GUVI Data Calibration Procedure:
Converting from raw counts to radiance in rayleighs

This document describes the calculations required for the calibration of the GUVI imaging mode raw data into radiances on a pixel-by-pixel basis, including corrections for instrumental backgrounds and scattered light. Calculation of associated uncertainty (variance) estimates is also described. This document supersedes the GUVI Calibration LID, which describes an old algorithm that has been made obsolete by development of improved algorithms developed for the GUVI program.

The GUVI SIS telemeters down five colors that represent intensity measurements of five spectral features - HI Ly α at 121.6 nm, OI 130.4 nm, OI 135.6 nm, and two N_2 LBH band intensities. Conversion of each spectral feature follows a slightly different pattern. HI Ly α is a well-resolved line emission. OI 130.4 nm and OI 135.6 nm are slightly unresolved blended line emissions. The N_2 LBH features are band emissions. These band emissions will change in distribution as a function of absorber optical depth. In addition, the image of the slit is slightly curved on the detector and integrating over certain bins may only collect a fraction of the light in certain circumstances.

Most of the problems occur in dealing with the ***"responsivity"*** term. A large number of caveats become introduced about the precise meaning of the term responsivity. At different pitch angles the wavelength of a particular bin changes slightly. This causes the fraction of light from an individual spectral line which is intercepted by that bin to also change, i.e. more or less of the light will fall into another bin. An additional complication is that the slit function, the shape of the image of the slit, will change slightly with pitch angle along the slit. These changes will all be different for each slit and each detector. The GUVI SIS is more properly viewed as 6 separate scanning imaging spectrographs. Rather than assume that the bins will be specified in such a way that all of the light will be accumulated, we structure the calibration code – and the associated calibration tables - to deal with the possibility that all bins may not be included.

Table 1 below defines all of the fundamental (measured or provided as values or tables to the GUVI calibration algorithm) variables used in this document. The subscripts i, j, k, s, and d as used throughout this document refer to the ijk^{th} pixel of a scan, and indicate which slit and detector are in use. i is the color index (i=0,1,2,3,4), corresponding to Lyman-α (1216 Å), 1304 Å, 1356 Å, LBH-S, and LBH-L. j is the along-track pixel index and ranges from 0 to 14 for the GUVI spatial pixels. k is the across-track pixel index and ranges from 0 to 31 for limb pixels, and from 0 to 158 for disk pixels. s has values 0, 1, and 2, corresponding to the wide, medium, and narrow slit positions. d has values 0 and 1, corresponding to the primary and secondary (backup) detectors.

GUVI calibration software must identify the time at which a given observation has been made, and then apply the appropriate set of calibration tables corresponding to the color tables in use at that time.

Table 1 – GUVI Calibration Variable Definitions

C_{ijk}	Observed compressed counts in pixel *ijk* from a scan as obtained from a GUVI Level 1A file (L1A data may exist internally only).
R_{ijksd}	The responsivity of the GUVI instrument for pixel *ijk*, slit *s*, and detector *d*.
U_{ijksd}	The relative uncertainty in the GUVI calibration for pixel *ijk*, slit *s*, and detector *d*.
$\mathrm{OIRatio}_{k}$	The scaled ratio of the counts output by the GUVI detector to photon events observed at the detector input. This is an item in the GUVI telemetry that is measured for every step in a scan.
τ	The integration time for a single pixel measurement. This has a value of 34 ms for a limb pixel and 62.125 ms for a disk pixel.
τ^{dark}	The integration time for the four GUVI dark pixels.
C^{dark}	The mean of the observed counts in the dark pixels, which are measured once per GUVI scan.
τ^{long}	The integration times for the GUVI long background pixels. GUVI long backgrounds are measured on a 3x7 grid (3 spatial pixel intervals, 7 scan/mirror step intervals), and integrated for time intervals of [1.088, 1.674,1.674, 1.674, 1.674, 1.674, 1.488] seconds, finishing at scan/mirror steps [31, 26, 53, 80, 107, 134, 158]. The first 32 steps are on the limb (1.088 = 32x0.034 seconds/ limb step), whereas the next six intervals are distributed across the 159 disk scan steps.
C^{long}	The observed counts in the long background pixels, which are measured 7 times per scan at 3 spatial locations, as described above.
σ	A symbol used to prefix another symbol, indicating the standard deviation of a value. σ^2 indicates the value's variance (which is just the square of the σ value).
M_{ijsd}^{dark}	The dark count mask for the GUVI instrument.
M_{ijsd}^{1304}	The 1304 scattered light mask for the GUVI instrument.
M_{ijsd}^{1216}	The Lyman-α scattered light mask for the GUVI instrument.
M_{ijsd}^{long}	The out-of-band scattered light mask for the GUVI instrument.
LF_{iijsd}	The total fraction of the counts from the emission line corresponding to color *i(1)* that falls within the color table boundaries defined for color *i(2)* for spatial pixel *j*, slit *s*, and detector *d*, e.g., LF_{12} would refer to 1304 emission that falls within the 1356 colortable mask.

