THE LWS RELATIVE SPECTRAL RESPONSE FUNCTION

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ABSTRACT

The Long Wavelength Spectrometer (LWS) Relative Spectral Response Function (RSRF) is derived using data from in-orbit observations of Uranus. This paper outlines the evolution of the response function, from the ground tests before ISO's launch, to the current version. The accuracy of the derived function is discussed in the context of the in-orbit detector behaviour, and in the context of the LWS spectra, fitting it to an overall far-infrared photometry scheme.

Key words: ISO – LWS

1. INTRODUCTION

The Long Wavelength Spectrometer (LWS) (Clegg et al. 1996) operated in the range 44-197μm in either medium ($\Delta\lambda/\lambda$ ~200–300) or high resolution ($\Delta\lambda/\lambda$ 10,000) mode. In the medium resolution mode the LWS was used as a grating spectrometer with the wavelength range being covered by ten detectors, each overlapping in wavelength range to allow for redundancy. A Ge:Be detector was used for the 40–50μm range, five unstressed Ge:Ga detectors for the 50–110μm range and four stressed Ge:Ga detectors for the 110–197μm range. For the high resolution mode a Fabry-Pérot (FP) interferometer was placed in the beam. The detectors were independently mounted and calibrated and each had a bandpass filter ensuring only in-band, order sorted, radiation reached each detector. The instrumental spectral response of each detector was measured both on the ground and in-flight. These measurements were made under different circumstances, therefore no direct comparison can be made and the in-flight measurements have been adopted for the LWS calibration scheme.

Section 2 details the pre-flight calibration of the Relative Spectral Response Function (RSRF). Section 3 then describes why and how this was changed in-flight and details the changes made in various versions of the offline processing (OLP). Section 4 describes the throughput calibration and Section 5 details how the current RSRF was tested against Uranus. It also outlines which other well understood sources are available for verification. Section 6 describes what monitoring was done in-orbit to check that the RSRF was stable.

2. PRE-LAUNCH DEVELOPMENT

The ground-based determination of the RSRF was done using the full instrument in the test cryostat (Lim and Swinyard 2003). The ten individual response functions were measured at each bias using an internal black body operating in the range 4–150 K and with the temperature optimised individually for each detector. As the test facility did not have a cold telescope simulator, an external neutral density filtering scheme was needed. As this gave a lot of attenuation, the black body used was placed inside the cryostat and hence acted as an extended source to the instrument. No tests with an external black body could be done due to the filtering required, therefore no comparison could be made between an RSRF determined using a point source and the one determined using an extended source. The RSRF profiles were written to an OLP calibration file (LCGR) in the form of a primary FITS table. This contained a three dimensional array (4,10,4096), i.e. for each of the 4096 grating positions and 10 detectors there was a value of wavelength, wavelength error, response and response error. The first version of the LCGR file was produced in October 1993 and updated in May 1995 following further analysis of the test data.

3. POST-LAUNCH DEVELOPMENT

3.1. EARLY VERSIONS

The calibration strategy of LWS relied on post-launch verification of the RSRF with updates expected from in-flight data. The prime target for this was Uranus as it was known to be bright, point-like in the LWS beam, flat, spectrally featureless and have a well established model. However the RSRF could not be verified early in the mission as the detectors were exhibiting unexpected behaviour (Leeks et al. 2003), and neither Uranus nor other suitable sources were visible. Therefore the first space version, produced in Performance Verification (PV) phase in March 1996, was based on smoothed profiles derived using a combination of NGC 7027 and S106 data with simple polynomial fits through the spectra. These were photometrically scaled using the ground-based profiles. This was a short-lived version and was replaced a few weeks later using Ceres data obtained in revolution 75 for detectors SW1–LW4. The first space version was retained for detector LW5 as Ceres is very faint for LWS in this wavelength region.

The transition from an extended source ground-based RSRF to a point source (Ceres) based RSRF was a dramatic one as, unknown before launch, faults in the LWS optics had caused

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LWS data to be fringed. The fringes should have been visible on extended sources and point sources off-axis. However as the RSRF had been generated with an extended source, the fringes were in-built into the pre-launch versions. These in-built fringes caused processed point source data to show fringing. Due to variations within the LWS beam, some extended sources also showed fringing and others did not. When a point source calibration was established, the situation was reversed with processed point source data not showing fringing while all extended source data and point source off-axis data did.

