

# Synchronization of the CMS Tracker

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## *Abstract*

An overview of the synchronization procedure for the CMS Tracker is given. The entire readout system of the Tracker, from the front-end APV readout chips to the back-end FEDs can be synchronized to  $\sim 1$ ns, in a standalone mode, during commissioning. The procedure is based on measuring and compensating for the relative delays at the FED between the arrival of APV synchronization pulses transmitted over the analogue optical links. After correction for the optical link fibre-lengths the Tracker can be made fully synchronous. A correction for the time of flight of particles and then a sweep of the phase adjustment of the clock to the Tracker will achieve absolute synchronization of the Tracker with the LHC collisions. Some simple checks allow verification of the coarse and fine timing settings, as well as monitoring of the Tracker synchronization during Physics running.

## I. INTRODUCTION

The CMS Silicon Strip Tracker[1] (SST) combined with the CMS Pixel system, aims to reconstruct and measure all charged particle tracks passing through the Tracker volume from a given collision event, as well as measure accurately the primary collision vertex and secondary vertices, where these charged tracks originated. The SST consists of an unprecedented  $210\text{m}^2$  of silicon, 10 million microstrip channels in total, instrumenting a volume of  $25\text{m}^3$ . The microstrips are laid out on 25000 silicon sensors, mounted on modules that are arranged in concentric layers in the barrel region and as a series of disks in the forward region. Depending upon the position in the Tracker, a single-sided module has either 512 or 768 microstrips that are read out by 4 or 6 APV[2] ASICs. Tracking data is transmitted from the APVs over 37000 analogue optical links[3] to 440 FEDs[4] located in the counting room.

To meet the performance objectives, the entire Tracker must be synchronized precisely with respect to the LHC beam collisions: the APVs at the front-end must be synchronized with respect to the incident particles and the readout system as a whole must also be properly synchronized in order to capture data from the correct bunch-crossing and to transmit this data with maximal signal-to-noise ratio.

Procedures for synchronization of the Tracker are described in this paper. Two steps are required, relative and then absolute synchronization: relative synchronization relates to the timing alignment of the front-end APVs with respect to each other and then the absolute synchronization is the timing

alignment of the Tracker with respect to the LHC beam collisions. Both relative and absolute synchronization procedures feature coarse and fine adjustments: coarse settings are aimed at synchronizing the system to the same 25ns LHC bunch-crossing, or 40MHz clock-cycle, whereas fine settings are related to sampling of the analogue data at the appropriate points in time, with a tolerance of only a few nanoseconds.

The procedures for synchronization have evolved from ideas that were inspired by work on detailed specifications and end-user requirements of Tracker system parts, in particular optical links and FEDs. Examples of specifications related closely to synchronization include the required precision of the optical link cable lengths and the definition of the timing features of the FEDs, such as the fine clock-skew and individual clock-skew adjustments on every optical input channel. The relative synchronization procedure has since been implemented in a basic, scalable form in recent Tracker beam-tests and system-tests[5]. The procedures presented here have therefore been validated on a small-scale, using prototype slices of the Tracker system, with readout and control hardware, software and protocols that were representative of the final system.

In the following sections we will outline first of all the factors influencing the synchronization of the Tracker, then the synchronization procedures will be described. Finally, we will also present some ideas for how to maintain synchronization during CMS physics running.

## II. CMS TRACKER SYSTEM AND TIMING ISSUES

The control and readout systems are illustrated schematically in Fig. 1 at a very basic level: one optical readout channel going into one FED, along with other front-end parts on the same control ring[6], driven by one FEC channel. Clock, trigger and resynchronization requests (and other TTC[7] signals) are sent to the Tracker partitions, and on to the FEDs and FECs using TTC optical links. The FECs pass on the TTC signals, along with slow control commands, to the various control rings, again using digital optical links[3], but these links are instead based closely on the Tracker analogue readout links.

Inside the Tracker volume, the timing and control signals are then received at digital opto-hybrids (DOH). Copper cables are then used to transmit these signals around a ring of CCU modules (CCUM)[6]. The CCUMs distribute the clock, trigger and control signals to the front-end hybrids (FEH) and

analogue optohybrids (AOH). On the AOH there are transmitters for either two or three optical links[3], depending upon the number of APVs present on the FEH. Time-multiplexed signals from pairs of neighbouring APVs are transmitted on each analogue link fibre channel to the FEDs. It should be noted that some control rings will include channels that are read out by more than one FED board.

