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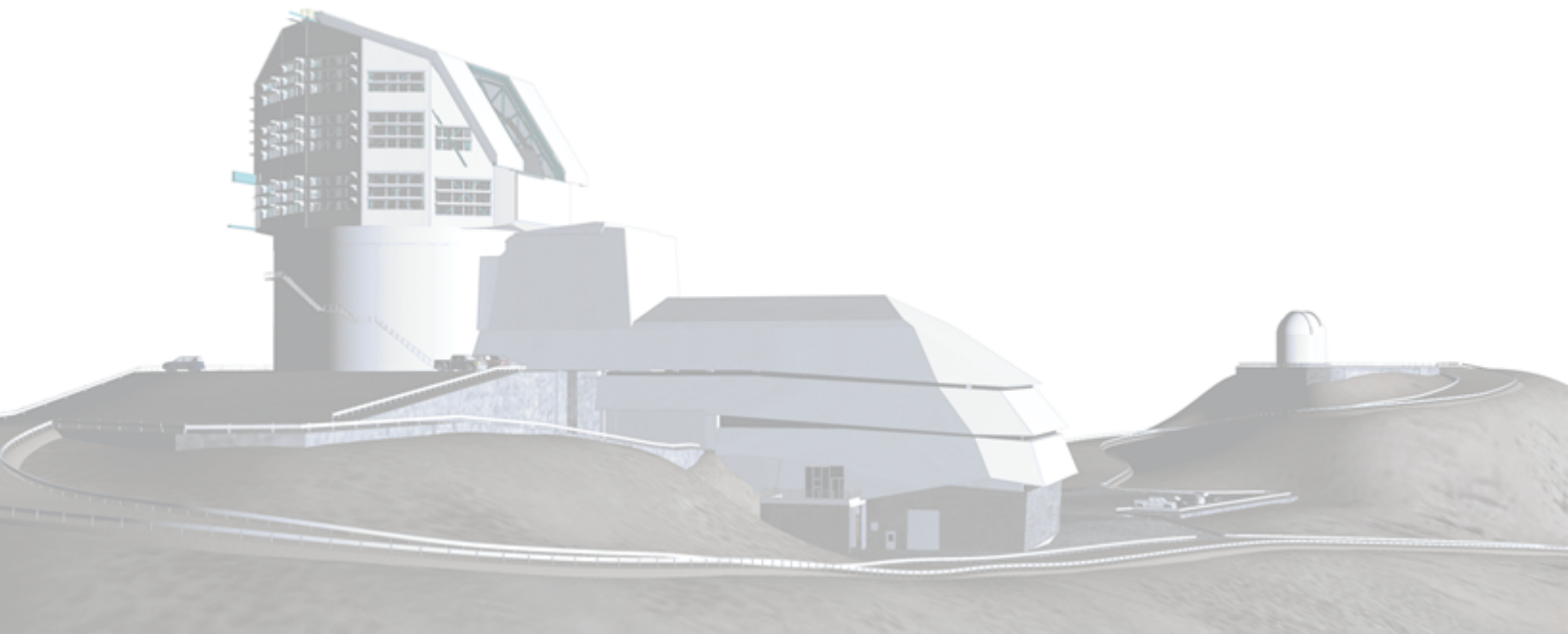
Camera Shutter Motion Analysis

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CTN-002

Latest Revision: 2025-08-06

DRAFT



Abstract

Profile fitting for camera shutter trajectory and timing analysis.

Draft

Change Record

Version	Date	Description	Owner name
1	2025-07-16	First Draft	Shuang Liang

Document source location: <https://github.com/lstt/ctn-002>

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Camera Shutter Motion Analysis

1 Data Structure

The shutter motion profiles are located at

`lsstcam-dc01.cp.lsst.org:/data/ccs-ipa-data/OBS_DAY/SEQ_NUM/`

and for each sequence number there're two motion profiles:

`SEQ_NUM_shutterMotionProfileOpen.json`, and
`SEQ_NUM_shutterMotionProfileClose.json`.

