Exercising CMS dataflows and workflows in computing challenges at the Spanish Tier-1 and Tier-2 sites

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Abstract.
An overview of the data transfer, processing and analysis operations conducted at the Spanish Tier-1 (PIC, Barcelona) and Tier-2 (CIEMAT-Madrid and IFCA-Santander federation) centres during the past CMS CSA06 Computing, Software and Analysis challenge and in preparation for CSA07 is presented.

1. Introduction
The CMS computing architecture [1] is based on a tier-organised structure of computing resources, based on a Tier-0 centre at CERN, 7 Tier-1 centres for organized mass data processing, and about 30 Tier-2 centres where user physics analysis is performed. The Tier-0 is in charge of storing the data coming from the detector onto mass storage, performs a prompt reconstruction of the data and distributes the data among the Tier-1 centres. The Tier-1 sites archive on mass storage its share of data, run data reprocessing, organized group physics analysis for data selection and distribute down the selected data to Tier-2’s for user analysis. Tier-1 centres also have the responsibility of storing Monte Carlo data produced at the Tier-2 sites.

CMS undertakes periodic computing challenges of increasing scale and complexity to test its computing model and Grid computing systems. The computing challenges are aimed at establishing a working distributed computing system that implements the CMS computing model based on an underlying multi-flavour grid infrastructure. CMS dataflows and data processing workflows are exercised during a period of about a month targeting specific performance and scale goals. Performance values are measured, problems are identified and feedback into the design, integration and operation of the computing system is provided.

The above mentioned data transfers and processing workflows have been exercised in the Computing, Software and analysis challenge during October 2006 (CSA06) at a scale of 25% of what is needed for operations in 2008, and will be exercised at a 50% scale during October 2007.

The Spanish Tier-1 and Tier-2 centres have actively and successfully participated in CSA06 and in the preparation work for CSA07. The Tier-1, PIC, is located in Barcelona. The Tier-2
distributed centre is a federation of two sites, CIEMAT in Madrid and IFCA in Santander.

Table 1 shows the existing computing resources at the Spanish centers and the corresponding ramp up for the coming two years.

|                | PIC Tier-1 | 2007 | 2008 | 2009 |
|----------------|------------|------|------|------|
| CPU (kSI2k)   | 300        | 700  | 1200 |      |
| Disk (TB)     | 80         | 300  | 600  |      |
| Tape (TB)     | 150        | 700  | 1600 |      |
| WAN (Gbps)    | 10         | 10   | 10   |      |

|                | CIEMAT-IFCA Tier-2 | 2007 | 2008 | 2009 |
|----------------|---------------------|------|------|------|
| CPU (kSI2k)   | 400                 | 800  | 1300 |      |
| Disk (TB)     | 100                 | 200  | 400  |      |
| Tape (TB)     | -                   | -    | -    |      |
| WAN (Gbps)    | 1                   | 2.5  | 10   |      |

2. CSA06 Computing, Software and Analysis challenge

The combined Computing, Software and Analysis challenge CSA06 [2] started on 2 October 2006, lasting approximately 6 weeks. It was designed to be a 25% capacity test of what is required for operations in 2008. The goals of the challenge were the following:

- Reconstruction at the Tier-0 at 40 Hz using the new CMSSW event processing framework.
- Distribution of raw and reconstructed data to the Tier-1 sites.
- Data skimming jobs at the Tier-1 sites and the resulted data propagated to the Tier-2 sites.
- Data analysis at the Tier-2 sites on the skimmed data.
- Demonstration of the re-reconstruction workflow at the Tier-1 sites.
- Demonstration of the calibration workflow, production of calibration/alignment datasets at the Tier-0, transfer to a Tier-1 and execution of calibration jobs at the Tier-1.

2.1. Hardware setup, computing services and workflows

Production computing resources and services were used for CSA06 at the Spanish sites. No dedicated setup was deployed for the challenge. All CMS resources were dedicated to CSA06 since production activities were not run during the challenge with the exception of user analysis at the Tier-2 sites.

