Adam's Timing Notes

Adam Orin

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1 Introduction

Our goal is, given the free running counter (FRC) value that the fiducial fast-photodiode stop pulse leaves the ACM, what FRC value should we turn the gate on for the lunar return?

Here is how the prediction polynomial works. You feed it a time, in units of days, since some reference time τ_0 which is given. It calculates how long the laser light will take to go from the telescope's center of rotation, to the desired reflector on the Moon, and back. The time we give it is the time that the TDC gets the ECL signal from the fast-photodiode. This is not the same time that the laser pulse is at the telescope's center. But in those few nenoseconds, the Moon will not move away much, and the polynomial gives the round trip time to within 10 ns.

In the following discussion, there are absolute times represented by a T, and relative times, represented by a ΔT. The absolute time of an event is the time after the laser light hits the fast-photodiode that the event occurs. The relative times are the time between two events.

2 Analytics

2.1 When to open the gate

Let $t = 0$ be the time that the laser light hits our fast-photodiode. The fast-photodiode signal feeds into the 9327 Discriminator. The 9327 outputs a TTL signal through a short cable to the ACM, which triggers the ACM to open the gate for the fiducial return. The 9327 also sends a NIM signal through a long cable to the Booster board, which is converted to an ECL signal, which is fed into one of the TDC's 16 inputs. Let T_{FPDECL} be the time that the ECL signal from the fast-photodiode reaches the TDC. A few tens of nanosecs later, the ACM sends a stop pulse to the TDC, at time $T_{FIDSTOPACM}$. And a couple nanosecs later, the TDC receives the ACM's stop pulse, at $T_{FIDSTOP} \equiv T_{FIDSTOPACM} + \Delta T_{DLY}$. ΔT_{DLY} is the amount of time it takes the stop pulse to get from the ACM to Booster, then to the TDC.

At the same time that the laser light is hitting the fast-photodiode, it is roughly at the ?focus of our optical system?. Let's call the time that the laser reaches the focus T_{FOCUS}. As stated, $T_{FOCUS} \approx 0$, to within a nanosecond. The laser pulse has to travel through our optics, out the quaternary, off the tertiary, up to the secondary, down to the primary, and up to the center of the telescope. Let us call the time that it takes the takes the laser light to get from the focus to the center of the telescope ΔT_{SCOPE}.

We feed $T_{FIDSTOPACM}$ into the prediction polynomial, and the polynomial tells us the laser's trip round trip time from the telescope's center and back. Let's call this time ΔT_{PRED}. We know $\Delta T_{PRED} \approx 2.5$ sec.

Now that the laser light is well on it's way back, we turn on the gate that enables our APD detectors. Let us call the time that the ACM turns the gate on $T_{LUNGATE}$.

The laser pulse has returned to the telescope, and travels back through to the focus. Now it has to go through the receiver to the APDs. Let us call the time it takes the laser light to go from the focus to the APDs $\Delta T_{RECEIVER}$.

If we add the bits together, the laser light will reach the APDs at time

$$T_{FOCUS} + \Delta T_{SCOPE} + \Delta T_{PRED} + \Delta T_{SCOPE} + \Delta T_{RECEIVER} \quad .$$

Then, the APDs avalanche, an ECL signal is generated, and the ECL signal travels up the twisted pair ribbon cable to the TDC. Let us call the relative time between the laser light hitting the APDs to the ECL reaching the TDC ΔT_{APD}. And let us call the absolute time that the lunar ECL signal reaches the TDC T_{LUNECL}. We know that the time the lunar ECL signal reaches the TDC is the time the laser light takes to get to the APDs, plus the time it takes for the signal to go from the APDs to the TDC:

$$T_{LUNECL} = [T_{FOCUS} + 2\Delta T_{SCOPE} + \Delta T_{PRED} + \Delta T_{RECEIVER}] + \Delta T_{APD}$$

Finally, the TDC gets a stop pulse from the ACM/Booster. This happens at a time

$$T_{LUNSTOP} \equiv T_{LUNGATE} + GW + \Delta T_{DLY}$$

where ΔT_{DLY} is again the amount of time it takes the stop pulse to get from the ACM to Booster, then to the TDC. And GW is the **programmed** width of the gate.

So, for the fast-photodiode, the TDC will read out a time $T_{FIDSTOP} - T_{FPDECL}$. Our goal is to open the lunar gate at the right time to make the TDC read out the same time from the lunar photons. The time that the TDC will read out from the lunar photons is $T_{LUNSTOP} - T_{LUNECL}$.

