EMPIRICAL ASPECTS OF THE LWS PHOTOMETRIC CALIBRATION

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ABSTRACT

The empirical model of Uranus used for the flux calibration of the Long Wavelength Spectrometer (LWS) data is described. The detection of Martian rotational modulation with the LWS and the level of agreement between the measured and predicted brightness temperatures indicate that the relative accuracy and the absolute photometric accuracy of the LWS calibration are both within $\sim 3\%$. A comparison of LWS spectra of Uranus and Mars against their respective models confirms the reliability of using Uranus as a calibrator.

Key words: Mars, Uranus, LWS flux calibration

1. INTRODUCTION

To flux calibrate the data from the Long Wavelength Spectrometer (LWS) on board the European Space Agency's Infrared Space Observatory (ISO), several possible calibrators were considered, including the asteroids, Mars, Callisto and Neptune. The role of these objects as calibrators is discussed comprehensively by Orton & Burgdorf (2003). Ceres was used as a calibrator early in the mission (see Lim et al. 2003a) until Uranus became visible to ISO. Uranus was selected to be the LWS prime flux calibrator because it is less variable than Mars and spectrally featureless in the far infrared (FIR). The fact that it is of medium brightness ($\sim$ 1000 Jy at 100 μm) means that it does not saturate the LWS detectors. Furthermore, being a point–like source in the LWS beam, it is unaffected by the complex off–axis LWS beam geometry (Lloyd 2003).

2. THE URANUS MODEL

The Uranus model for calibrating the LWS is a synthesis of globally averaged Voyager Infrared Interferometer Spectrometer (IRIS) data up to 50 μm (Conrath, B., private communication), James Clerk Maxwell Telescope (JCMT) data covering the 0.35–2 mm wavelength range (Griffin & Orton 1993) and a radiative transfer atmospheric model similar to the one described in Griffin & Orton (1993). A model of Mars based on radiometry measurements from Mariners 6 and 7 (Wright 1976 and Wright & Odenwald 1980) was in turn used to calibrate the Uranus JCMT data.

Figure 1 shows the adopted model for Uranus, which is essentially a combination of the Voyager IRIS model below 50 μm and the JCMT/atmospheric model with a +0.5 K offset above 50 μm. The primary purpose of this small offset, in comparison to the $\sim$ 10% uncertainty in the Mars model, was to achieve consistency with the Voyager IRIS model.

This adopted model of Uranus has been the LWS prime flux calibrator since Offline Processing (OLP) version 7.0.

3. MARTIAN ROTATIONAL MODULATION RESULTS

Sidher et al. (2000) used ten LWS full grating scan observations (Astronomical Observation Template (AOT) LWS01) of Mars to demonstrate that the observed $\sim 3\%$ rotational modulation of the FIR disk–averaged brightness temperature can be detected with the LWS and that it compares very favourably with the predictions of the thermophysical model developed by Rudy et al. (1987). Figure 2 shows the observed and predicted modulation in each detector (except SW1 which is excluded because it suffers from memory effects) as well as a detector–averaged modulation. All these observations were processed as 1/4 second integration ramps by discarding the second–half of each 1/2 second ramp in order to eliminate the non–linear behaviour seen in some LWS detectors. However, some residual non–linear effects are still present in some detectors, especially in LW1 to LW4.

The Rudy et al. (1987) model treats the surface as a smooth sphere with fixed dielectric constants for the polar and mid–latitude regions. The dielectric constants were derived from polarisation measurements at 2 and 6 cm. The other inputs to the model included a thermal inertia map of the surface from the Viking Infra Red Thermal Mapper (IRTM) as well as a surface albedo map from visual bolometry. Despite excluding the Martian atmosphere and ignoring the effect of dust storms in the model, the LWS results agree remarkably well with the predictions.

The estimate for the disk–averaged surface emissivity is 0.90, which is close to the value of 0.95$\pm$0.03 calculated by Burgdorf et al. (2000) from an analysis of Martian water vapour lines. The Rudy et al. (1987) model could be adjusted to improve agreement with the results in the last panel of Figure 2 but independent evidence is needed to support such a change, especially as the predicted brightness temperatures are already within the error-bars of the measured brightness temperatures.

