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Camera Shutter Motion Analysis

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CTN-002

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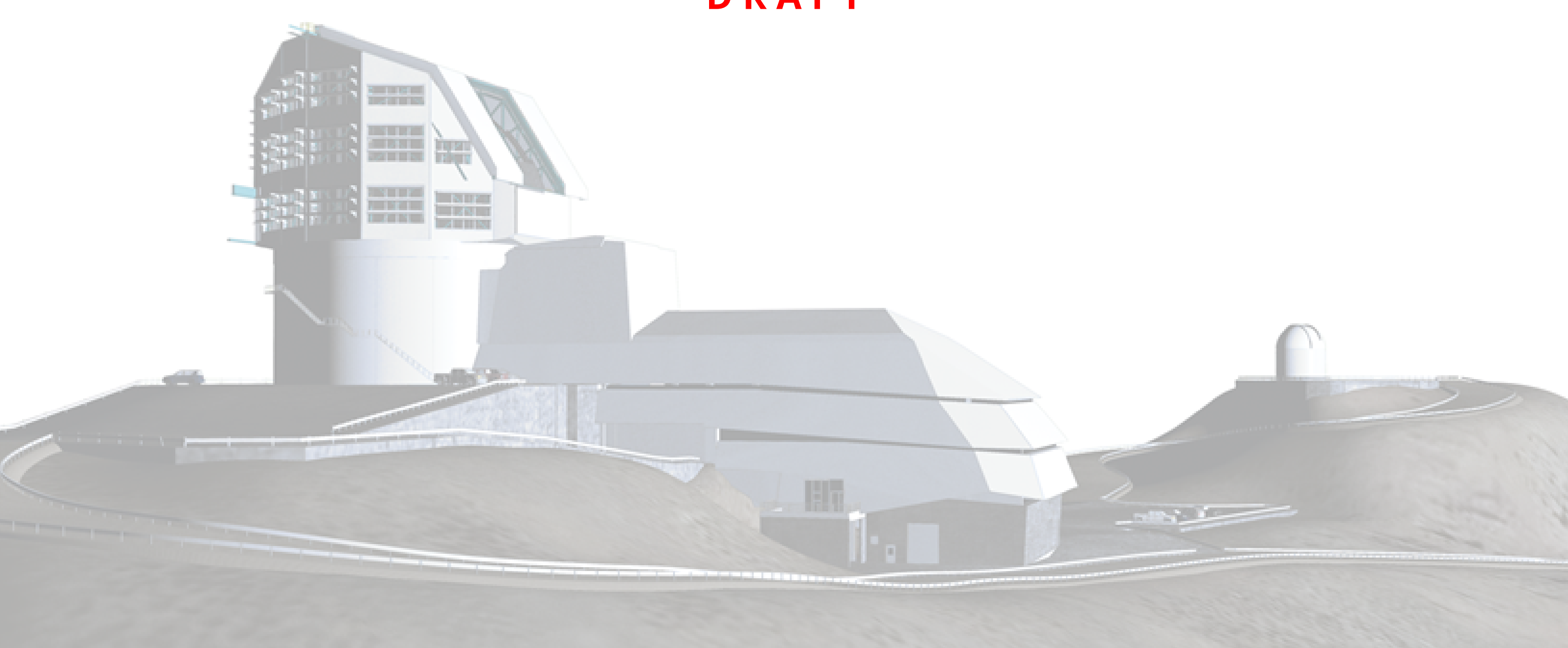

Abstract

Profile fitting for camera shutter trajectory and timing analysis.

Change Record

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

Document source location: `https://github.com/lsst/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 positition.

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 startTime to get a relative timing,

$$t \to t - \text{starTime}, \tag{1}$$

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:

$$t \to t/\text{actionDuration}. \tag{2}$$

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

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

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 ~ 0mm from the PLUSX side and goes to ~ 750mm 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 positve-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

