Cross-Calibration Status: Mid-Mission Report

Version 1.2 [external]
SAI/97-041/Dc
June 17, 1997

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ISO Calibration Laison

Abstract

The status of cross calibration observations and their analysis as of approximately half way through the ISO mission is presented in order to show the level of agreement among the calibrations of the ISO instruments. Both internal (among ISO instruments) and external (between ISO instruments and other data sets, primarily IRAS and COBE-Dirbe) cross calibrations are considered. This paper is concerned specifically about absolute flux calibration; wavelength calibration is not specifically addressed here. Overall agreement among the major instrument modes is comparable to pre-launch expectations for $\lambda \lesssim 50\,\mu$m and somewhat worse at longer wavelength, where, however, the analysis is incomplete and based on relatively weak sources. Overall calibrations have improved sinificantly since our first report (May 96) and are expected to continue to improve in the coming few years.

1 Introduction: What are Cross-Calibrations?

Cross-calibrations can be used (i) as consistency checks, and (ii) as true calibrations. In the first instance observations of a source by a pair of instruments are compared to ensure consistency: if the results do not agree (to within the stated uncertainties) then the calibration procedure of one of the instruments (though possibly both) is incorrect. If the results are consistent, then it is usually assumed that both are correct. In the second instance, results from the less accurate instrument(s) are calibrated with data from the more accurate one(s), in which case this is straight calibration.

In the case of ISO, the above concept can be applied both to pairs of ISO instruments that overlap in wavelength range, and also to ISO instruments vs. other instruments, e.g. IRAS, COBE-Dirbe or MSX-Spirit III. In all cases the comparison must ensure proper handling of differences in beam sizes, filter profiles, spectral resolution, and differing absolute calibration systems.

The absolute flux calibration of three of the four ISO instruments (CAM, PHT, and SWS) is based primarily on results of the Ground-Based Preparatory Programme (GBPP, Jourdain de Muizon & Habing 1992) and of the Cohen, Walker, Witteborn et al. (CWW) absolute calibration programme (Cohen et al. 1992a, Cohen et al. 1992b, Cohen et al. 1995), though the long wavelength filters of PHT also use planets and asteroids to cover the bright and intermediate part of their dynamic range, and while the absolute flux calibration of LWS is currently based on Uranus alone[1]. Both the GBPP and the CWW are based on stars, and are entirely consistent with one other.

[1] At the time of writing, observations of Neptune have been obtained, and observations of Mars are being planned. The LWS absolute calibration will be revised with those results.

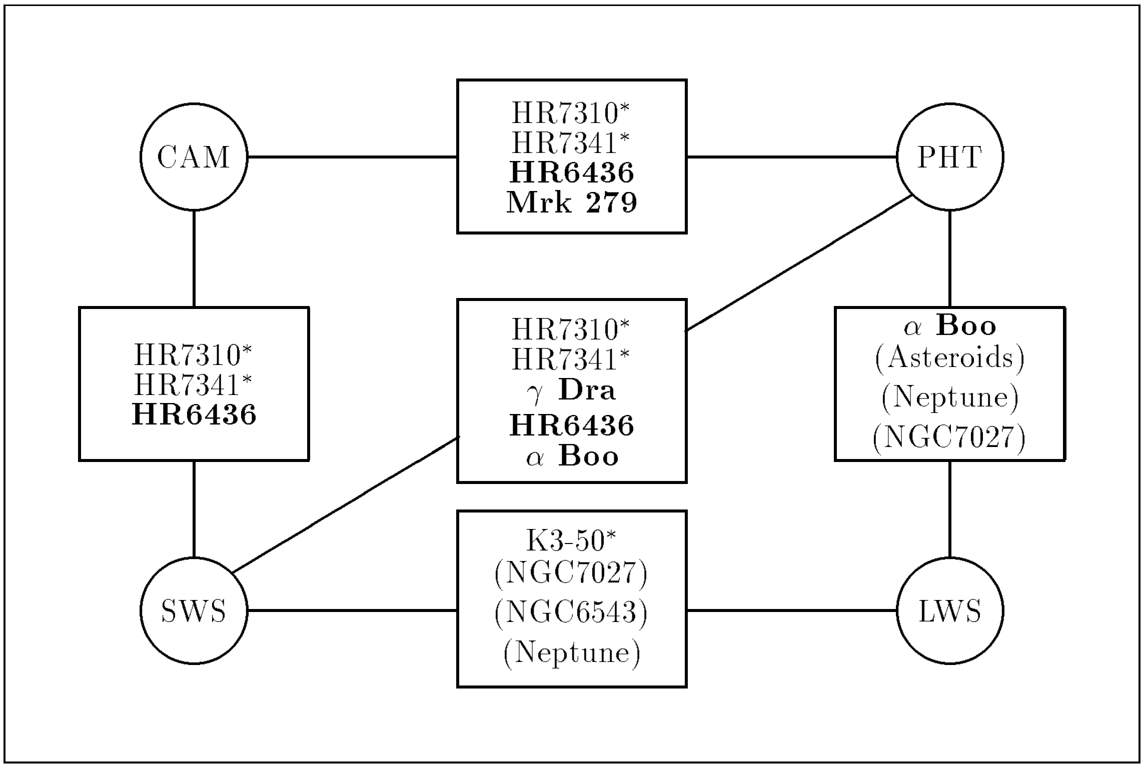

Figure 1: Cross-calibration diagram for photometric measurements. Sources marked with an asterisk were originally analysed in Paper I; for the sources in parentheses either the observations are planned, or the analysis is still in progress.

