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ABSTRACT / SUMMARY

This paper discusses the business, administration, reliability, and usability aspects of storage systems at the Oak Ridge Leadership Computing Facility (OLCF). The OLCF has developed key competencies in architecting and administration of large-scale Lustre deployments as well as HPSS archival systems. Additionally as these systems are architected, deployed, and expanded over time reliability and availability factors are a primary driver. This paper focuses on the implementation of the "Spider" parallel Lustre file system as well as the implementation of the HPSS archive at the OLCF.

INTRODUCTION

Oak Ridge National Laboratory's Leadership Computing Facility (OLCF) continues to deliver the most powerful resources in the U.S. for open science[*]. At 2.33 petaflops peak performance, the Cray XT5 Jaguar delivered more than 1.5 billion core hours in calendar year (CY) 2010 to researchers around the world for computational simulations relevant to national and energy security; advancing the frontiers of knowledge in physical sciences and areas of biological, medical, environmental, and computer sciences; and providing world-class research facilities for the nation's science enterprise.

The OLCF is actively involved in several storage-related pursuits including media refresh, data retention policies, and file system/archive performance. As storage, network, and computing technologies continue to change; the OLCF is evolving to take advantage of new equipment that is both more capable and more cost-effective. A center-wide file system (Spider) [1] is providing the required high-performance scratch space for all OLCF computing platforms, including Jaguar. At its peak, Spider was serving more than 26,000 clients and providing 240 GB/s aggregate I/O throughput and 10 PB formatted capacity. For archival storage OLCF uses the high-performance tape archive (HPSS). Currently HPSS version 7.3.2 at OLCF is housing more than 20 PB of data with an ingest rate of between 20–40 TB every day. This paper presents the lessons learned from design, deployment, and operations of Spider and HPSS and future plans for storage and archival system deployments at the OLCF.

THE BUSINESS OF STORAGE SYSTEMS

Storage requirements for both Spider and HPSS continue to grow at high rates. In September 2010, two new Lustre file systems were added to the existing center-wide file system. These two file systems increased the amount of available disk space from 5 to 10 PB and will help improve overall availability as scheduled maintenance can be performed on each file system individually. The addition of these file systems provided a 300% increase in aggregate metadata performance and a 200% increase in aggregate bandwidth. Additional monitoring improvements for the health and performance of the file systems have also been made.

In August 2010, a software upgrade to version 7.3.2 on the HPSS archive was completed, and staff members began evaluating the next generation of tape hardware. Implementation of this release has resulted in performance improvements in the following areas.

- *Handling small files*. For most systems it is easier and more efficient to transfer and store big files; these modifications made improvements in this area for owners of smaller files. This has been a big gain for the OLCF because of the great number of small files stored by our users.

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- *Tape aggregation*. The system is now able to aggregate hundreds of small files to save time when writing to tape. This has been a tremendous gain for the OLCF.
- *Multiple streams or queues (class-of-service changes)*. This has enabled the system to process multiple files concurrently and, hence, much faster, another huge time saver for the OLCF and its users.
- *Dynamic drive configuration*. Configurations for tape and disk devices may now be added and deleted without taking a system down, giving the OLCF tremendously increased flexibility in fielding new equipment, retiring old equipment, and responding to drive failures without affecting user access.

Following this upgrade, in April 2011, twenty STK/Oracle T10KC tape drives were integrated into the HPSS production environment. This additional hardware is proving to be very valuable to the data archive in two distinct ways. The new drives provide both a 2× read/write performance improvement over the previous model hardware and a 5x increase in the amount of data that can be stored on an individual tape cartridge. Along with improved read/write times to/from these new drives, the OLCF now benefits from being able to store 5 TB on each individual tape cartridge– effectively extending the useful life of the existing tape libraries. This has allowed the OLCF to postpone its next library purchase until the first half of FY12.

The OLCF HPSS archive has experienced substantial growth over the past decade (Figure 1). The HPSS archive currently houses more than 20 PB of data, up from 12 PB a year ago. The archive is currently growing at a rate of approximately 1PB every 6 weeks, and that rate has doubled on average every year for the past several years.

