Distributed analysis in ATLAS

A. Dewhurst\textsuperscript{1}, F. Legger\textsuperscript{2}, on behalf of the ATLAS Collaboration

\textsuperscript{1}STFC - Rutherford Appleton Laboratory, United Kingdom
\textsuperscript{2}Ludwig-Maximilians-Universit"at M"unchen, Munich, Germany
E-mail: federica.legger@cern.ch

Abstract. The ATLAS experiment accumulated more than 140 PB of data during the first run of the Large Hadron Collider (LHC) at CERN. The analysis of such an amount of data is a challenging task for the distributed physics community. The Distributed Analysis (DA) system of the ATLAS experiment is an established and stable component of the ATLAS distributed computing operations. About half a million user jobs are running daily on DA resources, submitted by more than 1500 ATLAS physicists. The reliability of the DA system during the first run of the LHC and the following shutdown period has been high thanks to the continuous automatic validation of the distributed analysis sites and the user support provided by a dedicated team of expert shifters. During the LHC shutdown, the ATLAS computing model has undergone several changes to improve the analysis workflows, including the re-design of the production system, a new analysis data format and event model, and the development of common reduction and analysis frameworks. We report on the impact such changes have on the DA infrastructure, describe the new DA components, and include recent performance measurements.

1. Introduction
Due to the demanding requirements of storage space and processing power needed to analyse LHC data, the ATLAS\textsuperscript{1} computing model is based on distributed resources\textsuperscript{2}. For the first LHC run (Run 1, 2010-2012), the computing model foresaw, as primary data format for analysis, the so-called Analysis Object Data (AOD), to be analysed within the Athena framework\textsuperscript{3}. However, most ATLAS physicists preferred to work with reduced data formats, Derived Physics Data (DPD)\textsuperscript{4}, which were the result of dedicated slimming, skimming and thinning procedures\textsuperscript{5}. Skimming is defined as the reduction of events, whereas slimming and thinning involve the reduction of objects. The most popular derived formats were ROOT flat ntuples (D3PD), existing in several flavors tailored to the needs of specific physics groups. The total size of a single version of AODs or D3PDs was of the order of PBs. The same events existed in several formats and several copies, while the full reconstruction of the event was only possible from the AODs. To improve the use of storage and computing resources, a common data format was studied during the long shutdown (2013-2014)\textsuperscript{6}. The new format, the xAOD, merges the advantages of the previous formats, the AOD and D3PD. Both Athena and ROOT-based analysis are possible on the xAODs. The use of a single data format allows for optimization of both local and remote read/write access using data-structure-aware caching mechanisms such as TTTreeCache\textsuperscript{7}. The data reduction is now centrally managed using a common reduction framework\textsuperscript{8}. A common analysis framework has been developed (its use is recommended but...
not enforced) to provide a common event model and to ease the application of recommendations from the Combined Performance (CP) groups [9].

Alongside these important changes for analysis, the ATLAS production system and distributed data management system have been revisited to match the challenges for the LHC Run 2, bringing important changes to the grid workflows also for user analysis. In Section 2, the various components of the DA system are discussed, underlining the most interesting new features and consequences for ATLAS grid users. Consolidated activities, such as HammerCloud [10, 11, 12], the automatic testing service for grid sites, and DAST, the user support mailing list, are also described. The performances of the DA system are shown in Section 3.

2. Distributed Analysis for LHC Run 2

The primary event reconstruction of LHC data is done at the Tier-0, the computing facility at CERN and its recent extension at the Wigner Research Centre for Physics, and at the Tier-1s, primary computing facilities worldwide. Monte Carlo (MC) production is done at Tier-1s, and at secondary facilities around the world, the Tier-2s. The derivation framework is run at Tier-1s and Tier-2s, to reduce the data size from the original PB scale of the reconstruction output for a typical physics sample down to a few TB. The derived DxAOD are expected to be 1-2% of the original data size for collider data, and 5-8% for MC data. The above activities are referred to as central production.

The final DxAOD datasets are distributed to the Tier-1s, the Tier-2s, and additional analysis facilities, the Tier-3s, where they can be analyzed by ATLAS users. The access to grid resources from ATLAS users is the scope of the distributed analysis system. The user workflows typically involve further data reduction to produce the final ntuples (of the order of GB) to be downloaded and further processed using local non-grid resources (batch systems, PROOF [13] farms, etc). The ATLAS computing model for Run 2 is schematically drawn in figure 1.

![Figure 1. The ATLAS computing model for LHC Run 2.](image-url)
The PanDA workload management system \cite{14} is used by both users and central production to execute jobs on ATLAS grid sites. Pilot jobs are sent to a central queue operating on WLCG \cite{15}, Open Science Grid (OSG) \cite{16}, ARC (Advance Resource Connector) \cite{17}, and NorduGrid \cite{18}. The ATLAS production system has undergone major changes during the shutdown, and a completely new system, ProdSys2, is in use since December 1st, 2014 \cite{19}. ProdSys2 is based on tasks rather than individual jobs, giving better flexibility and scalability to the system. The introduction of tasks allows for more complex user workflows, such as chaining jobs. Such workflows were already possible with the previous system, but the bookkeeping had to be done by the user. DEFT, the Database Engine for Tasks, and JEDI, the Job Execution Design Interface are the ProdSys2 components most relevant to users \cite{20}. With JEDI, scout jobs (jobs running on a minimal subset of events) are executed first to estimate the needed grid resources. If all scout jobs fail, the task is automatically stopped by the system. The job brokering and management has been moved to the PanDA server side. This allows for simplification of the client tools (both PanDA and Ganga \cite{21} are supported) resulting in shorter submission times. An automatic re-trial mechanism for failed jobs is integrated into JEDI. JEDI is in use for analysis jobs since August 2014.