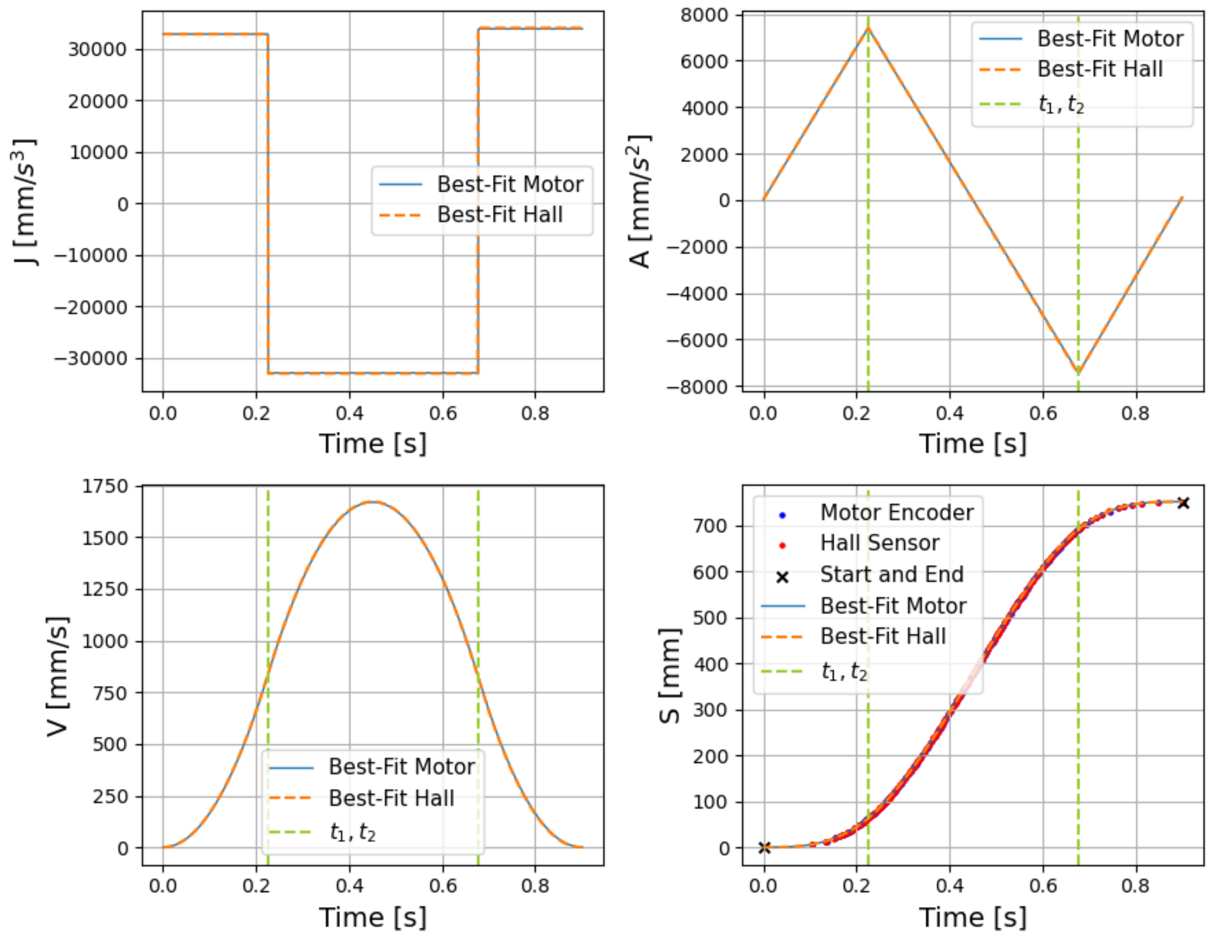

FIGURE 1: An example of a shutter motion profile. The plots show fitted jerk, acceleration, velocity and displacement respectively, of the MINUSX-side blade open/PLUSX-side blade close. Motor encoder and Hall sensor measurements of the profile are also shown in the last panel.

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

$$t \to t - t_0, \tag{4}$$

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:

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

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

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,

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

where

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

Integrating for velocity:

$$v(t) = \begin{cases} \frac{1}{2} j_0 t^2, & 0 < t < t_1 \\ \frac{1}{2} j_1 t^2 + A_1 t + V_1, & t_1 < t < t_2 \\ \frac{1}{2} j_2 t^2 + A_2 t + V_2, & t_2 < t < T, \end{cases} \tag{9}$$

where

$$\begin{aligned} V_1 &= \frac{1}{2}(j_0 - j_1) t_1^2 - A_1 t_1, \\ V_2 &= \frac{1}{2}(j_1 - j_2) t_2^2 + (A_1 - A_2) t_2 + V1. \end{aligned} \tag{10}$$

Finally,

$$s(t) = \begin{cases} \frac{1}{6} j_0 t^3, & 0 < t < t_1 \\ \frac{1}{6} j_1 t^3 + \frac{1}{2} A_1 t^2 + V_1 t + S_1, & t_1 < t < t_2 \\ \frac{1}{6} j_2 t^3 + \frac{1}{2} A_2 t^2 + V_2 t + S_2, & t_2 < t < T, \end{cases} \tag{11}$$

with

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

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

$$a = A_1 + j_1 t = 0 \tag{13}$$

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_{mid} = (startPosition + endPosition)/2. It is found by solving the cubic equation

$$\frac{1}{6}j_1 t^3 + \frac{1}{2}A_1 t^2 + V_1 t + S_1 - S_{\text{mid}} = 0 \tag{14}$$

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 finiding 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