THE ISO SWS CALIBRATION: STRATEGY AND LESSONS LEARNED

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ABSTRACT

Instrument calibration can be seen as having several different components; clearly there is the use of specific calibration tools according to specific procedures on well defined data sets to yield calibration parameters. Also the application of such calibration parameters to data is part of the general process of instrument calibration. Possibly the most important part of the instrument calibration process is the actual design and development of the various calibration tools and procedures. Especially critical is the possibility for instrument specialists to efficiently incorporate refined instrument understanding into standard calibration and data processing steps.

The experience obtained in developing SWS calibration strategies when going from pre-ground test theory through instrument level tests, performance verification, operations and post operations are discussed. The importance of a flexible and adaptable data analysis environment as well as continued access to all test data -i.e. both pre-flight and in-flight- is illustrated.

Key words: SWS, calibration

1. INTRODUCTION

One of the main problems when operating an astronomical observatory is how to calibrate that observatory, i.e. how to convert the signals at the output of the instruments into quantities that are useful for astronomical analysis. For space born observatories calibration is an especially hard task since in that case there is no -or at best very little- possibility to physically adapt the scientific instruments following improved understanding of their operational behaviour.

For the Short Wave Spectrometer (SWS - de Graauw et al. 1996) on board the Infrared Space Observatory (ISO - Kessler et al. 1996) obtaining a proper understanding of the instrument before it was hurled into space and adopting flexible calibration procedures was of the essence to be able to calibrate data obtained with it. The following sections describe the strategy adopted to establish the calibration for the SWS and the experiences gained from this process.

2. SWS INSTRUMENT CALIBRATION

2.1. The SWS calibration domains

For a spectrometer like the SWS fundamentally there are two domains to be calibrated; the wavelength and the intensity domain. These two domains are essentially independent and thus can be treated separately. For SWS the intensity domain can be further split into the absolute and relative flux density scales.

The accuracy of the wavelength calibration of the grating spectrometer section of the SWS was required to be very high -better than 7 times the resolution of about R$\sim$2000- since this is the basis for the wavelength calibration in the Fabry-Pérot section of the instrument (for details on the instrument principles see de Graauw et al. 1996). The wavelengths falling on the SWS detectors are fully determined by the optical geometry of the instrument and the relevant calibration components are the ‘angles’ (detector offsets w.r.t the optical axis) and the ‘grating scale’. Since the instrument was expected to be at a constant temperature the geometry and thus the wavelength calibration was not expected to change during the mission. The wavelength calibration was determined and verified using both an internal calibration source as well as astronomical sources with well defined spectral line emission (see Valentijn et al. 1996).

Being a *spectro*meter and not a *photo*meter the requirements on the accuracy of the absolute intensity scale are less stringent for SWS. It was expected that this scale would be largely determined by the properties of the SWS detectors themselves and that it would change slowly, on time scales of hours if not days. The absolute flux scale was determined by a process of iterations by updating the calibration for SWS observations of stellar sources and updating the detailed models for these stars (see Schaeidt et.al. 1996, Shipman et al. 2003 and reference therein). An internal calibration source was used to transfer the flux scale from these external calibrators to individual observations.

Since the main use of a spectrometer is to compare spectral features at different wavelengths the calibration of the relative spectral responsivity needs to be very accurate. The spectral responsivity depends on the properties of the filters in the light path and on the detector material. It was expected to be constant during the mission and this was verified by observing sources with ‘smooth’ spectra. More details on the spectral responsivity calibration are given by Vandenbussche et al. (this volume).

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2.2. Example SWS calibration problems

There are a number of 'features' in SWS data that need to be understood to be able to usefully use the data for scientific analysis. A number of these 'features' can be categorised as calibration problems, some remain features to be dealt with by the astronomer analysing his data. Probably the least satisfying in this latter category are the 'spikes' due to cosmic ray hits onto the detectors. Especially the band 4 Ge:Be detectors suffer greatly from these hits, and to date no satisfying method for removing the resulting artifacts in the SWS data has been found (see figure 1).

