TITLE: Prelaunch Calibration Files for RSDP

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1. Introduction

The FOC IDT is obligated to provide the calibration files and parameters needed by the Routine Science Data Processing (RSDP) system for the purposes of routine calibration of science data in the “pipeline.” This report describes the plan to generate these calibration files and parameters prior to launch. Also required are the “reference relations” necessary for proper calibration. These reference relations are used by RSDP to determine which calibration files and parameters to use for a particular instrument mode. This report describes the methods that will be used to generate these reference relations.

This report does not address all aspects of calibration; rather, we address those aspects that directly relate to optimizing RSDP calibrations. For more complete discussions, see the Liege calibration report (Malaise 1981). This report is not intended as an introduction to the FOC or its calibration—we presuppose a high level of familiarity with the FOC and its calibration. The reader will find the necessary background information in the FOC instrument handbook (Paresce 1985) and the PDA (Photon Detector Assembly) handbook (Morgan 1979).

2. Calibration Principles

We will describe the calibration principles, partly to clarify notation, partly to highlight practical difficulties, and partly to serve as a basis for comparison with RSDP. While, as will be described in later reports, the basis of the correction methods used in RSDP is incomplete and certainly not ideal, nevertheless calibration files must be generated consistent with the requirements of RSDP. We should, however, attempt to use other knowledge of FOC behavior to ameliorate RSDP shortcomings. That issue will be addressed in the next section; the notation that we use is that employed by the ISB to describe the reference parameters, which is, turn based on the notation that is used in SE-06 (TRW 1986)
TRW document that specifies what RSDP is to do. Unfortunately, SE-06 does not have symbolic notation for all the parameters, and frequently uses the same symbols to describe different parameters or data. Thus there is not always exact correspondence between the notation of this report and SE-06.

Denote the raw received image by \( r(i,j) \) where \((i,j)\) represent the frame and line coordinate of the image and \( r(i,j) \) represents the number of counted photons at that sample and line coordinate (the frame value is equivalent to \( y \) position and the line value corresponds to the \( x \) position). If we have an arbitrary source brightness distribution \( B(\alpha, \delta, \lambda) \) where \( B(\alpha, \delta, \lambda) \, d\lambda \) is the average rate of photons between wavelengths \( \lambda \) and \( \lambda + d\lambda \) from sky coordinates \((\alpha, \delta)\) incident on the telescope primary, then \( B(\alpha, \delta, \lambda) \) is related, on the average, to the photon flux on the photocathode faceplate of the detector by

\[
\mathcal{F}(i,j,\lambda) = R_{\text{OTA}}(\lambda) R_{\text{FOC}}(\lambda) T_f(\lambda) \int \int B(\alpha, \delta, \lambda) P_{\delta i}(\alpha - \alpha_i, \delta - \delta_i, \lambda) \, d\alpha \, d\delta
\]

where \( \mathcal{F}(i,j,\lambda) \) is the photon flux density at the detector faceplate at \((i,j)\),
\( R_{\text{OTA}}(\lambda) \) is the reflection efficiency of the OTA optics,
\( R_{\text{FOC}}(\lambda) \) is the reflection efficiency of the FOC optics,
\( T_f(\lambda) \) is the net transmission efficiency of the filters in the optical path,
and \( P_{\delta i}(\alpha, \delta, \lambda) \) is the point-spread function of the optics.

The integer coordinates \((i,j)\) correspond to a region on the detector faceplate that will be mapped by the detector onto the frame and line coordinate \((i,j)\) of the resulting image produced by the detector. This region on the faceplate is also mapped, in the other direction, onto a \((\alpha, \delta)\) region on the sky. Similarly, the coordinates \((\alpha_i, \delta_i)\) are the positions in the sky that map onto pixel \((i,j)\) in the image. This mapping may be time variable, and, because of how the detector works, results in geometric distortion of the image. The point-spread function is generally a function of position in the telescope field of view and therefore has been shown as a different function for each \((i,j)\). We shall neglect the fact that the detector actually integrates the flux incident on the detector faceplate over a small region rather than sampling it at a point. This approximation should be of no consequence for everything that follows.

The image produced by the detector, \( r(i,j) \), is related to \( \mathcal{F}(i,j,\lambda) \) by

\[
r(i,j) = t_e \int_0^\infty q_d(i,j,\lambda) \mathcal{F}(i,j,\lambda) \, d\lambda + t_e d_c(i,j)
\]

where \( q_d(i,j,\lambda) \) is the quantum efficiency of the detector, \( t_e \) is the exposure time, and \( d_c(i,j) \) is the dark count rate. The dark count rate is the average rate of spurious photon counts due to internally generated events of whatever cause (photocathode thermionic emission, false counts, or particle hits for example). Thus we have

\[
r(i,j) = t_e \int_0^\infty R_{\text{OTA}}(\lambda) R_{\text{FOC}}(\lambda) q_d(i,j,\lambda) T_f(\lambda) \int \int B(\alpha, \delta, \lambda) P(\alpha - \alpha_i, \delta - \delta_i, \lambda) \, d\alpha \, d\delta \, d\lambda + t_e d_c(i,j)
\]

We have not included any effects of detector nonlinearity in this model of detector response although it clearly exists. Since the nonlinearities are not well understood, they cannot
currently be removed in calibration. Effectively, we must assume the detector is operating in the linear regime.