For CAM, PHT, and SWS, calibration consistency at wavelengths $\lesssim 100\,\mu$m is essentially implicit: the instruments teams select a few reference stars on which to base their calibration, then check the calibration against those stars and also against other stars in the system. If there is agreement then calibration consistency is satisfied implicitly. This is in fact exactly what happens with wavelength calibration, and the wavelength calibration programmes have been so successful that cross-calibration in wavelength is not normally seen as necessary.

At wavelengths $\gtrsim 100\,\mu$m the situation is more complicated as not only stars, but also asteroids and planets are used in the calibration. While the results of the CWW and the GBPP programmes are believed accurate to $\pm 5\%$ or better, the uncertainties in asteroid and planet model spectral energy distributions is larger, and in the case of the asteroids it is additionally complicated by their variability. It follows that **the most critical part of the the cross calibrations is ensuring that the LWS calibration is consistent with the other instruments.** This is also the most difficult part as the link has to be made through PHT, and as the dynamic range overlap between PHT and LWS is limited.

The verification is performed as much as possible by selecting suitable sources, observing them, and comparing the results: these are expected to agree to within each instruments' declared uncertainties. In those cases where a model is available for the source, the results are compared also to the model. For each pair of instruments the comparison should be carried out for both extended and point-like sources, it should cover the full range of wavelength overlap, and also significant part of the dynamic range overlap.

While apparently a straightforward process, in practice there are a number of difficulties involved in the comparison: different instrument apertures, differing filters (even the "common" filters, while similar, are significantly different), different resolving powers, and limited common dynamic range (especially between the photometers and the spectrometers). But the main difficulty is that **global uncertainties are not yet well defined for all instruments,** and thus the current result of the comparison is mainly a statement of the magnitude of the deviation between the observations and the models, or, in a few cases, between the observations of a pair of instruments.

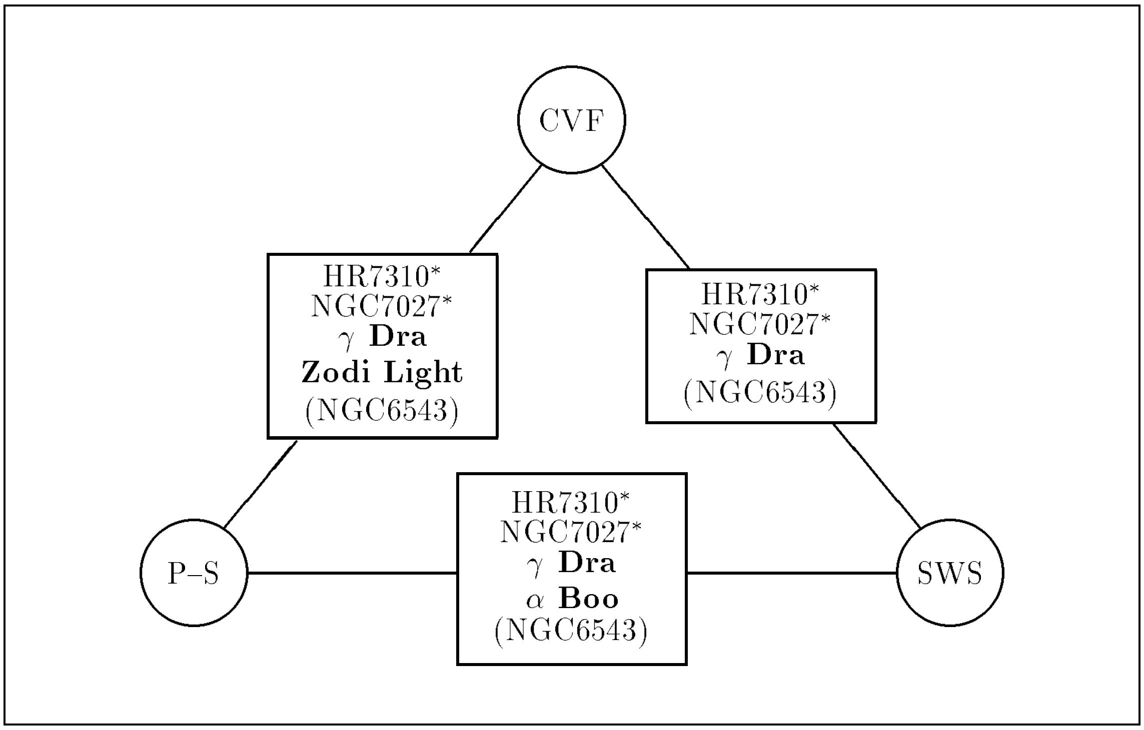

Figure 2: Cross-calibration diagram for three spectrometers; LWS is not included because of the lack of wavelength overlap. Sources marked with an asterisk were originally analysed in Paper I; for the sources in parentheses either the observations are planned, or the analysis is still in progress.