One of the examples of a true improvement in the calibration understanding and subsequently in the data processing is shown in figure 2. The top panel shows the original calibration for band 2 data which are seriously affected by detector memory effects. The two traces indicate that the two scans which are always executed in opposite wavelength directions are seriously misaligned. After application of a detector memory effect correction algorithm (see Kester 2003) the result shown in the bottom panel is obtained. The correction perfectly aligns the scans and reveals a feature around 6.7 μm which was not visible originally.

3. The SWS calibration strategy

In the process of calibrating an astronomical instrument like the SWS one is trying to establish the inverse of the transfer function F that represents the instrument transforming the incident sky radiation $S_{sky}(\lambda)$ to measured output signal $V(t)$:

$$V(t) = F(S_{sky}(\lambda)) \rightarrow S_{sky}(\lambda) = F^{-1}(V(t)) \tag{1}$$

Obviously such a transfer function includes all elements of the instrument i.e. detection system, mirrors, lenses, filters, telescope etc. Since in practice the complete function is almost never fully known analytically, the problem is decomposed into a number of (hopefully) orthogonal components that can each

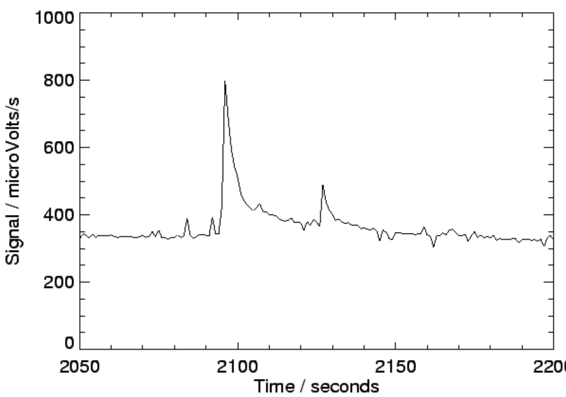

Figure 1. A typical trace of the output of a band 4 detector. The data show a strong glitch with a decaying tail affecting several tens of seconds worth of data. To date no proper method for removing such glitches from band 4 data has been identified.

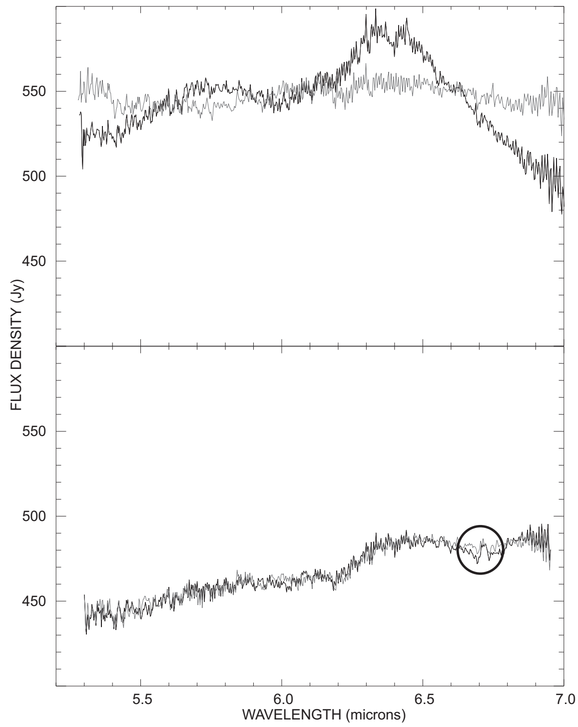

Figure 2. SWS data improvement as a result of the detector memory effect correction algorithm (see text). The feature around 6.7 μm (indicated by the circle) is not visible in the original data.

be calibrated independently. As an example the transmission curves of filters are determined separately from the absolute sensitivity of the detectors.

