1 IBIS Gain Table Determination

ESSENTIAL CONSIDERATIONS

• Deriving the gain table for the IBIS data is in some sense similar to the situation for slit spectra when the slit is tilted with respect to the camera axis (or even curved). In both cases one must account for the fact that the solar spectrum is intertwined into the spatial distribution of measured intensity. This is very different than what is required for the construction of gain tables for "typical" imaging devices such as broadband filters.

• The most important effect for a Fabry-Perot-based imaging spectrograph is a spatially dependent shift of the central wavelength of the instrumental profile at different positions in the field of view. In the case of an instrument like IBIS that uses a classical mount, the increasing angles of incidence at greater distances from the optical axis introduce a shift that increases smoothly with radial distance.

The distribution of the shifts for such an instrument is well described by a paraboloid in the (x,y) plane of the image. Due to the alignment procedures employed in setting up IBIS, the center of the paraboloid is often very close to the center of the image, but offsets of several pixels are normal. Both the center of the parabola, and its amplitude are to be determined during the procedure for gain determination. The maximum profile shift (at the edge of the circular field) ranges from a maximum of $\approx$ 90 mÅ at 6000 Å to $\approx$ 115 mÅ at 8500 Å. The amplitude of the shift is linearly dependent on wavelength and will not vary sensibly within the range of any given prefilter. The location of the optical center may vary among prefilters due to the optical wedge in the filter substrates or the detector offsets introduced during the focus translation. When looking at the actual data without any correction, spectral lines from the edge of the FOV will appear *redshifted* with respect to ones acquired near the center of the FOV.

• The prefilter, located in between the two FPIs, produces effects similar to the interferometers, i.e. the angle of incidence of the beam produces blueshifts in the prefilter profile at different parts of the field. However, given its physical characteristics (greater index of refraction, significant tilt with respect to the optical axis, etc.), the apparent pattern of its shifts within the FOV is significantly different compared to the radial shifts of the interferometers. The tilt of the prefilter moves the center of its parabolic shift distribution well outside of the field of view. Sampling an off-center portion of the paraboloid results in prefilter profiles with shifts that appear to have a planar trend across the field of view (nearly vertical because of the orientation of the tilt axis). Note that because of the relative width of the prefilter profile with respect to the transmission profile of the interferomters, the dominant effect of the shift of the prefilter profile is a variation in overall transmission, not any modification of the shape or wavelength position of interferometer instrumental profile.

GAIN TABLE DERIVATION: Measures and definitions

Uniform solar signal: The first step is to obtain an equal solar illumination on all points in the field of view. The *flat field* series attempts this by obtaining multiple ($\geq 50-100$) images, at each wavelength tuning position, randomly located in one area of the solar surface, typically near disk center. Additional blurring from telescope motion or deformations of the AO mirror provide further mixing of the solar intensity patterns. The actual data cube that is derived from averaging the various samples at each wavelength position in the flat field series is $F(x, y, \lambda)$ Assuming that in principle the averaging procedure is effective, the incident illumination at each spatial pixel will have the same wavelength-dependent (solar) spectral profile, $S(\lambda)$, where λ is the sampling is given by the wavelength tunings of the scan.

Instrumental tuning blueshift: However, as mentioned above, the instrument introduces a spatially dependent shift of the wavelength tuning. This is equivalent to having a varying offset of the wavelength scale for each spatial position in the FOV. The distribution of the instrumental wavelength shifts as a function of position in the field of view is given by $b_i(x, y)$. Care must be applied to retrieve the actual system response by accounting for the wavelength shift of the solar spectral profile.

Wavelength scale definition: Let us then assume a reference pixel within the FOV, (x_c,y_c), corresponding to, for simplicity, the position of the center of the pattern of tuning blueshift (*i.e.* the pixel corresponding to the optical axis). The averaged spectral profile at this pixel is $S(\lambda_r)$, where λ_r is the *reference* wavelength scale pertaining to this pixel. This wavelength scale is given by the voltages applied to the interferometers, the associated plate spacing variations, and produces a sequence of images when scanning a spectral line[1]. On this reference wavelength scale, for each position in the field of view, the expected solar profile is expected to be the same (due to averaging) but shifted from that obtained at the reference position, and can be written as $S(x, y, \lambda) = S(\lambda_r + b_i(x, y))$, where $b_i(x, y)$ is the distribution of the instrumental profile shifts defined above.