The above expression for \( r(i, j) \) can be rewritten as

\[
r(i, j) = t_i \int_0^\infty Q(i, j, \lambda) T_f(\lambda) F(i, j, \lambda) \, d\lambda + t_c d_c(i, j)
\]

where \( Q(i, j, \lambda) = R_{OTA}(\lambda) R_{FOC}(\lambda) q_d(i, j, \lambda) \) is the net quantum efficiency at each pixel (again minus any contribution from the filters) and \( F(i, j, \lambda) = \int \int B(a, \delta, \lambda) P_{i,j}(\alpha - a, \delta - \delta_j, \lambda) \, da \, d\delta \).

\( F(i, j, \lambda) \) can be thought of as the photon flux at the detector if all the optics before the detector were perfectly efficient. The expression has been grouped into these factors since they are convenient in determining the calibration parameters. It is not important in calibrating a science image to determine the quantum efficiency of each component; all that really matters is the net quantum efficiency. The contribution due to the filters has been separated out since there are so many different combinations of filters. It is much simpler to calculate \( T_f(\lambda) \) for each filter combination rather than calculate \( Q(i, j, \lambda) T_f(\lambda) \) for each combination. The same \( Q(i, j, \lambda) \) can be used for all combinations of filters.

The goal of calibration is to determine \( Q(i, j, \lambda), T_f(\lambda) \), and \( d_c(i, j) \) so that the observer may determine \( F(i, j, \lambda) \) from \( r(i, j) \). Determining \( B(a, \delta, \lambda) \) from \( F(i, j, \lambda) \) is not considered part of calibration, but instead, scientific interpretation of the data. By taking a long exposure with the shutter closed one can determine the dark count rate \( d_c(i, j) \); long exposures of monochromatic flat fields at many wavelengths when coupled with knowledge of the absolute flux of the source (and any nonuniformities in the flat field) can approximate \( Q(i, j, \lambda) \); and laboratory measurements can determine \( T_f(\lambda) \). The problem remains to determine \( F(i, j, \lambda) \) from \( r(i, j) \). If the source is monochromatic or the effective bandpass of the net filter transmission curve is narrow enough that the source spectrum and \( Q(i, j, \lambda) \) are effectively constant in the bandpass, determination of \( F(i, j, \lambda) \) is straightforward. If these conditions are not satisfied—what we call the wideband case— the problem becomes more complicated. We will discuss this further in section 4.1.2.

There are two sources of geometrical distortion previously alluded to: that due to the optics and that due to the detector imaging process. The first is relatively small over most of the image (perhaps as much as a few pixels at the edge of the f/48 field of view) and is assumed to be very stable. The second is not small and may not be stable. It is a potential source of calibration problems. One can think of the detector as binning the distribution of photons on the photocathode in a grid. This grid of bins is not regular and perhaps not stable in the size of the bins. The effect of this is that equal increments in either \( i \) or \( j \) at different pixels do not correspond to equal offsets or even identical directions on the faceplate of the photocathode. One consequence is that resulting images are difficult to exactly correct geometrically. For example, changes in the distortion between images used to determine the detector response \( Q(i, j, \lambda) \) and the science image \( r(i, j) \) will render the straightforward photometric correction discussed above invalid since the same pixel in \( Q(i, j) \) and \( r(i, j) \) do not correspond to the same location on the faceplate. The reseau marks on the faceplate serve as landmarks and make it possible to remove geometric distortion as long as the scale size of the curvature in the distortion is larger than the spacing between reseau marks. The details of removing geometric distortion will not be discussed here.
except to mention the general principles. Flat fields must be taken frequently enough to make the changes in the geometric distortion between flat fields small. The reseau are then accurately located to produce reseau positions in pixel coordinates. These locations are used with a set of reseau positions corresponding to a undistorted image to resample the science image and generate a new image whose pixel coordinates correspond to a regular and fixed grid of points on the faceplate.

3. Routine Science Data Processing

Since we are describing plans to generate the necessary calibration data for RSDP, a brief description of RSDP is in order. A detailed description may be found in the latest version of SE-06. RSDP recognizes three types of data: normal images; spectrograph images; and flat fields. The processing carried out on an image depends on the type of image. The processing steps for normal images are

1. Dark count correction.
2. Intensity transfer function correction.
3. Unzoom zoomed image.
4. Relative detective efficiency correction.
5. Absolute detective efficiency correction.
6. Geometric distortion correction.

The processing steps for spectrographic images are

1. Dark count correction.
2. Intensity transfer function correction.
3. Unzoom zoomed images.
4. Geometric distortion correction.
5. Spectrographic image detective efficiency correction.

The flat fields have only one processing step: Reseau finding.

A brief description of these processing steps follows.

1. DARK COUNT CORRECTION. This step attempts to remove background counts due to spurious events generated inside the FOC (e.g. photocathode thermionic emission) rather than externally generated background counts (e.g. scattered light, Zodiacal light, or diffraction). The correction is performed by subtracting the a
dark count image, scaled by the exposure time of the incoming image, from the incoming image.

2. INTENSITY TRANSFER FUNCTION CORRECTION. This step attempts to correct for the nonlinear response of the FOC at high count rates. The method used by RSDP consists of using a piecewise linear approximation to the intensity transfer function obtained from flat fields at several different count rates. Each pixel of the incoming image has its own corresponding piecewise linear intensity transfer function used to linearize the count rate at that pixel. Since this approach is completely inappropriate for images other than flat fields, this correction will be effectively skipped. (See Giaretta (1983, 1984a, b, c) for discussions regarding why the ITF correction is inappropriate).