Most of the calibration components for SWS were expected to change very little with respect to their pre-flight values and only slowly with time during the mission. Therefore the basic strategy was to separate equation 1 into a pre-flight value and in-flight updates

$$V(t) = F_0(S_{sky}(\lambda)) \times F_t(S_{sky}(\lambda)) \tag{2}$$

where the updates are *small*: $F_t \sim 1$.

The decomposition of the transfer function for different orthogonal calibration components X, Y, Z etc. is then done separately for the pre-flight values and updates:

$$F_0(X, Y, Z, \ldots) = F_0(Z) \times F_0(Y) \times F_0(Z) \ldots \tag{3}$$

and

$$F_t(X, Y, Z, \ldots) = F_t(Z) \times F_t(Y) \times F_t(Z) \ldots \tag{4}$$

/noindent The process of calibrating the instrument is then the determination first of the pre-flight calibration and subsequently determining the updates. The updates are iterated on as time goes on reflecting further improvements in the understanding of the instrument and its calibration. It should be noted that this mechanism of using a solid pre-flight baseline and small in-flight corrections applies not only for the calibration components themselves, but *also* (in parallel) for the algorithms used to derive calibration parameters as well as those that are used to apply them to observational data (see figure 3).

A very important element in the calibration strategy of SWS is that since calibration parameters and procedures need to be applied to standard science observations (AOTs), it is logical to use standard observations to determine calibration parameters as well. Thus wherever feasible within the constraints of available calibration time the standard AOTs were used for calibration observations. Furthermore, to keep the calibration process for the various ILTs repeatable we standardised early on on the test procedures used on ground. Wherever possible these were designed to mimic the procedures as intended to be used in-flight, ideally already using AOT-like scripts. As a result even after the end of the ISO mission it was still possible to directly compare specific calibration data taken in the earliest ILTs with calibration observations taken in-flight.

3.1. Changes in calibration components

As already indicated above an update in (the application of) a calibration component can reflect different things;

1. Physical changes in the instrument.
   Finding and quantifying such physical changes is the main objective of trend analysis; investigating how and by how much the behaviour of the instrument changes with time. Such changes clearly occur between different cool-downs of the instrument and (thus) also between pre-flight and in-flight. For SWS much information on such changes could be tracked by monitoring the response to the internal calibration sources.
2. Changes in the insight in the physics of the instrument and the calibration sources (internal and external).
   With the extensive use of the instrument, especially during Instrument Level Tests (ILTs) but also in ISO operations, a lot of insight was obtained regarding the physics of elements of the instrument. This is especially the case for the behaviour of the detector materials under various conditions (temperature, intensity of the incident radiation, particle hits). During ILT such improved understanding lead to modifications in the instrument design and in-flight to modifications in the SWS operational modes and calibration procedures.
3. Changes in the (software) implementation of the calibration process.
   To be able to determine calibration parameters as well as to apply these to observation data a large suite of software tools is used for SWS (see also Wieprecht et al. 2003). Thus one way of changing a calibration component is by adjusting the procedure to determine and/or apply that component. For SWS indeed the various tools have evolved significantly from pre-flight to post-mission, but always in a controlled fashion (see Huygens et al., 2003; Wieprecht et al. 2003).

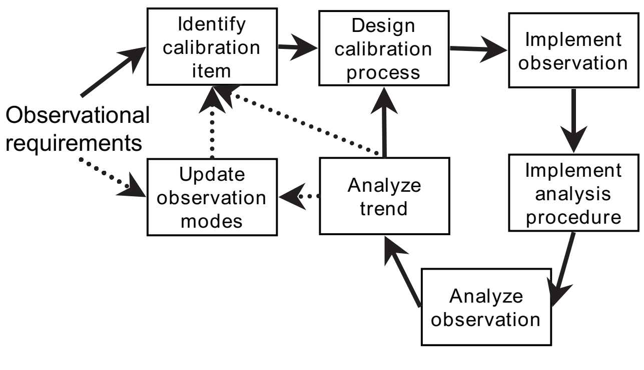

Figure 3. Schematic indicating the iterative nature of updating calibration components as well as their derivation and application procedures.

