

Commissioning and Calibrating the CMS Silicon Strip Tracker

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Abstract

The data acquisition system for the CMS Silicon Strip Tracker (SST) is based around a custom analogue front-end ASIC, an analogue optical link system and an off-detector VME board that performs digitization, zero-suppression and data formatting. A complex procedure is required to optimally configure, calibrate and synchronize the 10^7 channels of the SST readout system. We present an overview of this procedure, which will be used to commission and calibrate the SST during the integration, Start-Up and operational phases of the experiment. Recent experiences from the CMS Magnet Test Cosmic Challenge and system tests at the Tracker Integration Facility are also reported.

I. THE DATA ACQUISITION SYSTEM

The CMS Silicon Strip Tracker (SST) is unprecedented in terms of its size and complexity, providing a sensitive area of $>200 \text{ m}^2$ and comprising 10^7 readout channels. Fig. 1 shows a schematic of the control and readout systems for the SST. The control system [1] comprises 300 “control rings” that start and end at the off-detector Front-End Controller (FEC) boards and is responsible for distributing slow control commands, clock and Level-1 triggers to the front-end electronics. The signals are transmitted optically from the FECs to front-end digital opto-hybrids via digital links, and then electrically via “token rings” of Communication and Control Units (CCUs) to the front-end electronics.

The readout system is based around a custom front-end ASIC known as the APV25 chip [2], an analogue optical link system [3] and an off-detector Front-End Driver (FED) processing board [4]. The system comprises 76k APV25 chips, 38k optical fibres (each transmitting data from a pair of APV25 chips) and 440 FEDs. The APV25 chip samples, amplifies, buffers and processes signals from 128 channels of a silicon strip sensor at the LHC collision frequency of 40 MHz. On receipt of a Level-1 trigger, pulse height and bunch-crossing information from pairs of APV25 chips are multiplexed onto a single line and the data are converted to optical signals that are transmitted via analogue fibres to the off-detector FED boards. The FEDs digitize, zero-suppress and format the pulse height data from up to 96 pairs of APV25 chips, before forwarding the resulting event fragments to the CMS event builder (EVB) and online computing farm.

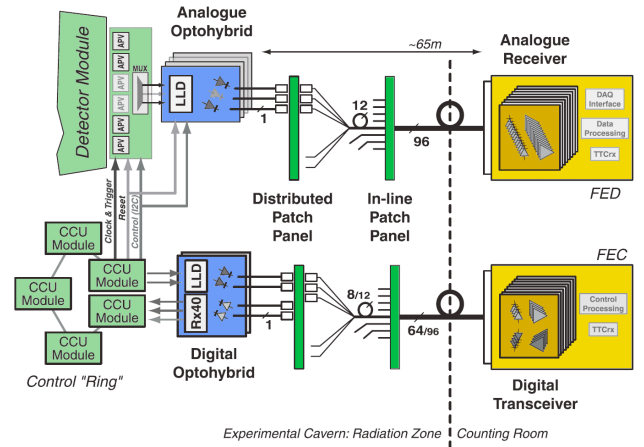


Figure 1: The SST control system uses ~ 300 control rings (based around the FEC and CCU boards) to propagate clock, trigger and slow control information to the front-end. The SST readout system is based around the APV25 chip, an analogue optical link system and the off-detector FED board.

The event data enter the EVB as a set of fragments distributed over ~ 700 FEDs (440 of which are used by the SST readout system). The task of the EVB, shown schematically in Figure 2, is to collect all the fragments, assemble them into a complete event, and then forward the event to a processing node on the computing farm. The average event size for CMS is expected to be $\sim 1 \text{ MB}$, meaning that, for a L1 trigger rate of 100 kHz, the event builder network must be able to handle an aggregate throughput of 100 GB/s.