3. ZOOMED IMAGE CORRECTION. This step generates two pixels for every pixel in the zoomed image so that the output will correspond (approximately) to a square region on the sky. This step requires no calibration data.

4. RELATIVE DETECTIVE EFFICIENCY CORRECTION. This step attempts to correct for the spatially nonuniform response of the FOC. It is accomplished by multiplying the incoming image by the inverse of the corresponding “typical” flat field.

5. ABSOLUTE DETECTIVE EFFICIENCY CORRECTION. This step attempts to scale the pixel values so that they represent the incident number of photons to the detector rather than the number of photons detected.

6. GEOMETRIC DISTORTION CORRECTION. This step corrects for the geometric distortion of the image produced by the FOC. This is accomplished by providing the observed reseau positions obtained from the a flat field believed to have the same distortion and the true reseau positions. This is the RSDP equivalent of the RAL (Rutherford Appleton Laboratory) program GEOMM.

7. SPECTROGRAPHIC IMAGE DETECTIVE EFFICIENCY CORRECTION. This step attempts to correct the spectrographic images for spatial nonuniformity of response and at the same time make the resulting pixel values represent the incident number of photons at the corresponding range of wavelengths. Like the relative detective efficiency correction, this is accomplished by multiplying the incoming spectrographic image by the inverse of a response image. The values of each of the pixels of the response image are the absolute detective efficiencies of those pixels.

8. RESEAU FINDING This step uses models of reseau profiles to search predetermined regions of flat fields for the reseau mark. The RSDP version of this program is the functional equivalent of the RAL program RSFIND.

Further details of the reference data required for each of these processing steps are given in Appendix A.

RSDP requires additional information in the form of “reference relations.” These reference
relations basically tell the RSDP programs which calibration data (files or parameters) to use for a given instrument mode. The instrument mode for the purposes of RSDP is defined by the values of the following.

1. Optical relay being used (f/48, f/96, or f/288)
2. Pixel format (normal or zoomed).
3. Spectrograph mirror mode (in beam or out).
5. Offset of the image relative to the full 1024×1024 area available.
6. Size of image in lines and samples.

The reference relations can be thought of as several large tables—one for each type of calibration data—where each line of the table specifies a unique combination of values for the instrument mode parameters listed above. For each of these lines is listed a calibration filename or calibration parameter value that is to be used by the corresponding RSDP program. For example, the relative detective efficiency correction program will use the table for inverse flat fields to determine the filename of the inverse flat field to use—in this case determined by the optical relay, spectrograph mirror mode, and filter wheel positions. One can readily see, considering the number of filter wheels, filter wheel positions, and frame offsets, that there will be a huge number of instrument modes, thus the need to restrict the number of supported modes. Bear in mind, however, that many different modes may use the same calibration file or parameter, but one must explicitly list all the combinations that use that calibration file or parameter. Each RSDP program looks at only a subset of the instrument mode parameters. Only combinations of those mode parameters are relevant in the reference relation table associated with that program; all the other mode parameters are ignored.

It is essential to remember that all the relevant calibration data and reference relations must be available to RSDP before RSDP begins to process data. In particular, there is no capability whatsoever for RSDP programs to dynamically generate, or modify calibration data or reference relations. Any intelligence about which calibration data to apply to specific images must reside in the reference relations alone.

To summarize, RSDP calibration of normal images (not spectrograph) consists of first calculating

\[ r_2(i, j) = \frac{r(i, j)}{t_e - d_e(i, j)} g(i, j) w \]

where \( g(i, j) \) is the relative DE correction (unitless), \( w \) is the absolute DE correction (ergs/count/angstrom), and \( d_e(i, j) \) is the dark count correction (counts/pixel/second). The quantities \( g(i, j) \) and \( w \) are described in more detail in section 4.1. The specific calibration data, \( g(i, j) \), \( w \), and \( d_e(i, j) \) are selected on the basis of the instrument mode used to obtain the science image \( r(i, j) \). The intensity transfer function (ITF) correction has not been included here because it will be bypassed. A geometric distortion correction is applied
to $r_2(i,j)$ to produce the RSDP result. The geometric correction is applied in a way that conserves flux.

The RSDP calibration of spectrographic images consists of calculating

$$r_i(i,j) = r(i,j)/t_e - d_c(i,j)$$

where $d_c(i,j)$ is again the dark count correction. A geometric distortion correction is applied to $r_i(i,j)$ to produce $r_2(i,j)$. The output of RSDP is generated by calculating $r_2(i,j)d(i,j)$ where $d(i,j)$ is the detective efficiency correction. For the spectrographic modes $d(i,j)$ incorporates both relative and absolute calibration that was previously represented by $g(i,j)w$ in the non-spectrographic modes. It also takes into account the variation of $\lambda$ with $(i,j)$.