Planning around such extreme growth rates, from both a physical resource perspective and an administrative perspective, while operating within a limited budget capacity, presents several challenges. The fact that tape technology and performance traditionally lags behind that of its disk/compute counterparts presents a fiscal challenge in supporting such a large delta in the amount of data taken into the archive each year. We are forced to purchase additional hardware (tape libraries, tape drives, data movers, switches, etc.) each year in order to meet operational and performance requirements. Add in the fact that much, if not the majority of the archived data needs to remain archived for multiple generations of media (a very significant amount of resources are spent in the process of repacking data from older tapes onto newer media), and a tremendous amount of money is spent simply maintaining "status quo" of the archive each year.

The OLCF recognizes that such a model of exponential archive growth is unsustainable over the long-term. We have taken steps to mitigate this problem and slow the growth rate down by introducing quotas on the amount of data users can store in their respective home and/or project areas within the archive. In addition, we recently made a request to the Top 10 users of the archive to purge any unnecessary data from the archive, and that request to voluntarily remove data yielded well over 1 PB of data that was purged from the archive.

The OLCF has two Sun/STK 9310 automated cartridge systems (ACS) and four Sun/Oracle SL8500 Modular Library Systems. The 9310s have reached the manufacturer end-of-life (EOL) and are being prepared for retirement. Each SL8500 holds up to 10,000 cartridges, and there are plans to add a fifth SL8500 tape library in 2012, bringing the total storage capacity up to 50,000 cartridges. The current SL8500 libraries house a total of 16 T10K-A tape drives (500 GB cartridges, uncompressed), 60 T10K-B tape drives (1 TB cartridges, uncompressed), and 20 T10K-C tape drives (5 TB cartridges, uncompressed). The tape drives can achieve throughput rates of 120–160 MB/s for the T10KA/Bs and up to 240 MB/s for the T10K-Cs.

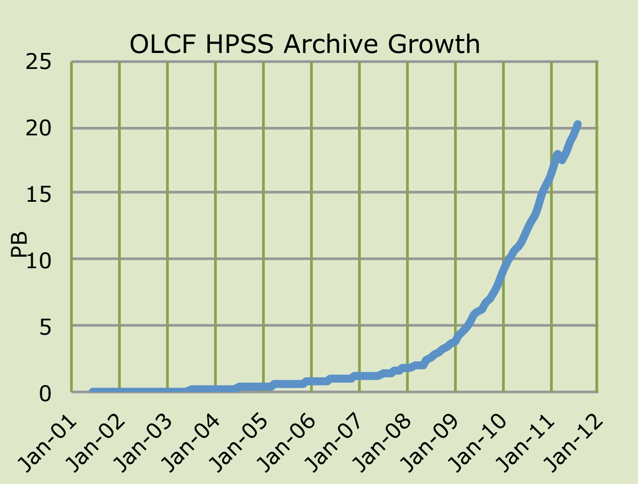

Figure 1. ***OLCF HPSS Archive Growth***

OLCF follows a collaborative open source development model for its scratch space storage system. A multi-national and multi-institutional collaboration, OpenSFS [2] was formed in 2010 by ORNL, LLNL, Cray, and Data Direct Networks. The goals of the OpenSFS organization are to provide a forum for collaboration among entities deploying file systems on leading edge high performance computing (HPC) systems, to communicate future requirements to the Lustre file system developers, and to support a release of the Lustre file system designed to meet these goals. OpenSFS provides a collaborative environment in which requirements can be aggregated, distilled, and prioritized, and development activities can be coordinated and focused to meet the needs of the broader Lustre community. This collaborative open source development model allows the OLCF to have more control and input in high-performance scalable file system development. OpenSFS recently awarded a development contract for future feature development required to meet the requirements of our next-generation systems. OpenSFS has been extremely successful in organizing the Lustre community, providing a forum for collaborative development, and embarking on development of next-generation features to continue the progression of the Lustre roadmap. OpenSFS is working closely with its European counterpart (EOFS) and has signed a memorandum of understanding to align our respective communities. At LUG 2011 all communities aligned with OpenSFS providing a unified platform from which to carry Lustre well into the future, meeting not only our current petascale requirements but providing an evolutionary path to meeting our Exascale requirements.

