THE LWS CALIBRATION STRATEGY

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ABSTRACT

The calibration strategy of LWS was developed prior to the launch of ISO through setting up and understanding the instrument on-ground tests. The strategy was followed in operations and was largely executed successfully. However difficulties in combining calibration time with target visibility, and one hardware problem (the long wavelength Fabry-Pérot (FPL) tracking), had an impact on the detailed schedule of the performance verification (PV) phase. When ISO entered routine operations, the calibration was not complete and two PV revolutions had been surrendered for later use. This paper describes the evolution of the calibration strategy in the context of the ISO mission from the perspective of the LWS Instrument Dedicated Team (LIDT) based in VilSpa, and the extended LWS instrument team based at consortium institutes. Its aim is to draw up a set of lessons learned which may be useful for future missions.

Key words: ISO – LWS

1. INTRODUCTION

Prior to the launch of ISO, ground testing had established an initial full calibration of the Long Wavelength Spectrometer (LWS) (Clegg et al. 1996). The testing had also allowed an in-depth knowledge of the instrument to be gained, hence the in-orbit calibration scheme and procedures could be formulated in detail allowing the planning of the instrument commissioning and PV phases. However very little was known about how the ground based calibration of LWS would be applicable in the space environment and, as no similar instrument had been previously launched, the LWS calibration strategy had to be developed to both adhere to the constraints of the ISO mission and yet be adaptable enough to be changed if the LWS exhibited any unexpected behaviour.

The ISO mission plan was for the instrument to be commissioned during the spacecraft commissioning phase (SCP) which started for LWS in revolution 8 and ended in revolution 21. During PV phase, (revolutions 23–78) the LIDT along with instrument experts had one in four revolutions to both verify instrument behaviour and establish an initial astronomical calibration. For the remainder of the ISO mission, the routine operations phase, a regular monitoring of the LWS behaviour was to take place.

In-flight however a series of surprises in the actual instrument behaviour meant that some of this strategy had to be changed. In particular, PV phase calibration was continued into Routine Phase and the calibration was also continuously refined as new astronomical sources became visible. This paper outlines the overall strategy employed by the LIDT and instrument experts, both in the context of the preparation for PV phase and the reaction to the surprises during the SCP and PV phases. The second part of the paper will detail how this initial calibration was monitored and improved upon during Routine Phase. Some of the new instrument behaviours which occurred during Routine Phase and the strategy for dealing with these is discussed. We also outline the approach taken during the Post-operations Phase. Individual aspects of this calibration activity are detailed in other papers at this conference and these will be referred to.

2. PREPARATION BEFORE LAUNCH

The detailed preparation of the in-flight calibration began about eighteen months prior to launch at about the same time as personnel for the LIDT were being employed. This was done in the framework of the In-Orbit Calibration Requirements Document (IOCRD) which gave a high level overview of the calibration requirements and methods to implement them. The establishment of the instrument calibration relied on parameters being established in a particular order and this order was built into the PV phase schedule. The main emphasis was on getting the calibration files, needed to optimally operate the instrument (the uplink files), ready at the earliest possible stage. This would allow the four LWS astronomical observation templates (AOTs) to be optimised and tested before the planned release at the end of PV phase. The LIDT and instrument experts worked towards setting up the Calibration File Derivation Procedures (CFDPs). These procedures were documented in detail

Proceedings of the Conference "The Calibration Legacy of the ISO Mission", VilSpa, Spain, February 2001
ESA SP-481, 2003, eds. L. Metcalfe, A. Salama, S. B. Peschke & M. F. Kessler

and in most cases calibration software was developed to follow these procedures. The calibration software was organised into a package known as CALIBAN. This software was written to run under VMS. Although the offline processing (OLP) software was written in FORTRAN, the calibration software was written in IDL which allowed quicker and easier updates by scientists.

