Lunar Gate Prediction and Placement

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1 The Goal

We want to position the turn-on of the lunar APD/TDC gate with enough control that we:

- know what TDC value is going to result from lunar photons;
- set the mean position of the lunar TDC value at a prescribed target value;
- control the spread of TDC values to be contained within a 20 ns TDC range;
- match the lunar TDC range to that of the fiducial photons.

To do so requires knowledge of various system timing delays, an accurate lunar range prediction, and a measure of when the laser actually fired. In this document, we assume the timing delay model is well-developed elsewhere, and proceed to establish the framework for positioning the gate.

2 The Timeline

A crude timeline is represented in Figure 1. The laser fires, reaching the fast-photdiode (FPD) at about the same time it reaches the telescope focus (near T/R mirror). Roughly 20 ns later, the Ortec 9327 unit produces a NIM timing signal, which is cable-delayed approximately 150 ns, followed by a 5 ns conversion to an ECL pulse that arrives at the TDC as a START pulse. Meanwhile, the laser propagates through the telescope, emerging from the primary mirror and crossing the telescope mount's axis intersection about 42 ns after passing through focus. It is from this point that the lunar distance prediction is based. A time, T, later, the laser pulse returns to the reference location at the intersection of axes. Approximately 48 ns later, the laser light reaches the APD, and about 20 ns after this an ECL START pulse reaches the TDC.

The points in Figure 1 that matter insofar as gate position is concerned are the points at which the ECL signals reach the TDC. Therefore, we define $\Delta t_{\rm FPD}$ as the time interval between the laser's reaching the axis intersection and the receipt of the cable-delayed fast-photodiode START signal at the TDC. Likewise, $\Delta t_{\rm APD}$ is the time interval between the arrival of the lunar laser pulse at the axis intersection and the receipt of the lunar photon START pulse at the TDC. $\Delta t_{\rm FPD} \approx 133$ ns, and $\Delta t_{\rm APD} \approx 68$ ns.

After the laser is fired, we will gather the time registered on the TDC corresponding to the fast-photodiode, $\rm TDC_{FPD}$. If $t_{\rm FPD}$ is the absolute time of this event, then we know that the lunar photons will register as TDC

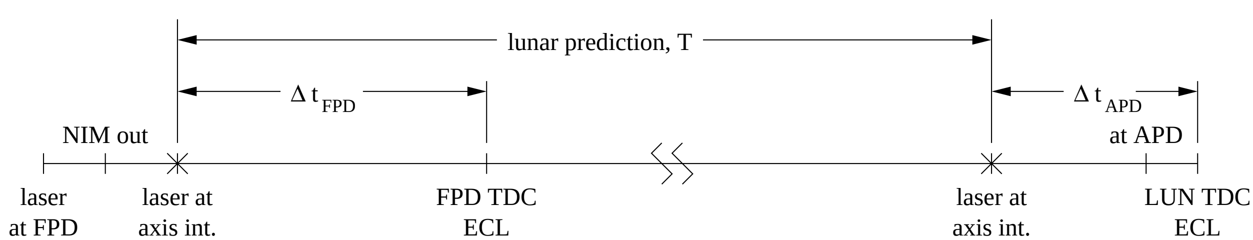

Figure 1: Rough timeline of significant events. The FPD is the fast photodiode.

STARTs at time $t_{\rm LUN} = t_{\rm FPD} + T - \Delta t_{\rm FPD} + \Delta t_{\rm APD}$, where T is the predicted round-trip travel time to and from the axis intersection. We define $\Delta t \equiv \Delta t_{\rm APD} - \Delta t_{\rm FPD}$ so that the reported lunar TDC START arrives a time $T + \Delta t$ after the FPD START. We call Δt the parameter `dskew` in the `housctl` program. The appropriate value for Δt is approximately -65 ns.