Prefilter: The observed spectral profile at each pixel will actually be a combination of the solar profile $S(\lambda)$ and the prefilter profile that apodizes (or windows) the solar signal. For the reasons explained above, the effective shape of the prefilter transmission profile will be the same throughout the field of view, $P_r(\lambda)$, but shifted differently at each point in the field. The spatial distribution of the shifts, $b_p(x, y)$, will be different than the Fabry-Perot instrumental blueshift distribution (because of the difference in the index of refractions).

Due the tilt on the prefilter, this variation appears as a strong planar gradient across the images. While the spatial distribution of shifts for the prefilter is constant for each prefilter, the amplitude of the resulting intensity gradient at any given tuning position will vary with the position and shape of the overall prefilter profile in the region around the nominal wavelength setting. For example, the the intensity gradient will be more pronounced when tuned to a wavelength corresponding to the steeper wings of the profile (where the $\Delta I/\Delta\lambda$ is greater).

The result is that the input spectral profile observed at each position is a combination of the shifted spectral profile and the shifted prefilter profile, or

$S_i(x, y, \lambda) = S(\lambda_r + b_i(x, y)) \cdot P(\lambda + b_p(x, y))$.

In order to perform a pixel-wise correction of the prefilter transmission, we would have to know $b_p(x, y)$ with a relative degree of accuracy, but this shift distribution can be hard to recover from individual datasets. Instead, we can simplify the process by separating the correction into two fundamental components: the spatial distribution of intensity variations caused by the prefilter at each wavelength tuning position, $\Delta p(x, y, \lambda_r)$, and the trends in prefilter transmission across the sampled wavelengths, $P(\lambda)$. This latter will also be called the reference prefilter transmission profile.

System Response: The measured signal $F(x, y, \lambda_r)$ obviously contains not only the solar and prefilter profile, $S(\lambda_r) \cdot P(\lambda)$, but also the overall system response. As normally taken into account, the overall system response at each pixel contains response variations, such

[1]We stress that the choice of wavelength scale is, for the purpose of this discussion, arbitrary, and all the considerations that follow will apply on any other choice. Indeed, the wavelengths used in the IBIS acquisition programs are *relative* to the measured center of the prefilter transmission profile, so that only wavelength *differences* need be considered.

as vignetting, transmission changes, detector quantum efficiency variations, etc, which are given by $g(x,y,\lambda_r)$.

Formulae. We can now combine these different elements in order to describe the observed flat field data cube:

$$F(x,y,\lambda) = g(x,y,\lambda)\,\Delta p(x,y,\lambda)\,P(\lambda)\,S(\lambda_r + b_i(x,y)) \tag{1}$$

If we can determine $S(\lambda_r)$ and $b(x,y)$ then it is possible to determine the system response as:

$$g(x,y,\lambda)\,\Delta p(x,y,\lambda)\,P(\lambda) \;=\; \frac{F(x,y,\lambda)}{S(\lambda_r + b(x,y))} \tag{2}$$

where the g and Δp are combined into an overall response and $P(\lambda)$ provides the relative transmission at each wavelength tuning.

GAIN TABLE CALCULATION: Procedure

The gain procedure starts with the derivation of the line core position for the solar line present in each pixel (x,y) of the FOV, by using the measured $F(x,y,\lambda)$. From these values we can then determine $b_i(x,y)$ through recovery of the relative shifts of the line profile at each spatial pixel. To reduce both solar and measurement noise, it is better to fit this map of shifts with a 2-D, second-order polynomial, in order to construct a smooth surface $b_s(x,y)$. The fit gives also the position (x_c,y_c) of the center of the pattern.

For an instrument using classically mounted FPI, the instrumental blueshift should be a simple elliptical paraboloid, with only x and y quadratic terms. Large-scale spatial illumination gradients, like those potentially introduced by the prefilter, could introduce other components to the polynomial fit of the line-core positions. Since these components do not reflect a true wavelength shift of the spectral profiles (but rather a wavelength-dependent intensity trend that will be removed by the flat-fielding procedure), these non-quadratic components should be discarded from when defining the the instrumental blueshift map.