GUVI Calibration Steps

1. Data decompression

The GUVI data must be decompressed using the decompression lookup table. Uncertainties associated with the decompression are obtained from the decompression error lookup table.

$$\begin{aligned} C_{ijk}^{decomp} &= \text{Decompression Lookup Table}\,(C_{ijk}) \\ \sigma C_{ijk}^{decomp} &= \text{Decompression Error LookupTable}\,(C_{ijk}) \end{aligned}$$

Note that the uncertainty due to decompression is not strictly a standard deviation since it does not have Gaussian statistics. The value from the decompression error lookup table simply indicates the range of true counts that are possible for a decompressed value (e.g., 16 ± 1). For the moment it is being treated as a standard deviation for the purpose of propagation of errors.

2. Determine Poisson statistics for the observed counts

The uncertainty of an individual pixel is estimated as the square root of the number of counts.

$$\sigma^2 C_{ijk}^{temp0} = \begin{cases} \sigma_0 & \text{if } \mathrm{C}_{\mathrm{ijk}}^{\mathrm{decomp}} = 0 \\ C_{ijk}^{decomp} + \sigma^2 C_{ijk}^{decomp} & \text{otherwise} \end{cases}$$

where σ_0 has a value of either 0 or 1, depending on whether this variance is intended for use in coadding multiple pixels together into superpixels or not. A value of 0 is appropriate to support coadding, while a value of 1 is appropriate as the best estimate that can be made of the uncertainty in a single pixel with no counts.

3. Correction for detector dead time

The GUVI detector does not report every photon event as a count in the telemetry. This is particularly true when the event rate is large. However, the detector does measure the total number of events and provides a scaled value of the output-to-input event ratio in the telemetry, which can be used to correct the observed count rate.

$$\begin{aligned} C_{ijk}^{temp1} &= (64/OIRatio_k) \times C_{ijk}^{temp0} \\ \sigma^2 C_{ijk}^{temp1} &= (64/OIRatio_k)^2 \times \sigma^2 C_{ijk}^{temp0} \end{aligned}$$

4. Correction for instrumental dark rates

The GUVI instrument measures instrumental dark counts with 4 separate "dark pixels". These values are used to scale a dark pixel mask to obtain an estimated dark level that is then subtracted from each pixel.

$$C_{ijk}^{temp2} = C_{ijk}^{temp1} - M_{ijsd}^{dark} \times C^{dark} \times (\tau / \tau^{dark})$$

$$\sigma^2 C^{dark} = \begin{cases} 1 & \text{if } C^{dark} = 0 \\ C^{dark} & \text{otherwise} \end{cases}$$

$$\sigma^2 C_{ijk}^{temp2} = \sigma^2 C_{ijk}^{temp1} + (C^{dark} \times (\tau / \tau^{dark}))^2 \times \sigma^2 M_{ijsd}^{dark} + (M_{ijsl}^{dark})^2 \times \sigma^2 C^{dark} \times (\tau / \tau^{dark})^2$$

At present, this correction step is generally not applied because the GUVI dark pixels seem to see varying amounts of scattered light at a level substantially larger than the miniscule "true" dark level. In the event that this correction is applied, the variance of the dark mask is currently assumed to be zero, which simplifies the above equation somewhat.