Although the LWS was set up and calibrated prior to flight, it was known that the calibration would have to be checked inflight and some of the fundamental calibration would need to be re-established. In particular it was expected prior to launch that the Fabry-Pérots (FPs) would need to be aligned in-orbit. In essence there was very little choice in the selection of the main astronomical calibration standards as LWS was operating in a largely new wavelength regime. For photometric calibrators, stars and most asteroids were considered to be too faint while objects such as Jupiter and Saturn were too bright, Mars was not expected to be visible, therefore the only objects available were Uranus, Neptune and bright asteroids. This added considerable constraints to the planning as these objects had very limited visibility by ISO. For the grating and FP wavelength calibration, unpublished KAO data were used and sources were selected from a master list, depending on visibility. This list was supplied to the LWS consortium from IPAC and NASA AMES.

The strategy was translated into detailed scheduling for the September 1995 launch date, however after the LIDT arrival in VilSpa this date slipped to November and the scheduling had to be re-done. Another re-scheduling exercise took place when the launch date slipped a further week.

2.1. Lessons learned – Pre-launch

The IOCRD was a good framework to start the detailed planning of the LWS calibration. The setting up of CFDPs was a necessary exercise. However the need to extensively document the CFDPs took time away from LIDT training and familiarisation with the procedures. The CFDP documentation was largely perceived as a 'paper exercise', a perception which was proved correct when it was not referred to in-flight. The detailed scheduling took place fairly near the time of launch. This was partly due to planning tools not being available until about a year before launch and partly due to not having sufficient data on the line-sources. IPAC's role in putting together the line list data was extremely useful. The successive re-planning exercises were difficult for the morale of the staff concerned and also reduced the efficiency of the observing programme.

The LIDT was formed only a year before launch and although this team had been formed for ISO operations, it would have been useful if the team had been formed earlier. This would have allowed members to better familiarise themselves with the details of the instrument calibration. It would also have been beneficial for the team members to have become better acquainted before facing the stress of moving to a new working environment in a new country.

3. Commissioning Phase

The aim of the SCP was to allow the spacecraft and its instruments to be checked out and an initial assessment of the performance made. LWS was switched on for the first time in revolution 8 and the initial tests involved checking the functionality of the instrument subsystems. LWS was found to be functioning normally. However, when the detectors were switched on for the first time it was noted that a lot of glitches were occurring. Analysis of this data showed that the glitch-like effect was actually caused by spontaneous spiking in the detectors (Swinyard et al. 2000). Further characterisation showed that the spontaneous spiking was due to the detectors being much more responsive in space than on the ground. Therefore the operating bias needed to be reduced (Leeks et al. 2003). The actual glitch rate measured after the bias reduction was as expected, although at the higher end of pre-flight predictions.

The affect of glitches was more severe than pre-flight predictions. Many of the glitches disturbed detector responsivity and this took some seconds to return to normal. Tests with reset times showed that increasing the number of resets decreased the time taken for detector response to return to normal following glitches. Hence the ramp length was reduced from the 2 s pre-flight value to a 1/2 s in-flight value. These two changes in the instrument operation led to an overall reduction in sensitivity (Leeks et al. 2003). Towards the end of each revolution the accumulated charge on the detectors was causing instability, hence a bias boost curing was introduced at the time of the ground station hand-over, roughly midway through the revolution. This occurred during dedicated engineering time and had no effect on the ISO science time.

3.1. Lessons learned – Commissioning Phase

The LWS commissioning during SCP was successful. This was largely due to the tests carried out in space being extensively rehearsed on the ground, and there was also a continuity of personnel performing the tests. The space performance of the detectors, particularly the responsiveness and reaction to glitches, could not be predicted by ground tests, and the LWS team were both prepared and able to make adjustments to the instrument setup as deemed necessary.