The synchronization conditions required for the different parts of the system are summarized in Table 1 for both low-luminosity LHC start-up and high luminosity LHC running conditions. Coarse and fine timing settings, adjustable at the level of 25ns and 1ns respectively, are available at various points in the system. On the FEH there is a PLL and on the FECs and FEDs there are coarse and fine skew registers for the clock. The APVs also have a coarse (latency) setting that will be programmed as part of the synchronization.

Considering the timing issues affecting the Tracker, first at the coarse 25ns bunch-crossing level; the Tracker must be operated such that upon receiving a trigger, all the readout channels capture data from the same bunch-crossing and that this should be the bunch-crossing associated with the trigger. At the front-end, the APVs should therefore be synchronized relative to each other. Also, the correct latency setting between write and read pointers, set identically on all APVs, should provide synchronization between the Tracker and the rest of CMS. Finally, for the FEDs, it is a requirement that during Physics data-taking, when the FED is operating in the standard frame-finding mode[8], it should sample APV data-frames synchronously across the 96 input optical channels.

For the best signal/noise performance of the readout system, the particle signals must be sampled at their peak by the APV. This is illustrated in Fig 2, which shows the APV time-response in ‘peak’ and ‘deconvolution’ modes[2]. During low luminosity running, at LHC start-up, the APVs will be operated in peak-mode and the front-end synchronization can be relaxed to the level of 25ns. For high luminosity running, to avoid pile-up of signals in the Tracker, deconvolution-mode will be used. In this latter case, the APVs must be synchronized to within a few nanoseconds to the emission of signals from the silicon strips, since up to 4% of signal will be lost for every nanosecond that the APV is sampling away from the optimum position on the detector signal.

Also, the signals transmitted through the optical links must be sampled by the FEDs in the counting room at the appropriate time, after the signal has settled. This requirement on settling time is necessary due to the limited bandwidth of the electronics (<100MHz) used in the readout system and optical link. Therefore, regardless of LHC luminosity conditions and APV running mode, the FED sampling of the signal from the analogue optical links must always be well-synchronized to the optical link signal, ideally sampling at around 20 to 23ns after the start of a given signal pulse.

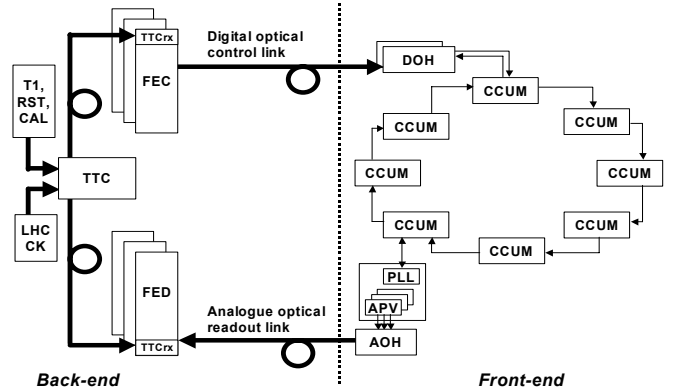


Figure 1: A slice of the Tracker readout and control system. Bold lines indicate optical links and fine lines indicate copper links.

Table 1: Synchronization requirements for the Tracker system. ‘Coarse’ requires synchronization to a given bunch crossing or clock cycle and ‘fine’ means that a smaller timing window is required.

Synchronization Requirement	Low luminosity	High luminosity
APV trigger latency	Coarse (25ns)	Coarse (25ns)
APV frame finding at FED	Coarse (25ns)	Coarse (25ns)
APV sampling of detector signals	Coarse (25ns) ‘peak’ mode	Fine (3ns) ‘deconvolution’
Optical link sampling at FED	Fine (3ns)	Fine (3ns)

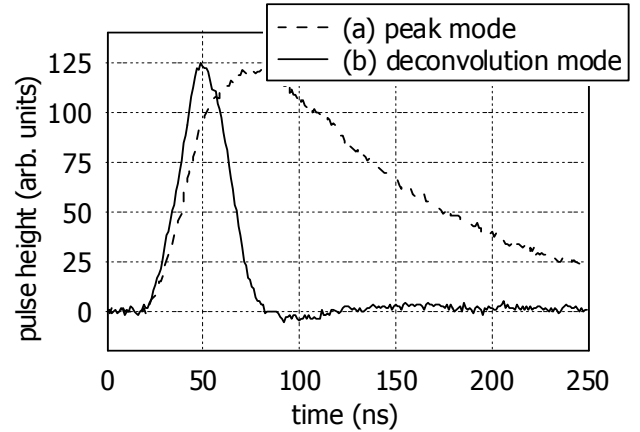


Figure 2: APV time response in (a) peak-mode and (b) deconvolution mode [2].