The event builder uses two stages of switch networks. The first stage comprises 64 *FED builders* that perform a first pass of data concentration by taking data from up to 8 sources (pairs of FEDs) and building super-fragments via a small 8×8 switch network connected to ReadoutUnits. In the second stage, complete events are built using the *Readout Builder*, which comprises 64 BuilderUnits receiving super-fragments (of the same event) from the 64 ReadoutUnits via a large 64×64 switch network. The BuilderUnits buffer and forward complete events to FilterUnit processes that are hosted on the computing farm, which apply the HLT algorithms and perform online event filtering and monitoring. This two-stage architecture allows the EVB

system to be scaled from a single Readout Builder (comprising 64 Readout- and BuilderUnits) at Start-Up to eight Readout Builders (providing a 512x512 network) for the final complete system.

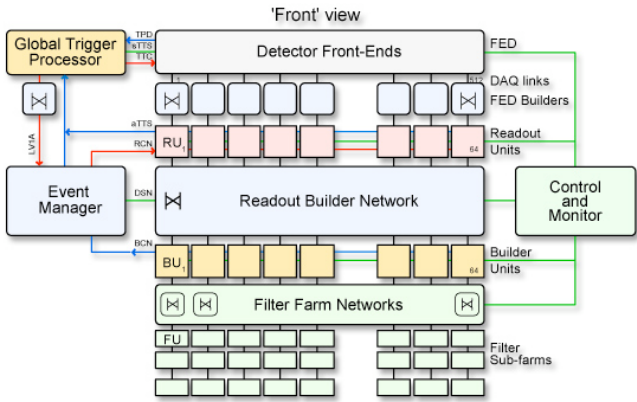


Figure 2: The CMS event builder, comprising a two-stage switch, that reads data fragments from the detector front-ends (via ~ 700 FEDs) and constructs complete events for processing by the High-Level Trigger algorithms running on the Filter Farm nodes.

II. COMMISSIONING THE SST

The procedure required to bring the detector into an operational state suitable for physics data-taking is complex and comprises several independent *commissioning tasks* that configure, calibrate and synchronize the various hardware components of the readout system. These tasks will be used to commission and validate the detector during the integration, Start-Up and operational phases of the experiment. In addition, error diagnostic and online monitoring tools are being developed that will monitor the functional state of the readout system and guarantee data integrity during detector operation. A brief overview of the commissioning tasks is given below.

Detector partitioning and cabling:

The trigger partitions within the SST (four are envisaged for the final system) are detected using hardware scans that identify all front-end devices and off-detector FEDs that share a common trigger source. In addition, the cabling of the readout optical link system, comprising 38k fibres that connect the front-end APV25 chips to the off-detector (back-end) FEDs, is determined by scanning through the front-end laser devices that drive the optical links and biasing each device in turn so that “light” is observed in the FED data for a single channel, establishing the connection (and any possible faults).

Front-End Module:

Biasing of the $\sim 15k$ strip sensors will be tuned using an automated procedure that will perform high voltage scans and guarantee that each sensor is fully depleted. For the front-end APV25 chip, the analogue pulse shape is tuned to achieve optimal S/N and efficiencies, and the various bias and gain settings of the chip are tuned for optimal performance, such as the gain of the multiplexer stage and the analogue baseline level (to optimize the usage of the available dynamic range).

Readout optical link system:

The bias and gain for each channel of the front-end laser devices

(that drive optical signals from pairs of APV25 chips to a single FED channel) are tuned in order to optimize the usage of the available dynamic range provided by the FED-based ADCs.

Front-End Driver:

The ADC sampling time for each of the 96 channels of a FED must be adjusted so as to optimize the sampling of the data. In addition, the calibration constants (such as pedestals and noise) used by the zero-suppression firmware algorithms and reconstruction software used by the HLT are measured.

Timing alignment:

Internal synchronization [5] of the SST front-end is achieved using “tick mark” features within the APV25 data stream. This procedure effectively accounts for signal propagation delays in the control system. Global synchronization of the SST system to LHC collisions and other sub-detectors will be achieved using collision data and a track-based analysis. A correct global timing alignment is crucial, as signal is attenuated by $\sim 4\%$ per ns misalignment for the nominal operating modes.