3.2. The Uranus RSRF

Uranus was first observed by LWS as soon as it became visible in revolution 133 and this observation was used to set up the main RSRF calibration observation which took place in revolution 158 (April 1996), one of two surrendered PV phase revolutions. Nearly ten hours were spent observing Uranus and the data obtained were used to generate the first versions using a total throughput calibration (OLP versions 4,5). The other surrendered revolution (rev 317, Sept 1996) was also used for scanning Uranus and the lessons learned from Routine Phase up to that point were applied in planning this observation.

The calibration observation was done after an observation where the detectors had not been exposed to a bright source. The illuminators were not used before the observation as in-orbit experience had shown that the illuminator flashes affected the detectors. Three illuminator sequences were used during the mission. Before revolution 237, the pre-launch version was used where the illuminators were flashed for a short time at two levels, and this is referred to as type 1. After the on-board software update for parallel mode, a mistake meant that ramps of 1 s duration instead of 1/2 s were being used for the same illuminator sequence, giving half the number of ramps, this is referred to as type 2. The type 3 sequence was implemented after the LWS switch off period and used one intermediate level for a longer time period. After the revolution 317 observation, the type 1 and type 3 illuminator sequence were each done five times and these sequences form the basis of the illuminator reference calibration file.

Data from the revolution 317 observation were used for OLP versions 6–8. LWS did not implement an OLP version 9. Uranus was also used for routine monitoring and now after the mission this data has been used for the final OLP version (version 10).

4. THROUGHPUT DERIVATION

The early versions of the LWS pipeline reflected the pre-flight set up in separately calibrating for the detector responsivity and illuminator output. This changed in OLP 4 when an empirical throughput calibration was established. The RSRF was essentially established from the observed Uranus photocurrent (A) divided by the flux model, in $\mathrm{Wcm^{-2}\mu m^{-1}}$, giving an RSRF in $\mathrm{AW^{-1}cm^{2}\mu m}$. For historical reasons the grating element was also removed, so the LWS RSRF is currently expressed in $\mathrm{AW^{-1}cm^{2}}$. This provides a reference responsivity at the time of the Uranus observation. The illuminator reference file also relates to this responsivity and is produced from the illuminator sequence in revolution 317 and fine tuned using the monitoring observations. Note, this is a point source calibration and an adjustment must be made for extended sources.

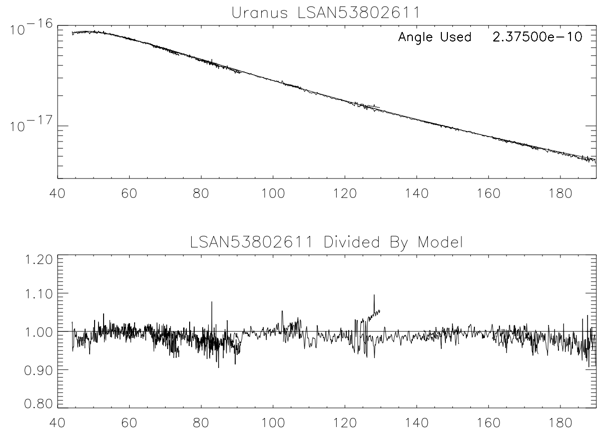

Figure 1. Uranus data from revolution 538 plotted with the model (top panel) and ratioed with the model (bottom panel).

5. VERIFICATION

5.1. Verification with Uranus

To verify that the calibration had been correctly implemented, the individual observations of Uranus were processed and checked against the model. Figure 1 shows a typical monitoring observation of Uranus and its flux model for that revolution. For most of the LWS range the calibrated spectrum follows the model, however there is an apparent down curve with SW1 at the shortest wavelengths and LW5 at the longest wavelengths. Figure 2 shows the SW1 detector data averaged and divided by the model for the nine observations of Uranus using the type 3 illuminator flash (after revolution 442). The revolution 538 observation is the first one on the panel and here it can be seen that the apparent down-turn in Figure 1 is due to a flux offset for this detector. This is probably due to an inaccurate responsivity drift calibration during the pipeline processing. Other apparent features in Figure 2 are due to noise.