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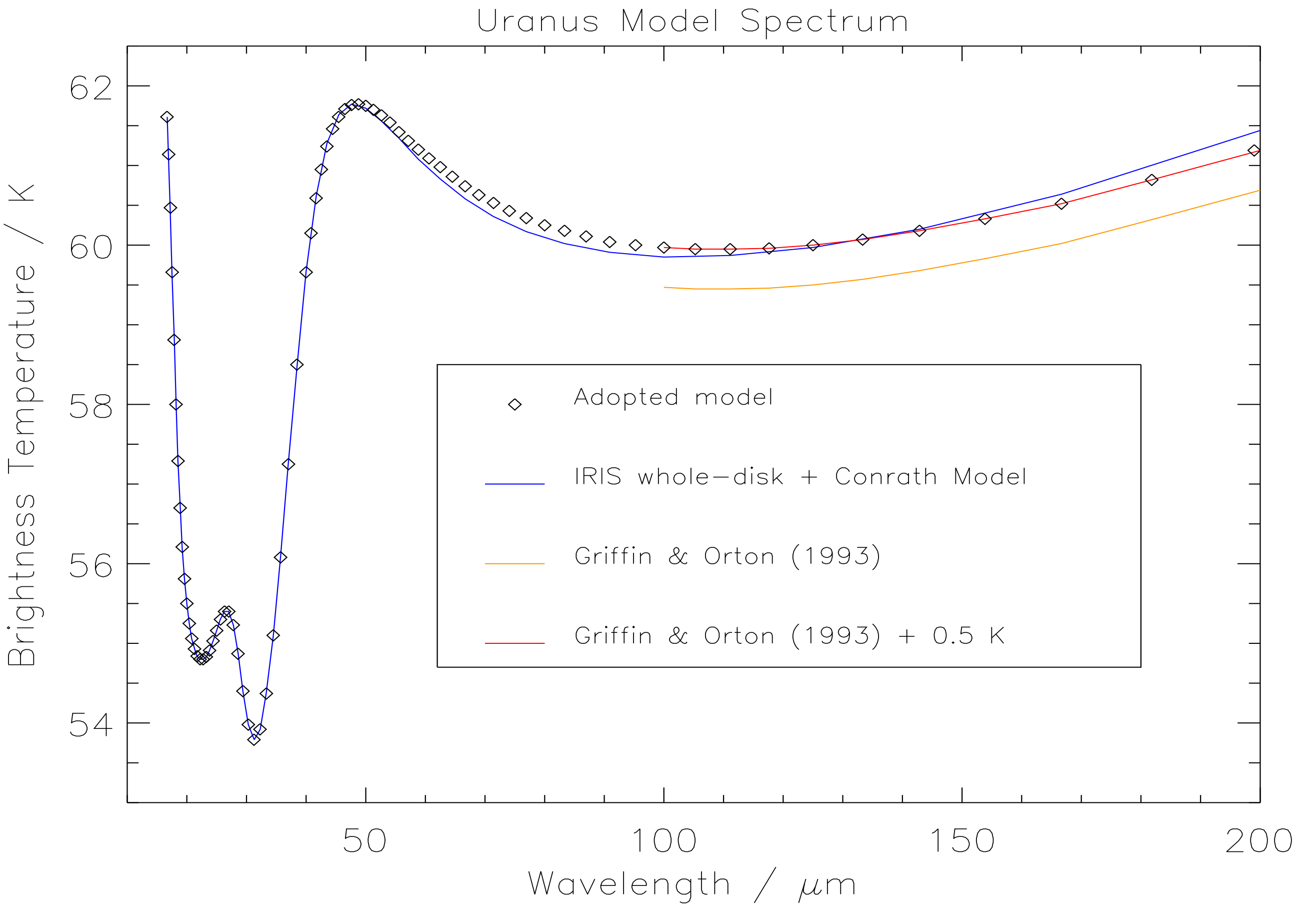

Figure 1. The empirical model of Uranus used as the LWS prime flux calibrator, indicated here by the diamond symbols.

4. COMPARISON OF URANUS AND MARS

In order to compare the LWS spectra of Uranus and Mars with their respective models we used nine AOT LWS01 observations of Uranus taken between ISO revolutions 538 and 874 and one LWS01 observation of Mars from ISO revolution 608. The Mars observation was one of the ten observations discussed in section 3. For each Uranus spectrum we calculated its ratio with the Mars spectrum. Using the models of Uranus and Mars as outlined in sections 2 and 3, a similar set of ratios was also calculated for the respective models. A “ratio of these ratios” was then calculated for each wavelength λ by using the following expression:

$$R(\lambda_i) = \frac{R_o(\lambda_i)}{R_m(\lambda_i)} \qquad (1)$$

where $R_o(\lambda_i)$ is the observed spectral ratio and $R_m(\lambda_i)$ is the modelled spectral ratio for the i^{th} Uranus observation. For perfect agreement between the data and models the ideal value of $R(\lambda_i)$ should be unity. Figure 3 plots $R(\lambda_i)$ as a function of wavelength for all nine observations. It is important to note that $R(\lambda_i)$ is plotted for the full wavelength range for each detector and not just for the nominal range. The high degree of repeatability of the Uranus observations is evident, especially at the centres of the detector bandpasses. Furthermore, it can be seen that the increased scatter tends to occur outside the nominal wavelength range for each detector. For each observation the value of $R(\lambda_i)$ is binned over a small wavelength interval and then averaged across all nine observations. These values are indicated by the points with the small error bars (viz. $\sim$ 1%) in Figure 3. The maximum departure from unity of this bin–averaged ratio of ratios is typically $\sim$ 3%. Unfortunately the same is not always true at all wavelengths for the LW1–LW4 detectors. For the worst detector residual non-linearities and memory effects lead to a deviation of $\sim$ 15%.