3.2. Tracking time variations in the calibration of SWS

For the different calibration components it is of importance to have proper mechanisms to track changes across the relevant time scales. As an example for the SWS flux calibration variations on time scales of seconds to tens of seconds were monitored by comparing the outputs of different detector elements which were measuring the same signal at slightly different times during an observation. Drifts in the flux scale over months up to a few years on the other hand were monitored by regularly observing one of the flux standards γ Dra (see figure 4).

One of the examples of an update to the operational procedures for SWS applied in-flight was the deletion of the photometric check using the wavelength switch (see also figure 4). The wavelength switch forced the instrument during an observation to regularly measure the astronomical source at a preset wavelength. At that wavelength in principle it always should yield the same output signal which then can be used as a reference. This wavelength switch was thought to be needed for the tracking of sensitivity changes over time scales of a few hundred seconds. Unfortunately due to the rapidly changing signal level during the switch the detector sensitivity was negatively affected in that it started changing rapidly as well. This effect was discovered early in the mission, and the wavelength switch was deleted from the operational procedure.

3.3. Documenting SWS calibration

To be able to describe the requirements on the accuracies for calibration components, the procedures to derive and/or apply them and to track their status an integrated SWS calibration documentation system was set up. This system functioned more-or-less like an SWS calibration 'data base' in that it contained all SWS calibration information from the first ILT through the end of operations and linked textual descriptions with actual observation and analysis scripts. Changes to this documentation and procedure set were applied under a strict configuration control system. As a result both the status and