Figure 3 shows detector LW5 for the same nine observations. Two of these observations in revolutions 698 and 706 are affected by the stressed detectors de-coupling from the 1.7 K helium film and hence producing spurious features as the responsivity varies. From the remainder it can be seen that the down-turn on LW5 is real for these observations. The other calibration, for observations before revolution 442, does not show this, although large up- and down-turns are seen. This down-turn is caused by an inappropriate dark current being subtracted, either during processing, or while generating the

RSRF. The RSRF has been generated with a range of dark current values, however this has not successfully removed this behaviour. Another problem is that Uranus is a relatively faint source at 180μm, ideally a brighter source should be used but none are available. One may argue that the calibration could be improved by determining the average offset at all LW5 wavelengths then using these values to adjust the RSRF. However, this turnover is only apparent in Uranus and fainter sources and such an action may interfere with a good calibration for brighter sources while still not addressing the fundamental problem of an indeterminate dark current. Also, this would then invalidate a good calibration for the period before revolution 442.

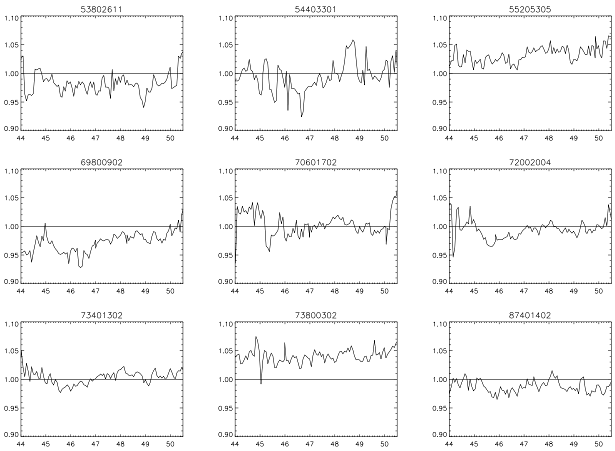

Figure 2. Uranus data from detector SW1, averaged and divided by the Uranus flux model generated for that revolution. Note: due to separate illuminator sequences these observations have a different photometric calibration to those before revolution 442. On top of each panel is the observation (TDT) number, the first three digits of which indicate the revolution.

5.2. Verification with other objects

There are very few objects that can be used to verify the RSRF over the LWS flux range. Objects such as Saturn and Jupiter saturate the detectors. Mars has a well defined continuum model but has a lot of water lines and also saturates some detectors. Sidher et al. (2003) have done detailed comparison work and have demonstrated that the majority of detectors are linear up to Mars fluxes and that the calibration scheme can reproduce the Mars model. This work also directly confirms the fidelity of the Uranus model as the Mars model is more accurately established and a more common standard. Neptune is also a possible check but here the LWS data are being used as an input to generate a new model. Work on the asteroids is ongoing (Müller and Lageros 2003) and the LWS observations of Ceres, Pallas, Vesta and Hygiea are currently being checked. Callisto could provide a further check as it has a smooth black body like spectrum, however the LWS observations of Callisto are severely affected by straylight from Jupiter. Stellar spectra from α Boo and α Tau are weak sources for LWS. They

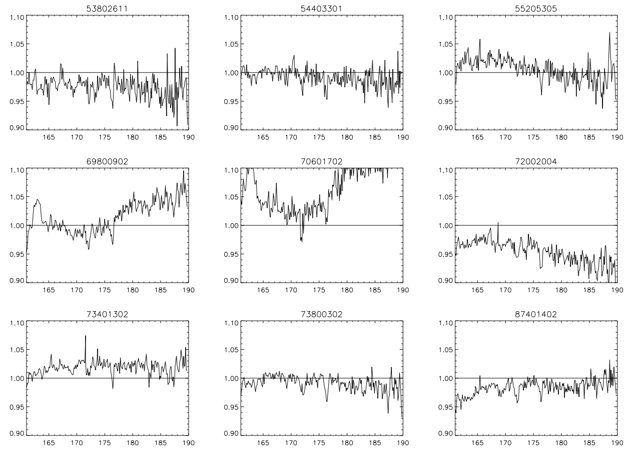

Figure 3. Uranus data from detector LW5, averaged and divided by the Uranus flux model generated for that revolution.

show very good agreement with their spectral energy distribution templates (Cohen 2003) although the spectra are affected by the near-infrared leak feature (Gry et al. 2001) and can only be used outside the spectral regions affected.

