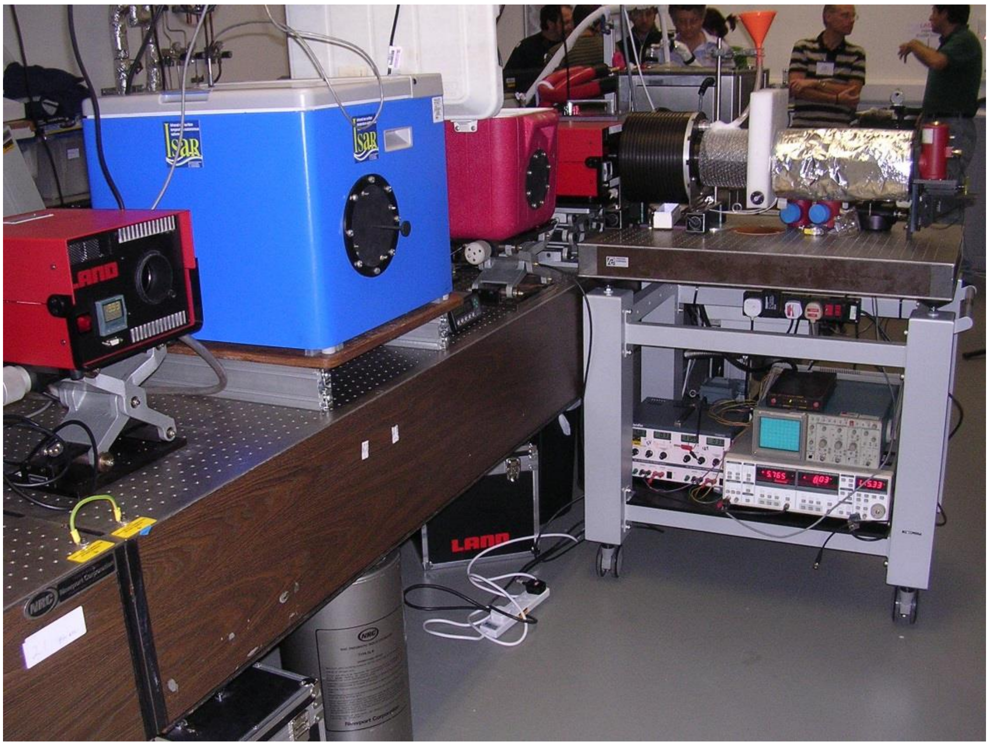

Figure 1: The AMBER radiometer measuring the radiance temperature of the participants' blackbodies during the 2009 Workshop at NPL.

Figure 2: ISAR radiometer (on the left) monitoring the temperature of the NPL reference blackbody during the 2009 Workshop.

Stage 2 of the 2009 Workshop took place at RSMAS in May 2009 and involved a similar procedure to stage 1, except that laboratory measurements of participants' blackbodies were done using the NIST Thermal-Infrared Transfer Radiometer (TXR), while laboratory measurements of participants' radiometers were calibrated using the NIST Water Bath BlackBody (WBBB). The performance of 9 radiometers operating on 14 measurement channels was compared during Stage 2. Figure 3 shows the NIST TXR radiometer monitoring the temperature of the Southampton University blackbody during the 2009 Workshop. Figure 4 shows the ISAR and SISTER radiometers being tested during stage 2 of the 2009 Workshop

Figure 3: The NIST TXR radiometer monitoring the temperature of the Southampton University blackbody during the 2009 Workshop.

Figure 4: The ISAR and SISTER radiometers being tested during stage 2 of the 2009 Workshop

Table 1 summarises the difference between the radiance temperature of the blackbodies measured by AMBER and the temperature stated by the participants during two runs measured at NPL on the 21st and 22nd of April 2009. The first two blackbodies (RAL and Southampton University) were water bath blackbodies and their measurements are in "error" by less than 20 mK, whereas the temperature of the last two blackbodies (GOTA and Valencia University) was electrically controlled and they exhibited differences below 200 mK. Table 2 summarises the difference between the radiance temperature of the NPL VTBB and the temperature measured by the participants during two runs measured at NPL during the 2009 Workshop. All participants, except RAL measure larger differences, as the temperature of the VTBB decreases. The agreement of radiometers which include internal blackbodies is much better than radiometers which do not.