For archival storage systems OLCF is participating in a collaborative proprietary closed source model led by IBM. OLCF is currently providing more than 2 FTEs for this collaboration. While this model provides faster development cycles and better maintenance support compared to the open source collaborative model, the cost and business related risks associated with the private company leading the development project are the drawbacks of this model.

OLCF resources are classified as medium-confidentiality and low-availability according to the Federal Information Processing Standards (FIPS). While OLCF recognizes the cost benefit of using commodity storage hardware, the current state of technology does not allow us to deploy such technology in our archival storage systems. However, as these technologies continue to mature, it might be possible to take advantage of commodity storage hardware.

THE ADMINISTRATION OF STORAGE SYSTEMS

The day-to-day administration of a large parallel file system requires coordination between not only the members of the team working on the file system (both hardware and software), but coordination throughout the computational center as these activities have the potential to cause service outages and impact performance. The OLCF has successfully deployed packages for version control of key administration scripts, as well as centralized configuration management to handle individual node configuration convergence.

The OLCF uses Nagios [3] to monitor the health of the components of the system. Custom checks have been implemented to additionally validate the correctness of the file system – specifically are the devices mounted where they are supposed to be. Additional performance monitoring of the Lustre Network layer (LNET) are done for the Lustre servers and routers in Nagios. Currently this information is not archived for future analysis it is only used for failure detection.

We use the Lustre Monitoring Toolkit [4] developed at Lawrence Livermore National Laboratory (LLNL) to grab periodic Lustre level performance snapshots. Our current dataset is quite small so it is not useful for future predictions, but we have seen interesting trends.

Finally the OLCF has written a tool that can query the Application Programming Interface (API) to the DDN S2A9900 storage controllers. We use it to monitor the performance of the backend controllers. Currently we capture Read and Write Bandwidth and IOPS. This quick glance of the overall system performance can give administrators a fast track to problem diagnosis if say the IOPS are orders of magnitude higher than the Bandwidth. In that case we know to search out an application that is using one of the Lustre OST's served by that DDN 9900.

Being a center-wide file system, Spider is key to simulation, analysis, and even some visualization for the OLCF. Great care is taken to preserve system uptime, and maintenance activities are deferred to at a minimum once per quarter downtime. This outage affects all users of OLCF compute resources, but can help to address performance issues and overall system maintenance tasks that are harder to do real-time. Much of our administrative tasks are coordinated and done live, but with the Jaguar XT5 resource in maintenance period to limit the potential issues for users if something were to go wrong. An example is the DDN controller firmware. We can upgrade one controller out of every couplet, reboot it, and then do the partner controller without causing a file system outage. This can help push the potential quarterly outage to twice per year or even once per year depending on the software releases from DDN.

After a hardware failure caused partial file loss from the Lustre file system, a full root cause analysis led to procedural changes as well as changes in e2fsprogs packages, and spurred development of fast metadata and Lustre object storage targets for determining files that are affected by a large failure of the RAID devices on the backend.

Change Control

The OLCF has used the configuration management package CFengine [5] for several years. In our implementation of CFengine we have chosen to manage configuration files at a node level (host), a cluster level (groups of hosts related by system task), the operating system level (for each version of the OS), and a generic level that applies to all systems within the center. Additional work has gone in to configure systems that are diskless requiring some workarounds within Cfengine and the rest of the OLCF infrastructure.

In our case we use it to manage the configuration of the Lustre OSS/MDS/MGS servers – we are unable to use it to manage the storage controllers themselves. Additionally we use version control to manage the configuration of the Ethernet switches and routers for simple rollback. Managing the configuration of the Lustre file system is somewhat more difficult, but we wrote scripts and configuration files that describe the file system and can be used to start/stop the file system as well as monitor the health and status of the file systems.

