1 Absolute Flux Calibration

Absolute flux calibration is performed using observations of a **standard candle**, an astronomical source with stable flux density that is well modelled over a broad range of radio frequencies. Two sets of observations are made: an artificial noise source is switched on and off while the telescope is pointed at 1) the standard candle and 2) a nearby patch of sky that is assumed to be empty. Examples of such observations are shown in Figure 1. The integration lengths for the on- and off-source observations need not necessarily be equal if the data represent mean flux densities. In PSRCHIVE, two different assumptions can be applied to the analysis of these observations:

1. **Adjusted Gain:** The absolute gain of the system is adjusted at the start of each observation and may be different when pointing at the standard candle and pointing away from the standard candle. Gains are typically adjusted in order to maintain linearity when the observing system has limited dynamic range.

2. **Fixed Gain:** The absolute gain of the system is not adjusted, but may be different when the noise source is on and the noise source is off. Gains are typically held constant when the system can be safely assumed to have sufficient dynamic range. Any variation in gain between on and off states of the noise source is typically unintentional; it is usually evidence that the artificial noise source signal is too strong, such that it drives the system into a nonlinear regime.

1.1 Adjusted Gain

By default, `fluxcal` assumes that the absolute gain of the system is adjusted at the start of each observation. In this case,

$$\begin{aligned} H_{\rm on} &= g_{\rm on}(S_{\rm sys} + S_0 + C_0) \qquad & H_{\rm off} &= g_{\rm off}(S_{\rm sys} + C_0) \\ L_{\rm on} &= g_{\rm on}(S_{\rm sys} + S_0) \qquad & L_{\rm off} &= g_{\rm off} S_{\rm sys} \end{aligned}$$

where $g_{\rm on}$ and $g_{\rm off}$ are the unknown absolute gains of the instrument while pointing on and off the standard candle, $S_{\rm sys}$ is the unknown system equivalent flux density, S_0 is the known flux density of the standard candle, and C_0 is the unknown flux density of the receiver noise source. Then,

$$f_{\rm on} = \frac{H_{\rm on}}{L_{\rm on}} - 1 = \frac{C_0}{S_{\rm sys} + S_0} \tag{1}$$

and

$$f_{\rm off} = \frac{H_{\rm off}}{L_{\rm off}} - 1 = \frac{C_0}{S_{\rm sys}} \tag{2}$$

and

$$\frac{1}{f_{\rm on}} - \frac{1}{f_{\rm off}} = \frac{S_0}{C_0} \tag{3}$$

Equation 3 is solved for C_0, then Equation 2 is solved for $S_{\rm sys}$.