Table 1: Difference between the radiance temperature of the blackbodies measured by AMBER and the temperature stated by the participants during two runs measured at NPL on the 21st and 22nd of April 2009.

Participant	Set temperature °C	Temperature "error" 21st April run mK	Temperature "error" 22nd April run mK
RAL	30	14	6
Sister	20	-8	-5
	10	-15	-14
Southampton	30	-7	3
ISAR	20	-16	-14
	10	-19	-18
GOTA	30	-176	-188
La Laguna Univ.	20	-152	-181
Canary Island	10	-164	-177
Valencia Univ.	30	-167	-185
LAND P80P	20	-143	-166
	10	-74	-87

Table 2: Difference between the radiance temperature of the NPL VTBB and the temperature measured by the participants during two runs measured at NPL during the 2009 Workshop.

	Set Temperature °C	NPL VTBB 1st measur. mK	NPL VTBB 2nd measur. mK
RAL	30	-24	
SISTER	20	-25	-33
	10	-16	-19
	5	-6	-23
Southampton	30	6	
ISAR	20	126	28
	10	87	69
	5	77	
OUC	30	59	48
ISAR	20	94	64
	10	145	136
	5	237	279
KIT	30	190	152
Heidronics	20	30	
KT - 15	10	-208	
	5	-632	

	Set Temperature °C	NPL VTBB 1st measur. mK	NPL VTBB 2nd measur. mK
Canary	30	87	
10.65 µm	20	199	139
	10	204	185
	5	243	
IPL	30	333	-178
CE312-2	20	150	240
10.57 µm	10	716	655
	5	888	
Valencia	30	66	
CE312-1-Unit 1	20	82	101
10.8 µm	10	140	145
	5	208	
Valencia	30	104	
CE312-1-Unit 2	20	204	168
10.8 µm	10	289	237
	5	328	

Stage 2 of the 2009 Workshop included the testing of the same radiometers alongside each other, located on the RSMAS pier, completing direct day-time and night-time measurements of the skin temperature of the sea. Figure 5 shows participants' radiometers measuring the SST from the pier at Miami University during the 2009 Workshop.

Figure 5: Participants' radiometers measuring the SST from the pier at Miami University during the 2009 Workshop. From the left to right, the radiometers of the University of Laguna, MAERI, ISAR and SISTER radiometer can be seen.

SST measurements from the Miami University pier were completed between Tuesday 12th of May and Thursday 14th May. Day-time and night-time measurements were completed, as well as measurements under "clear sky" and under cloudy conditions. Some radiometers provided SST measurements at more than one angle. Due to reliability issues, not all radiometers were able to operate continuously, hence there are gaps in the SST measurements of some participants. Figure 6 shows SST measurements taken by the four continuously-reading radiometers from about 16:00 UT on May 12th to about 17:00 UT on May 13th. Figure 7 shows the difference in the measurement of SST of all the radiometers relative to the measurements taken by the ISAR radiometer, the radiometer which was able to provide measurements during the entire observation period.