We can additionally use the DDN API tool to query the configuration of the storage controllers and note a deviation from the baseline configuration specified. Work is ongoing to both correctly define the baseline as well as what acceptable deviations and periods of deviation are before notifying administrators. The storage controllers are configured to send their log data to a centralized syslog server that is running the Simple Event Correlator [10] and SEC can alert for matches to pre-configured rules. We also have SEC configured to send all log data captured over a 1 hour period to the administrators for help in solving issues like failed disks or diagnosing performance problems like SCSI commands timing out.

Our current configuration management solution does not perform validation of the configuration or syntax checking for the configuration itself. The next generation configuration management solution (BCFG2) contains input validation and syntax checking on commit.

The OLCF has both development testbeds and a pre-production testbed for verifying both changes as well as system upgrades. We have however not found any bugs at this small scale that have saved problems when the change/upgrade is deployed. Some problems only reveal themselves under sufficient load.

Cyber Security

For the Spider parallel file systems at the OLCF we commit to quarterly OS patching (matching the above mentioned quarterly planned system outages), based on analysis of risk and the location in the network. This is a delicate balance of keeping the system stable/available and satisfying the desires of Cyber Security personnel in keeping systems at the most recent patch levels. The HPSS side has weekly maintenance windows (not always taken), and has the ability to roll out security patches through those windows. Outages of the archive do not affect the production compute clusters where outages for the Spider file systems would take down the compute resources.

One example of how we can demonstrate certain file systems only being available to certain nodes is via the /proc file system on the Lustre OSS and MDS servers. We have a category 3 sensitivity file system and are working to monitor the mounts of that file system via the proc file system on the Lustre servers. If a client that is not authorized to mount the file system is detected an alert is sent to the security team and logs from the non-authorized node are gathered to see who was logged in at the time of the un-authorized access.

The OLCF has three categories of data protection that map to “publicly available information” (Category 1); data that is proprietary, sensitive, or has an export control (Category 2); or data that has additional controls required based on the sensitivity, the content being proprietary, or export control (Category 3). The OLCF has a very small amount of Category 3 data and has a separate file system for Category 3 processing. The OLCF uses Discretionary Access Controls (the Unix group memberships) for controlling access to data. The OLCF project ID is a logical container for access control; where sets of users are members of projects and have access to the same information. These mappings also carry over to the HPSS archive.

Additionally the OLCF sets secure defaults for permissions on scratch, project, and HPSS directories. The default of project team only for project areas, and user only for user scratch areas, Global home areas, and HPSS “home areas”. These permissions are enforced through our configuration management process (Cfengine), and users can change them by requesting the change via our help@nccs.gov e-mail address.

Managing the Unix group memberships for users closely is a requirement in our environment as these group memberships control access to data that can be considered under export controls or confidential under industrial partnership agreements. Ongoing audits of the memberships of groups is part of the day-to-day accounts processing done by our User Assistance Group and the HPC Operations Infrastructure team. Additional logging infrastructure is being setup in conjunction with the Lustre purging process developed through cooperation with Operations staff at NERSC.

Technology refresh

A key goal of the Spider parallel file system was to decouple the procurement and deployment of storage systems with that of large-scale compute resources at the OLCF. This goal has been realized and we are currently in the process of procuring our next generation file system for OLCF. To ease transition to these new file systems, for a period of 1 – 2 years, the current generation and next generation file systems will be operated in parallel. We have had success in migrating users between file systems, but the process is not without pitfalls and prone to compute users not paying attention to e-mail notifications and then having their jobs terminate abnormally as their application may expect to use a file system that is no longer in operations. Operating the file systems concurrently will allow users to make a gradual transition thereby minimizing the impact to our users.

Based on our enhanced understanding of I/O workloads of scientific applications, garnered from over 12 months of continuous monitoring of our file system environment coupled with a detailed understanding of our applications I/O kernels, we have developed an extensive set of benchmarks to evaluate storage system technologies offered by vendors. Our benchmarks are designed in a way that they mimic the realistic I/O workloads and also allow integrated and traditional block-based storage solution providers to bid on our RFP.