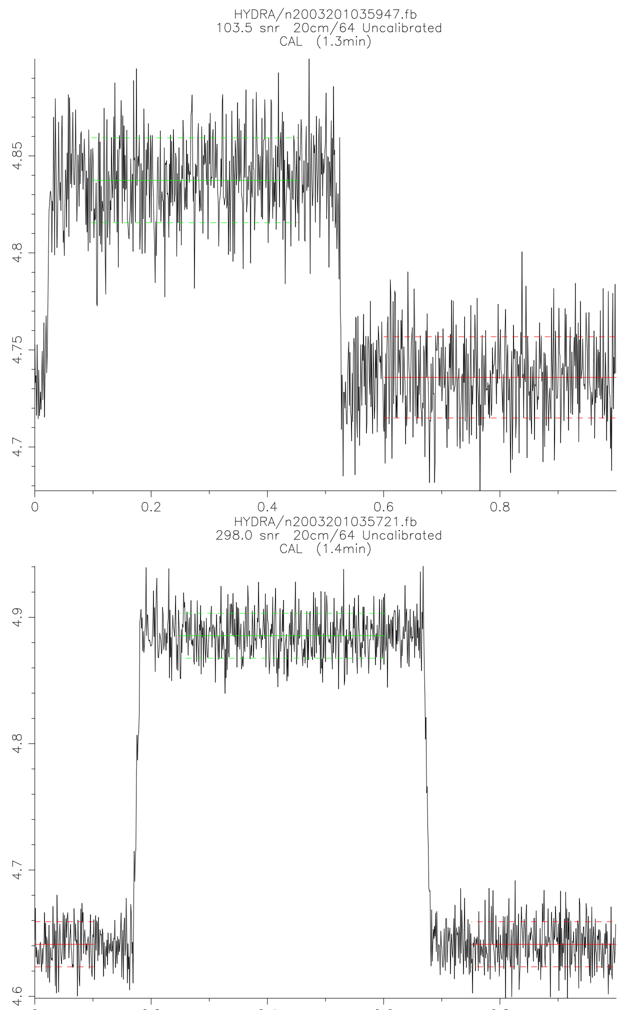

Figure 1: Observations of the Parkes Multibeam receiver noise source. The total intensity from a single 500 kHz channel was integrated for approximately 80 s. In the top panel, the telescope was pointed at 3C 218 (Hydra A); the mean on-pulse power (green) is used to estimate H_{on} and the mean off-pulse power (red) is used to estimate L_{on}. In the bottom panel, the telescope was pointed 2 deg north; the mean on-pulse power is used to estimate H_{off} and the mean off-pulse power is used to estimate L_{off}.

In practice, when using the Adjusted Gain model, $f_{\rm on}$ (Equation 1) is computed for each on-source observation and integrated into an inverse-variance-weighted average; likewise $f_{\rm off}$ (Equation 2) is computed for each off-source observation and integrated into a separate inverse-variance-weighted average. After all on- and off-source observations have been integrated, Equation 3 is computed. Averages are computed for $f_{\rm on}$ and $f_{\rm off}$ (instead of $H_{\rm on}$, $H_{\rm off}$, $L_{\rm on}$, and $L_{\rm off}$) because the gains, $g_{\rm on}$ and $g_{\rm off}$, may vary from observation to observation, such that inverse-variance-weighting would give lower weight to observations made with greater gain.

First-order error propagation is used to compute the variances of $f_{\rm on}$ and $f_{\rm off}$; however, owing to the non-linear nature of Equations 1 and 2, the derived uncertainties are likely incorrect at some level. Because these variances are used in the weighted averages, inaccuracies in error propagation might possibly contribute to greater scatter of the derived values of $S_{\rm sys}$.

1.2 Fixed Gain

If the absolute gain of the system is not adjusted at the start of each observation, `fluxcal -g` assumes that the gain may *unintentionally* vary between noise source on and noise source off states. Unintentional variation in gain may arise from a non-linear component in the signal chain (e.g. an amplifier that is driven into compression, or a directional coupler with an impedence that depends on the strengths of the input signals). In this case,

$$H_{\rm on} = g_{\rm H}(S_{\rm sys} + S_0 + C_0) \qquad H_{\rm off} = g_{\rm H}(S_{\rm sys} + C_0)$$
$$L_{\rm on} = g_{\rm L}(S_{\rm sys} + S_0) \qquad L_{\rm off} = g_{\rm L}S_{\rm sys}$$

where $g_{\rm H}$ and $g_{\rm L}$ are the unknown absolute gains of the instrument while the receiver noise source is on and off, respectively. Then,

$$f_{\rm H} = \frac{H_{\rm on}}{H_{\rm off}} - 1 = \frac{S_0}{S_{\rm sys} + C_0} \tag{4}$$

and

$$f_{\rm L} = \frac{L_{\rm on}}{L_{\rm off}} - 1 = \frac{S_0}{S_{\rm sys}} \tag{5}$$

and

$$\frac{1}{f_{\rm H}} - \frac{1}{f_{\rm L}} = \frac{C_0}{S_0} \tag{6}$$

For a system that responds linearly to its inputs, the gain ratio,

$$r_g = \frac{H_{\rm on} - H_{\rm off}}{L_{\rm on} - L_{\rm off}} = \frac{g_{\rm H}}{g_{\rm L}}, \tag{7}$$

should be equal to unity. Furthermore, because $g_{\rm H}$ or $g_{\rm L}$ are nominally equal, there are multiple ways to define the absolute gain of the system, which is given by either $g_{\rm H}$ or $g_{\rm L}$ or some average of the two (e.g. either the algebraic or geometric mean). In the case of nonlinear response to a strong artificial noise source, g_{L} most closely reflects the response of the system to an astrophysical signal. Under this assumption, the absolute gain of the system is given by

$$g_{\mathrm{L}} = \frac{L_{\mathrm{on}} - L_{\mathrm{off}}}{S_0} \tag{8}$$

Equation 6 is solved for C_0, Equation 5 is solved for S_{sys}, and Equation 8 defines the absolute gain that can be used to calibrate sources observed with the same instrumental configuration without any need for an observation of the artificial noise source.

In practice, when using the Fixed Gain model, inverse-variance-weighted averages are computed for H_{on}, H_{off}, L_{on}, and L_{off}. Equations 4 through 8 are computed only after all on- and off-source observations have been integrated.