The procedure for commissioning the sub-detector is now well defined and many of the individual tasks have been implemented for some time. The collaboration has several years experience of commissioning small prototype systems, both in the laboratory and during several beam tests (with many using a 25-ns bunched beam to replicate the LHC conditions). Experience with larger-scale systems, such as the large sub-structures assembled at the various tracker integration centres, is also significant. The final sub-detector is currently being assembled at surface-level within the Tracker Integration Facility (TIF) on the Meyrin site, prior to installation in the underground cavern at Point 5. This period of assembly and integration will be used to maximize our experience and understanding of the detector performance prior to Start-Up.

The one remaining area of the commissioning procedure which requires further study is the global synchronization of the SST to LHC collisions and the other sub-detectors of the CMS experiment. These studies are beginning now and the procedure will be validated (as far as possible) through simulation and analysis of data containing cosmic tracks, collected at the surface prior to installation at Point 5.

III. THE DATA ACQUISITION SOFTWARE

The scale and complexity of the SST readout system imposes significant requirements on the data acquisition software that is used to steer the commission tasks and operate the system. Many of these requirements, such as distributed computing, event building, database integration, online monitoring, error handling, etc, are satisfied by the two official software frameworks developed for the CMS experiment, called XDAQ and CMSSW, and the various framework applications defined within them.

XDAQ [6] is the online software framework and provides a core set of services and tools, including: a fast communication protocol for peer-to-peer messaging between processes registered with the framework; a slower communication protocol for configuration of the framework processes; a finite-state machine schema; and event builder and memory manage-

ment tools. CMSSW [7] is the offline framework, within which software for physics simulation, data handling, reconstruction, physics analysis and High-Level Trigger (HLT) algorithms is developed. The framework also provides services such as a conditions database and online monitoring.

The data acquisition (DAQ) software [8] for the SST has been designed to use both the XDAQ and CMSSW frameworks. Dedicated DAQ loops have been implemented to perform the various commissioning tasks. Each loop configures and controls the readout and (local) trigger systems using various *supervisor* applications that interact with the hardware. Communication between the various hardware supervisors, distributed across several PCs, is achieved using the XDAQ framework, which allows to automate the data acquisition loops and so remove the need for repetitive run control sequences and complex book-keeping. The loops ensure that the appropriate data samples are accumulated for the subsequent (task-specific) analyses. Any configuration information required by the data analysis during the DAQ loop (eg, such as an identifier for the device being configured and its configuration) is encoded within the data stream itself. In this way, the analysis is entirely data-driven and no database access is required during the DAQ loop itself.

The analysis software determines the optimized hardware configurations and calibration constants from reconstructed calibration pulses, timing delay curves, dynamic range curves and other features of the APV25 data stream. The optimized configurations and calibrations are then stored in a dedicated database and are used to configure the readout system for subsequent periods of data-taking.

Unlike the various hardware supervisor applications that are implemented within the XDAQ framework, the analysis software for the commissioning procedure is implemented within the CMSSW framework. The DAQ software uses the standard CMS event building tools and the CMSSW framework so that an online, distributed data analysis can be performed and real-time feedback achieved during detector commissioning. The FED data are assembled into complete events by the CMS event builder and streamed to multiple FilterUnit processes hosted on the computing farm, which use the CMSSW framework to perform data analysis and monitoring. The same analysis software can later be used offline for more detailed studies.

Distributed data analysis is an essential feature of the DAQ software, so that it can handle the huge data volumes generated by the increasingly large readout system as the SST is assembled. The DAQ software uses the standard CMS software frameworks and tools wherever possible, for which support and maintainance is guaranteed for the lifetime of the experiment. In this way, the amount of custom software development (specific to the SST sub-detector), code duplication and maintainance is minimized. Additionally, the possibility to take advantage of new framework tools as they become available is maximised.

Importantly, the chosen design is also sufficiently flexible to allow transparent use of both local or global computing resources. When performing *local* data acquisition, the computing resources available to the SST are in the form of VME crate PCs (one per crate) and possibly a small dedicated machine cluster (comprising <10 PCs). The VME crate PCs host the various hardware supervisor, event building and data analysis processes.

The FED data are read via the VME backplane and event building is performed using a Gbit ethernet network. This operating mode will be the default during the integration and Start-Up phases of the experiment.