Figure 1 shows the bandwidth and approximate latencies (half of the round trip time) of the different network sections between CERN and the Spanish sites. The traffic from CERN reaches Spain through the Geant-2 network infrastructure with a bandwidth of 10 Gbps. In Spain, Rediris, the Spanish academic network, transports the traffic with a bandwidth of 2.5 Gbps. In Catalonia, the Anella Cientifica network interconnects academic and research centres. The bandwidth available to PIC at the time of the challenge was limited to 1 Gbps with a guaranteed share of at least 800 Mbps. The total latency CERN-PIC is about 20 msec. PIC-CIEMAT and PIC-IFCA latencies are 9 msec and 15 msec respectively.

10 Gbps links have been deployed in 2007 in Spain as part of the Geant-2 infrastructure. PIC has recently joined the LHC Optical Private Network [3], a dedicated network infrastructure for the LHC Tier0 and Tier1 networking.

Figure 2 depicts the dataflows, workflows and computing resources involving the Spanish sites during CSA06. All resources are accessed via the LHC Computing Grid (LCG [4]) infrastructure and the dataflows and workflows are conducted using LCG middleware and tools as well as CMS-specific services built on top of them.
Figure 1. Network diagram showing the bandwidth and approximate latencies (half of the round trip time) of the different network sections between CERN and the Spanish sites.

Figure 2. Dataflows and workflows in CSA06 at the Spanish sites. The disk and CPU capacities are also shown in the picture.

PIC received from CERN a continuous data stream of reconstructed data, at an average rate of 22 MB/s. As described in the next section, data skimming and re-reconstruction was conducted at PIC, while analysis on the skimmed samples was run at CIEMAT and IFCA. In addition, data in a suitable format for calibration and alignment were forwarded to IFCA from CERN via PIC for alignment studies. A minimum of 70 TB of storage capacity and 150 CPUs were required for a nominal-sized Tier-1 to participate in the challenge. PIC, with a size between 1/2 and 1/3 of a nominal Tier-1, contributed with 50 TB of dCache-managed [5] disk space and 150 CPUs. No data migration/recall to/from tape was exercised at PIC. The disk space capacity was distributed between 15 file servers each providing 3-4 TB. The large distribution of the storage capacity distributes the load of the simultaneous read/write operations (data transfers, processing jobs reads and writes) on the disk servers. A minimum of 5 TB and 20 CPUs were requested for a nominal Tier-2. CIEMAT contributed to the challenge with 30 TB of disk space under Castor [6] and 200 CPUs. IFCA deployed 12 TB of disk space under DPM [7] and 90 CPUs.

Data transfers are managed by the CMS data transfer and placement system PhEDEx [8]. PhEDEx consists of a set of global and local agents at the sites that communicate through a central database. Relatively large files, of about 2.5 GB, were transferred to the sites to minimize
the number of files and improve performance of network and storage systems. This lesson was learnt in the past DC04 data challenge [9] where the large number of small files caused a serious overhead in data operations. Data files are organized in data blocks, an arbitrary set of files, that are replicated and tracked together by the CMS data management system. One or more data blocks constitute a dataset defined in terms of physics content. The description of the data is kept in the global Dataset Bookkeeping Service [10], with an oracle database back-end at CERN. Completely replicated blocks and datasets are published by PhEDEx in the global Dataset Location Service [11], a catalogue that keeps track of the location of the data at sites at the level of file blocks. Local physical file names (PFN) and data access protocols at the sites are resolved at run-time by the jobs through a local Trivial File Catalogue (TFC), a set of logical to physical file name conversion rules. In this approach, the structured namespace provided by the local storage system is used as a catalogue. The fileblock-based replication and the TFC-based resolution of PFNs largely minimizes the interaction with database catalogues and the Grid information system which results in a higher reliability, performance and scalability.

The Tier-0 and each Tier-1 site run a File Transfer Service (FTS[12]). All transfers from the Tier-0 are managed by the FTS server at the Tier-0 and all transfer between Tier-1 and Tier-2 sites are managed by the FTS server at the Tier-1 associated to the Tier-2 involved in the transfer. The FTS servers allow to implement bandwidth shares between different virtual organizations, allow to configure the transfer parallelism in each channel and are able to queue transfer requests. The FTS servers interact with the local storage at the sites via the SRM[13] interface which provides an uniform interface to the different implementations of pool managers (CASTOR, dCache, DPM). GridFTP [14] is used as data transfer protocol over the WAN.