We want the TDC time read out on the fiducial to be the same as the TDC time read out by the lunar.

$$\begin{aligned} T_{FIDSTOP} - T_{FPDECL} &= T_{LUNSTOP} - T_{LUNECL} \\ &= [T_{LUNGATE} + GW + \Delta T_{DLY}] \\ &\quad - [T_{FOCUS} + 2\Delta T_{SCOPE} + \Delta T_{PRED} + \Delta T_{RECEIVER} + \Delta T_{APD}] \\ &= T_{LUNGATE} + GW + \Delta T_{DLY} - T_{FOCUS} - 2\Delta T_{SCOPE} \\ &\quad - \Delta T_{PRED} - \Delta T_{RECEIVER} - \Delta T_{APD} \end{aligned}$$

so

$$\begin{aligned} T_{LUNGATE} &= T_{FIDSTOP} - T_{FPDECL} - GW - \Delta T_{DLY} + T_{FOCUS} \\ &\quad + 2\Delta T_{SCOPE} + \Delta T_{PRED} + \Delta T_{RECEIVER} + \Delta T_{APD} \end{aligned}$$

We are going to tell the ACM how many FRC clock ticks after $T_{FIDSTOPACM}$ to turn the gate on. That is going to be

$$\begin{aligned} T_{LUNGATE} - T_{FIDSTOPACM} &= -T_{FPDECL} - GW + T_{FOCUS} \\ &\quad +2\Delta T_{SCOPE} + \Delta T_{PRED} + \Delta T_{RECEIVER} + \Delta T_{APD} \end{aligned}$$

Let's list the important variables above and remind ourselves what they represent:

- $t = 0$: Our reference event is when the laser pulse reaches the fast-photodiode.
- $T_{LUNGATE}$: This is the absolute time that the ACM sends the gate to the APDs for the lunar return.
- $T_{FIDSTOPACM}$: This is the absolute time that the ACM sends the stop pulse to the TDC for the fiducial return. Houston Control records this time, as a FRC value. It then figures out how many FRC pulses after this to open the gate for the lunar return.
- T_{FPDECL}: This is the absolute time that the ECL signal from the fast-photodiode reaches the TDC. If it takes a long time for the fast-photodiode signal to reach the TDC, then $T_{FIDSTOPACM}$ will need to be bigger to come after the T_{FPDECL}. Which means that we need to open the gate earlier, relative to $T_{FIDSTOPACM}$ to catch the lunar return. Hence the minus sign.
- GW: This is the gate width. Since the stop pulse has to get to the TDC less than 100ns after the ECL signal from the APDs, we can't move the falling edge of the gate. The falling edge of the gate is pinned down in time, so if the gate width in increased, the rising edge has to come earlier. Hence the minus sign.
- T_{FOCUS}: This is the absolute time that the laser pulse reaches the focus of our system before heading to the Moon. If it takes a long time for the light to get here, then the light will return from the Moon later, and we will have to open te gate later. Hence the plus sign.
- ΔT_{SCOPE}: This is the relative time it takes the light to get from the focus to the center of the telescope. The center of the telescope is the center of rotation. If it takes the laser light a long time to leave the telescope, then the light will return from the Moon later, and we will have to open the gate later. Hence the plus sign. And the laser has to travel through the telscope twice, once on the way out and once on the way in. Hence the prefactor of 2.
- ΔT_{PRED}: This is the relative time it takes the light to go from the center of the telescope, to the Moon, and come back to the center of the telescope. Our prediction polynomial gives us this number to within 10ns. Of course, if the Moon was further away, we would have to wait longer to open the gate. Hence the plus sign.

- $\Delta T_{RECEIVER}$: This is the relative time it takes the returning laser light to get from the focus of our system to the APDs. Again, if it took a long time for the light to get to the APDs, we would open the gate later. Hence the plus sign.

- ΔT_{APD}: This is the relative time it takes the APDs to avalanche, for the avalanche to create an ECL signal, and for that signal to reach the TDC. If it takes a long time for the signal to reach the TDC, then from the TDC's point of view, the laser light came in later, and we open the gate later. Hence the plus sign.