4. PV Phase

The performance verification phase had three main aims: to characterise how well the instrument was performing, to establish the fundamental calibration and to verify the four AOTs in order to allow them to be released for use. In order to do this the four instruments worked on a four revolution rotating schedule. Essentially, one revolution was spent observing, two for data analysis and one for re-planning following any changes needed with respect to the pre-planned schedule. For LWS, the PV schedule was divided into urgent, high, medium and low priority observations. The urgent observations required analysis before planning the next revolution. The high priority observations required analysis within one week, and the medium priority observations had to be analysed before the AOTs could be released. Naturally, the aim was to have as few urgent priority observations as possible. However, given the constraints of releasing the four AOTs by the end of PV phase this could not be entirely avoided, particularly in the early revolutions. The nominal PV phase was executed as planned pre-launch for the first four revolutions, however the instrument team changed this nominal schedule in order to react to some instrument behaviour and problems.

4.1. FP offset scanning

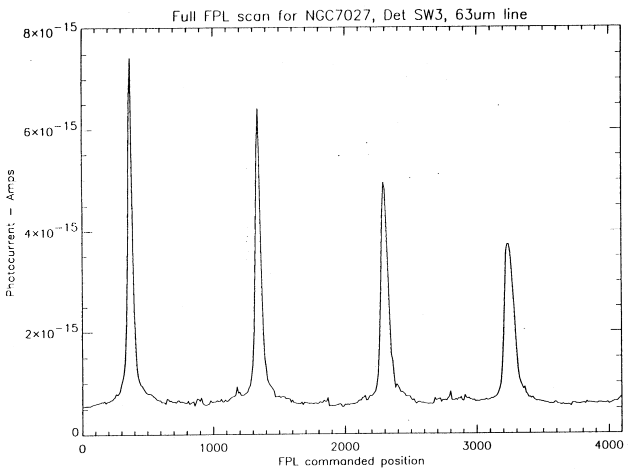

Figure 1. A full FPL scan of the 63μm [OI] line in NGC 7027. This scan was done with a single set of offsets and shows the loss of parallelism as the scan progresses.

The main impact on the PV phase schedule occurred as a result of needing more than the originally scoped time for the FP alignment exercise. After setting up the grating, the FPs were each scanned end to end over one line. Four orders on each FP were selected for offset scanning to establish the parallelism and to check the tracking. Two problems affected the schedule. The first was due to human error in the planning of the second set of short wavelength Fabry-Pérot (FPS) offset measurements. The offset scanning took place in the wrong direction from the starting point. The planning needed to be done on a revolution to revolution basis as the first set of offset scans needed to be analysed before the second set could be planned. This error cost about half of a revolution of ISO time. The second impact was the result of a hardware problem in the FPL tracking. Figure 1 shows an FPL scan through four orders on the 63μm [OI] line in NGC 7027. Although FPL is well aligned at the start of the scan this alignment is lost through the scan. The cause of this cannot be determined for certain but it is likely to have been due to a broken wire in the FPL tracking mechanism. To overcome this problem the alignment was found for four orders over the scan range and a position dependent calibration was implemented. Subsequently FPL worked well throughout the mission, however a total of two extra revolutions had been used. This slippage in the schedule meant that the FP wavelength calibration could not be completed by the end of PV phase and therefore the two FP AOTs could not be commissioned on schedule.

4.2. Detector performance

A second impact on PV phase was the different behaviour of the detectors in space to that seen on the ground. As the instrument had to be operated differently to what had been previously envisaged, the new setup had to be characterised, tested and some attempts were made to try new modes of operation. Early in PV phase, fast scanning was recommended for all observations to mitigate the effects of glitch tails i.e. a glitch affecting all data at one grating position, however it was known that this mode would have the drawback of introducing transient effects into the data. Bias optimisation took place for the operation of the illuminators and for each detector to ensure that the initial values determined in SCP phase were optimal. A test was made on the operating temperature of the unstressed detectors as increasing the temperature had decreased the spike rate on the ground. However in space, there was no effect on the spike rate but as expected the dark currents increased. By the end of PV phase we understood the optimal way to operate the LWS grating mode in space, we had completed a first version of the grating wavelength calibration, and although we had not completed the photometric calibration we felt able to release the two grating mode AOTs.