As the names suggest, each file corresponds to an open/close motion of one of the two shutter blades: PLUSX and MINUSX. Some related meta information can be found in each file:

`startTime`: motion start time.
`startPosition`: position of blade when motion started.
`targetPosition`: target end position.
`endPosition`: action end position.
`targetDuration`: target duration of motion.
`actionDuration`: action duration of motion.
`side`: "PLUSX" or "MINUSX", labeling two blades of the shutter.

In addition, two sets of measurement of the shutter motion (time and position) are included: `encodeSamples` and `hallTransitions`, as well as the fitted motion parameters: `motorEncoderFit` and `hallSensorFit`. The following sections explain the fitting model in detail.

2 Preparing for Fitting

Both the motor encoder and the Hall sensors measure time stamps in TAI timescale and provided in both ISO and MJD format. We first subtract the start`Time` to get a relative timing,

$$t \rightarrow t - \text{startTime}, \quad (1)$$

then append the end measurement (`actionDuration`, `endPosition`) as the last pair of the motion data (t, s) . Next we normalize the time stamps by duration:

$$t \rightarrow t / \text{actionDuration}. \quad (2)$$

Finally, the start position is subtracted from or subtracts the displacement s depending on motion direction, and normalized by 750mm:

$$s \rightarrow \begin{cases} (s - \text{startPosition}) / 750\text{mm}, & \text{endPosition} > \text{startPosition} \\ (\text{startPosition} - s) / 750\text{mm}, & \text{endPosition} < \text{startPosition}. \end{cases} \quad (3)$$

In this set-up, the model always takes $t \approx [0, 1]$ and maps to $s \approx [0, 1]$, simplifying the fitting procedure. After the fitting, model parameters are scaled up to recover their physical units, with time parameters (t_0, t_1, t_2) multiplied by `actionDuration`, and jerk parameters (j_0, j_1, j_2) multiplied by $750 \cdot \text{actionDuration}^{-3}$.

3 Three Jerks Model v1

The shutter motion profile is a piecewise constant jerk motion, as shown in Figure 3. The position coordinate starts at $\sim 0\text{mm}$ from the PLUSX side and goes to $\sim 750\text{mm}$ at the MINUSX side. So when the MINUSX side opens/PLUSX side closes, the shutter blade starts with a positive jerk j_0 , then jumps to a negative jerk j_1 at a pivot time t_1 , and jumps again to a positive jerk j_2 at the second pivot time t_2 . For the other direction – PLUSX side opens/MINUSX side closes – the shutter experiences negative-positive-negative jerk jumps. But as the model is fitted on normalized data, it will always report positive-negative-positive jerks.

In addition to the above model parameters, a special parameter t_0 is introduced to measure a possible lag between the meta keyword `startTime` and the actual motion start time. The parameter essentially moves all measured time stamps by a tiny amount in order to better