4. Calibration Plan

Our general approach to producing the calibration files will be to produce at least two versions. The first "cut" will be our attempt to generate all the necessary calibration reference data files fairly quickly, although there may be known shortcomings to the process used to generate the files. The purpose is to learn the areas of difficulty, to find where data is missing, and to have a complete set of calibration data in place and ready for use early on. This will allow testing of RSDP to begin at an earlier stage and will provide insurance in case we encounter unexpected difficulties in generating calibration reference data of the desired quality. In producing the second cut calibration files we will attempt to generate higher quality calibration data files that will be acceptable for actual use by RSDP. Time and resources permitting, we may be able to take further cuts at the calibration reference data files to improve their quality. At this point however, we need to keep in mind that our efforts may be of little benefit in improving RSDP calibration quality without changing RSDP itself, or that we are better off improving calibration procedures outside of RSDP.

We will, in general, use the versions of the RAL programs being implemented in CDBS (Calibration Data Base System) to process the calibration data to produce the calibration files. Detailed descriptions of the programs available may be found in the FOC package within IRAF. Furthermore, any additional software we find necessary to develop to generate the calibration files will be added to CDBS if it appears to fill a longer term need—for example, software to generate the reference relations.

4.1 Normal Images

4.1.1 Relative Detective Efficiency and Dark Count Correction

An important point to remember regarding RSDP calibration is that the geometric correction is applied last, which as we will discuss in a later note, is not ideal. This has important consequences for the accuracy of the calibrated data, and the requirements for calibration files. Since the incoming science image may not have the same geometric distortion as the dark count and relative DE (Detective Efficiency) images, any small scale features in either (less than 10 to 20 pixels in size) will be misaligned with the location of the small scale
features on the science image. For example, a scratch in the relative DE image will not be aligned with the location of the scratch in the science image. Not only will the effect of the scratch on the science image not be corrected, a "shadow" scratch will be introduced elsewhere.

Even if the geometric stability is absolutely stable, there are likely to be misalignment problems that result from video format-related distortion. Distortion can arise from imperfections in the magnetic focusing of the image intensifier or the imaging in the television tube. The distortion associated with the television tube appears to remain more or less constant with respect to the resulting image and independent of the video format whereas the intensifier distortion will scale with the video format. The end result is that the net distortion will change with video format even if the distortion in the individual components is not varying in time. Since large format images will be used if possible for generating relative DE images their distortion will most likely not match that of smaller formats. Without due care in preparing the calibration files, the result of the current RSDP calibration sequence would be to worsen the effect of small scale defects in the faceplate response or dark count rate.

It therefore makes no sense to retain small scale information in either the relative DE or dark count images. We propose applying a simple filter of approximately $10 \times 10$ pixels to smooth these images. As a side effect this reduces the required number of counts in each pixel for producing acceptable relative DE and dark count images for signal-to-noise purposes.

Flat field images at as many wavelengths as available will be used to generate the relative DE images. If possible, $1024 \times 512$ zoomed images will be used to produce relative DE images that cover the useable faceplate area. If there is a lack of visible-wavelength flat fields taken with the monochromator, it may be necessary to use LED exposures to obtain wavelength coverage in the visible. We may also generate extra relative DE images to fill in holes in the wavelength coverage using some interpolation scheme. Because of geometric distortion, we may find that we must either geometrically correct the relative DE files or scale different pixels differently by an amount corresponding to their distorted size on the faceplate. No amount of processing or cleverness can overcome a fundamental lack of calibration data, however. For example, if the detector response is not sampled at enough wavelengths, or there are no full field exposures, we will not be able to fill these holes with out more ground-based or in-orbit calibration data.

The fact that there is little data from PFM4 inside the FOC with external illumination means that vignetting may not be accounted for in the prelaunch relative DE files. Since most of the PFM2 calibration data was obtained when the detector was in a different optical relay, it will also be difficult to properly account for the vignetting of the instrument. Since vignetting is a property of the FOC optics it may be possible to determine the vignetting of the optical chain that uses the same PDA by comparisons between PDA exposures and FOC exposures, but there are a number of potential complications. At worst we will have to ignore vignetting or use theoretical predictions of vignetting. Resolution of these issues, although important, have lower priority because of the potential complexity and labor involved in straightening them out with scanty data.
4.1.2 Absolute Detective Efficiency

As mentioned in section 2 \( F(i, j, \lambda) \) and \( r(i, j) \) are related by

\[
r(i, j) = t_e \int_0^\infty Q(i, j, \lambda) T_f(\lambda) F(i, j, \lambda) \, d\lambda
\]

In general, one cannot determine the \( \lambda \) dependence of \( F(i, j, \lambda) \) from \( r(i, j) \) alone. Lacking any knowledge of \( \lambda \) dependence prevents determination of \( F(i, j, \lambda) \). If we assume the flux is of the form

\[
F'(i, j) h(\lambda)
\]

Then

\[
r(i, j) = F'(i, j) t_e \int_0^\infty Q(i, j, \lambda) T_f(\lambda) h(\lambda) \, d\lambda + t_e d_e(i, j).
\]

Once \( h(\lambda) \) is known, determination of \( F'(i, j) \) is straightforward. We wish to determine the energy flux rather than the photon flux. They are related by

\[
F_e(i, j, \lambda) = \frac{hc}{\lambda} F(i, j, \lambda)
\]

There are at least two ways of approaching absolute calibration of science images. The simplest is to assume that the source emits all its flux at one wavelength, then all one needs to do is evaluate \( Q(i, j, \lambda) T_f(\lambda) \) at that wavelength for each pixel to determine the flux of the source. This is a poor assumption for most sources, however. Another approach is to assume the source has a particular wideband flux distribution and determine the spectral flux density of that source. This has the disadvantage of requiring that integrals be performed over all wavelengths. It, of course, will lead to large errors if the source's flux distribution is very different from that assumed. Any method that assumes one spectral shape for all sources will have this problem. We will assume for all calibrations that the source has a flat energy flux spectrum, i.e. \( F_e(i, j, \lambda) = F_e'(i, j) \).