Data skimming and re-reconstruction processing workflows at the Tier-1 sites are carried out using ProdAgent (PA) [15]. PA was originally developed for Monte Carlo production and was later extended to deal with the Tier-1 workflows. Those workflows are very similar to the case of multi-step MC processing where production jobs have to read input data to process (for example, reconstruction of previously produced simulated data). Furthermore, PA is currently being extended to execute the Tier-0 data processing workflows.

PA is built as a set of loosely coupled components that cooperate to carry out production workflows. Components are python daemons that communicate through a local mysql database. Work is split into these atomic components that encapsulate specific functionalities. PA includes components for job creation, submission and tracking, error handling and job cleanup, data merging and publication into global DBS/DLS/data transfer system. The interface to the different Grid flavours is done via plug-in’s for the job creation, submission and tracking components. It is fairly simple to add new systems and customization.

Figure 3 shows the production workflow with PA. Processing jobs are sent to sites which store produced data at the local storage elements. File PFNs are resolved by means of the local TFC. Jobs report back to ProdAgent which triggers data merge jobs sent to the sites hosting the unmerged data. Job resubmission on error is automated. Data processing, bookkeeping, tracking and monitoring occurs in the local-scope databases of the ProdAgent instance. After successful processing, data bookkeeping and location information is promoted to the global scope databases and the data transfer system to make the produced data available for analysis and replication.

Processing jobs access conditions data (calibration and alignment constants) via a local squid-based web cache [17]. A distributed hierarchy of independent cache servers is introduced between the clients and a central database server. The FroNTier package[18] is used to encode the communication between database clients and server.

Analysis of skimmed data samples is done at the Tier-2 sites using CRAB [19]. CRAB is a tool that allows users to run the CMSSW[20] processing and analysis framework on the Grid. It takes care of data discovery in the DBS/DLS catalogues, job preparation, submission,
monitoring and output retrieval. In Figure 4 the analysis workflow with CRAB is sketched together with the data transfer workflow conducted by PhEDEx.

In addition to user analysis, a central job load generator (JobRobot) was run to continuously submit (fake) analysis jobs to the sites in order to reach the required level of job load.

Job monitoring and bookkeeping information is sent to a central database, the CMS Dashboard [21]. All CMS workload tools (ProdAgent, CRAB, JobRobot) send real-time information to the Dashboard (site name, exit code, etc). The Dashboard also gets job state information from the Grid workload management system.

Both for production and analysis purposes, CMSSW software versions are pre-installed at the sites in a shared filesystem accessible from the farm worker nodes. The installation is centrally
managed by the CMS software manager that submits Grid installation jobs to the sites.

Sites establish locally shares and priorities for different job types (production, analysis, software installation). Different job types are mapped to different local unix users using VOMS [22]. VOMS is a system to classify users that are part of a Virtual Organization on the base of a set of attributes that will be granted to them upon request and to include that information inside Globus-compatible proxy certificates.

2.2. Pre-CSA06 Monte Carlo production

During summer 2006 the production of the required Monte Carlo samples for the CSA06 challenge was conducted. It was the first large scale production with ProdAgent. Four teams were in charge of running production, one of them at CIEMAT. Production resources were distributed among production teams so that each team ran jobs at specific sites. This way each team was in charge of contacting specific site administrators to follow up potential problems with production at the sites. Only sites with a proved record of reliability and sufficient resources were included in the production team’s white list.

50 million events were requested for CSA06 and 67 million events were finally produced between all four production teams. The CIEMAT team contributed with 17 million events, 2.3 M of which were generated at CIEMAT and 0.8 M at PIC.

Table 2 shows job failure percentages (relative to all submitted jobs) for different failure reasons. The largest number of failures correspond to application failures and Grid inefficiencies (about 7% each). Application failures include failures reading the input data. Grid related failures include failures in global Grid services (RB, information system) and failures of Grid services at the sites (CE, WNs). Grid job failures typically occur when the exit code of the job cannot be communicated back to the RB (e.g. jobs that get killed due to hardware failures at the WNs or killed by the batch system after expiring the allocated time slot) or at job submission time when the destination site temporarily disappears from the Grid information system. Failures in storing the output file into the local storage account for about 4% of the errors. Around 2% of the jobs fail when accessing the experimental software from a shared repository (typically via NFS). The overall job efficiency is about 80%. Failed jobs are automatically resubmitted by the production system so that in the end most jobs are done.

| Failure reason                             | Percentage |
|--------------------------------------------|------------|
| Application failure (including data access)| 6.6%       |
| Output data stage-out                      | 3.8%       |
| Experiment software configuration/access   | 2.3%       |
| Grid related failures                      | 6.7%       |
| Total                                      | 19.4%      |

Table 2. Job failure rates.