2.2 Minimum gate width

Now, the gate width has to be large enough that the APDs are ready to accept light when the laser pulse arrives from the Moon. Let $T_{APDRDY} = T_{LUNGATE} + \Delta T_{APDRDY}$ be the time that the APDs are ready to accept lunar photons. And ΔT_{APDRDY} is the time between the gate signal leaving the ACM, and the APDs being ready to accept photons. The APDs have to be ready earlier than the lunar return light reaches the APDs:

$$T_{APDRDY} < T_{FOCUS} + 2\Delta T_{SCOPE} + \Delta T_{PRED} + \Delta T_{RECEIVER} \qquad .$$

If we sub in for T_{APDRDY} then $T_{LUNGATE}$, we find

$$GW > \Delta T_{APDRDY} + (T_{FIDSTOP} - T_{FPDECL}) - \Delta T_{DLY} + \Delta T_{APD} \qquad .$$

$(T_{FIDSTOP} - T_{FPDECL})$ is the time that the TDC reports for the fast photodiode's fiducial. This is less than 100 ns, so we can just use 100 ns here.

We also need to add in 12 ns, becuase the TDC can only report start-stop pairs separated by 12 ns or more.

2.3 Gate in relation to laser

An interesting time is the relative time between the ACM sending out the fiducial gate, and the laser light hitting the APDs:

$$B16 - A23$$

Another interesting time is the relative time between the ACM sending out the lunar gate, and the laser light hitting the APDs:

$$\begin{aligned} & T_{LUNGTE} - [T_{FOCUS} + 2\Delta T_{SCOPE} + \Delta T_{PRED} + \Delta T_{RECEIVER}] \\ = \; & (T_{FIDSTOP} - T_{FPDECL}) - \Delta T_{DLY} - GW + \Delta T_{APD} \end{aligned}$$

3 Numerics

Let's get some numbers for these things:

	Delay (ns)	DESC	Delay
A		**Time A**	
A1	0	Laser pulse hits photodiode	
A2	A1+5	Photodiode signal reaches 9327 (guess) MEAS	cable
B		**Time B - Photodiode signal reaches 9327**	

	Delay (ns)	DESC	Delay
B		**Time B - Photodiode signal reaches 9327**	
B1	B + 4	9327 NIM output (measured in lab, 050912)	logic
B2	B1 + 149	NIM start pulse reaches Booster (measured?) MEAS	cable
B3	B2 + 6	ECL start leaves Booster (guess) MEAS	logic
B4	B3 + 0	Start pulse reaches TDC (guess) MEAS	cable

	Delay (ns)	DESC	Delay
B		**Time B - Photodiode signal reaches 9327**	
B11	B + 16	9327 TTL output HIGH (measured in lab, 050912)	logic
B12	B11 + 7	9327 TTL signal reaches PIN at ACM (est) MEAS	cable
B13	B12 + (14,34)	CAL_ST output HIGH on ACM (measured in lab, 0509)	logic
B14	B13 + 4	OPEN outout HIGH on ACM (measured in lab, 0509)	logic
B15	B13 + 12	GTE output HIGH on ACM for fiducial (measured in lab, 0509)	logic
B16	B13 + 17	APD output HIGH on ACM for fiducial (measured in lab, 0509)	logic
B17	B16 + 13	Fiducial gate reaches APD motherboard (estimate) MEAS	cable
B18	B17 + 45	First possible ECL output from APDs (rough meas)	logic
B19, A23	B18 + X	APDs avalanche from fiducial laser light	
B20	B19 + 6	Fiducial ECL start pulse leaves APD motherboard to TDC (guess) MEAS	logic
B21	B20 + 13	Fiducial ECL start reaches TDC (estimate) MEAS	cable
B22	B13 + FGW-3	STOP output HIGH on ACM for fiducial, record FRC value as reference time for lunar return (measured in lab, 0509)	logic
B23	B22 + 0	Fiducial stop pulse reaches Booster (guess) MEAS	cable
B24	B23 + 10	Fiducial stop pulse leaves Booster (guess) MEAS	logic
B25	B24 + 0	Fiducial stop pulse reaches TDC from Booster (guess) MEAS	cable

	Delay (ns)	DESC	Delay
A		**Time A**	
A11	0	Laser pulse at optics focus	
A12	A11 + 42.4	Laser pulse at telescope center, on way out (measured)	
A21	A12 + 30.3	Fiducial laser pulse at telescope center, after hitting corner cube (measured)	
A22	A21 + 42.4	Fiducial laser pulse at optics focus, on way in (measured)	
A23	A22 + 4	Fiducial laser pulse at APDs (estimate)	

	Delay (ns)	DESC	Delay
A		**Time A**	
A11	0	Laser pulse at optics focus	
A12	A11 + 42.4	Laser pulse at telescope center, on way out (measured)	
A13	A12 + PRED	Laser pulse at telescope center, after travelling to Moon	
A14	+ 42.4	Lunar laser pulse at focus	
A15	+ 4	Lunar laser pulse at APDs (estimate)	