A first cross calibration check (Moneti et al. 1996, henceforth Paper I) was performed on data obtained primarily during PV and reduced with an early version of the instruments' "Interactive Analysis" packages and with early calibration files. While the main results were acceptable (peak-peak scatter of $\lesssim \pm 30\%$ for $\lambda \lesssim 50\,\mu$m, and good agreement with IRAS), that analysis concentrated primarliy on bright point sources, and it was clearly recognized that cross calibration on faint and on extended sources is also necessary. Also, many observations in Paper I were obtained with the Calibration Uplink System rather than with the standard AOTs, the standard user modes.

In this paper we will present observations of six more sources, including two more IR flux standards, a third star, and two fainter sources from the science program (Mrk 279 and the Zodiacal light). As the data on the latter two sources is proprietary, the data will not be shown, though we acknowledge the owners of those data for allowing us to use it here. All processing is performed with recent versions of the analysis packages or is based on standard products derived from AOT observations.

2 The Cross-Calibration Requirements

Cross-Calibration requirements have been identified in Chapter 7 of the In-Orbit Calibration Requirements Document (IOCRD, original ref.: ISO/SSD-9003; SOC ref.: SAI/94-1320/Dc), and they are summarised in Table 1 which, for completeness, also indicates the status of verification: the columns "Obs.", "Red.", and "An." indicate with "Y" or "N" whether observations have been performed, the data reduced, and the analysis completed. A "P" in the "Obs" column indicates that the observations are planned.

Table 1: Cross-calibration requirements

Title	Obs.	Red.	An.
PHT filters vs. SWS spectra	Y	Y	Y
PHT filters vs. LWS spectra	Y	P	P
CAM filters vs. SWS spectra	Y	Y	Y
CAM filters vs. PHT filters	Y	Y	Y
CAM-CVF spectra vs. SWS spectra	Y	Y	Y
CAM-CVF spectra vs. PHT-S spectra	Y	Y	Y
SWS spectra vs. PHT-S spectra	Y	Y	Y
SWS spectra vs. LWS spectra	Y	Y	Y
CAM vs. IRAS photometry	Y	Y	Y
LWS vs. IRAS photometry	Y	Y	Y
PHT vs. IRAS photometry	Y	Y	Y
SWS vs. IRAS photometry	Y	Y	Y
CAM vs. COBE photometry	Y	Y	Y
PHT vs. COBE photometry	Y	Y	Y

Each requirement calls for verifying the consistency of the absolute flux calibration and, where appropriate, the wavelength calibration of each pair of instruments with overlap in wavelength range. For each instrument, only the most important modes are considered, and the task of cross-calibrating the different modes of each instrument is part of each instrument's calibration program. In the case of PHT and CAM, PHT-S and CAM-CVF are considered separate instruments when it comes to spectral cross-calibration with SWS.

The sources observed for Cross-Calibration analysis are best seen in Fig. 1 and 2, which we refer to as the "Cross-Calibration diagrams" for the photometers and for the spectrometers, respectively, though the latter does not include LWS because of the lack of overlap in wavelengths with the other two. In these figures the box between each pair of instruments lists the sources observed for cross-checking the results of that instrument pair. The sources in bold (γ Dra, α Boo, HR6436, Mrk 279, and the Zodiacal light) are the ones addressed in this paper.

3 Observations and Processing

3.1 γ Dra

γ Dra (HR6705) is a bright K5III star, well observed, located in a region of the sky that is accessible throughout the mission, and thus was chosen as a primary calibrator for PHT and SWS. As such it is important that measurements by different instruments be consistent, even though, being a calibrator, the results will not check that the calibration is transfered properly to scientific targets. γ Dra was observed with SWS, all three PHT subinstruments, and CAM-CVF. Full details of the observations and of the data processing are presented in a dedicated report (Breitfellner et al. 1997, http://isowww.estec.esa.nl/instr/ISO/XCAL/HR6705_24.html, henceforth Paper II), and the main points are repeated here for completeness.

PHT filter observations of source and background were obtained with P03 and P22, using all PHT filters, and using the standard apertures; ERD-level data were processed with PIA 5.4, and were then background subtracted and color corrected using the correction tables prepared by PHT IDT. A PHT-S spectrum obtained on Rev. 57 (i.e., during PV phase); no reference background was observed in this case. The data were processed with PIA 5.0 starting from ERD; the relative spectral response function (RSRF) was determined from several standard stars.

A full SWS spectrum was obtained on Rev. 377 (27/Nov/96) using AOT1, speed 4. The data were processed to SPD level by OLP, and further processing was done with SIA. This processing included re-aligning the different scans of each "AOT-band" to the same mean level, and rebinning the final result to a resolving power of ~ 400.