One of the biggest challenges in tape archiving lies in the area of media refreshment. While replacing, updating, or increasing the amount of front-end disk cache or servers responsible for data movement to/from disk and/or tape is a relatively straightforward and non-intrusive process, the process of media refreshment presents many challenges. In a large-scale tape archive such as that at the OLCF, where 10s of thousands of individual tape cartridges are managed, at any given time there may be thousands of tapes housing multiple PBs of data needing to be retired from service. Unfortunately, the data on those tapes no longer resides on disk cache in most cases, and must be read from the older tapes in order to be written to newer media. Under real life conditions, where resource constraints such as utilization on data mover server(s) and the number of drives available to mount such media are a reality, the process of refreshing older media can literally take years. For example, here at the OLCF we are actively retiring 10,000+ 9840B tapes from service, and based on the performance to date, we expect that process to continue for the next 2.5 to 4 years. The OLCF has recently purchased a small quantity of 9840D drives so we can read the 9840B tapes at a 30% faster rate—in order to bring us closer to the 2.5 year figure. While that process is underway, we are simultaneously retiring several thousand 9940 tapes from service, and that initiative is expected to take approximately one year to complete as well. Media refresh(es) will continue to be a "day-to-day" operation going forward. For purposes of planning and procurement, it is assumed that 5-10% of total HPSS system resources will be utilized for media refresh operations.

THE RELIABILITY AND AVAILABILITY OF STORAGE SYSTEMS

The OLCF tracks a series of metrics that reflect the performance requirements of DOE and the user community. These metrics assist staff in monitoring system performance, tracking trends, and identifying and correcting problems at scale, all to ensure that OLCF systems meet or exceed DOE and user expectations.

$$\mathrm{SA}=\left(\frac{\text{time in period} - \text{time unavailable due to outages in the period}}{\text{time in period} - \text{time unavailable due to scheduled outages in the period}}\right)\times 100$$

Scheduled Availability (SA) measures the effect of *unscheduled* downtimes on system availability. For the SA metric, scheduled maintenance, dedicated testing, and other scheduled downtimes are not included in the calculation. The SA metric is to meet or exceed an 85% scheduled availability in the first year after initial installation or a major upgrade, and to meet or exceed a 95% scheduled availability for systems in operation more than 1 year after initial installation or a major upgrade. Reference Table 1.

Table 1. OLCF Computational Resources Scheduled Availability (SA) Summary 2010–2011

System	CY 2010		CY 2011 YTD (Jan 1-Jun 30, 2011)		
	Target SA	Achieved SA	Target SA	Achieved SA through June 30, 2011	Projected SA, CY 2011
HPSS	95%	99.6%	95%	99.9%	>95%
Spider	95%	99.8%	95%	98.5%	>95%
Spider2	N/A	N/A	95%	99.9%	>95%
Spider3	N/A	N/A	95%	99.9%	>95%

Table 2. OLCF Computational Resources Overall Availability (OA) Summary 2010–2011

System	CY 2010		CY 2011 YTD (Jan 1-Jun 30, 2011)		
	Target OA	Achieved OA	Target OA	Achieved OA through June 30, 2011	Projected OA, CY 2011
HPSS	90%	98.6%	90%	98.9%	>90%
Spider	90%	99.0%	90%	96.5%	>90%
Spider2	N/A	N/A	90%	99.1%	~99%
Spider3	N/A	N/A	90%	99.2%	~99%

$$\mathrm{OA}=\left(\frac{\text{time in period} - \text{time unavailable due to outages in the period}}{\text{time in period}}\right)\times 100$$

Overall Availability (OA) measures the effect of both *scheduled and unscheduled* downtimes on system availability. The OA metric is to meet or exceed an 80% overall availability in the first year after initial installation or a major upgrade, and to meet or exceed a 90% overall availability for systems in operation more than 1 year after initial installation or a major upgrade. Reference Table 2. As indicated by these numbers, both HPSS and our Spider file systems provide extremely high availability. Overall availability of these systems continues to dramatically exceed our operational requirements. The decrease in overall availability in one of our Spider file systems in 2011 compared to 2010 was due to an increase in the number of dedicated system times taken to evaluate new features and stabilize the next Lustre release. Spider2 and Spider3 remained available during these dedicated system times thereby minimizing impact to users.