### III. SYNCHRONIZATION PROCEDURE

#### A. Relative synchronization

While receiving a clock signal, but in the absence of trigger signals, the APVs generate only synchronization pulses[2], otherwise known as ‘tick marks’ every 1.75 $\mu$ s, as shown in Fig, 3, which are transmitted by the analogue optical links to the FED. The ticks are output after a fixed delay

following the arrival of a resynchronization ('101') signal at the APV. The ticks can therefore be used as a precise probe of the relative timing differences between different APV chips around the Tracker system.

The ticks can be measured by triggering the FED in 'Scope' mode[8] with the raw data being read out via the VME interface. During the relative synchronization procedure the Tracker control, trigger and data acquisition activities will be local to the Tracker partition under test, running in a standalone mode, as opposed to using global Run Control, Trigger and DAQ resources.

By sweeping the fine skew settings in 1ns steps at the front-end PLLs, that distribute the clock to the APVs, the tick-marks can be reconstructed at the FED as in Fig. 4. The effect of the limited bandwidth of the readout chain is also clearly evident, illustrating that the optimum sampling point should occur close to the end of a given 25ns step.

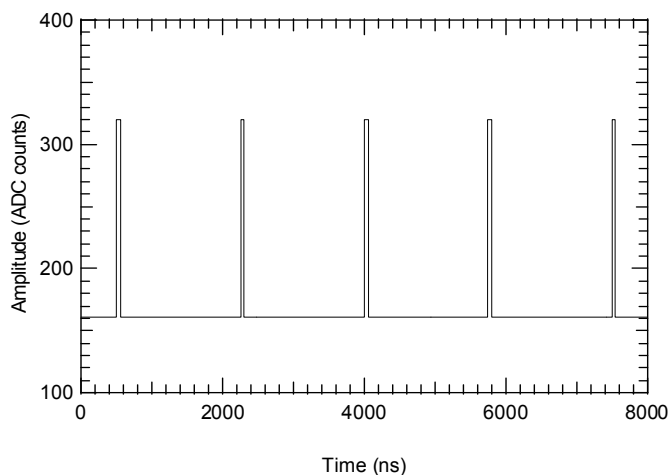


Fig. 3: APV tick mark output in the absence of triggers.

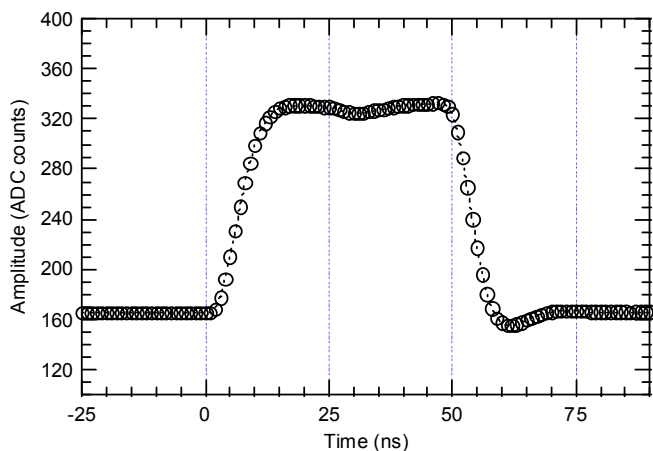


Fig. 4: APV tick signal shape reconstructed at the FED by sweeping the PLLs at the front-end hybrids in 1ns steps. The signals from two neighbouring APVs are multiplexed onto one analogue optical link channel.

For APVs in a given control ring, the relative delay between signals arriving at the FED is due to the difference in the analogue optical readout link fibre lengths added to the difference in the delay in the clock signals going around the control ring to the particular APVs.