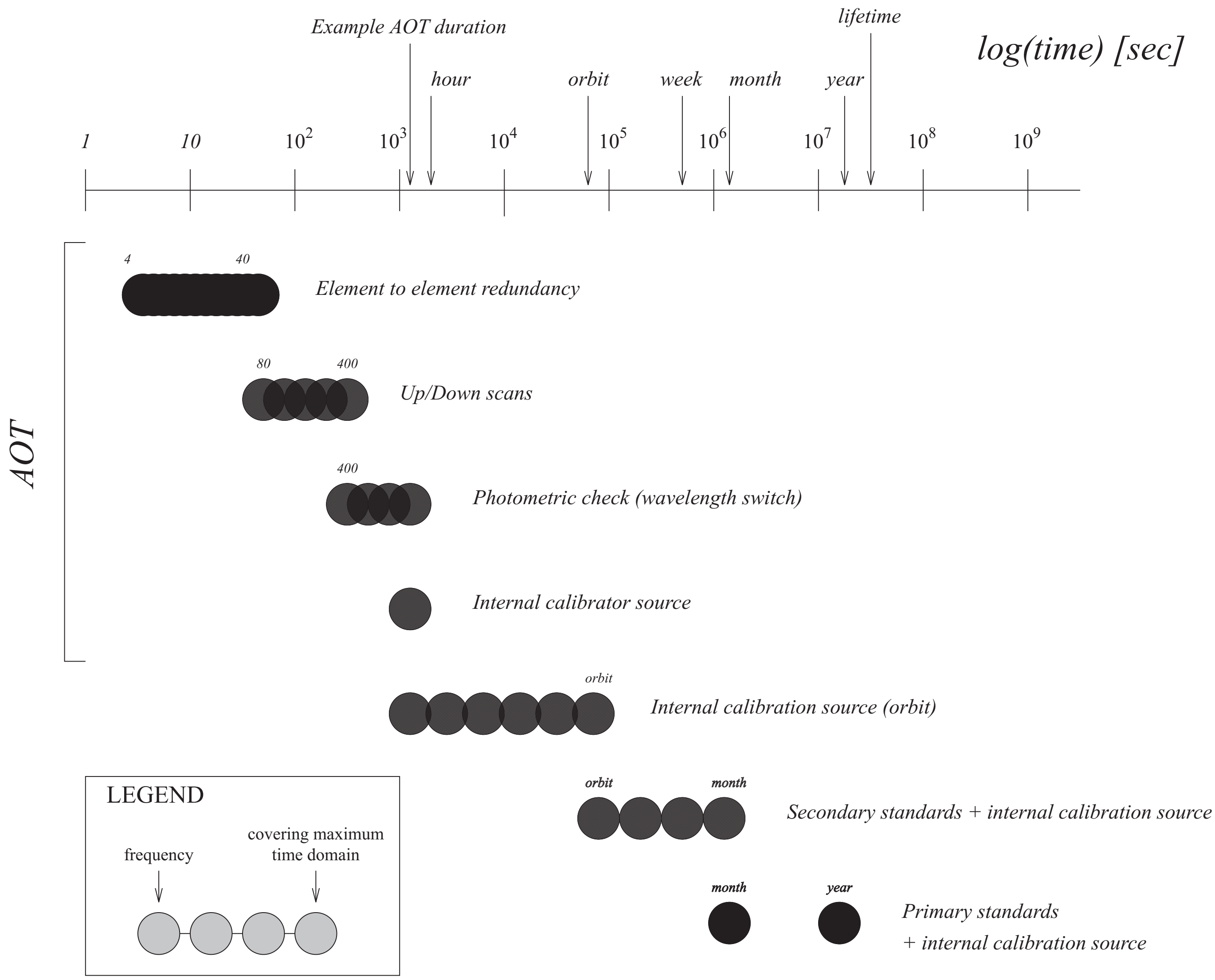

Figure 4. Different flux scale time dependencies for SWS are tracked by different operational procedures.

the history of SWS calibration could be reliably determined at any time during the mission.

Early in the process of analysing the calibration (accuracy) requirements, the requirements for the calibration analysis as well as the data processing software were established. As a result, together with setting up the calibration plans a reliable calibration processing environment could be designed and implemented. During the ILTs this reduction environment was used -and thus tested- extensively, and in flight only relatively small changes needed to be made to implement updates in the calibration analysis and standard data processing.

3.4. Calibration 'tools'

The tools to support the calibration work can be as important as the strategy. There are a number of different types of tools that are absolutely required to be able to successfully establish and maintain a proper instrument calibration:

– Strict configuration control on documentation and procedures is essential. This ensures traceability of calibration parameters and repeatability of calibrations. With a specially designed tool the SWS instrument dedicated team maintained strict control on the In Orbit Calibration Document, the Calibration Observation Batches and the Calibration Implementation Procedures.
– Flexible uplink control is absolutely necessary. To be able to try out new calibration schemes flexible commanding is needed (as provided by the Calibration Uplink System), while at the same time it should be easy to stay close to the standard commanding used in scientific AOT observations.
– A rich 'playground' with many calibration analysis tools is needed to be able to efficiently analyse calibration data. At the same time a proper development environment for these tools is required to allow rapid evolution of the tools and application procedures to follow improved instrument understanding (see also Wieprecht et al. 2003).

– The development environment must also be properly controlled to provide traceability for updates to the used calibration analysis procedures as well as for the calibration parameters (see also Huygen et al. 2003).

4. SWS CALIBRATION OVER THE MISSION PHASES

4.1. GROUND CHARACTERISATION

It is clear that determining an accurate pre-flight baseline is essential in the process of establishing the SWS calibration along the strategy as outlined in the earlier sections. Indeed, extensive ground tests were executed and data obtained in these tests were subsequently analysed in great detail. Overall this campaign was extremely successful and indeed resulted in a very solid pre-flight calibration:

– The wavelength calibration was completely characterised and the 'spectral' behaviour -also between cool downs- of the instrument was essentially fully understood. The procedures for updating the wavelength calibration was exercised and verified many times.
– The absolute flux scale was well understood in terms of its behaviour, but could not be settled definitely due to the lack of a proper input beam in the test setup (in-flight measurements actually showed the ground based values to be essentially correct).
– The relative spectral responsivity was very well determined on ground resulting in only relatively minor corrections in-flight. This was possible due to the availability of a very accurate black body source. The main disadvantage of the ground calibration here was that it was only valid for extended sources, corrections for point sources had to be measured in-flight.