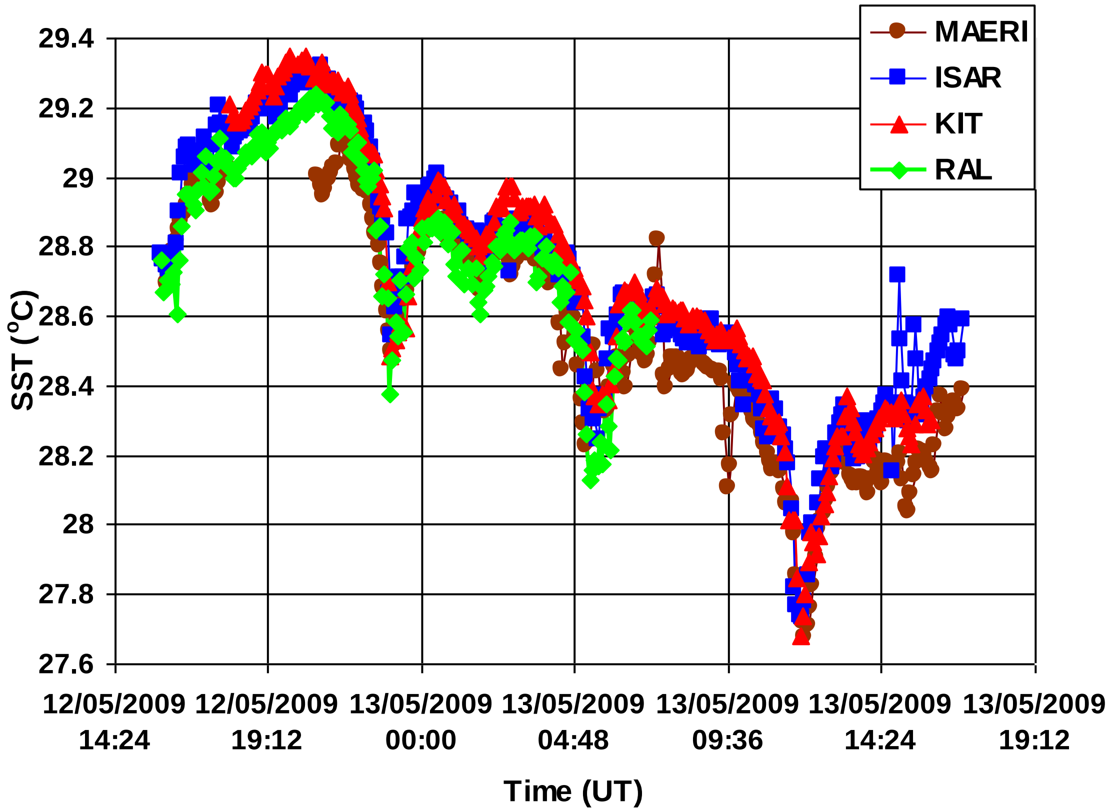

Figure 6: SST measured by the four continuously reading radiometers from about 16:00 UT on May 12 th to about 17:00 UT on May 13 th.