5. OI 1304/1356 color overlap

Some fraction of the 1304 signal is scattered into the other GUVI colors and must be removed. In cases where the lines are well resolved (typical when using the medium or narrow slits for imaging mode operations), the contributions from 1356 emission falling within the colortable boundaries defined for 1304 may be ignored, and correction proceeds according to the procedure outlined in the step below (6). When the 1304 and 1356 lines overlap on the detector, however, counts for the two colors must be solved for simultaneously. Calibration software should be configured to permit enabling and disabling this portion of the algorithm on an as-needed basis, perhaps triggered automatically by the slit used for a given observation. If 1304 and 1356 are computed via the procedure described in this step (5), then the 1304 scattered light correction implemented in the following step (6) should ***not*** be performed for the 1356 color.

In the dayglow, O I 1304 A will be about 10 times as bright as O I 1356 A in the nadir, with lesser amounts on the limb. At night the two lines will be comparably in intensity. Given the known resolution of the instrument and the fractional contribution of each emission line at a particular spectral bin (some of which lie in regions mapped to color 1, others in color 2), we have two equations with two unknowns. The observed blended counts (including the corrections applied in the steps above) at 1304 and 1356 A are C_{1jk}^{temp5} and C_{2jk}^{temp5}. If we designate, for example, the fraction of the observed counts in color 1 spatial pixel j that originated from emission line 2 in spatial pixel j by the line fraction coefficient LF_{21j} (fractional contributions having been summed over the appropriate spectral bins), then the following two equations apply:

$$C_{1jk}^{temp5} = LF_{11j} \times A_{1jk}^{temp6} + LF_{21j} \times A_{2jk}^{temp6}$$

$$C_{2jk}^{temp5} = LF_{12j} \times A_{1jk}^{temp6} + LF_{22j} \times A_{2jk}^{temp6}$$