3 Rough Gate Position

After the fiducial gate closes, we grab the free-running counter (FRC) value latched at the close of the gate. In an ideal world (with infinite clock resolution), we would position the lunar gate so that it closed at a time $T + \Delta t$ after the fiducial gate closed. In this case, the TDC interval measured for the lunar events would precisely match the TDC interval measured for the fast-photodiode: $\rm TDC_{LUN} = TDC_{FPD}$. But the gate may only be placed to 20 ns precision based on the ACM's 50 MHz system clock. Allowing this unavoidable range, we *could* take the integer part of the calculated FRC delay and go from there.

The floating-point version of the new FRC value is:

$$\mathrm{NFRC} = \mathrm{FRC} + \frac{T + \Delta t - G}{20\,\mathrm{ns}} - 1,$$

where G is the gate width in nanoseconds, the adjusted prediction $T + \Delta t$ is expressed in nanoseconds, and the -1 accounts for the unavoidable cycle delay in producing a gate out of the ACM. The gate width must be subtracted because the old FRC value is an end-of -gate value, and we need to know when to turn *on* the new gate.

Now if we take the integer part of this new FRC value: $\rm NFRC_{IP}$, we can expect the TDC interval measured for lunar photons to be $\rm TDC_{LUN} = TDC_{FPD} - 800 \times NFRC_{FP}$. Here, we use the approximation that the 20 ns range spanned by the possible values of the fractional part of NFRC will span 800 counts on the TDC (same as saying each bin is exaclty 25 ps). Note that a larger value of the fractional part means we are turning the gate on *earlier* by only using the integer part. So the STOP pulse (associated with the end of the gate) comes earlier, resulting in a smaller TDC interval—as reflected by the negative sign in the above relation.

4 Fine-tuning the Gate Placement

The recipe outlined above allows one to catch lunar photons, and predict the resulting TDC value based on that of the fast-photodiode. But we can do better. We would like to control precisely the TDC range explored by the lunar photons. As it sits above, the fast-photodiode spans 20 ns on the TDC, and the fractional part of NFRC spans another 20 ns, so that the total range spans 40 ns. Let's pick a target TDC interval for lunar returns, and restrict the range to 20 ns centered on this target. If we call the target τ_c (in TDC units, or bins), then for each shot we can evaluate the fast-photodiode offset from the lunar target:

$$\delta_{\rm FPD} = \mathrm{TDC_{FPD}} - \tau_c.$$

The target value is ideally set to the mean TDC value reported by fiducial photons, as it is these to which we want to match the lunar measurements. A further idealization would have the fiducial photons reporting the same TDC time as does the fast-photodiode—which can be accomplished via appropriate cable delays. In this case, τ_c will also be the mean TDC value associated with the fast-photodiode.

Armed with this knowledge, we can prevent the randomness of the laser fire with respect to the 50 MHz clock from influencing the position of the return pulse relative to the 50 MHz clock. Noting that the value of τ_c refers to the *center* of the intended lunar distribution, we must adjust the NFRC by a value of $+\frac{1}{2}$ so that the fractional part will on average land back at zero. The new prescription for the new FRC value is:

$$\mathrm{NFRC} = \mathrm{FRC} + \frac{T + \Delta t - G}{20\,\mathrm{ns}} - \frac{\delta_{\rm FPD}}{800} - 1 + \frac{1}{2}.$$

Now if the integer part of this expression is used to set the lunar gate, the fast-photodiode offset is nullified and the fractional part will ensure that the mean TDC value for the lunar gates settles on τ_c. The sign of the $\delta_{\rm FPD}$ term is negative because if $\delta_{\rm FPD}$ is large, it means that the TDC value for the FPD is large, and therefore the FPD is earlier than normal (or conversely, the gate was late with respect to the laser fire). If the gate was late for the fiducial, this needs to be corrected by making the lunar gate a little earlier. Thus one wants to reduce the NFRC value.

We can now predict the value of the lunar TDC measurement:

$$\mathrm{TDC_{LUN}} = \tau_c - 800 \times (\mathrm{NFRC_{FP}} - 0.5).$$

Note that the prediction no longer depends explicitly on the fast-photodiode TDC value. But this is deceptive, because the fractional part of the NFRC certainly depends on δ_{FPD}. The lunar TDC values will now cluster around τ_c by design, spanning ± 400bins (± 10 ns) around this value.