Figure 4 shows the minimisation of variance between the data and the models. The emissivity in the Mars model was varied by simply changing the dielectric constant and for Uranus a simple multiplicative factor was applied to the model shown in Figure 1. It is clear from the contours in Figure 4 that the variance minimum is fairly insensitive to the both the Mars model emissivity and the Uranus model factor, with the best fit values being 0.93 and 1.02 respectively. This estimate for the emissivity is fully consistent with the result of Burgdorf et al. (2000) and implies that the Martian emissivity in the Rudy model can be increased such that the detector–averaged result for the rotational modulation is in almost exact agreement with the measurements.

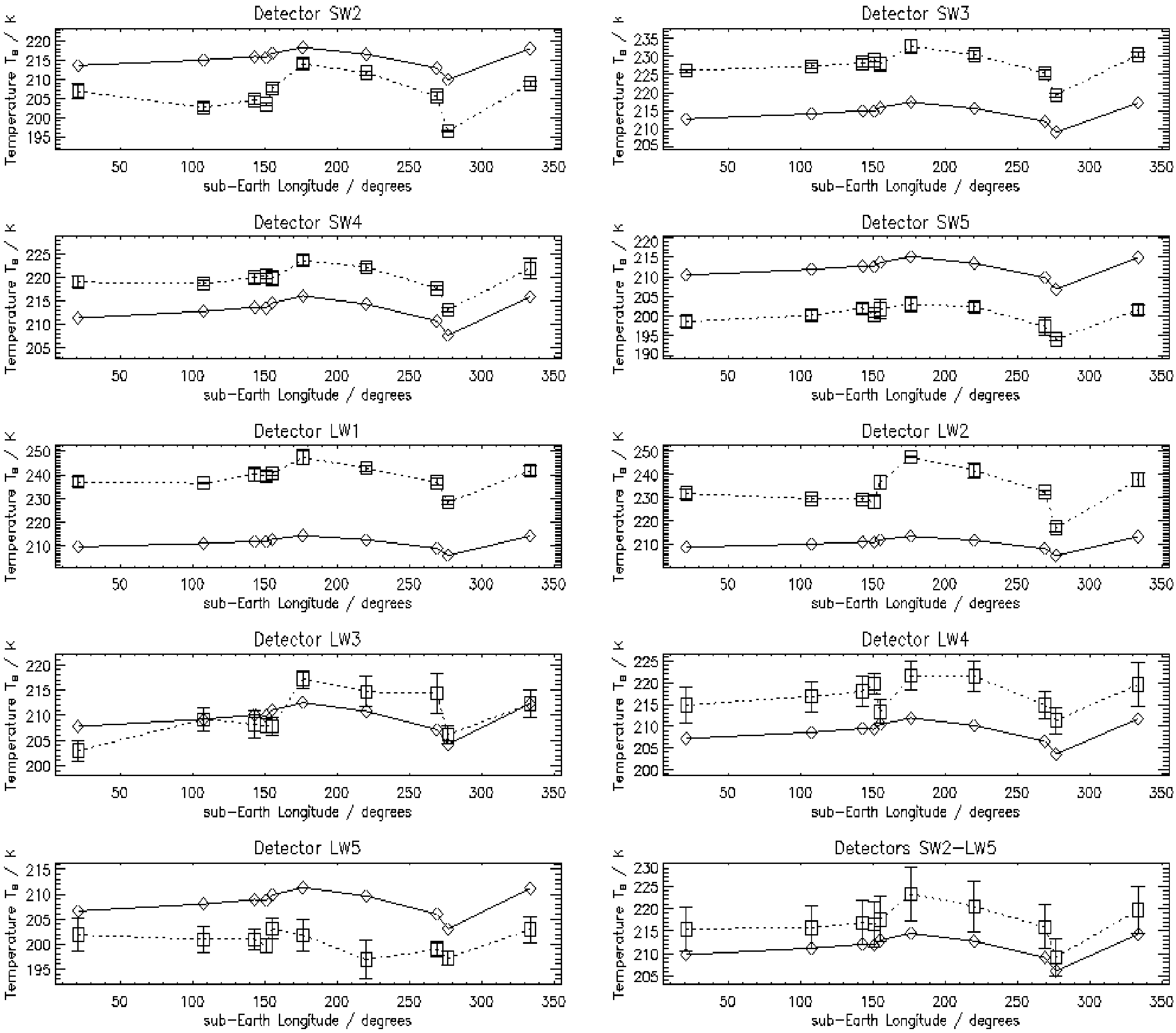

Figure 2. The modulation of the brightness temperature as a function of sub–Earth longitude for detectors SW2 to LW5. The last panel shows the brightness temperature averaged over all nine detectors.