Two CAM-CVF scans were obtained with the LW CVF (9—16.5 μm), one along increasing and one along decreasing λ, and sampling every other CVF resolution element. The results were processed with CIA, averaged, and corrected with a RSRF derived from HIC94890, HIC96441 and delta Draconis which are between 7 and 70 times fainter than γ Dra itself.

Note that all processing was carried during or before March 1997, thus all results reflect the status of the calibration files at that time. In Fig. 3 the ISO observations are compared to the CWW composite spectrum ($\lambda \lesssim 20\,\mu$m) and the CWW extrapolation ($\lambda \gtrsim 20\,\mu$m), which we use as reference; the dashed lines parallel to the CWW reference are displaced by $\pm 0.2\times$; all data are presented in a $\lambda^4 F_\lambda$ vs. λ plot in order to show clearly the differences.

Overall agreement is within $\pm 20\%$ of the reference, and is for the most part within the expectation for the early part of the mission. The largest deviations in the PHT photometry are at 15 and 25 μm, and beyond 90 μm. At the shorter wavelengths the discrepancy reflects the fact that these are among the first measurements performed in the sequence, and they suffer from significant drifts, which have been only partially corrected. At the longest wavelengths, one must note that the source is very faint, indeed fainter than the background, and that the P22 sequence used is not the correct one to use because of the long delay between source and background observation. The PHT-S results show important deviations at the beginning and end of its spectral range; these are ascribed primarily to detector transients, for which no correction has been applied, and partly to the RSRF, which is not finalised. The largest SWS deviation occurs at 10—15 μm and the error has been traced to the RSRF, which at the time of the analysis was determined from laboratory observations, and which is now being improved with on-orbit data. Finally, the CAM-CVF results are the ones the show the best agreement, with deviations being within just a few percent of the reference.

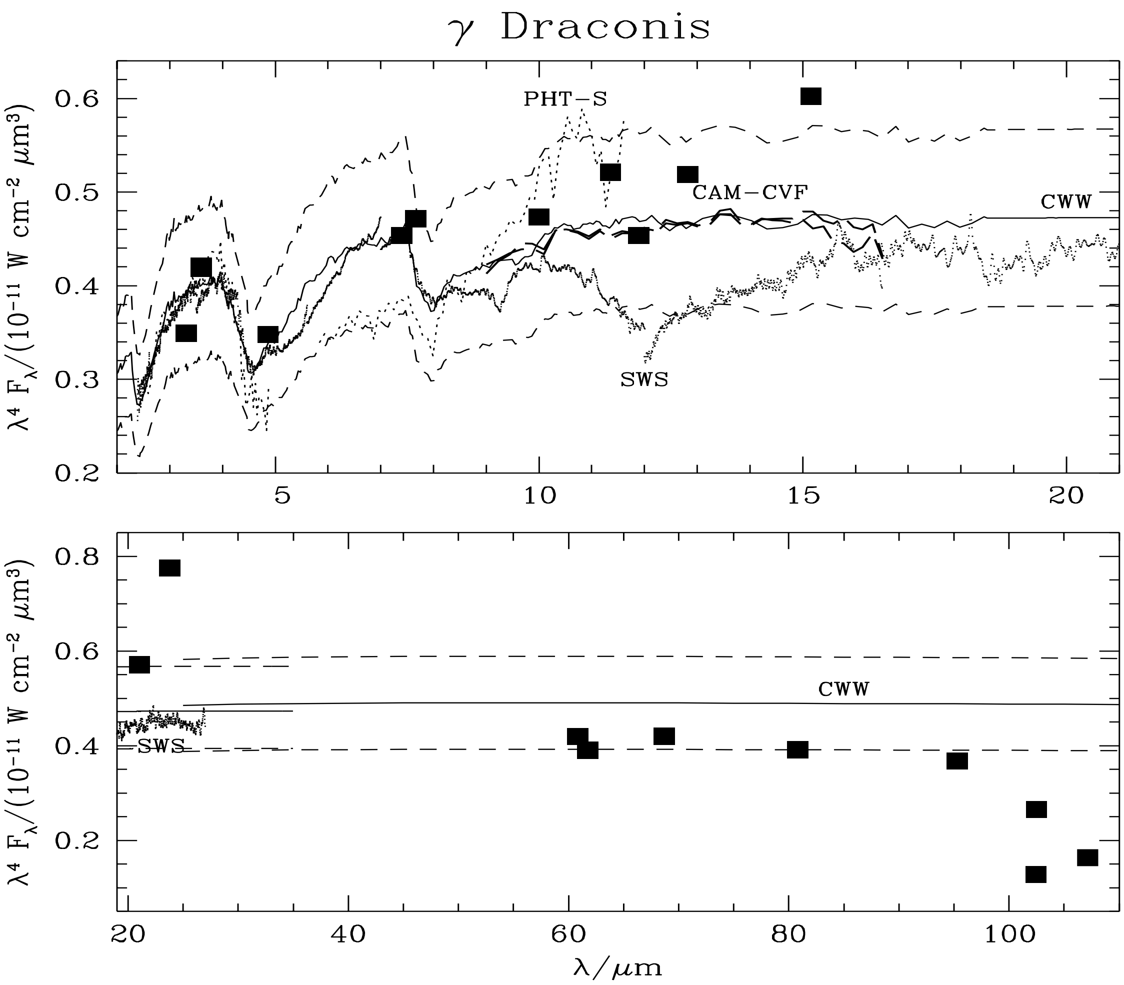

Figure 3: Comparison of ISO observations of γ Dra with CWW composite and with IRAS PSC. Full line: CWW composite and model; thin dashed lines: CWW composite $\pm 20\%$; dense dots: SWS spectrum; thin dots: PHT-S spectrum; thick dashed line: CAM-CVF spectrum; squares: PHT-P and C photometry.