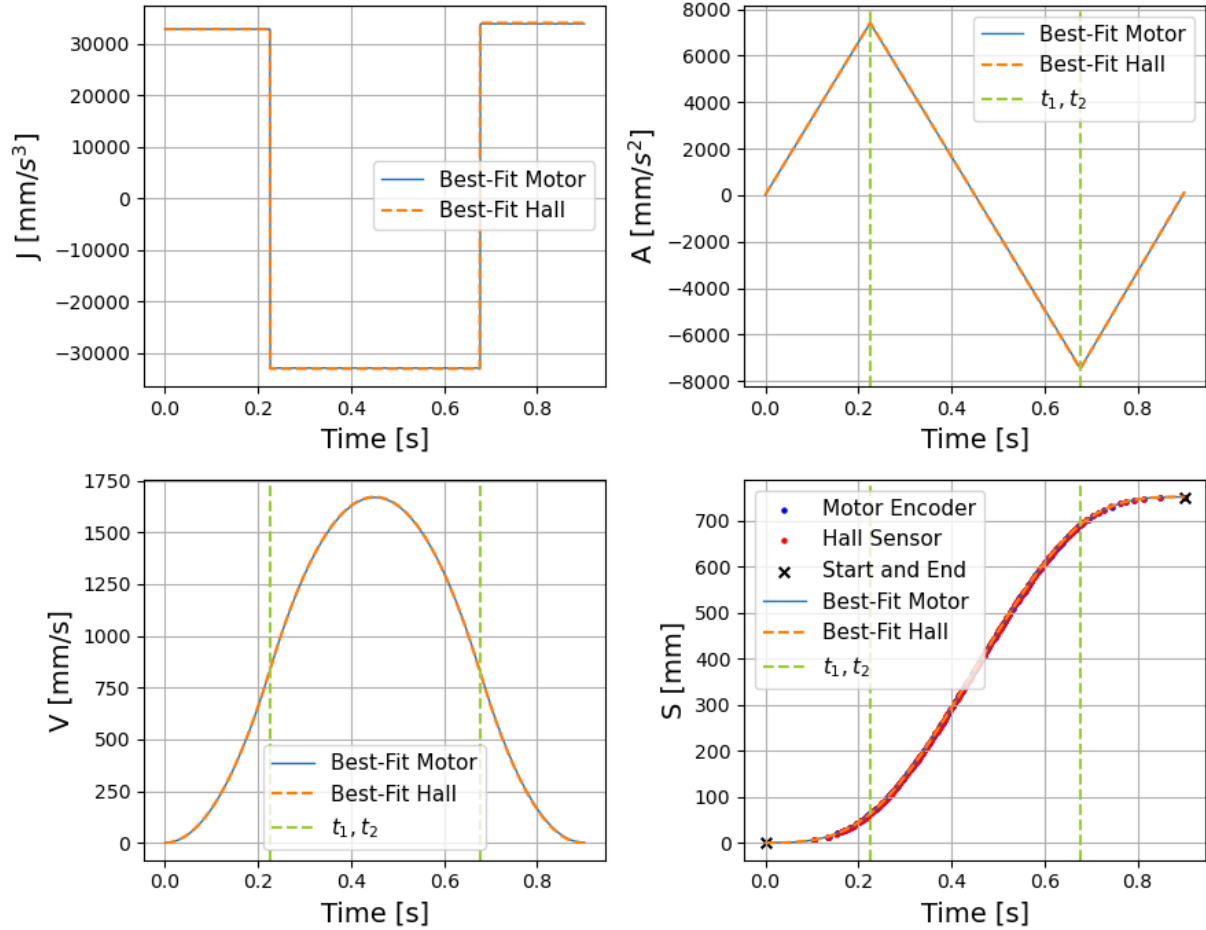


FIGURE 1: An example of a shutter motion profile. The plots show fitted jerk, acceleration, velocity and displacement respectively, of the MINUSX-side blade open/PLUSX-side blade close. Motor encoder and Hall sensor measurements of the profile are also shown in the last panel.

match a model profile that starts at 0. Notice that in the fitting, it is applied to the normalized time stamps,

$$t \rightarrow t - t_0, \quad (4)$$

but it is later scaled back to the unit of seconds and reported in the fitting results.

In summary, the three jerks model has 6 parameters:

t_0 : Starting time of motion,

t_1, t_2 : Turning points for jerk and acceleration,

j_0, j_1, j_2 : The jerk for three intervals.