The straightforward approach to absolute flux calibration is to create a unique absolute DE image for each possible combination of filter wheels. This absolute DE image, call it \( g_{abs}(i, j) \) would be used to multiply incoming dark count corrected science images to produce a flux calibrated image. From the previous expression for \( r(i, j) \) it is easy to see that

\[
g_{abs}(i, j) = \frac{hc}{\lambda} \int_0^\infty Q(i, j, \lambda) T_f(\lambda) \lambda d\lambda.
\]

Since there is an extremely large number of such combinations, this is impractical for the current form of RSDP. The problem has been solved by breaking the detective efficiency calibration into two parts—a relative DE correction and an absolute DE correction. That is, the science image is multiplied by \( g(i, j) w \) where \( g(i, j) \) corrects for nonuniform response (relative DE) and \( w \) scales the result to represent the correct flux. This product replaces \( g_{abs}(i, j) \) The idea is to use relatively few \( g(i, j) \) images (less than twenty to cover all wavelengths) and a \( w \) for each combination of filter wheels. In this way one needs only tens of thousands of \( w \)'s rather than tens of thousands of images.

This method entails loss of precision, however. For each combination of filter wheels there does exist in principle a detective efficiency image that when multiplied with the science
image, produces the absolute flux for each pixel (assuming the source has a flat spectrum). We will denote this ideal detective efficiency image by $g_s(i,j)$. In general, there is no way of choosing $w$ to make $g(i,j)w$ equal $g_s(i,j)$ at each pixel because there are fewer $g(i,j)$ images than there are combinations of filter wheels. The hope is, then, to choose $w$ so the difference between $g(i,j)w$ and $g_s(i,j)$ is not substantial. Two methods of determining $w$ come to mind. The first is to choose $w$ in order to make the average of the effective quantum efficiency used by RSDP ($q_s(i,j) = 1/g_s(i,j)$) over all pixels in some region equal to the average of the integrated quantum efficiency ($q_s(i,j) = 1/g_s(i,j)$) over all pixels in the same region. (The more straightforward approach of making the average of $g(i,j)$ and $g_s(i,j)$ the same is much more difficult for reasons discussed in more detail at the end of this section.) The other method is to minimize the least-squares difference between $q_s(i,j)$ and $q_s(i,j)$ over all pixels in some region. (We presumably want to exclude from these averages the edges of the fields where the response is poor.)

Next we must determine $q_s(i,j)$ in order to determine $w$. Since we have assumed that the source energy flux density is flat then

$$F(i,j,\lambda) = \frac{\lambda}{hc} F_\epsilon(i,j,\lambda) = \frac{\lambda}{hc} F_\epsilon(i,j).$$

This implies

$$r_1(i,j) = \frac{F_\epsilon(i,j)}{hc} \int_0^\infty Q(i,j,\lambda)T_f(\lambda)\lambda d\lambda.$$

where $r_1(i,j)$ is the dark count corrected image and $F_\epsilon(i,j)$ is the source spectral flux density as a function of pixel location. From this we see that

$$q_s(i,j) = \frac{1}{hc} \int_0^\infty Q(i,j,\lambda)T_f(\lambda)\lambda d\lambda.$$

That is, dividing $r_1(i,j)$ by $q_s(i,j)$ will result in $F_\epsilon(i,j)$, the absolute flux of the source. The average of $q_s(i,j)$ over all pixels is

$$\langle q_s(i,j) \rangle_{i,j} = \frac{1}{hc} \int_0^\infty \langle Q(i,j,\lambda) \rangle_{i,j}T_f(\lambda)\lambda d\lambda.$$

Thus the first method for calculating $w$ has

$$w = \frac{hc}{\int_0^\infty \langle Q(i,j,\lambda) \rangle_{i,j}T_f(\lambda)\lambda d\lambda} \langle 1/g(i,j) \rangle_{i,j}.$$

The second method has

$$w = \frac{hc}{\int_0^\infty \langle Q(i,j,\lambda)/g(i,j) \rangle_{i,j}T_f(\lambda)\lambda d\lambda} \langle 1/g^2(i,j) \rangle_{i,j}.$$

Note this method of calculating the $g(i,j)$ is equivalent to that used by the RAL software, but the $w$ factor is different. The original method assumes the $w$ factor was calculated from an effective wavelength from fits to the filter transmittance data.

One of these expressions must be evaluated for every combination of filter wheel settings that is supported in RSDP. The basic prescription for calculating $w$ (for the first method)

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consists of determining $Q(i, j, \lambda)$ for several $\lambda$ from flat field exposures, then calculating $(Q(i, j, \lambda))_{i, j}$ for those $\lambda$. Next, fit an appropriate analytic function $Q_f(\lambda)$ to the measured $(Q(i, j, \lambda))_{i, j}$. It is straightforward to obtain $(1/g(i, j))_{i, j}$—in fact, we will normalize $g(i, j)$ by making $(1/g(i, j))_{i, j} = 1$. All these quantities need only be calculated once and used repeatedly for calculations of $w$. For each $w$, $T_f(\lambda)$ needs to be calculated, this is a simple matter of multiplying the individual filter responses. The resulting $T_f(\lambda)$ and $Q_f(\lambda)$ are integrated to produce $w$. The net result is that an array multiplication and a one-dimensional integral need to be performed for each supported combination of filter wheels. This should not be a terrible computational burden to carry out for all possible combinations of filter wheels—that will be our goal, rather than enumerating a subset of combinations which would likely take more labor than the brute-force approach.