The IRAS PSC fluxes are not shown in Fig. 3 so as not to overcrowd it; they lie very close to the CWW spectrum (see Paper II), and thus are in good agreement with the ISO data.

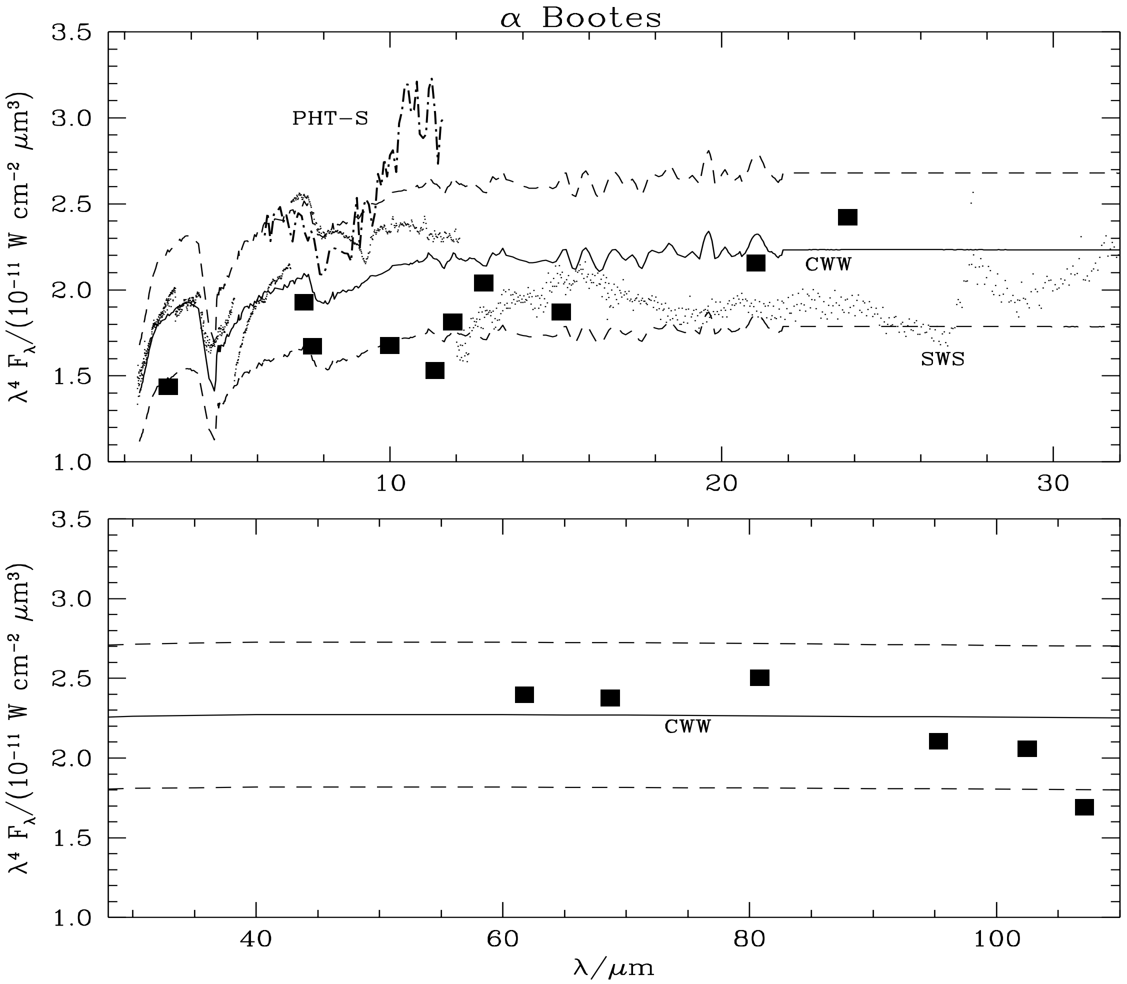

Figure 4: Comparison of ISO observations of α Boo with CWW spectrum. Full line: CWW composite and model; thin dashed lines: CWW composite $\pm 20\%$; dots: SWS spectrum; dot-dash line: PHT-S spectrum; and squares: PHT-P and C photometry.