With patience, one can work out the math of the model:

$$j(t) = \begin{cases} j_0, & 0 < t < t_1 \\ j_1, & t_1 < t < t_2 \\ j_2, & t_2 < t < T, \end{cases} \quad (5)$$

$$a(t) = \begin{cases} j_0 t, & 0 < t < t_1 \\ a_1 + j_1(t - t_1), & t_1 < t < t_2 \\ a_2 + j_2(t - t_2), & t_2 < t < T, \end{cases} \quad (6)$$

where $a_1 = a(t_1) = j_0 t_1$, and $a_2 = a(t_2) = a_1 + j_1(t_2 - t_1) = j_0 t_1 + j_1(t_2 - t_1)$. Re-organizing the terms,

$$a(t) = \begin{cases} j_0 t, & 0 < t < t_1 \\ A_1 + j_1 t, & t_1 < t < t_2 \\ A_2 + j_2 t, & t_2 < t < T, \end{cases} \quad (7)$$

where

$$\begin{aligned} A_1 &= a_1 - j_1 t_1 = (j_0 - j_1) t_1, \\ A_2 &= a_2 - j_2 t_2 = (j_0 - j_1) t_1 + (j_1 - j_2) t_2. \end{aligned} \quad (8)$$

Integrating for velocity:

$$v(t) = \begin{cases} \frac{1}{2}j_0t^2, & 0 < t < t_1 \\ \frac{1}{2}j_1t^2 + A_1t + V_1, & t_1 < t < t_2 \\ \frac{1}{2}j_2t^2 + A_2t + V_2, & t_2 < t < T, \end{cases} \quad (9)$$

where

$$\begin{aligned} V_1 &= \frac{1}{2}(j_0 - j_1)t_1^2 - A_1t_1, \\ V_2 &= \frac{1}{2}(j_1 - j_2)t_2^2 + (A_1 - A_2)t_2 + V_1. \end{aligned} \quad (10)$$

Finally,

$$s(t) = \begin{cases} \frac{1}{6}j_0t^3, & 0 < t < t_1 \\ \frac{1}{6}j_1t^3 + \frac{1}{2}A_1t^2 + V_1t + S_1, & t_1 < t < t_2 \\ \frac{1}{6}j_2t^3 + \frac{1}{2}A_2t^2 + V_2t + S_2, & t_2 < t < T, \end{cases} \quad (11)$$

with

$$\begin{aligned} S_1 &= \frac{1}{6}(j_0 - j_1)t_1^3 - \frac{1}{2}A_1t_1^2 - V_1t_1, \\ S_2 &= \frac{1}{6}(j_1 - j_2)t_2^3 + \frac{1}{2}(A_1 - A_2)t_2^2 + (V_1 - V_2)t_2 + S_1. \end{aligned} \quad (12)$$

4 Plotting Model with Data

The fitted parameters are scaled back to physical units and reported in the shutter motion files. Only 5 parameters (except t_0) are needed to calculate the model prediction. To compare the model with data, subtract both `startTime` and t_0 from the time stamps. The model position also needs to subtract `startPosition` if moving towards the positive direction (`startPosition < endPosition`), or be subtracted by `startPosition` otherwise.

5 Finding Midpoint of Motion

Two estimates of the mid-point of motion are calculated. One is the time when the velocity is at its maximum (i.e. when the acceleration is zero). It is found by solving

$$a = A_1 + j_1t = 0 \quad (13)$$

for t . Notice that the solution is in model time, i.e. the model start time t_0 needs to be added to the solution for a meaningful comparison. (However, t_0 is usually smaller than 1e-3 seconds, so it doesn't matter really).

The other estimate of midpoint is the time when the position is at $S_{\text{mid}} = (\text{startPosition} + \text{endPosition})/2$. It is found by solving the cubic equation

$$\frac{1}{6}j_1t^3 + \frac{1}{2}A_1t^2 + V_1t + S_1 - S_{\text{mid}} = 0 \quad (14)$$

with a simple Newton iteration. Again t_0 needs to be added to the solution to compare with the raw timestamps data.

The code for fitting the 6-parameter model and finding the midpoint is online.

A References

B Acronyms

Acronym	Description
CTN	Camera Technical Note
ISO	Information Security Officer
MJD	Modified Julian Date (to be avoided; see also JD)
OBS	Organisation Breakdown Structure
TAI	International Atomic Time