If one chooses the method of making the average of $g(i, j)$ and $g_a(i, j)$ the same, one finds that the resulting expression for $w$ involves calculating averages of reciprocals of integrals. While this is possible in principle, it requires such an average be calculated over the whole image field for each combination of filters rather than a calculation of average response over the whole image just once and performing an integral for each filter combination. The result is orders of magnitude more computation required.

4.1.3 Geometric Correction

Ideally, the geometric distortion should be determined from a flat field taken nearby in time to the science image. Since geometric distortion correction files that are prepared prior to launch will not be close in time to the science images, their calibration value is dubious. We must rate the production of geometric distortion correction files as a relatively low priority item for the sake of calibration alone. Nevertheless, we will attempt to provide geometric distortion correction files for all supported modes, mainly to exercise the system and to gain experience in the mechanics of generating a large set of such files. A different geometric distortion correction file will need to be generated for each video format (frame size, offset, frame format) and both detectors. Since there are a very large number of frame offsets and several frame sizes and formats, we must restrict the number of supported modes to very few offsets and frame sizes.

4.1.4 Reference Relations

An essential part of generating calibration data for RSDP is the creation and updating of the reference relations necessary for RSDP to select the appropriate calibration files for processing of science images. Because of the potentially large number of reference relations needed (perhaps hundreds of thousands), it will be necessary to generate most of them by software. This software, which has yet to be written, will automatically populate the reference relations with the names of the calibration files to be used for each mode, and in the case of the absolute detective efficiency factor, with the parameter value itself. Since the $w$ factor must be uniquely computed for each combination of filter wheels, it is natural to combine the software for calculating $w$ and filling the reference relations, at least for the absolute DE factor.

There are few enough selection criteria for dark count images that they can be easily enumerated directly. The ITF correction will be bypassed. The relative DE calibration
file for each mode will be chosen by calculating the centroid in wavelength (or alternately, the pivotal wavelength, see Koornneef et al. 1985) of the telescope plus detector response for that mode.

\[ \bar{\lambda} = \frac{\int_0^\infty Q(i, j, \lambda)T_f(\lambda)\lambda d\lambda}{\int_0^\infty Q(i, j, \lambda)T_f(\lambda)d\lambda} \]

\[ T_{\text{pivotal}} = \sqrt{\frac{\int_0^\infty Q(i, j, \lambda)T_f(\lambda)\lambda d\lambda}{\int_0^\infty Q(i, j, \lambda)T_f(\lambda)d\lambda}} \]

The relative DE calibration file that is closest in wavelength (closest in the multiplicative sense) to the centroid is the one that will be listed in the reference relations for that mode. There will be a different geometric distortion correction file for every supported frame offset, frame size, pixel format, and optical relay. In other words, there is a one-to-one relationship between geometric distortion correction files and their defining modes. This makes it straightforward to populate the reference relations for geometric distortion correction files though perhaps a little tedious depending on how many modes are supported.

4.2 Spectrographic Mode

4.1.1 Dark Count Correction

Dark count correction for spectrographic mode is the same as for the normal imaging mode. The method for generating the dark count correction files will be the same.

4.2.2 Geometric Correction

Unlike the case for normal images, RSDP performs geometric correction before applying the detective efficiency correction. Like the case for normal images, the geometric correction serves to remove the geometric distortion caused by the OTA optics and the detector itself. It also serves, for the spectrographic images, to linearize the dispersion relation so that the wavelength will be linearly related to the line number of the image. This will be accomplished by determining the detector distortion from a flat field nearby in time, combining this with the OTA distortion, removing this distortion from a spectral line calibration image, and using the resulting image to determine the dispersion relation. The dispersion relation will be used to determine what additional distortion correction is necessary to linearize the dispersion relation. That distortion correction is combined with the first two to produce the geometric correction that will be applied to the spectrographic science images. Unfortunately, most of the spectrograph orders appear to lack acceptable lines for this calibration purpose. We will have to extend the results from one order to all the others as far as the dispersion relation is concerned. The geometric correction will depend on the filter wheel settings as far as RSDP is concerned. This is to allow for the possibility that the component of geometric correction used to linearize the dispersion relation may be different for different orders—hence the dependence on filter wheel positions.

4.2.3 Detective Efficiency Correction
RSDP performs the relative and absolute detective efficiency correction in one step. That is, the received science image is multiplied by a detective efficiency image $d(i,j)$ equivalent to the $g_n(i,j)$ discussed for normal images. This is possible since there are relatively few useful combinations of filter wheels available for the spectrographic mode. Thus, the problem of determining $u$ does not exist. There were calibration images produced for the spectrograph mode for the purpose of photometric calibration. They were generated by stepping a photometrically calibrated monochromator in wavelength to produce spectrographic images with a series of bands, each representing the detected photons from the monochromator at each wavelength setting. The comparison of the measured intensities of these bands with their known intensities would have resulted in values for the detective efficiency for each of the bands. This sampling of detective efficiency at different spectral lines would have been used to generate the detective efficiency image by interpolating the values for the regions between the lines.