3.2 α Boo

The star α Boo (HR5340, Arcturus, spectral type K2III) is a widely used IR calibrator. It has been observed extensively by ISO, though not so regularly as γ Dra, because of visibility constraints, and is about a factor of 10 brighter than γ Dra. Because of its brightness it comes close to saturating PHT-P detectors at $\lambda \lesssim 10\,\mu$m. At long wavelengths, on the other hand, α Boo is moderately weak for PHT and *very weak for LWS*. In fact α Boo is far from being an ideal source for comparing LWS and PHT calibrations, and new observations have been obtained which will give much clearer results. Nevertheless it is useful to compare LWS and PHT results (i) in order to have a preliminary consistency check and (ii) because it is a star, and the photometric calibration of PHT and the other ISO instruments is based primarily on stars.

α Boo was observed with PHT-P and C on Rev. 452 (10/Feb/97), and the data were processed with a pre-release version of OLP 6.0. Background subtraction was applied to the PHT-C data, but not to the PHT-P data, where the sources is much stronger than the background. All results were color corrected using the tables prepared by PIDT. The PHT-S spectrum was obtained in Rev. 69 (in PV phase), and reprocessed for this work with PIA 6.2; only the PHT-SL part of the spectrum is considered here since the PHT-SS part was nearly saturated. A full range SWS spectrum was obtained with AOT1-speed 4 also on Rev. 452, and it was processed with OLP 5.3.

A full LWS grating scan was obtained on Rev. 448 and processed with the IDT version of OLP 6. No background subtraction was applied, and a comparison of the sky background measured by PHT-C with the CWW model spectrum shows that the background is $\lesssim 10\%$ of the source in the LWS wavelength range. Furthermore, a 15 min LWS measurement was obtained with the grating fixed. Background observations in the same mode were also obtained, and the data processed with the IDT version of OLP 6. This produces a 10-point spectrum of the source though the points seriously affected by the short wavelength leaks (SW1, SW2, LW1, and LW2, see http://isowww.estec.esa.nl/notes/lws-_0197.html for details) and the data beyond $150\,\mu$m, where the source is too faint, have not been plotted. Uncertainties in the fixed grating position data were derived from the RMS the individual measurements only, and are somewhat overestimated since the data could not be fully deglitched, and the remaining glitches contribute significantly to the noise.

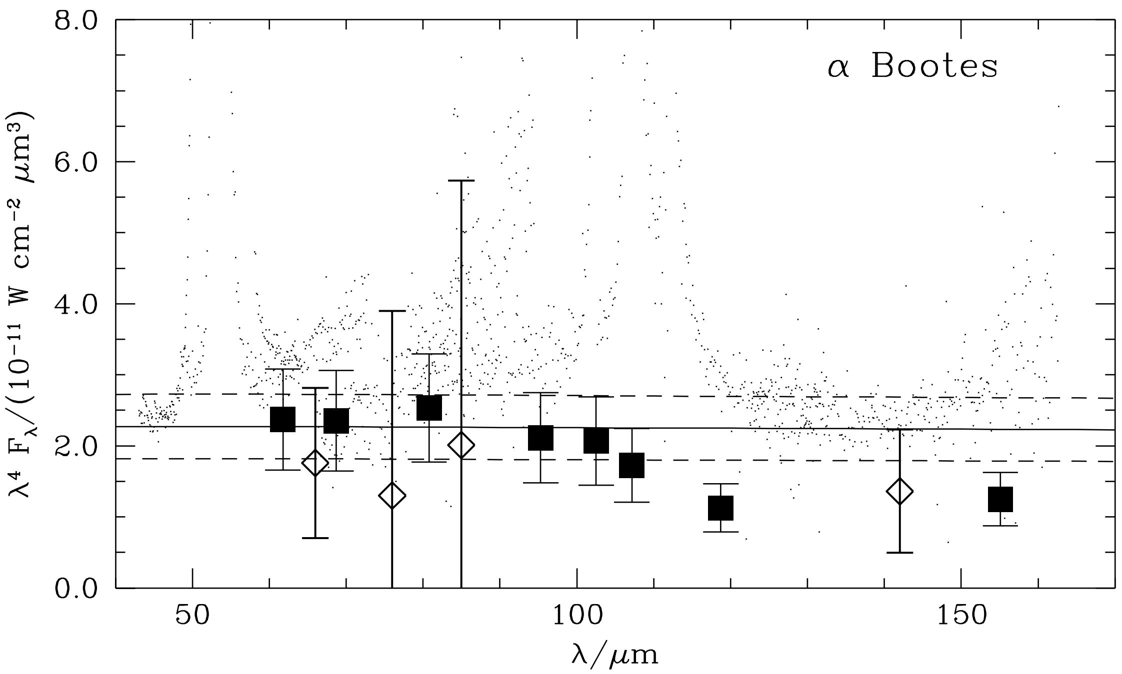

Figure 5: Comparison of ISO observations of α Boo with the CWW model. Full line: CWW model; thin dashed lines: CWW model $\pm 20\%$; dots: LWS spectrum; diamonds: LWS fixed-grating observations; filled squares: PHT-P and C photometry; It must be remarked that (i) the LWS spectrum is not representative of the performance of LWS (see text for details), and (ii) beyond $\sim 150\,\mu$m there is virtually no detectable signal.