To cope with the higher data volume expected for LHC run 2, the Distributed Data Management system has also been re-designed. In the new system, Rucio \cite{22}, quotas for groups and users are introduced, allowing for a better management of disk space. Datasets now have a lifetime, and transfers from disk to tape space are automatically managed. Rucio is fully integrated with ProdSys2, allowing for automatic transfer of user job outputs to local disk space. Metadata such as the number of events in a dataset can also be directly queried using the Rucio client tools. More than 1500 users are daily using ATLAS distributed resources. From 2008, ATLAS established a dedicated mailing list, the Distributed Analysis Support Team (DAST). A team of expert shifters (organized in two daily 8-hour shifts to cover the European and American time zones) provides user support on JEDI, Ganga and Rucio clients, site services and issues, physics analysis tools and monitoring systems related to grid activities. More than a thousand physicists have used the DAST service, with an average of 10000 emails exchanged every year on the mailing list.

ATLAS users may submit their grid tasks to more than 100 computing sites worldwide. To ensure a high quality of service and to optimize the usage of grid resources, automatic validation of the ATLAS sites is provided by HammerCloud. The HammerCloud framework is currently used by ATLAS, CMS and LHCb, and provides continuous site testing. Sites failing the HammerCloud tests are automatically excluded from job brokerage until they can successfully execute the test jobs. The auto-exclusion mechanism is in place for analysis queues since 2010, and for production queues since 2012.

3. Distributed Analysis performances

The usage of ATLAS grid resources for analysis jobs has been constant during the long shutdown, and increased in 2015, as shown in figure \ref{fig2}. The efficiency of analysis jobs is flat over time and is of the order of 80\% (see figure \ref{fig3}). The introduction of JEDI for analysis jobs, in August 2014, did not cause any disruption in the services to users. In figure \ref{fig4} the wallclock consumption of analysis jobs is shown, and the increase of user activity in 2015 is clearly visible. The wallclock consumption of failed and canceled user jobs amounts to \(~20\\%\). Canceled jobs include jobs which are terminated by both users and the PanDA system.

Failed jobs are categorized according to the exit code, thus allowing JEDI to retry the failures that are recognized as temporary by the system. Most of the analysis jobs failures are due to crashes in the user code and amount to about 30\% of the total. Failures due to the storage are around 20\%. However the remaining failures are not easy to categorize and therefore harder
to tackle. While production jobs mostly follow repetitive patterns and are easy to instrument, user jobs tend to have a much larger variety. The average duration of user jobs is less than an hour. User jobs tend to read only a small fraction (10-20%) of the input data, and typically produce several small output files. In total, user jobs read between 10 and 20 millions input file per week, and produce a weekly average of 5 millions output files (see figure 5).

Analysis jobs put a high load on the storage systems, which are usually the weak point of the grid infrastructure. To mitigate the number of job failures due to temporary problems of the local storage, remote file access through client software such as ROOT using the XRootD protocol has been deployed by ATLAS during the shutdown [23]. The Federated ATLAS XRootD system (FAX) is a storage federation treating the storage space at all ATLAS sites as a single distributed storage system. About 1% of all ATLAS failed jobs can successfully complete using FAX fail-over. Other standard access protocols based on https or WebDAV are currently under evaluation [24].

Figure 2. The number of concurrently running grid jobs for the various production and DA activities in the period March 2014-2015. Figure from [25].

4. Conclusions
During the long shutdown of the LHC, the ATLAS collaboration revised the typical analysis workflows to improve the user experience and the usage of computing resources based on the experience of Run 1. A common data format for analysis has been studied, to optimize the usage of disk space and allowing for more efficient I/O access. A centralized reduction framework provides data reduction from PBs to a few TBs. A new analysis framework and event model have been provided, with integrated grid clients for easy access to distributed resources and providing hooks to monitor and instrument user jobs. In parallel, a new production system (ProdSys2) introducing the concept of tasks also for analysis jobs has been developed. The new data management system, Rucio, implements user and group quotas to improve the management
Figure 3. The number of completed, failed and canceled user grid jobs in the period March 2014-2015. Figure from [25].

of distributed storage. All the above components have deep impacts on the user access and usage of the ATLAS grid infrastructure. The performances of the distributed analysis resources are stable over time. The efficiency of analysis jobs is about 80%, with most failures related to the user code. User support is provided to the physicist community by a dedicated mailing list. Grid sites are continuously tested using the HammerCloud framework to ensure that analysis jobs can successfully complete.
Figure 4. The CPU wallclock consumption of completed, failed and canceled user grid jobs in the period March 2014-2015. Figure from [25].

Figure 5. The number of output files produced by user grid jobs in the period March 2014-2015. Figure from [25].
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