4.3. Meetings and publicity

During PV phase there were LWS team meetings once every four revolutions. There were also two milestone meetings, one during revolution 56 and one just after PV phase, where the LIDT presented their results. In the first meeting, the LIDT were also required to give the outline schedule for the remainder of PV phase. The preparation time for these meetings, especially the first one on revolution 56 had a significant impact on the LIDT work schedule due to this occurring simultaneously with the FPL tracking analysis. During PV phase, an extra requirement was made in that the LIDT needed to be supply results for publicity purposes. After a suitable target was identified, an observation was then planned for execution in revolution 59, but failed due to a spacecraft controller error. It was repeated in revolution 63 but the repeat observation was affected by missing telemetry.

4.4. Lessons learned – PV Phase

The need for the tight and difficult-t-plan schedule was partly due to a requirement of ISO's limited lifetime, partly due to ISO's visibility constraints and partly due to the difficulty in finding suitable calibrators for LWS. None of these constraints were avoidable. For the LIDT and the instrument experts working at VilSpa with the LIDT, PV phase was a difficult experience. Although the long term assessment has shown that none of the problems encountered were particularly serious, they were sufficient to have an enormous impact on a tightly scheduled, success oriented PV phase, not least on staff morale and fatigue. From an LIDT perspective the revolution 56 milestone meeting took resources away from instrument assessment and PV phase re-planning. The second milestone meeting and an internal calibration review were a useful launch for Routine Phase, with the minutes from these meetings, along with the PV phase wrap-up report, providing useful documentation of the state of calibration at that time. It is an important consideration to determine suitable sources for publicity before a mission and to try to observe these as early as possible.

One of the drivers for PV phase was to have all AOTs fully commissioned three months into the mission. What actually occurred was that two AOTs were commissioned, although a first cut of the downlink calibration was not available. The other two AOTs were released later. The non-release of two AOTs had an impact on the Routine Phase scheduling as corresponding observations had to be blocked. For future missions a staged release of AOTs could be considered, especially in cases like LWS, where the simpler modes were also those modes favoured by the majority of observers. In the LWS case, where a completely new wavelength range was being explored for the first time, many observers opted to use grating observations to get a first assessment of sources which they then investigated in detail using the FP mode.

Another lesson is that it is not necessary to have a complete downlink calibration at the start of the mission. Instead it is sufficient to have a good enough understanding of the instrument to be able to execute the AOTs correctly and most efficiently for good science. The combination of the ground testing and in-orbit characterisation achieved this. Improvements to the LWS pipeline processing, calibration files and interactive analysis are still being made well into the Post-operations Phase.

5. ROUTINE PHASE - CALIBRATION

The Routine Phase started with the calibration time baseline of four instruments sharing one revolution in seven. I.e. nominally about four hours per week per instrument. As the mission progressed this baseline changed and the same time allocation was not limited to a strict seven day cycle. LWS fundamental calibration was not completed in PV phase, two extra revolutions had been used for the FP alignment and two revolutions were surrendered for later use when Uranus would be visible. The combination of using the two extra revolutions plus calibration targets becoming visible as the mission progressed led to routine phase calibration actually containing a combination of monitoring and fundamental calibration. The LIDT and members of the LWS consortium participated in LWS Data Analysis Group (LDAG) meetings. These meetings were chaired by the principal investigator. The progress in calibration and analysis was discussed and new problems were raised. Initially LDAG meetings were held about once every six weeks. The frequency of meetings decreased to about once every three months about a year into the mission, then once every six months in Post-operations Phase.

5.1. Photometric calibration

The photometric calibration is currently based on the Routine Phase observations of Uranus (Lim & Swinyard 2003). The photometric calibration has been checked for applicability to the asteroids (Müller & Lagerros 2003) and extensive work has been done to define this calibration on a Mars model basis (Sidher et al. 2003). For Neptune the LWS data is being used to refine the model. The LWS photometric calibration also agrees very well with the stellar SED templates developed by Martin Cohen for α Boo and α Tau. The current FP photometric calibration relies on the grating calibration plus an FP throughput calibration with the transmission and resolution based on observations of Mars.