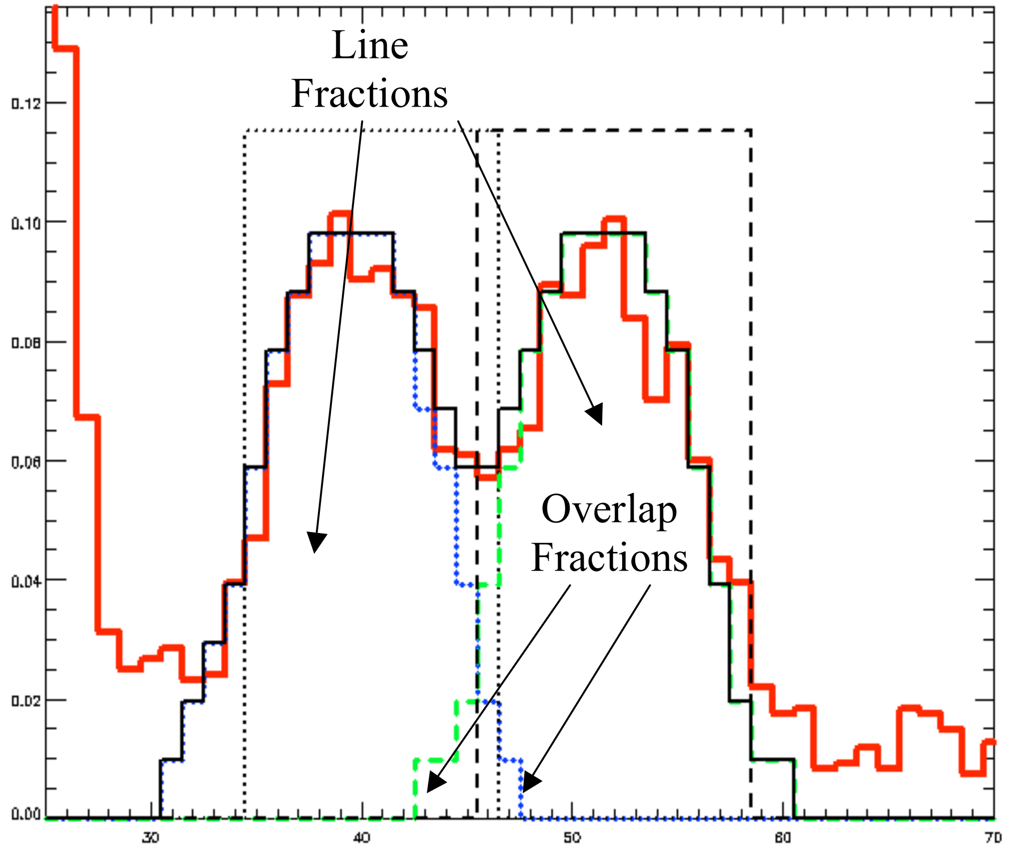

Figure 1 - The sum of 124 scans of spectrograph mode data (red) from a single spatial pixel is overlaid with the 1304 (black,dotted) and 1356 (black,dashed) colortable boundaries and the laboratory measured 1304 (blue,dotted) and 1356 (green,dashed) line shapes. The portion (fractional area under the curves above, each of which is normalized to 1) of each color that falls within that color's own color table boundaries constitutes the "line fraction"; the portion that lies within the adjacent color's color table boundaries constitutes the "overlap fraction".

We can then extract the unblended counts corresponding to the true emissions from the entirety of each spectral line (via matrix methods or brute force), A_{1jk}^{temp6} and A_{2jk}^{temp6}:

$$A_{1jk}^{temp6} = \frac{LF_{22j} \times C_{1jk}^{temp5} - LF_{21j} \times C_{2jk}^{temp5}}{LF_{11j} LF_{22j} - LF_{12j} LF_{21j}}$$

$$A_{2jk}^{temp6} = \frac{LF_{11j} \times C_{2jk}^{temp5} - LF_{12j} \times C_{1jk}^{temp5}}{LF_{11j} LF_{22j} - LF_{12j} LF_{21j}}$$

The unblended counts falling within the designated colortable masks, C_{1jk}^{temp6} and C_{2jk}^{temp6}, are then:

$$C_{1jk}^{temp6} = LF_{11j} \times A_{1jk}^{temp6} = LF_{11j} \times \frac{LF_{22j} \times C_{1jk}^{temp5} - LF_{21j} \times C_{2jk}^{temp5}}{LF_{11j} LF_{22j} - LF_{12j} LF_{21j}}$$

$$C_{2jk}^{temp6} = LF_{22j} \times A_{2jk}^{temp6} = LF_{22j} \times \frac{LF_{11j} \times C_{2jk}^{temp5} - LF_{12j} \times C_{1jk}^{temp5}}{LF_{11j} LF_{22j} - LF_{12j} LF_{21j}}$$

Note that in the absence of any overlap ($LF_{i1i2j} = 0, i1 \neq i2$), these expressions reduce to the simple identity

$$C_{1jk}^{temp6} = LF_{11j} \times A_{1jk}^{temp6} = C_{1jk}^{temp5}$$

$$C_{2jk}^{temp6} = LF_{22j} \times A_{2jk}^{temp6} = C_{2jk}^{temp5}$$

The resulting uncertainties are then:

$$\sigma^2 C_{1jk}^{temp6} = \left(\frac{LF_{11j}}{LF_{11j} LF_{22j} - LF_{12j} LF_{21j}} \right)^2 \times \left[\left(LF_{22j} \right)^2 \times \sigma^2 C_{1jk}^{temp5} + \left(LF_{21j} \right)^2 \times \sigma^2 C_{2jk}^{temp5} \right]$$

$$\sigma^2 C_{2jk}^{temp6} = \left(\frac{LF_{22j}}{LF_{11j} LF_{22j} - LF_{12j} LF_{21j}} \right)^2 \times \left[\left(LF_{11j} \right)^2 \times \sigma^2 C_{2jk}^{temp5} + \left(LF_{12j} \right)^2 \times \sigma^2 C_{1jk}^{temp5} \right]$$

We have assumed that the variances of the line fraction coefficients and the covariances of the blended counts are zero (although this is obviously not strictly true for the blended counts).