When using the global DAQ systems, the FED data are read out via their SLink interface [9], event building is performed using the CMS event builder, and the data analysis processes are hosted by the global computing farm (the crate PCs will host only the hardware supervisor processes). The data analysis is performed using the same CMSSW-based libraries as for the local DAQ mode.

One added complication when operating with global resources is that of trigger management. When running in local DAQ mode, trigger generation is under the control of the DAQ software. For the global DAQ mode, the trigger is issued centrally by the CMS global trigger system. It is envisaged that dedicated commissioning runs will be scheduled with reduced trigger rates that can be used as desired by the various sub-detector systems. In this case, the DAQ software will configure the readout system on-the-fly during the run. The configuration of the readout system for a given event will be encoded in the data stream and used by the data analysis running on the global computing farm.

The ability to use the global DAQ resources is important, as this mode of operation offers vast improvements in terms of trigger rates and CPU processing power with respect to that available when using local DAQ. Due to large data volumes generated by the system during commissioning runs (typically ~ 750 kB/trigger/crate), trigger rates are severely limited when the FEDs are read out via the VME backplane; system tests have shown that data rates of ~ 5 MB/s were achieved for a fully populated VME crate (16 FEDs), thus limiting trigger rates to just ~ 7 Hz. This compares unfavourably with a possible trigger rate of ~ 2 kHz when reading out via SLink. This increase in trigger rate is highly desirable for those commissioning tasks that require precise measurements (and therefore large statistics), such as track-based timing alignment to synchronize the SST to LHC collisions.

IV. CMS MAGNET TEST COSMIC CHALLENGE

The recent CMS Magnet Test Cosmic Challenge (MTCC) provided an ideal opportunity to test the DAQ software under operating conditions similar to those expected for the final experiment. The tracking unit, shown in Figure 3, comprised 130 modules within two Tracker Inner Barrel (TIB) half-shells, four Tracker Outer Barrel (TOB) rods and two Tracker End-Cap (TEC) petals. One FEC board and four control rings were used to control the front-end, and four FEDs were used by the readout system.

Several important milestones were achieved during the test. The DAQ software was fully integrated with the SST configuration database and the CMS Run Control environment. These developments allowed expert users, trained by the DAQ team prior to the test, to commission (and re-commission when necessary) the complete system via the Run Control interface in just a few hours. Complete prototypes of the Detector Control and Detector Safety Systems were used for the first time, as was a pro-

totype error logging and diagnostic system, providing real-time feedback on the operational status of the readout system. Once commissioned, stable running of the system using the global DAQ was possible for several hours. Approximately 25 million events were collected, of which 10 million events were collected with a magnetic field of up to 4 Tesla. Detailed detector alignment and tracking studies are now being performed offline.

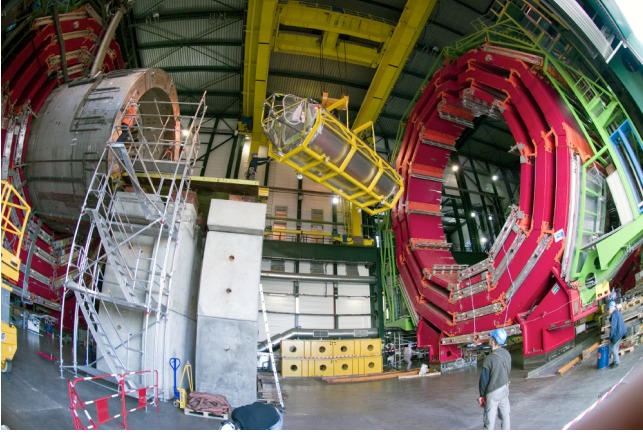


Figure 3: Installation of the tracker setup for the MTCC.

Online monitoring of the data quality using CMSSW software was also achieved for the first time. A small computing farm was used to parallel-process the raw event data and perform: unpacking of the raw event data from the FED buffer payloads; creation of the basic hit objects (known as *digis*) handled by the reconstruction software; assignment of the digis to a readout module (and therefore a geometrical position) using cabling information; booking and filling of histograms to provide online monitoring information. Remote online monitoring was demonstrated using a web-based client that subscribed to the monitoring histograms available on the computing farm nodes.