5.2. Wavelength calibration

High signal-to-noise, highly oversampled measurements of bright emission lines had been performed early in PV phase to check the grating wavelength calibration. However the in-flight wavelength calibration has been performed with the large database of full grating range observations obtained during Routine Phase for the weekly monitoring (see Section 6 and Gry et al. 2003). Little was known about which sources would be suitable for the establishment and monitoring of the FP wavelength calibration and several sources were tried including NGC 3603 (used early on), S106, NGC 6543, AG Car, G36.3−0.7 and G0.6−0.6. The FP wavelength calibration was then established just using NGC 7027, G36.3−0.7 and G0.6−0.6 as these were found to be most suitable (Hutchinson et al. 2003).

5.3. Beam characterisation

The beam sizes (one for each detector) were first determined using two sets of observations of Uranus: a cross-scan in the RA-Dec frame of reference with the grating in a fixed position and a cross-scan in the spacecraft frame of reference with a full grating scan at each point. The beam sizes determined were smaller than expected. Also early in the mission fringing had been found in grating mode, for observations of extended sources, indicating a problem with the LWS optics. A programme was instigated to determine the cause of this by making adjustments to the LWS optical model. When it became clear that Mars would become visible by ISO a special request was made to spend time observing Mars at various points over the LWS beam. This observation has proved invaluable and has helped the LWS team determine the full optical behaviour (Lloyd 2003). The characterisation of the edges of the beam was made with cross-scan observations of Saturn.

5.4. Other calibration

There were several other calibration aspects looked at during Routine Phase. Attempts were made as early as PV phase to understand the range over which the LWS detectors were linear. This was established to be below about 10 000 Jy at 100μm. Saturn and Mars were observed specifically for strong source characterisation (Leeks et al. 2003). Sensitivity to polarisation was checked and not found using two observations of the crab nebula. Straylight checks were also made using off-axis observations of Saturn and Jupiter. The blanks (offset FPs) were also checked for transmission using bright sources.

6. ROUTINE PHASE – MONITORING

It was an important consideration in the calibration strategy to have as few targets for monitoring as possible as the time available only allowed for one or two objects to be observed for each monitoring purpose. For photometric monitoring, G298 and S106 were used as bright sources, and γ Dra was used as a faint source. However this was dropped as the S/N ratio was not sufficient. Uranus was observed whenever visible and Neptune was observed whenever time allowed. For the grating wavelength calibration, NGC 6543 was observed almost continually throughout the mission with NGC 6826 being observed as often as possible, while a few other sources were observed less often (Gry et al. 2003). For FP wavelength calibration monitoring NGC 3603 was used early in the mission but was deemed unsuitable. Later NGC 7027 and NGC 7023 were used extensively (Hutchinson et al. 2003).

6.1. Mission events

Several events occurred during the ISO mission which required a strategy for checking the instrument behaviour following them. The first unexpected event occurred in revolution 196 when ISO was put into safe mode following a violation of the Earth constraint. Extra calibration time was allocated in revolution 203 and a check with the monitoring targets showed the instrument was operating normally. The other main event which affected the satellite was a solar flare which hit the satellite in revolution 722 (Burgdorf & Harwood 2003). This caused the loss of more that half the LWS data for that revolution with many observations declared as failed. The flare had no impact on LWS apart from the high glitch rate while it was passing the satellite.

Two other events were LWS specific. In revolution 380 the LIDT made a request for LWS to be switched off. The trend analysis was indicating that the interchange wheel was not reaching its final position before the start of some observations. This was an intermittent problem hence difficult to detect. Analysis of ground test data indicated that the wheel stepper motor was likely to be losing traction and a simple solution was to drive it at a slower speed, requiring a change in the onboard software. LWS was switched on and parallel mode operated from revolution 397. A test observation using the on-board software patch was made in revolution 442 and LWS operations resumed in revolution 447. The only impact this period had on the LWS was the positive impact that the LW2 detector was 40% less responsive after this period than before. A further reduction in stepper motor speed was made later in the mission without affecting operations.