More details on the SWS ground characterisation are given by Feuchtgruber (Feuchtgruber et al. 2003).

4.2. CHECK-OUT AND PV

With the well determined pre-flight calibration the in-orbit check out and performance verification phases could be planned ahead of time in great detail. A strict time line was set up to first verify the ground calibration and subsequently -when justified by in-flight data- adjust calibration parameters and/or procedures.

The schedule as indicated in figure 5 was executed essentially as planned. As a result virtually all planned characterisations of the SWS instrument were completed by the end of the PV phase. All calibration parameters were determined to within the required accuracy, many were significantly better. More importantly generally the changes with respect to the ground calibration were indeed found to be small.

Unfortunately the PV phase also yielded some disappointments. The most notable was the reduced sensitivity of the instrument with respect to what was expected pre-flight. Secondly the glitch rate (for an example glitch see section 2.2) was perceived to be significantly higher than expected (the same was found by other instrument groups). More detailed analysis showed that this was not the case but that none of the instrument experts had ever seen glitches during ground tests due to the much higher level of background noise. Thirdly a problem was found with the band 3 detectors for which the bias voltage had to be adjusted to be able to operate them properly. Unfortunately this also lead to a reduction in sensitivity at wavelengths between 12 and 30 μm.

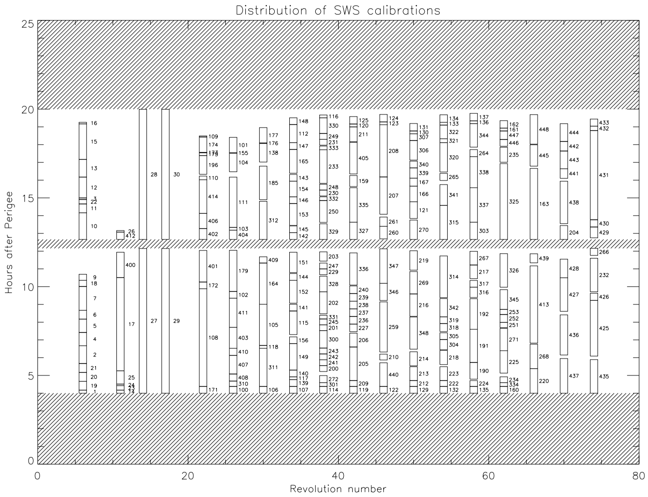

Figure 5. Schematic showing the various SWS calibrations as planned and executed during the Performance Verification phase.

4.3. ROUTINE OPERATIONS

Also for routine operations a pretty much fixed plan was used to monitor and obtain further detail on the calibration of the SWS instrument. In the weekly calibration revolutions the same observations and procedures were often repeated resulting in an ever growing data base useful for trend analysis and obtaining improved statistics on calibration parameters.

Most of the observations carried out to check the wavelength calibration showed no change whatsoever. Data taken to monitor the absolute flux were less straightforward to interpret; there were indications of systematic variations at the level of 10%, but no clear conclusion with respect to cause could be drawn. The most problematic exercise was the correction of the spectral responsivity calibration from extended source to point source. Especially for the longer wavelengths this work was seriously hampered by the lack of suitable calibration sources (for a more detailed discussion on the spectral responsivity for SWS see Vandenbussche et al. 2003).

With the basic calibration properly settled the high stability of the SWS instrument allowed the characterisation of a number of other instrumental effects to enable more detailed astronomical studies. These effects were the influence of cosmic ray hits (see Heras et al. 2003), detailed analysis of effects due signal capture process in SWS (Lahuis et al. 2003), the detailed shape of the SWS beam profile (Beintema et al. 2003), fringing in the signals due to Fabry-Pérot interference in filters and detector material (Kester et al. 2003) and the correction of detector memory effects (Kester 2003).