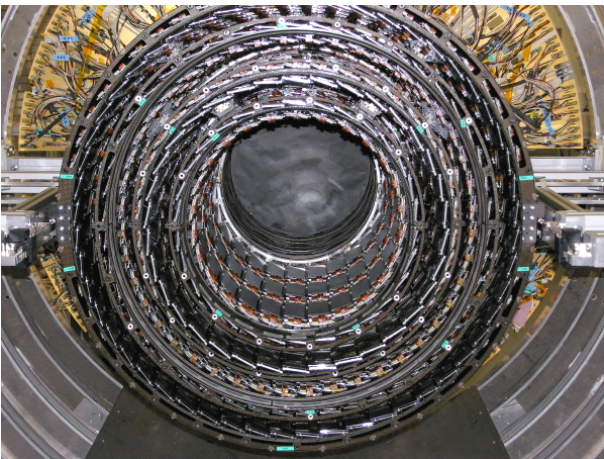


Figure 4: Assembly of the inner barrel at the TIF.

V. TRACKER INTEGRATION FACILITY

The Tracker Integration Facility (TIF) is a large clean room environment in which the final SST is being assembled and commissioned. Large sub-structures, such as the TIB, are delivered from the various integration centres around the world and installed within the final mechanical support structure. The facility provides all the necessary services to fully commission and validate the detector prior to being transported to Point 5 and installed within the underground cavern. It is envisaged that final commissioning of the system will be done at the level of a tracker partition; this corresponds to approximately 2.5 M readout channels (ie, $\sim 25\%$ of the total). Nine VME crates will be fully populated with FEDs in order to read out the tracker partitions in a configuration that is essentially identical to that which will be used for the final system. The DAQ software will be hosted on the VME crate PCs and online (distributed) analysis will be performed in order to provide real-time feedback.

Large sub-structures from all four partitions of the tracker have been installed at the TIF. Figure 4 shows the completed TIB backward sub-structure, comprising four barrel layers. Cabling of the detector front-end to the off-detector FEDs is in progress and large-scale validation tests have recently started.

In addition to the TIF, a Tracker Analysis Centre (TAC) has been installed on the CERN Meyrin site, in close proximity to the TIF. The centre will provide a small computing farm and mass storage so that the large data volumes generated during commissioning can be analysed in more detail offline. It is envisaged that the TAC will evolve into the tracker operations centre for experts and users alike during CMS operation.

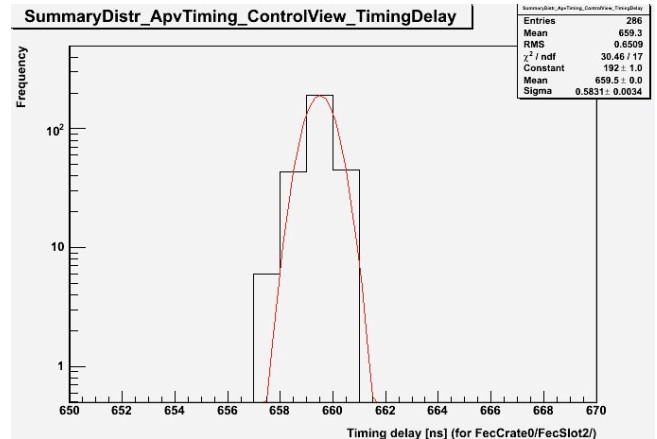


Figure 5: Timing delays measured for 286 channels of the readout system (where a “channel” in this sense refers to a pair of APV25 chips). The channels have been synchronized to better than 1 ns.

The analysis components of the DAQ software will be used both online to commission the detector and offline to perform detailed studies at the TIF and TAC. Detector experts are now using new tools developed within CMSSW that perform analyses of the raw data and generate summary plots that show system-wide information. An example is shown in Figure 5, which shows the timing delays measured for 286 channels of

the readout system (where a “channel” in this sense refers to a pair of front-end APV25 chips). The figure demonstrates that the 286 pairs of front-end chips (that read signals from $\sim 73k$ detector strips) have been synchronized to better than 1 ns.