The other LWS specific event was the appearance of intermittent spurious features in LWS data late in the mission. These features were only seen in the stressed detectors and had a small constant flux, therefore were only visible on faint objects. The features were caused by the responsivity of the stressed detectors becoming unstable. This instability is thought to have been due to a loss of coupling in the 1.7 K thermal strap from LWS to the He tank, possibly a break in the He film where the strap joined the tank. The LIDT manually checked all LWS observations after revolution 650 and, where possible, the affected observations were re-scheduled. As LWS monitoring observations were of relatively bright objects, this problem was actually picked up by LWS users who reported the problem to the LIDT.

6.2. Lessons learned

The actual time spent monitoring calibration was about 2–3 hours per week. The decision to observe a few objects as often as possible was a good one. The usefulness of this strategy is illustrated by a sudden change in the wavelength calibration that occurred between calibration revolutions 342 and 349. As we had monitoring observations in both revolutions 342 and 349, we could determine the time of change accurately. The use of a few well observed objects allowed the repeatability to be reliably determined and monitored for the three periods relating to the three different illuminator sequences used but we were fortunate that in general LWS was a reliable and repeatable instrument. Due to time limitations, risks had to be taken e.g. for photometric monitoring, the choice of a few sources meant that only a limited flux range was covered and it was only through LWS observers input that the LIDT were alerted to the presence of the spurious features. For grating wavelength monitoring, NGC 6543 only has three very bright lines, other lines were monitored from sources less well observed. The FP wavelength monitoring was problematic as it was difficult to find suitable sources. Hence many candidates were observed by the FP before sources were found and monitoring was established. The need to put some fundamental calibration in routine time meant that some calibration was not completed until late in the mission. E.g. the complex analysis of the LWS beam has only been done in the Post-operations Phase. However, these calibration aspects are not those that require monitoring. The LDAG meetings provided an excellent framework for sharing information between all people interested in getting the best scientific output from LWS data. The high frequency of meetings early in the mission was particularly useful as our understanding of the instrument was developing rapidly and recommendations for the optimal instrument operation, such as the bias setting, could be made at an early stage and endorsed by the whole team.

7. POST-OPERATIONS

The ISO Post-operations Phase commenced just after the mission ended in April 1998, lasting until December 2001. This phase was used by the LWS team to deepen the understanding of LWS calibration and improve the quality of the data. The general approach was for individuals within the team to concentrate on one area where the calibration was poorly, or not at all understood, and to make improvements in that area. Where possible this work has been done in collaboration with other instrument teams in the context of cross-calibration working groups. E.g. beam properties and transients. Other aspects were LWS specific e.g. parallel/serendipity mode processing, and FP wavelength calibration investigations. The post--operations period has been very productive and a lot of LIA development has resulted from an improved understanding of the instrument behaviour. This period has also been used to start work on cross-calibration with IRAS (Chan et al. 2003).

8. SUMMARY

The LWS calibration strategy provided a good framework for the LWS team to meet most of the LWS calibration goals. Sufficient calibration observations were made but some calibration activities would have benefited from more time. Also it should be noted that in general LWS was a linear, well behaved, instrument which allowed risks to be taken with the observation strategy. The ability to surrender two PV phase revolutions and use two revolutions in Routine Phase was essential to our photometric calibration and the beam characterisation, both of which required long measurements. The specially requested time to characterise the beam using Mars was simply invaluable. Without this observation we would not have achieved an understanding of the LWS optics. The overall concept of a PV phase followed by a routine phase is a long established one which is generally useful. However flexibility is required to deal with instrument problems and a staged AOT release might be a consideration for future missions. The routine monitoring was adequate to show the stability of the wavelength and photometric calibrations but there was insufficient time for the monitoring to pick up problems such as the near-infrared leak and spurious features that appeared towards the end of the mission, both of which were reported by observers. Therefore having input from a wider consortium which became experienced in LWS data from an early stage was of great benefit to the LIDT.

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