While it is now possible to extract $F(x_c,y_c,\lambda_r)$, there are unknown system response variations, $g(x_c,y_c,\lambda_r)$ and $\Delta p(x_c,y_c,\lambda_r)$, that make it undesirable to use this single profile as a relative reference for all the positions in the field of view. Instead it is necessary to sum the observed profiles over the some extended area in order average out the effects of the local response variations. In order to perform this averaging, each observed profile must be shifted by an amount given by the relative value of $b_s(x,y)$, given by:

$$F(x,y,\lambda_r - b_i(x,y)) = g(x,y,\lambda - b_i(x,y))\,P(\lambda - b_i(x,y))\,\Delta p(x,y,\lambda - b_i(x,y))\,S(\lambda_r) \tag{3}$$

This is equivalent to the correction of spectral shifts applied to slit spectra for measurements in which the slits are not perfectly linear and orthogonal to the dispersion and detector axes. Because this process involves an interpolation between samples wavelength positions, it is implicitly necessary to have measurements of F at multiple wavelengths. This is the typical case, but not mandatory case for bidimensional spectrometry when scanning spectral profiles.

These individually shifted profiles are summed to produce a reference profile S_m (combining both the solar reference profile and the prefilter) as:

$$S_m(\lambda_r) = \frac{1}{n}\frac{1}{m}\sum_{x=0}^{n}\sum_{y=0}^{m} F(x,y,\lambda - b_i(x,y)) = < g_\lambda >< \Delta p_\lambda >< P(\lambda_r) > \; S(\lambda_r) \tag{4}$$

where the values in brackets indicate the average of the quantity over the entire summed area. The above indicates a sum over a rectangular area, but more typically this procedure uses a circular area (centered on x_c, y_c) for integration. Because the gain and spatial prefilter transmission variations are defined as relative variations, we can define their averaged values to be equivalent to unity at each wavelength and they do not influence the shape of reference profile.

We note that these averaged values referenced above do not refer strictly to a common wavelength since the shifts applied to the observed profiles introduces a mixing of system response and prefilter components from nearby wavelengths. Some of the wavelength dependence of some system responses (detector efficiency, optical vignetting, etc.) are expected to be small and relatively smooth.

The prefilter transmission however can change more significantly and we need to be careful to choose a region of integration that does not introduce a bias in the measured average profile. In particular, we need to use a region for which the averaged prefilter transmission profile does not differ significantly from the prefilter profile at the reference position (x_c, y_c). This can be somewhat complicated by the presence of small scale features in the prefilter transmission profile, namely interference fringes ('or "wiggles"'). However, evaluations using a synthetic prefilter profile (including fringes) and a typical map of prefilter profile shifts, indicates that a radius of integration of approximately 200 (full-resolution) pixels (corresponding to a radius of about 20 arcseconds), should keep the offsets between the reference and averaged profile to less that one percent[2].

Having the reference profile for each prefilter $P_r(\lambda)$, which has been seen to be stable for many years, we can derive the values for $P(\lambda_r)$, using the wavelength steps of the observations. Since the wavelength scale used to define the observations is relative (to the estimated peak transmission of the prefilter) and the prefilter profile may be offset due to tilt or temperature variations, it is necessary to find an optimal offset $(\delta\lambda_p)$ of the reference prefilter profile with respect the observed spectral profile. This can be done by comparing the observed spectral profile, either the mean flat field profile $S(\lambda_r)$ or the Imaging Spectral Scan profile taken in the morning (for wavelength calibration) that covers a the full range of the prefilter. In this way, the values of $P(\lambda_r)$ can be determined, divided out of $S_m(\lambda_r)$, and $S(\lambda_r)$ to be isolated.

Then, with this averaged reference profile and the surface describing the profile shifts, the determination of the gain simply becomes the ratio of the observed flat field profile at each position x, y and the appropriately shifted averaged reference profile:

$$g(x,y,\lambda_r)\,\Delta p(x,y,\lambda_r)\,P(\lambda_r) = \frac{F(x,y,\lambda_r)}{S(\lambda_r + b_s(x,y))} \tag{5}$$

The *gain table* data cube, consisting of the product of g, Δp, and P, is then applied pixelwise to the images obtained at the corresponding values of λ_r. And thus is the data corrected and made wonderful.

[2]If needed, this estimate can be tested for a specific calibration sequence by comparing the profiles generated by summing over circular regions with successively larger radii and determining at which radius the average profile significantly deviates from the central reference profile.