The lengths of fibre in the analogue link will be known with a precision better than 20cm, therefore the delay contribution from the readout link can be subtracted with an accuracy of 1ns. This leaves only the delay due to the position of the APV in the given control ring which is the delay that must be compensated in order to bring APVs around a control ring into relative synchronization. Also, any differences in copper cable lengths between the APVs and analogue optohybrids (AOH) should also be included, though these should be very small. The programmable delays at the various front-end PLLs around each ring can then be set to compensate for the measured time-offsets for the APVs in each ring, bringing all the APVs in a given control ring into relative synchronization.

This procedure is followed for all the control rings in the Tracker separately (but most likely in parallel). The same method is then used to synchronize between the different rings throughout the whole Tracker. Only a small number of channels (at least 1) are required to be checked for each ring and compared with other rings, in order to measure the relative delays between APVs on different control rings. These delays are due to the variations in fibre lengths in the digital optical links transmitting TTC signals to the FECs, and then from the FECs to the control rings inside the Tracker.

Also, any difference in lengths of TTC links to the different FEDs will introduce an additional relative delay. Clearly the lengths of the TTC links to the FEDs need to be known for this procedure to work and a simple solution would be, for example, to insist on the same lengths of fibre bringing the clock and trigger to all FEDs.

The lengths of the TTC links to the FECs and then the optical links between the FECs and the front-end DOH do not however need to be known. These optical links are all upstream of the APVs in a given ring and their delay contributions are therefore already included when the tick arrival time is measured at the FED.

As in the case of an individual control ring, the relative timing between APVs on different rings can then be compensated by further adjustment of the delay registers at the front-end PLLs. All the APVs in the Tracker system can therefore be brought into relative synchronization by following the preceding method.

Finally, again based on a further sweep of the PLL fine skew at the front-end, the coarse and fine timing skew settings at the FED can also be adjusted to ensure that the FED samples the optical signals at the optimum position and that the data sent to the subsequent front-end FPGA in the FED (for subtract of pedestals, common-mode noise etc) is synchronous across all the input channels.

A time-of-flight correction can also be applied at the front-end PLLs to compensate for the expected delay in the arrival

of particles at the sensors, based on the distance of the sensors to the nominal interaction point at the centre of CMS. Again, any modification at the front-end PLLs must be mirrored with an identical adjustment of the FED sampling skew.

It is expected that these steps in the procedure will be fully automated, and will not take a significant amount of time to carry out. It should not be necessary to make the full synchronization often and the optimum skew settings for PLLs and FEDs will be stored in a database, the values of which can be downloaded to the Tracker hardware in preparation for a Physics run.

The current status of this procedure is that it has been implemented in the XDAQ framework[5] and, in a recent CMS Tracker beam-test, APVs on two control rings were synchronized using this method.

### B. Absolute synchronization

Once the LHC beam becomes available and collisions start, both the coarse and fine synchronization can be checked and refined, in order to bring the Tracker into absolute synchronization. This means that the Tracker is synchronized to the same bunch crossing with respect to the other parts of CMS, as well as to the LHC beam, and precisely synchronized with respect to the collisions occurring within the bunch crossings.

For the precise synchronization of the Tracker with the LHC collisions it will be necessary to reconstruct the pulse shapes generated in the APVs by particles passing through the silicon detectors. The phase of the clock to the APVs can be scanned, again using the front-end PLL skew settings, over a window of several bunch-crossings to build up the pulse shape. Track-reconstruction will be necessary to exclude hits and clusters generated by looping, or low-momentum secondary particle tracks, that might otherwise distort the timing and amplitude of the reconstructed pulse-shape. Then, based on the measured pulse-shapes, it should be possible to choose the optimum sampling point for the APV and re-adjust the PLL delay if necessary.

Based on the need for high statistics and tracking to reconstruct the pulse shapes it is foreseen to use the global TRIDAS resources for this final part of the synchronization.

## IV. MAINTAINING SYNCHRONIZATION

Synchronization errors are expected to occur during operation of the Tracker due to component failures, glitches, or SEU, etc. at various points in the system. Only a few simple examples are considered here. It should be noted that these problems are not necessarily expected to occur at a high frequency and they represent only some of the issues that have been addressed during the definition of the user requirements of various components, such as the FED[4].

At a global level, the synchronization of the Tracker with the rest of CMS can be checked by comparing the Tracker data with other sub-systems, e.g. ECAL, muons, to check for consistency between events recorded in each sub-detector.