It will not be possible to use these calibration images directly for this purpose for two reasons. First, the spectrograph calibration images have large regions of very low counts—low enough to prove nearly useless for large regions of some of these images. Second, there are no spectrograph calibration images of the detector that is currently in the f/48 relay. We may be able to determine the grating efficiency as a function of wavelength from the spectrograph calibration images taken with another detector by comparison with the absolute detective efficiency of that detector at all wavelengths based on flat fields in normal imaging modes. Then we can combine the grating efficiency with the absolute detective efficiency of the current detector at all wavelengths to produce the detective efficiency of the spectrograph modes.

4.2.4 Reference Relations

Because the number of modes for spectrograph images is relatively small, they will probably be filled manually.

4.3 Flat Field Images

RSDP will attempt to locate reseau marks in flat fields. Since the results of this reseau finding are currently not used elsewhere by RSDP, they serve no purpose. Therefore generating calibration data for this aspect of RSDP is of low priority, though it may be done because it appears relatively easy to do.

5. Summary

Figure 1 summarizes the process for generating the calibration files. The figure shows the relation between the calibration data (the ovals), the processing involved (the boxes), and the resultant calibration files for RSDP. Figures 2, 3, and 4 show the processing necessary to generate the calibration files for relative DE, distortion correction, and spectral DE, respectively. The processing steps shown may change depending on the quality and availability of the data, and any other problems we may encounter. They should be considered as proposed outlines for processing. Some of the figures refer to CDBS programs...
for FOC calibration. These programs are currently documented in the help files for the programs.

6. References


4. Giaretta, D., RAL Technical Note: Report on Non-Flat Field Photometry, June, 1984


APPENDIX A

Reference Data needed for RSDP

DARK COUNT CORRECTION
Reference Parameter: $dc(i, j)$

These reference data are in the form of a $1024 \times 1024$ array for normal images and a $512 \times 1024$ (sample×line) array for zoomed images. Each element $(i, j)$ of the array is associated with the corresponding pixel $(i, j)$ of the raw image to be calibrated. The value of that element of the array represents the photon count rate due to spurious photons and other photon events generated by the detector itself in the absence of external flux. This excludes other sources of background such as Zodiacal light, scattering, and diffraction. Presumably there will be one such array (each provided as a file) for each of the optical relays for the zoomed and normal modes resulting in a total of six. The values will be provided in units of counts per second.

INTENSITY TRANSFER FUNCTION PARAMETERS
Reference Parameters: $l(i, j, k), s, N$

These parameters were meant to be used to linearize the observed count rates. Since we now know the algorithm that RSDP uses to linearize the observed count rate is inappropriate, this calibration will effectively be bypassed. For the purposes of satisfying RSDP, however, the ITF parameters must be provided. An array $l(i, j, k)$ of size $a \times b \times 1$ where $a \times b$ (sample×line) is the image frame size will not modify image data if $l(i, j, 1) = 1$ for all $(i, j)$ if $s = 1$ and $N = 1$. There will have to be as many of these arrays (each in a separate file) as there are frame sizes in the initially supported set of modes.

RELATIVE DETECTIVE EFFICIENCY CORRECTION
Reference Parameter: $g(i, j)$

These reference data are in the form of a $1024 \times 1024$ array. The purpose of this array is to attempt to correct for the nonuniformity of response of the FOC as a function of pixel location. This is accomplished by calculating the resultant image $r_1(i, j)$ by using

$$r_1(i, j) = g(i, j) \times e(i, j)$$

for all the possible $i, j$ in the dark-count-corrected image, denoted by $e(i, j)$. Note that $g(i, j)$ is the inverse of the “typical flat field.” Presumably there will be several files, each file representing a different $g(i, j)$ array, that will be used for different wavelength observations. The elements of $g(i, j)$ are unitless.
ABSOLUTE DETECTIVE EFFICIENCY CORRECTION

Reference Parameter: \( w \)

This is a single parameter. Its purpose is to correct for the less-than-unity quantum efficiency of the FOC so that the resulting images represent the incident number of photons rather than the number of photons detected. The resulting image, denoted \( r_2(i,j) \) is calculated using

\[
r_2(i,j) = r_1(i,j) \times w = c(i,j) \times g(i,j) \times w.
\]

Presumably there will be a different \( w \) for each combination of optical relay and filter wheel positions in the set of initially supported modes. The actual values of \( w \) will be supplied in the reference relations described later. The units of \( w \) are photons per count.

SPECTROGRAPHIC IMAGE DETECTIVE EFFICIENCY CORRECTION

Reference Parameter: \( d(i,j) \)

These reference data are in the form of a 1024x1024 array. The purpose of the array is to correct received spectrograph images for the nonuniform response of the FOC as a function of pixel location and to correct for the less-than-unity quantum efficiency of the FOC. The resulting image, denoted \( r_x(i,j) \), is calculated using

\[
r_x(i,j) = d(i,j) \times c(i,j)
\]

Presumably, there will be three such arrays \( d(i,j) \) (each supplied as a separate file)—one for each blocking filter. The units of \( d(i,j) \) are photons per count.