Summary plots are essential when commissioning the detector, as they provide immediate feedback that can be easily interpreted by non-experts, allowing problems to be quickly identified and located. These summary plots can be generated online (and offline if necessary) by the DAQ software and are viewable at remote sites using web technology.

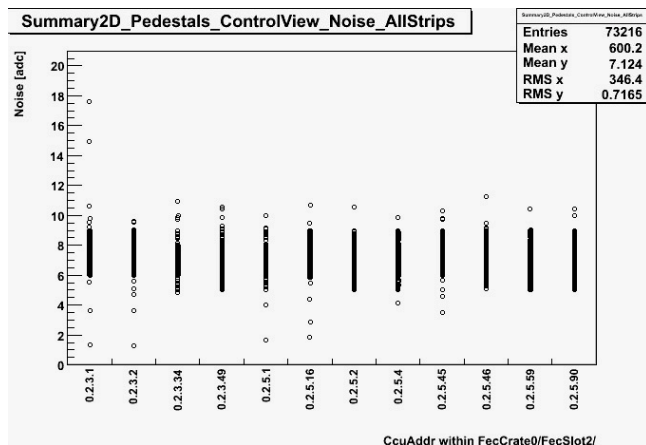


Figure 6: Channel noise (where a “channel” in this sense is at the level of a single detector strip), binned according to which rod the channel (detector strip) belongs. The twelve bins represent twelve different rod structures that are controlled by two control rings.

An example of a typical summary plot is shown in Figure 6. The plot shows the noise measured for $\sim 73k$ channels (where a “channel” in this sense is at the level of a single detector strip) of a TOB structure being commissioned at the TIF. The noise values are organized (binned) according to which sub-structure the channel belongs. For the example shown, each bin contains noise values from front-end modules controlled by the same CCU module (each of which controls a *rod* structure comprising six or twelve front-end modules). The plot clearly shows that a (non-calibrated) channel noise of ~ 8 ADC counts is typical. Dead and noisy channels, exhibiting abnormally low and high noise values respectively, are clearly seen. The plot highlights the excellent quality and uniform behaviour of the tested system, with just a handful of detector strips ($\ll 0.1\%$) exhibiting anomalous noise values.

The CMSSW software is sufficiently flexible to produce a range of summary plots that display information on all aspects of the detector quality and performance. These plots act as an excellent diagnostic tool and will be used extensively during assembly and integration of the final silicon strip tracker.

VI. CONCLUSIONS

The CMS Silicon Strip Tracker (SST) requires complex procedures to optimally configure, calibrate and synchronize its 10^7 readout channels. The DAQ software provides the implementation for these procedures in a scalable design (using distributed computing) that will be able to handle the large data volumes produced during detector commissioning. The DAQ software is now a mature project and will be used to validate the quality and performance of the detector during the integration, Start-Up and operational periods of experiment.

Several important milestones were achieved during the recent CMS Magnet Test Cosmic Challenge, including the successful use of: the DAQ software to commission the system, detector control and safety systems, error diagnostic tools, and online monitoring. Stable operation of the readout system was achieved using both local and global data acquisition resources.

The final sub-detector is currently being assembled and commissioned at the Tracker Integration Facility. The DAQ software is being used to commission the sub-detector and new analysis tools will allow detailed online and offline studies to quantify the detector quality and performance prior to installation at Point 5.

REFERENCES

- [1] F. Drouhin *et al*, CMS-CR 2004/032.
- [2] M. French *et al*, Nucl. Instr. Meth. A534 (2001) 359-365.
- [3] J. Troska *et al*, Nucl. Sci. Symp. 1 (2002) 233-237.
- [4] J. Coughlan *et al*, CERN-LHCC-2002-034, p.296-300
- [5] K. Gill *et al*, CERN-LHCC-2003-055, p.289-293
- [6] <http://xdaqwiki.cern.ch/>
- [7] cmsdoc.cern.ch/cms/cpt/Software/html/bibitem/
- [8] L. Mirabito *et al*, CMS-IN 2003/021, CMS-IN 2004/019
- [9] H.C. van der Bij *et al*, IEEE Trans. Nucl. Sci, 44/3, p.398