Of course if the Rudy model is not changed the implication is that the spectral radiance of the Uranus model can be increased by $\sim$ 2%. The Voyager IRIS systematic calibration uncertainty is well established at $\sim$ 1% (Pearl, J. & Orton, G.S., private communication). However they concede that a 1–2% contribution could arise from uncertainties in integrating over the disk of Uranus – either by mis–judging its limb darkening if it was observed in the centre of their non–uniform field of view or from assembling an appropriate set of components of the whole–disk equivalent radiance from spatially resolved samples that were taken from various latitudes and various emission angles and subsequently weighted and summed. Despite this caveat we choose not to recommend a change in the adopted Uranus model. It is worth stressing, however, that the LWS photometric calibration accuracy of $\sim$ 3% already exceeds our expectations for isolated point–like sources of medium brightness.

5. CONCLUSIONS

We conclude that the photometric accuracy of the LWS instrument for point–like sources in the beam with fluxes as high as Mars (25,000 Jy at 100 μm) is within $\sim$ 3%. This result is significantly better than the 10–15% accuracy achieved early in the mission (Swinyard et al. 1998).

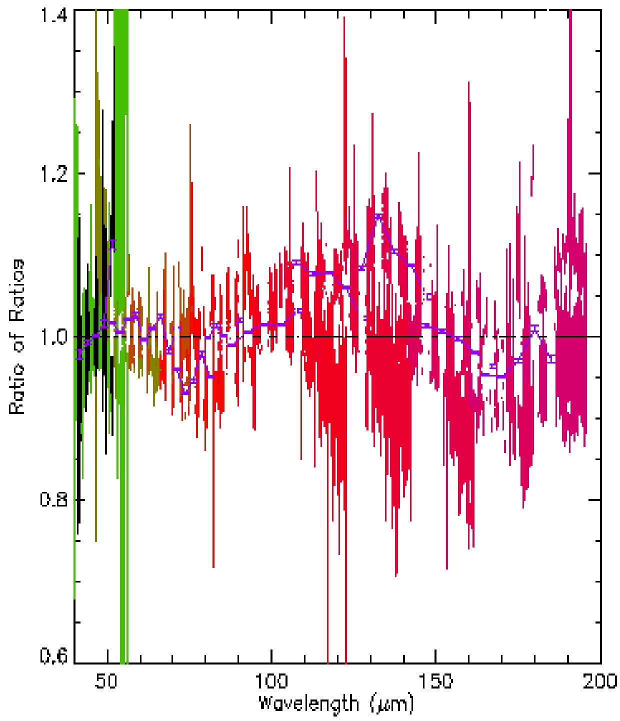

Figure 3. Ratio of the measured and modelled spectra of Uranus and Mars. The wavelength intervals over which the ratios are binned appear as white "patches" along the y-axis.

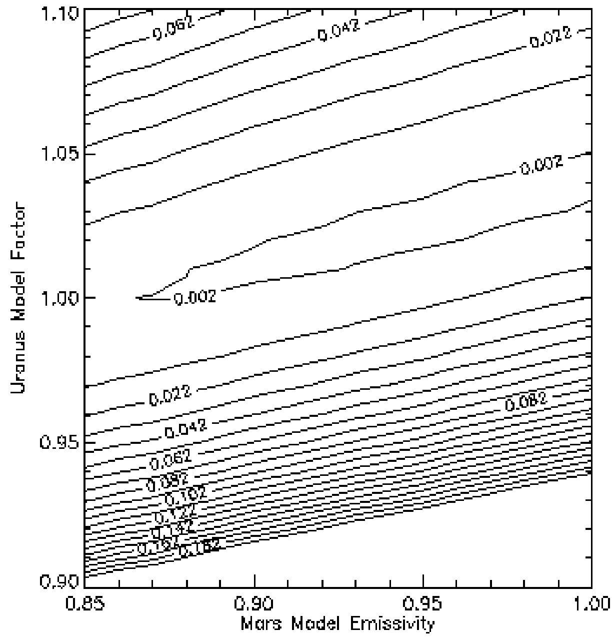

Figure 4. Contour plot of the best fit models of Uranus and Mars.

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