6. Monitoring

Monitoring the RSRF is easy, in principle. I.e. find a bright source and keep observing it, checking that the spectral shape of the spectrometer output remains the same. In practice however, ISO's visibility constraints and the need to keep a balance in the calibration observations meant that no source was observed continuously throughout the mission. Uranus was used for monitoring from revolution 317 until the end of mission, and 15 observations were made. Earlier in the mission S106 and G298 had been used and observations of these sources continued until the end of the mission. NGC 6543 was used extensively for wavelength monitoring and was also of some use in establishing the repeatability of the RSRF calibration as it had been observed over 80 times, however this can only be a gross check as NGC 6543 is quite a faint source for LWS. Figure 4 shows all 22 observations of G298 averaged and plotted on the same scale (top panel). Early in the mission the SW1 detector was operated at a lower bias which is not calibrated separately in OLP, hence for these observations the SW1 scans appear at a lower flux level. The bottom panel shows the detail for detector LW2. Figure 5 shows the same plot for NGC 6543. These monitoring observations indicate that the RSRF has remained stable throughout the mission and that LWS spectra are very reproducible. It is also worth noting that for this and other bright objects the LW5 spectrum shows no apparent down-turn.

7. Summary – Lessons Learned

The pre-flight version of the RSRF was derived using a uniformly extended source within the cryostat. In-flight however the RSRF was derived from a point source and due to the complex nature of the LWS beam the two can not be easily com-

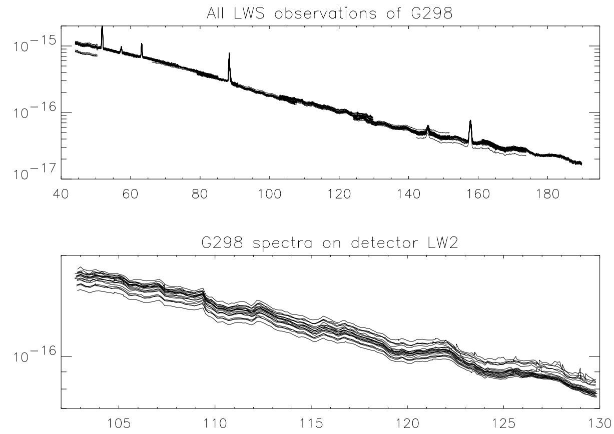

Figure 4. The RSRF monitoring observations of G298, covering the period from revolution 51 to revolution 650 (top panel). Detail on detector LW2 is shown on the bottom panel.

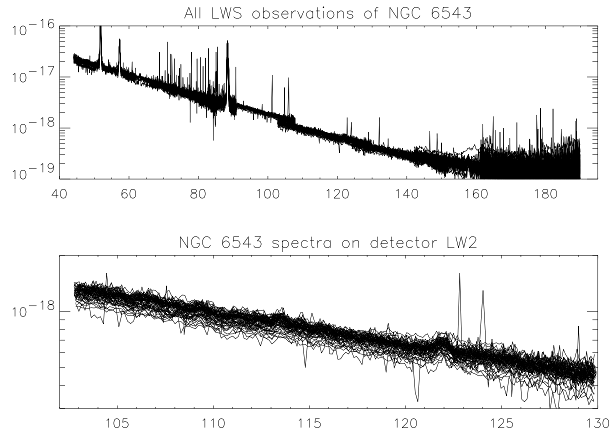

Figure 5. The RSRF monitoring observations of NGC 6543, covering the period from revolution 51 to revolution 650 (top panel). Detail on detector LW2 is shown on the bottom panel.

pared. Fortunately for LWS, an in-orbit version was possible. In space, there are no objects with a truly featureless spectrum and if LWS had higher sensitivity, features in Uranus might have formed part of the spectral response. The choice of Uranus was, in a sense, the only one, but it was also a good one. The Uranus model has provided a spectral response function that has been scrutinised over the LWS flux range and so far no features, apart from the HD 112μm line, have been found. The agreement, through LWS data, with the Mars model, also lends confidence to this calibration. The major problem with Uranus is that, for LWS, this is at best a medium flux object, and although it has a flat spectrum, it is still faint at the long wavelength end. However, the advantage of this is that the detectors are still well within their linear range and no correction needs to be made for ramp de-biasing. The RSRF is known to be good for the period before revolution 442, but observations of Uranus indicate an overall downward slope for the calibration after revolution 442. This might be refined if two different dark current values were used for detector LW5 and hence two different response curves generated. However this would severely affect the point-to-point signal-to-noise ratio on the RSRF for that detector.

The RSRF and photometric calibration of LWS is very repeatable, reaching 1–2% over the mission for a bright object. At the end of the mission we have used observations with the same sampling rate as most observers used, to mitigate the affects of transients (Caux 2003). Also a transient-corrected version is available in LWS Interactive Analysis. The revolution 158 and 317 observations were done at the slowest sample rate and are not currently used. For future missions the space based RSRF data should be taken in a similar mode to that used by most observers.

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