6. Correction for 1304 scattered light

For colors other than 1356 (or all colors when overlap correction is not performed above), some fraction of the observed counts originate from 1304 scattering into the other GUVI colors; these counts must be removed. As was the case for the dark count correction, an instrumental scattering mask determined from calibration is scaled by the background corrected 1304 counts to obtain a correction for the other colors. There is no need to correct the 1304 color for this effect (i.e., the i=1 component of the 1304 scattered mask may be set to zero).

$$C_{ijk}^{temp3} = C_{ijk}^{temp2} - M_{ijsd}^{1304} \times C_{1jk}^{temp2} \qquad \text{for i} \neq 1$$

$$\sigma^2 C_{ijk}^{temp3} = \sigma^2 C_{ijk}^{temp2} + (C_{1jk}^{temp2})^2 \times \sigma^2 M_{ijsd}^{1304} + (M_{ijsd}^{1304})^2 \times \sigma^2 C_{1jk}^{temp2} \quad \text{for i} \neq 1$$

For i=1 C_{ijk}^{temp3} and its variance are the same as C_{ijk}^{temp2} and its variance. At present the variance of the 1304 scattered light mask is assumed to be zero, which simplifies the above equation somewhat.

7. Correction for 1216 scattered light

Some fraction of the 1216 signal is scattered into the other GUVI colors and must be removed. As was the case for the 1304 scattered light correction, an instrumental scattering mask determined from calibration is scaled by the background- (and 1304-) corrected 1216 counts to obtain a correction for the other colors.

$$C_{ijk}^{temp4} = C_{ijk}^{temp3} - M_{ijsd}^{1216} \times C_{0jk}^{temp3} \qquad \text{for i} \neq 0$$
$$\sigma^2 C_{ijk}^{temp4} = \sigma^2 C_{ijk}^{temp3} + (C_{0jk}^{temp3})^2 \times \sigma^2 M_{ijsd}^{1216} + (M_{ijsd}^{1216})^2 \times \sigma^2 C_{0jk}^{temp3} \quad \text{for i} \neq 0$$

For i=0 C_{ijk}^{temp4} and its variance are the same as C_{ijk}^{temp3} and its variance.

At present the variance of the 1216 scattered light mask is assumed to be zero for all cases, which simplifies the above equations somewhat.

8. Correction for long background scattered light

The expanded (from 3x7 to 14x191) long background pixels are corrected for the contributions from dark counts, scattered 1304, and scattered 1216 using the corrected dark, 1216, and 1304 counts and their corresponding background pixel masks. The remaining counts, presumably now due only to the long background scattered light component, are multiplied by the long background scattered light mask for each color; the resulting background is subtracted from that color.

$$C_{ijk}^{temp5} = C_{ijk}^{temp4} - M_{ijsd}^{long} \times LB_k^{temp4}$$
$$\sigma^2 C_{ijk}^{temp5} = \sigma^2 C_{ijk}^{temp4} + (LB_k^{temp4})^2 \times \sigma^2 M_{ijsd}^{long} + (M_{ijsd}^{long})^2 \times \sigma^2 LB_k^{temp4}$$

At present the variance of the out-of-band scattered light mask is assumed to be zero, which simplifies the above equation somewhat.

9. Conversion to intensity

The integration time and measured responsivity (in counts/R/s) are used to determine the measured brightness in each pixel.

$$
\begin{aligned}
I_{ijk} &= C_{ijk}^{temp5} / (\tau \times R_{ijksd}) \\
\sigma^2 I_{ijk}^{meas} &= (\tau \times R_{ijksd})^{-2} \times \sigma^2 C_{ijk}^{temp5} \\
\sigma I_{ijk}^{cal} &= U_{ijksd} \times I_{ijk}
\end{aligned}
$$

A distinction is made here between the uncertainties in the result due to measurement (i.e., statistical) errors as opposed to calibration-induced biases. The uncertainty in the calibration is obtained from the {disk/limb} calibration error ratio variable in the APL calibration files. At the time of this writing, U_{ijksd} is generally a constant value of 0.1 (10%).

Change Log

Version 1.0, October 2007 – Initial draft, borrowing heavily from (more complex) SSUSI calibration procedure (P. Strauss, Aerospace Corporation, and B. Wolven, JHUAPL)
Version 1.1, November 2007 – Additional revisions to accomdodate difference in SSUSI and GUVI long background pixel measurements and subtraction; transferred some data-related material from instrument ground cal report to this document (B. Wolven, JHUAPL)