The results are plotted in Fig. 4 and 5. Overall agreement is somewhat less good than in the case of γ Dra: band 2B of SWS is significantly steeper than the CWW reference, band 2C is significantly higher, and bands 2A and B are somewhat low. The 10—15 μm dip is also seen here, though the short wavelength part is all lifted up with band 2B. The PHT-S spectrum shows a strong positive deviation beyond 10 μm, and, curiously, it is consistent with the already high SWS spectrum between 6 and 10 μm.

The PHT-P results are mostly below the CWW reference, though only the 11.9 μm datum deviates by more than 20%, and the PHT-C results show good agreement except for the longest wavelength observation, where the source is the weakest, and where possibly the background was overestimated.

The LWS vs. PHT results (Fig. 5) provide a *preliminary* check of calibration consistency between these two instruments which are calibrated with different standards. The PHT data are the same as in Fig. 4 with a nominal $\pm 30\%$ error bar added. The LWS data are severely affected by the short wavelength leaks, and no attempt has been made to remove them, and a problem with the dark current removal is noticeable in the SW1 and SW2 channels (see positive slope of the continuum). But in regions outside of the leaks, and within the scatter of the points, the LWS spectrum agrees very well with the CWW model, indicating that **there is no large inconsistency between the LWS calibration and the calibration of the other instruments.**

3.3 HR6436

HR6436 (spectral type A2V, $K = 4.54$) was selected for being a rather faint star which is not used as a photometric standard, but for which a GBPP model is available to compare with the observations. It was observed with CAM, PHT, and SWS on Rev. 426 (15/Jan/97).

CAM and PHT photometry was obtained with SW1, LW2, LW10, and LW3 filters of CAM ($\lambda = 3.6$, 7.0, 11.5, and 15 μm) and the P3.6, P7.3, P11.5, and P16 of PHT. Sky background was observed for the $\lambda > 10\,\mu$m filters. Two SWS wavelength ranges were also observed (3.52—3.55 μm, which cover the isophotal wavelengths for the SW1 and P3.6 filters for this star, and 3.75—3.85 μm, which is a standard band used in SWS photometric checks, and includes the isophotal wavelength of the GBPP Ln filter). Processing was done with the current CIA, PIA, and SIA, and the results are in Fig. 6.

While SWS shows reasonably good agreement with the model, the CAM and PHT results deviate significantly. The 3.6 μm results are within 20% of the model, but on opposite sides, the $\sim 7\,\mu$m results of CAM and PHT are close to each other but $\sim 25\%$ above the model, and the longer wavelength results deviate even more, with the PHT-P 15 μm point being about 10$\times$ brighter than expected and consequently well off the plot.

The reason for the disagreement is not understood at this time. The CAM LW2 and LW3 raw data shows some saturation, but this would yield an apparent signal which is below expectation. Some of the PHT deviation may be due to uncorrected transient effects. Had the PHT and CAM data agreed with each other, one could argue that something about the source had changed drastically, but this is not the case. HR6436 is not known to vary in the visible, and the IRAS 12 μm datum is in good agreement with the model, which is in turn based on narrow band 2.2 μm obtained at a different epoch.

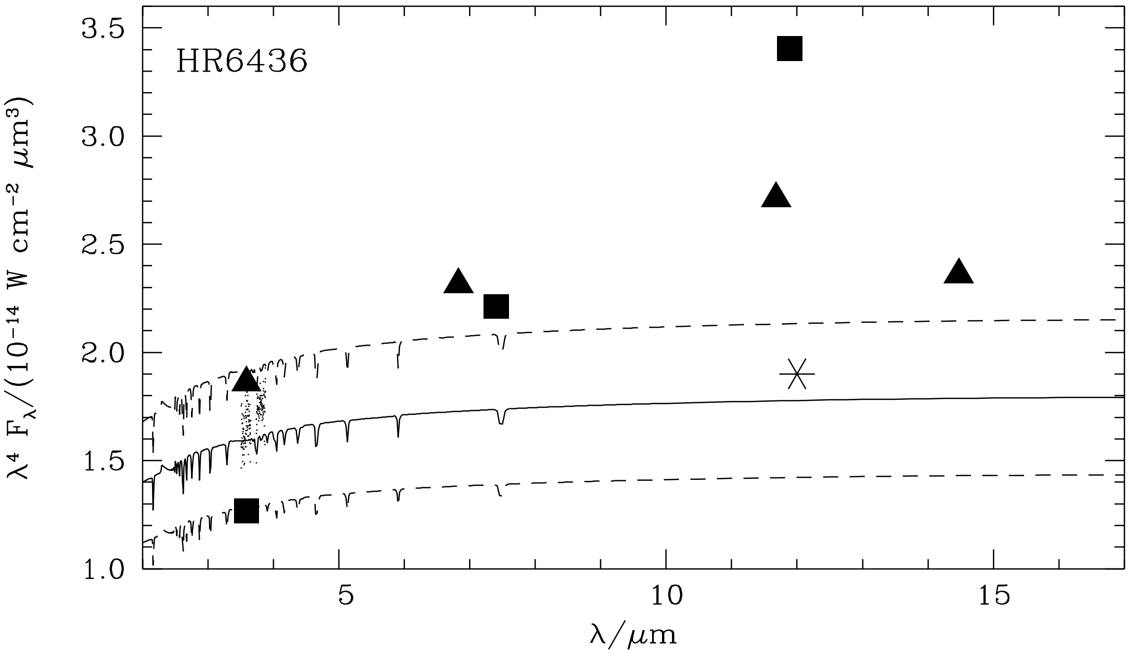

Figure 6: PHT-P and CAM observations of HR6436 compared to GBPP model. Filled squares are PHT-P photometry processed with PIA, of which the 15 μm point is not plotted for being much higher than the plotted range; filled triangles are CAM photometry, 6-point star is the IRAS 12 μm point. The continuous line is the GBPP model and the dashed lines are the GBPP model ±20%.