At the level of individual FEDs, there will be several counters, such as trigger counter and bunch crossing counter that will allow the synchronization to be checked. It is expected that incorrect counter values for triggered events will be flagged in the DAQ system. Furthermore each FED will monitor the occupancy in triggered events, such that the occupancy distribution can be compared with the LHC bunch-intensity distribution[9].

At the front-end, the delay registers in the PLLs, or the APV latency, could become corrupted by SEU. This could create problems at either the coarse or fine synchronization level, depending upon which bits are upset. Changes in either the APV latency or PLL coarse delay will generate incorrect pipeline locations in the APV output data header. The pipeline addresses are detected in the APV signal headers by the FED and are compared, for every channel, with the address expected for a given triggered event. The expected pipeline address is transmitted to the FEDs from the APVE[10] via the TTC system.

APVs detected as being out of synchronization will be flagged by the FED, but no further action may be taken, depending upon the cumulative number of APVs that have been flagged as bad at that point. It remains to be decided whether the data on bad APV channels would be suppressed or not at the FED. A re-synchronization ('101') request will be made after the number of faulty APVs becomes sufficiently great. The APV and PLL clock-skew register settings could also be checked and re-written if these were the errors occurred.

Also, any problem in the coarse timing within a given FED, for example at the ADCs in the FED, would mean a loss of synchronization on one or more channels. Samples would be taken in the wrong clock cycle and an error would be detected as a APV pipeline location. Any bad channels will be flagged. As with the APVs, it is expected that a certain number of FED channels will be allowed to go out of synchronization before a reset request is issued to the FED(s).

Fine skew setting changes due to errors or other problems, at either the back-end or front-end, will be more difficult to detect. A small change of only a few nanoseconds will probably make little difference to the performance to a given readout chain, but larger changes would move the sampling point away from the optimal position. For the analogue readout system in the Tracker, this will result in a loss of signal/noise performance.

Loss of signal, or increase in noise could however be caused by many factors other than loss of synchronization. Understanding the importance of these and other related problems will require more work and more accumulated experience in beam tests and system tests in order to define efficient error handling procedures. However, on-line monitoring of the signal/noise performance will be very useful for monitoring the synchronization as well as for the calibration of the final readout system.

## V. SUMMARY AND CONCLUSION

The CMS Tracker must be very well synchronized, at the level of a few nanoseconds at both back-end and front-end in order to perform as expected during Physics running. This will be achieved in two steps: relative synchronization during commissioning and then absolute synchronization.

Relative synchronization is the timing-alignment of all the APVs in the Tracker relative to each other. A simple and robust procedure is proposed that relies only upon existing features of the Tracker components and the knowledge of fibre lengths to the FED. By measuring the arrival times of APV ticks at the FED and then subtracting the contributions from the different fibre lengths to the FEDs the timing skews between APVs can be measured and compensated. The same procedure is also used to synchronize the FEDs to the input data frames: optimizing the signal to noise of the analogue readout chain and ensuring that data is also arriving synchronously on the different input channels to the FED front-end FPGA.

Absolute synchronization of the Tracker with the rest of CMS and to the LHC beam collisions, should then be relatively straightforward, having made the relative synchronization. First a time of flight correction can be made. Secondly, by monitoring the occupancy of the FED, the Tracker can be aligned with the rest of CMS and to the correct LHC bunch-crossing. Finally some basic track-finding, along with measurement of signal/noise around the Tracker, will determine what fine adjustments, if any, of the timing at the front-end need to be made.

Loss of synchronization will be detectable throughout the system during commissioning and during Physics data taking. For problems at the front-end, the FED will be able to flag individual APVs that are out-of synch. The occupancy of the FED will be monitored to check synchronization using the known LHC bunch-structure and the FED output data will include bunch-crossing and trigger counter values that will also allow any loss of synchronization to be detected.

The current status of the Tracker synchronization procedure is such that the relative synchronization method has already been employed successfully in recent system and beam tests. APVs on different control rings have been synchronized using an XDAQ implementation of the procedure, that is scalable to the final system. The requirements for the precision of knowledge of fibre lengths

have been defined and included in procurement contracts. Finally, the FED design includes all the necessary features to setup and monitor synchronization.

## VI. ACKNOWLEDGMENTS

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