	Delay (ns)	DESC	Delay
C		**Time C**	
C1	0	ACM FRC reaches programmed value	
C2	C1+?	LUN_ST output HIGH on ACM MEAS	logic
C3	C2+0	OPEN outout HIGH on ACM (measured in lab, 0509)	logic
C4	C2+8	GTE output HIGH on ACM for lunar (measured in lab, 0509)	logic
C5	C2+12	APD output HIGH on ACM for lunar (measured in lab, 0509)	logic
C6	C5+13	Lunar gate reaches APD motherboard (estimate) MEAS	cable
C7	C6+45	First possible ECL output from APDs (rough meas)	logic
C8, A15	C7+X	APDs avalanche from lunar laser light	
C9	C8+6	Lunar ECL start pulse leaves APD motherboard to TDC (guess) MEAS	logic
C10	C9+13	Lunar ECL start reaches TDC (estimate) MEAS	cable
C11	C2+LGW-15	STOP output HIGH on ACM for lunar (measured in lab, 0509) MEAS	logic
C12	C11+0	Lunar stop pulse reaches Booster (guess) MEAS	cable
C13	C12+10	Lunar stop pulse leaves Booster (guess) MEAS	logic
C14	C13+0	Lunar stop pulse reaches TDC from Booster (guess) MEAS	cable

$$T_{FPDECL} = \Delta A1 + \Delta A2 + \Delta B1 + \Delta B2 + \Delta B3 + \Delta B4 = 164 \text{ ns}$$

$$\Delta T_{SCOPE} = \Delta A12 = \Delta A22 = \Delta A14 = 42.4 \text{ ns}$$

$$\Delta T_{RECEIVER} = \Delta A23 = \Delta A15 = 4 \text{ ns}$$

$$\Delta T_{APD} = \Delta B20 + \Delta B21 = \Delta C9 + \Delta C10 = 19 \text{ ns}$$

$$\Delta T_{APDRDY} = \Delta C5 + \Delta C6 + \Delta C7 = 70 \text{ ns}$$

$$\Delta T_{DLY} = \Delta B23 + \Delta B24 + \Delta B25 = 10 \text{ ns}$$

Time between [ACM reading the FRC at the fiducial stop] and [ACM sending the gate for the lunar return]:

$$T_{LUNGATE} - T_{FIDSTOPACM} \quad = \quad -56 \text{ ns} - GW + \Delta T_{PRED}$$

$$\begin{aligned}
B25 - B4 = C14 - C10 \\
(\Delta A1 + \Delta A2 + \Delta B11 + \Delta B12 + \Delta B13 + \Delta B22 + \Delta B23 + \Delta B24 + \Delta B25) \\
-(\Delta A1 + \Delta A2 + \Delta B1 + \Delta B2 + \Delta B3 + \Delta B4) \\
= \\
(C1 + \Delta C2 + \Delta C11 + \Delta C12 + \Delta C13 + \Delta C14) \\
-(A15 + \Delta C9 + \Delta C10) \\
C1 = \\
(\Delta B11 + \Delta B12 + \Delta B13 + \Delta B22 + \Delta B23 + \Delta B24 + \Delta B25) \\
-(\Delta B1 + \Delta B2 + \Delta B3 + \Delta B4) \\
-(\Delta C2 + \Delta C11 + \Delta C12 + \Delta C13 + \Delta C14) \\
+((\Delta A11 + \Delta A12 + \Delta A13 + \Delta A14 + \Delta A15) + \Delta C9 + \Delta C10) \\
C1 = \\
(16 + 7 + (14, 34) + (FGW - 3) + 0 + 10 + 0) \\
-(4 + 149 + 6 + 0) \\
-(0 + (LGW - 15) + 0 + 10 + 0) \\
+((0 + 42.4 + PRED + 42.4 + 4) + 6 + 13) \\
C1 = -16 + (14, 34) + PRED + FGW - LGW \\
\mathbf{C1 - B22 = -LGW + PRED - 41}
\end{aligned}$$

Minimum gate width required:

$$GW \quad > \quad \text{ns}$$

For a 180 ns gate, the relative time between the ACM sending out the fiducial gate, and the laser light hitting the APDs:

$$B16 - A23 \quad = \quad \text{ns}$$

For a 180 ns gate, the time between [ACM sending the lunar gate] and [laser light hitting the APDs]:

$$= \text{ ns}$$