3.4 Mrk279

A comparison of a chopped PHT-S spectrum and CAM imaging photometry of Mrk279 obtained during revolution 80 (5/Feb/96) caused some anxiety in the past since the PHT-S and the CAM fluxes differed by nearly a factor of. Additionally, ground-based K and L-band results from the "Catalog of Infrared Observations" (Gezari et al. 1993) showed reasonable agreement with the PHT-S spectrum, though they were obtained many years earlier, and the source is variable, at least in the visible range.

The PHT-S spectrum of Mrk 279 was manually recalibrated by B. Schulz (PIDT) who included transient correction in his processing. Transients are modeled by an initial rapid jump followed by an asymptotic approach to the true level. In the case of weak signals, the asymptotic approach is very slow, and in a chopped (short) measurement it can be assumed that the signal measured is only the first jump. The magnitude of the jump as a fraction of the true signal has been calibrated for all pixels of PHT-S individually, and it is typically about 60%. Correction by this factor *brought the PHT-S signal in excellent agreement with the CAM filter measurements.* The fact that now both CAM and PHT-S measurements disagree with ground-based results is not deemed serious given that the latter were obtained 10 or more years ago, and that the source is known to vary.

3.5 Zodiacal Light

Zodiacal light observations were performed by CAM-CVF and by PHT-S, and they were processed by members of the instrument consortia who provided us wit the results to compare them. The CAM data are the same as in Reach et al. (1996) but reprocessed with more recent calibration files (specifically with an improved RSRF), and one of the PHT-S spectra was presented at the "First ISO Science Workshop" in ESTEC (Abrahám, Klaas and Schubert 1996). The result of the comparison cannot be shown at this time since the PHT data are still proprietary. Since the observations were obtained at different times and at different ecliptic coordinates, the data sets were normalized, and the comparison shows essentially identical spectral shapes between 6.5 and 12 μm. These results thus give a first indication that PHT-S and CAM give consistent results on extended sources. Furthermore, Reach et al. (1996) and Abrahám, Klaas and Schubert (1996) show excellent agreement between the CVF and PHT-S spectra and COBE/DIRBE photometry at 5 and 12 μm.

4 Summary and Open Points

The results of the previous section show acceptable agreement among the ISO instruments for all sources analysed except one, HR6436. Of the remaining sources, two are bright IR standards and two are scientific targets. Curiously we find very the best agreement in the measurements of the scientific targets, whereas for the bright standards, and for the brighter one in particular, significant deviations are found. The case of HR6436 remains unclear at this time.

It must be stressed that these results are not the final ones. Data reduction techniques are improving, especially regarding the treatment of the transient behaviour of the detectors. A re-calibration of these data with future reduction packages is expected to show improvement.

We conclude with a list of missing items, which naturally reflect future work.

1. PHT-LWS comparison: observations of Neptune have been obtained recently, but not in time for inclusion in this report; they will be used for flux comparison between LWS and PHT, and also to check for overall continuity between the LWS and the SWS spectra. Several asteroids have also been observed by both LWS and PHT, but the PHT observations are not AOT-based, and standard products are not available for them. Observations of the planetary nebulae NGC7027 and of NGC6543 are also available for analysis in this context, and will be used to check consistency on objects containing strong spectral lines.

2. ISO-COBE: while current works indicates good agreement, large maps have been made with PHT and CAM as part of several science programs. These can be integrated over the COBE-Dirbe beam to check for consistency.

3. Cross-Calibration on extended sources is limited to that pair of instruments and to the Zodiacal light. PHT has carried out a large program of ZL studies, and with those data the PHT-S spectra presented here can be checked against the filter photometry. In the case of CAM, agreement between CVF and filter observations of the ZL was shown by Reach et al. (1996).

The important point to note is that while the analysis is not complete, and it will not be complete until the instruments' uncertainties are understood, the data necessary for the analysis has been obtained. In addition to the data listed here, there is much more data in the archive that can be, and to some extend will be used for cross calibration analysis. It is thus fair to say that progress in the cross calibrations in on a good track, that all legs of the cross calibration diagram have been verified at least to some extent, and future work will concentrate on those parts were current verification is still preliminary.

Acknowledgements

This work would not have been possible without the extensive work of many in the instrument teams who have developed the instruments, defined the calibration plans both in the laboratory and in orbit, executed those plans, and analysed the data.

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