GEOMETRIC DISTORTION CORRECTION

Reference Parameters: \( G(m,n,p), M \)

These reference data are in the form of a 2x2x\( M \) array. The purpose of this array is to supply the necessary information to perform a geometric correction. The subarrays \( G(1,1,p), G(1,2,p), G(2,1,p), \) and \( G(2,2,p) \) represent the undistorted sample position, the undistorted line position, the distorted sample position, and the distorted line position of the \( p^{th} \) reseau mark where reseau marks are numbered in ascending order starting from the bottom left of the image across each row until the last reseau at the top left of the image. The parameter \( M \) represents the number of reseau marks in the undistorted image frame. Presumably there will be an array (each supplied as a separate file) for each possible combination of optical relays, pixel format, frame size, and frame offset that is in the initially supported set of modes. The units of \( G(m,n,p) \) are pixels.
RESEAU MARK MODEL PARAMETERS

Reference Parameters: \( t(m, n), S, T, DEPTH \)

These parameters are used to find reseau mark positions in flat fields. The array \( t(m, n) \) is an \( a \times b \) size array where both \( a \) and \( b \) may be between 5 and 11 inclusive. The array represents a small image of a reseau mark model where a value of 100 corresponds to no attenuation by the reseau mark and where 0 corresponds to total attenuation (no transmission) by the reseau mark. Thus \( m \) and \( n \) correspond to \( i \) and \( j \) in an image and represent relative sample and line coordinates. Up to 5 reseau marks can be combined in one file. There is one file per optical relay. Included in each file are three other parameters. \( S \) and \( T \) are the search range in lines and samples from the initial reseau positions specified in the reseau search positions file. \( DEPTH \) is used to specify the depth of correlation between at least one of the reseau models and a search area of a flat field that is required for the program RSFIND to declare that it has found a reseau mark in that area. Its value should be between 0 and 100 where 100 represents full correlation.

RESEAU SEARCH POSITIONS

Reference Parameter: \( R(m, p) \)

These reference data are normally in the form of a \( 2 \times 289 \) array. This array holds the search positions for the 289 reseau marks on the faceplate that are used by the program RSFIND. \( R(1, p) \) and \( R(2, p) \) represent the sample and line coordinate, respectively, of the \( p^{th} \) reseau mark where reseau marks are numbered in the same order that they are for the geometric distortion correction file. There will be a different array (provided as separate files) for the two detectors.
PROCESS FOR GENERATING CALIBRATION FILES

- Dark images → Smooth → Dark Count Files
- Relative DE flat fields
- Source non-uniformity date
- Flat field processing
- Absolute DE calculation
- Optical distortion
- Distortion model calculation
- Undistorted reseau positioning
- "Typical" flat fields
- Reseau location
- Line wavelengths
- Spectral line source images
- Monochromator absolute flux curve
- Monochromator spectral images
- Spectrographic DE and distortion calculations
- Current reseau models
- Table generator
- Real count files
- Intensity transfer function files
- Absolute DE files
- Geometric distortion file
- Reseau search position files
- Spectrographic DE files
- Reseau model files
- Reference relations

Figure 1.
FLAT FIELD PROCESSING

for each wavelength available

locate relevant images:
1) full field images
2) other format images (for testing)

locate, remove reseau marks and blemishes

correct for overflow

remove source nonuniformity

merge smaller formats (PFM4 only)

smooth

normalize

test on self in SDAS

invert, edit and reformat

Possible future refinements

correct for geometric distortion

correct for vignetting

Figure 2.
DISTORTION MODEL PROCESSING

for each format supported:

locate relevant images and reference positions

locate reseau using RSFIND

use GDFIT/RSDIST to fill in any missing reseau

fold in optical distortion correction using RSDIST/GDFIT/RTINT

for spectrographic modes, copy distortion results from spectrographic processing

test on self using GEOMM

test on other flat fields, analyze distortion changes

reformat

Figure 3.
SPECTROGRAPHIC DE and DISTORTION CALCULATIONS

For each supported spectrographic mode:

DE

Locate relevant photometric spectrograph images along with associated flat fields (for distortion correction), wavelengths and flux information.

Using flat field, geometrically correct photometric calibration images

Determine average photon count rate in each wavelength band as a function of position along the slit.

Compare these count rates with the actual photon flux as determined by calibration photomultiplier measurements (including source non-uniformity) to determine DQE as a function of wavelength and slit position.

Compare these values with the DQE determined in normal image mode at the corresponding wavelength to determine the efficiency of the grating and associated optics.

Combine the grating DQE with the normal image mode DQE to produce values for spectral DE for all wavelengths. This requires fitting a function to the measured efficiency of the grating at several wavelengths.

Reformat spectral DE file

Distortion

Locate relevant line source spectrograph calibration images with line wavelengths.

From flat field determine geometrical distortion and apply correction to line image.

Determine rotation angle of spectrum with respect to scan direction, rotate image to align.

Use spectral lines in image to distort image in order to produce linear dispersion.

Determine the net effective geometric correction necessary to rotate and produce linear dispersion on a spectrographic image already corrected for detector distortion.

Apply this distortion correction to spectrograph DE file.

Combine all distortion corrections including detector distortion correction, spectrum rotation and spectrum linearization into one geometric correction and send to distortion model processing (to be used for correction of science spectrograph images.

Figure 4.