Efficient site support is critical for production efficiency. Most job failures are related to site problems (temporary glitches in site Grid services, problems reading and storing data in the local storage system, local batch system and WN misbehaviour, access to experimental software). A fast reaction of site admins is required to minimize production inefficiencies.

2.3. Tier-1 and Tier-2 operations

The CSA06 challenge had a staged start-up, beginning with reconstruction at the Tier-0 followed by data distribution to the Tier-1/Tier-2 sites and finally adding the event data processing workflows. We discuss in the following subsections data transfers, data skimming and reconstruction at PIC and user analysis demonstrations at CIEMAT and IFCA.
2.3.1. Data transfers  The tier-1 centers were expected to receive data from CERN at a rate of 25% the rate expected for 2008 and serve data to Tier-2 sites. Table 3 summarizes for every Tier-1 the expected and achieved rates.

| Site  | Nominal (CSA) Rate | Last 30 Day average | Last 15 Day average | Outage (Days) | MSS used |
|-------|--------------------|---------------------|---------------------|---------------|----------|
| ASGC  | 15 MB/s            | 17 MB/s             | 23 MB/s             | 0             | YES      |
| CNAF  | 25 MB/s            | 26 MB/s             | 37 MB/s             | 0             | YES      |
| FNAL  | 50 MB/s            | 68 MB/s             | 98 MB/s             | 0             | YES      |
| ZIK   | 25 MB/s            | 23 MB/s             | 28 MB/s             | 3             | NO       |
| IN2P3 | 25 MB/s            | 23 MB/s             | 34 MB/s             | 1             | YES      |
| PIC   | 10 MB/s            | 22 MB/s             | 33 MB/s             | 0             | NO       |
| RAL   | 10 MB/s            | 23 MB/s             | 33 MB/s             | 2             | YES      |

Table 3. Nominal and achieved transfer rates for the Tier-1 centers during CSA06.

PIC was expected to get data at an average rate of 10 MB/s during the whole duration of the challenge. It achieved an average rate of 22 MB/s with a transfer success rate above 97%. Transfers were running most of the time backlog free, except for concrete periods where a large amount of data were intentionally injected for transfer to test bursty transfers. About 60 TB of data were transferred from CERN to PIC while 30 TB and 15 TB were transferred from PIC to CIEMAT and IFCA respectively. The quality getting data from PIC for both CIEMAT and IFCA was excellent during the whole challenge.

Bursty data transfers from CERN to the Tier-1 sites were exercised during the challenge to test the ability to recover from large backlogs caused by potential transfer problems. During bursty transfers between CERN and PIC, an average rate of 80 MB/s was sustained during several hours with no transfer errors, saturating the available network bandwidth between CERN and PIC.

In the CMS computing model each Tier-1 center hosts a copy of the whole sample of reconstructed data in AOD format, which contains a subset of the reconstruction information. However, it is anticipated that during the first years of the experiment data analysis will need access to the complete reconstruction information. Since the reconstructed data is split between the Tier-1 centers, efficient transfers of skimmed samples will have to be possible from any Tier-1 to any Tier-2 site. The simultaneous transfer of a dataset from PIC to many Tier-2 sites was exercised in CSA06. The dataset was successfully transferred to 25 sites simultaneously.

Transfers from the Tier-1 centers to the Tier-2 sites are bursty in nature in the CMS computing model. Skimmed data at the Tier-1 sites have to be transferred to the interested Tier-2 sites as fast as possible as they become available. A bursty transfer from PIC to CIEMAT was exercised. 5 TB of data were transferred during 24 hours at an average rate of 60 MB/s with perfect transfer quality.

Non-regional transfers from a Tier-1 other than PIC to CIEMAT and IFCA were also successfully exercised. Data were transferred from FNAL Tier-1 to both CIEMAT and IFCA at a rate about 20 MB/s with a good transfer quality.