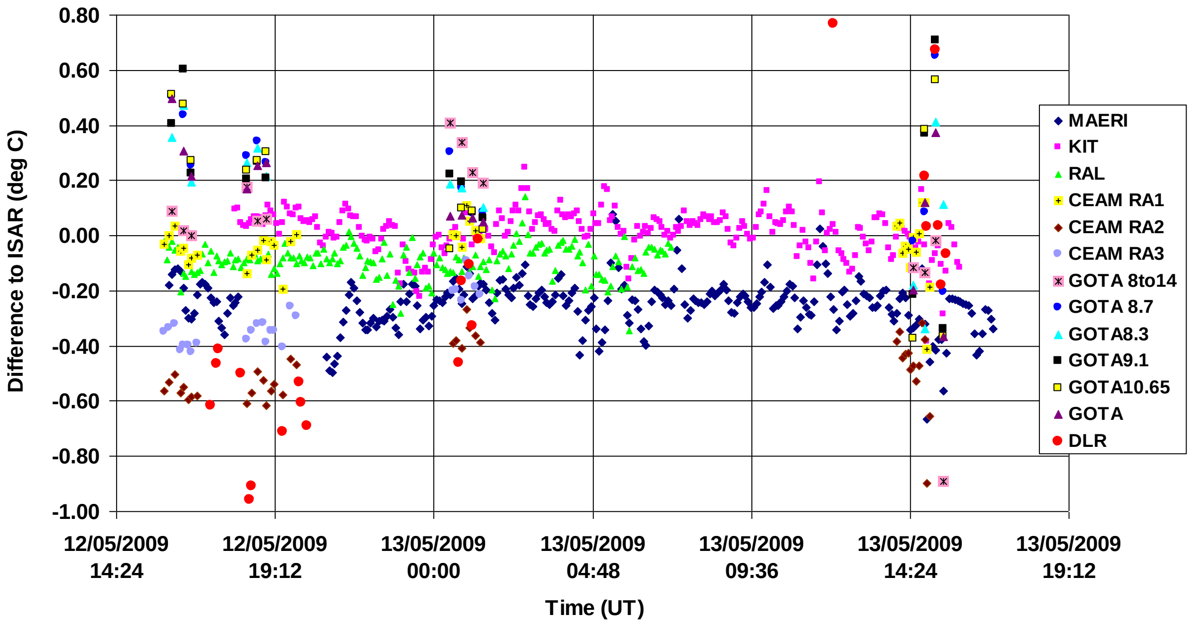

Figure 7: Difference in the measurement of SST of all the radiometers relative to the measurements taken by the ISAR radiometer taken during the 2009 Workshop.

Both AMBER and the NPL variable temperature blackbody are not readily portable, so they were not taken to RSMAS. For similar reasons, the NIST TXR and WBBB were not brought to NPL. Linkage between the two stages was established though participants radiometers used in both stages, serving as transfer standards.

The uncertainty of measurement was estimated according to the *ISO Guide to the Expression of Uncertainty in Measurement* (QA4EO-CEOS-DQK-006). In order to achieve optimum comparability, a list containing the principal influence parameters for the measurements and associated instrumentation was given to the participants. The participating laboratories were encouraged to adapt the list to their instruments and procedures. All uncertainty values were given as standard uncertainties, in other words for a coverage factor of $k = 1$. Figure 8 shows the plot of the mean of the differences of the radiometer readings from the temperature of the NPL variable temperature blackbody (blue circles), maintained at a nominal temperature of 10 °C. The uncertainties are clearly indicated. The red squares show the points corresponding to the RSMAS blackbody [2]. Figure 9 shows the plot corresponding to a blackbody temperature of 30 °C.