The stability of both the SWS instrument and the calibration analysis procedures were put to the test once more after the liquid He had been depleted. In a three week period following the 'end-of-He' observations were carried out using the SWS band 1 detectors which were still sensitive enough to be useful for astronomical work. In this period during which the instrument slowly heated up from a few °K to several tens °K both the wavelength and the absolute flux calibration could still be easily tracked using the standard procedures essentially as designed pre-flight.

5. LESSONS LEARNED

5.1. Plans and systems

- The strategy of initial/pre-flight calibration values with subsequent incremental changes worked very well for SWS. One obvious prerequisite is that the calibration work *must* start in the lab!
- The procedural setup used for calibration requirement analysis as well as for calibration planning for PV and routine phases was very effective.
- The integrated development of the SWS calibration plans and the data analysis systems required for the calibration proved effective in that the data reduction tools -or at least their early incarnations- became available already during the ILTs. Thus both the calibration strategy as well as the algorithms were tested extensively before flight.
- The strategy of using the same procedures pre-flight as in-flight and using AOTs for calibration as well as for science was very successful; most ILT data for SWS can still be analysed, and almost all SWS calibration observations can be processed like normal science data.
- Flexibility in instrument commanding (CUS) facilitates calibration by allowing instrument specialists to experiment with updates to operating modes.
- To be able to efficiently tackle the (slowly) changing instrument calibration infrastructure to support change is essential (both for calibration analysis systems as well as for data processing software).
- Getting updated calibration knowledge implemented in the standard processing software (OLP code and calibration files) proved very hard because the relevant systems were not designed to incorporate changes. As a result it was difficult to get improvements available for end users.
- The absence of a connection between the uplink and downlink systems required the instrument team to create and maintain traceability mechanisms internally. This reduces visibility on the calibration progress for the outside world.
- Maintaining documentation can be a very tedious job. Implementing a proper documentation (and data) management system significantly eases the burden of documenting the calibration status.

5.2. The people

- At the start of operations there were serious 'walls' between the PI-team and the various ESA groups. These walls initially were hurting progress but due to the good working spirit together we succeeded in knocking them down.
- It was found to be hard and time consuming to (fully) transfer instrument experience to new team members. The most efficient training for operations is obtained during the ground tests, so make sure hardware/ILT personnel are also put in the operational team.
- For the workers in the front line it is important to keep aims realistic. Promising a high fidelity calibration at the end of PV is nice PR but puts undue pressure on those that have to provide that calibration.
- Good contact between instrument teams and astronomical 'modelling' groups is essential: e.g. for SWS the flux calibration was bootstrapped with stellar models from the SWS scientific community.

6. CONCLUSIONS

The experience gained in the process of calibrating the SWS instrument can be summarised as follows;

1. Expect the instrument to change, so build systems that can cope with change.
2. Do as much preparatory work in the pre-flight tests as possible, then likely the in-flight changes are small.
3. Wherever possible in operations make a plan and try to stick to it.
4. Always stay in touch with the science community as the general astronomers provide a huge base of information with respect to possible improvements in instrument calibration.

REFERENCES

Beintema, D. et al., 2003, this volume
Feuchtgruber, H. et al., 2003, this volume
de Graauw, Th., Haser, L.N., Beintema, D.A. et al., 1996, Astron. & Astr., **315**, L49
Heras, A.M. et al., 2003, this volume
Huygen, R. et al., 2003, this volume
Kessler, M.F., Steinz, J.A., Anderegg, M.E. et al., 1996, Astron. & Astr., **315**, L27
Kester, M.F. et al., 2003, this volume
Lahuis, F. et al., 2003, this volume
Schaeidt, S.G., Morris, P.W., Salama, A. et al., 1996, Astron. & Astr., **315**, L55
Shipman, R. et al., 2003, this volume
Valentijn, E.A., Feuchtgruber, H., Kester, D.J.M. et al., 1996, Astron. & Astr., **315**, L60
Vandenbussche, B., 2003, this volume
Wieprecht, E. et al., 2003, this volume