2.3.2. Data skimming and re-reconstruction  Data skimming was conducted at the Tier-1 sites. Skimming jobs could run any number of filters producing the corresponding output files with the selected events. ProdAgent was used to carry out the skimming workflow. It automatically prepared the skimming jobs for the sample to be filtered, submitted and tracked them and finally automatically launched the corresponding merge jobs.
Several skimmings were run at PIC in a sample of 3 million events. It took about 2 days to skim the sample. Few seconds were required to process each event. Job efficiencies (Grid, application, stage out) efficiencies were close to 100%.

The re-reconstruction workflow was demonstrated at the Tier-1 sites at the end of CSA06. The goal was to reprocess at least 100k events at every Tier-1. PIC reprocessed about 900k events. It took two days to reprocess the data. In average 10 seconds were needed to re-reconstruct one event of the data sample used in the reprocessing exercise. The improved calibration and alignment constants used in the data reprocessing were accessed via the local FroNTier cache. Events were reprocessed with high efficiency at PIC. There was only about 1% inefficiency in the Grid submission of jobs.

2.3.3. Data analysis A wide variety of physics analysis demonstrations were prepared by the physics groups for CSA06 in order to test the analysis workflow. Figure 5-left shows the distribution between the sites of analysis jobs submitted by users during CSA06. A substantial number of analysis jobs was run at the Spanish sites. Few thousand analysis jobs were run at CIEMAT, IFCA and PIC with high efficiency. In order to stress the workload management system and to demonstrate a scale of job submission above 10000 jobs/day Grid-wide, fake analysis jobs were centrally submitted by means of a JobRobot which prepared and submitted fake analysis jobs according to the data published by the sites. These jobs complemented the smaller scale of user analysis jobs and stressed the storage system at the sites by reading data. Above 500k jobs were submitted by the JobRobot. CIEMAT received and executed with high efficiency a large number of JobRobot jobs as can be seen in Figure 5-right. PIC also ran a large number of JobRobot jobs with a somewhat lower application efficiency.

Figure 5. Distribution between the sites of CSA06 user analysis (left) and JobRobot fake analysis (right) jobs.

3. CSA07 pre-challenge
In preparation for the CSA07 challenge, a large sample of simulated events was produced over summer 2007 using the Tier-1 and Tier-2 computing resources. Out of the 100 M events generated in only two months, CIEMAT produced about 10 M. That was the largest contribution from a Tier-2 site. In average more than 5000 CPUs were continuously used (320 at CIEMAT).

Figure 6 shows the distribution of CMS jobs as a function of time during the last 12 months. Jobs are classified according to the activity. The peak around November 2006 corresponds to the CSA06 challenge, dominated by JobRobot jobs. From January 2007 job execution in CMS has been dominated by Monte Carlo production. It is also visible an increasing activity of analysis jobs.
Figure 6. CMS jobs executed during the last 12 months classified by activity.

Data transfers have been also exercised in preparation for the CSA07 challenge. Figure 7 shows the transfer rates between the different CMS sites during the last 12 months. The peak around October 2006 corresponds to the data transfer activity during CSA06. Data transfers ramped up from April 2007 up to a level of 800 MB/s which corresponds to 0.6 Petabytes per week. This level has been sustained since then for months reaching a data volume of 10 PB distributed worldwide.

Figure 7. CMS data transfers during the last 12 months.
4. Summary

CSA06 has been extremely useful and successful as a complete exercise of the CMS workload management and data management systems, execution of many of the CMS workflows and stress tests of site facilities. The Spanish Tier-1 and Tier-2 played an outstanding role.

The intended functionality was demonstrated in the challenge. However, several dataflows and workflows in the CMS computing model were missing in CSA06. Data transfers between Tier-1 sites, non-regional transfers Tier1-Tier2 and Tier-2 to Tier-1 transfers were not exercised; reprocessing recalling from tape large amounts of data, to exercise the management of the disk cache in front of tape was not practiced; Monte Carlo production at the Tier-2 sites was not concurrently run with analysis activities; the Tier-0 did not include High Level Trigger processing and the storage manager. A new combined challenge, CSA07, is scheduled for September 2007 to simultaneously perform all CMS computing and offline activities at the 2008 50% scale. It will surely profit from the experience gained during the preparation and execution of CSA06.

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