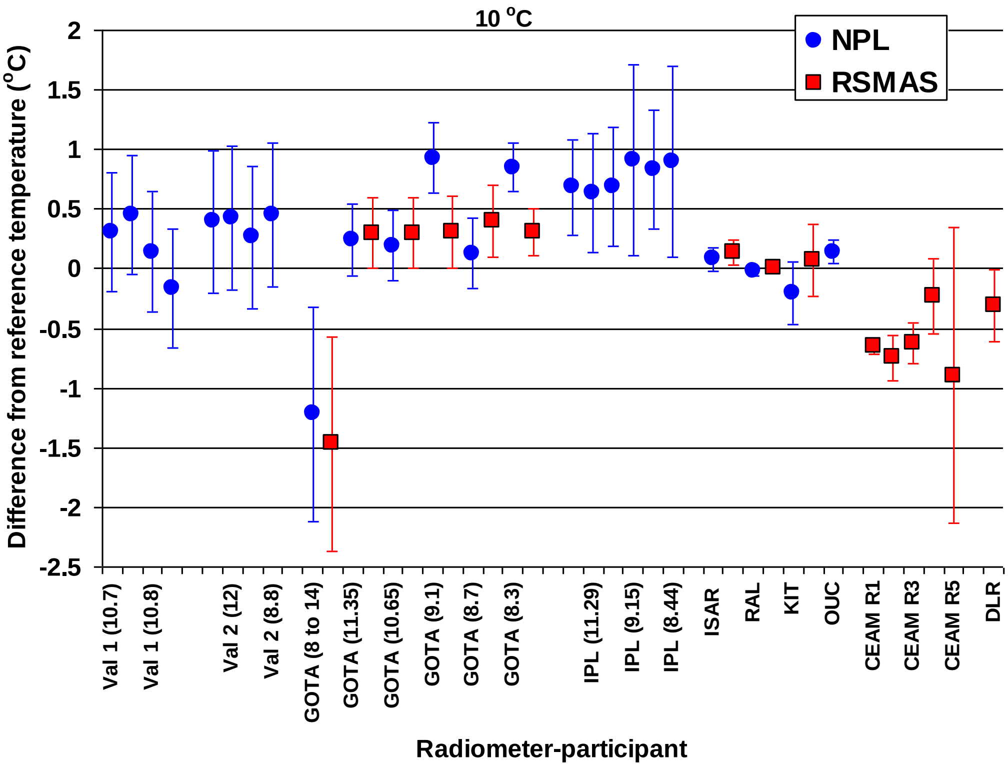

Figure 8: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL variable temperature blackbody (blue circles), maintained at a nominal temperature of 10 °C. The red squares show the points corresponding to the RSMAS blackbody.

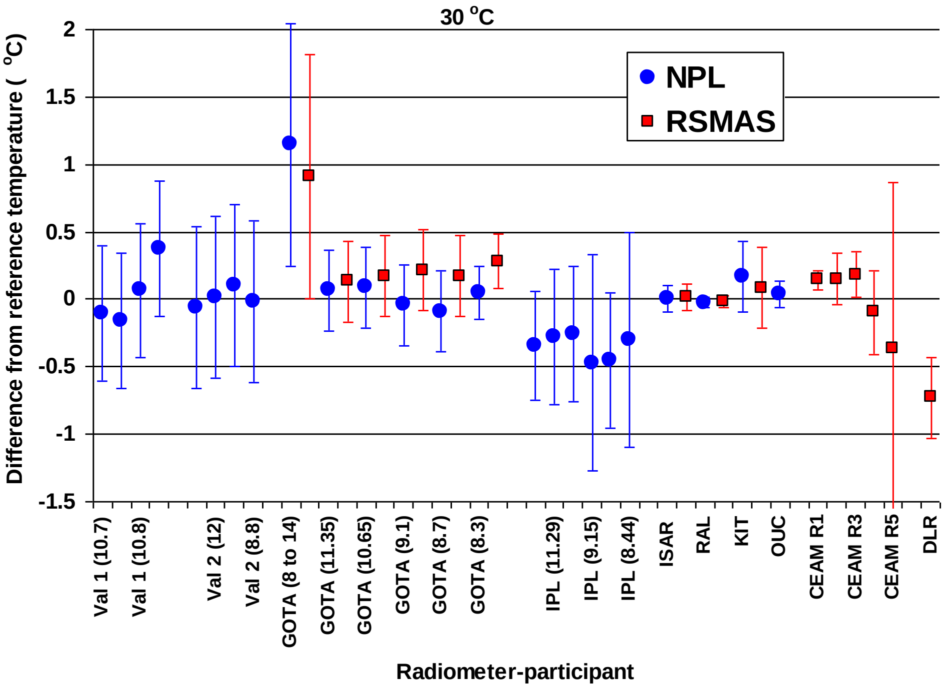

Figure 9: Plot of the mean of the differences of the radiometer readings from the temperature of the NPL variable temperature blackbody (blue circles), maintained at a nominal temperature of 30 ºC. The red squares show the points corresponding to the RSMAS blackbody.

Finally, Figure 10 shows the participants of the 2009 Workshop posing on the pier at Miami University at the end of the 2009 comparison.

Figure 10: Participants of the 2009 Workshop on the pier at Miami University

REFERENCES

1. Barton, I. J., Minnett, P. J., Maillet K. A., Donlon, C. J., Hook, S. J., Jessup, A. T. and Nightingale, T. J., 2004," The Miami 2001 infrared radiometer calibration and intercomparison: Part II Shipboard results", *Journal of Atmospheric and Oceanic Technology*, 21, 268-283.

2. Theocharous, E., Usadi, E. and Fox, N. P., "CEOS comparison of IR brightness temperature measurements in support of satellite validation. Part I: Laboratory and ocean surface temperature comparison of radiation thermometers", NPL REPORT OP3, July 2010