Within HPSS, DB2 is used as the storage mechanism for all file/device metadata (ownership, status, location, etc.). DB2 has been proven in the field over many years and is well known for its reliability and availability features.

The front-end disk cache for the HPSS tape archive is comprised of several RAID6 arrays, with individual LUNS "owned" by mover servers responsible for data flow to/from disk. Currently, in our configuration here at the

OLCF, each mover has a single FC or IB path to a target LUN, but we are actively working on modifying that configuration in order to provide multipathing for our disk cache.

HPSS has the ability to store data on multiple levels of tape if so desired. Here at the OLCF, by default, data is written to one level of tape when migrated from the front-end disk cache. Users have the option of specifying a different “Class of Service” in order to have their data written to two levels of tape—providing an extra level of protection in case a media problem is encountered. Due to cost concerns, that is only encouraged and/or recommended for critical data.

While currently not in use at OLCF, HPSS does have High Availability capabilities based on Red Hat Linux cluster services. In this model, HPSS can provide failover redundancy for critical HPSS components—core server, data movers, and gateway nodes.

A feature that will soon be incorporated into HPSS is RAIT–Redundant Array of Independent Tape. RAIT will provide an additional level of redundancy and fault tolerance related to media failures without suffering the full cost penalty associated with the traditional method of having data on more than one level of tape.

Maintenance Activities

Maintenance activities for the Spider file systems are planned for once per quarter and planning for the “next” maintenance window begins shortly after the “previous” maintenance ends. It starts with a post-mortem analysis of the previous maintenance, and then developing a list of items to perform. At ~2 weeks pre-outage tasks are capped for the upcoming maintenance. A full outage plan is developed including any dependencies that the Lustre team has on other teams inside HPC Operations. This plan is documented on the internal wiki, and is shared through several normally scheduled weekly meetings as well as any outage/maintenance prep meetings. Coordination with the Facilities group is also necessary if one of the reasons for the outage is work being done to the power or cooling infrastructure. This planning process helps us to document upcoming changes/modifications, record their completion date, and also learn from issues that may come up during the maintenance – making the next maintenance hopefully smoother. They also help to enforce overall system knowledge in the administrative team and enforce, through the evaluation of the planned steps, a best practices approach to system administration.

Data Integrity

For Spider the RAID protections are the only data protections that are in place system wide. Applications can choose to add data protections in their simulation and modeling, but we’ve found that if we enforce anything it hinders performance and may not be what the application needs. End-to-end checksums are currently under evaluation for the next-generation Spider deployment.

End-to-end checksums is a feature recently introduced to HPSS. While not currently in use at OLCF, checksum utilities allow a user to perform a checksum of file content and place the results in a User Defined Attribute for later comparison if/when the file is retrieved [6]. At this time at the OLCF, individual users/departments in some cases perform pre and post retrieval checksums in order to verify data integrity.

24 x 7 Support Model

In support of a 24x7 operation, we use Nagios to monitor the correct configuration of the file system, and either through SMS messaging or direct phone calls from the 24x7 Computing Operations Center, notify the on-call administrator for the system of any critical event that causes availability to be degraded or lost. In the event of facility events during off hours, the Operations Center will call the HPC Operations Group Leader and then will notify affected teams. In the case of the Lustre team, scripts have been developed to quickly put the DDN controllers into power saving mode, power down the OSSes, MDSes, etc. to lower the heat load in the room. The DDN S2A9900 controllers have a disk sleep mode that parks the heads and spins down the disk.

THE USABILITY OF STORAGE SYSTEMS

Conventional methods for addressing I/O bottlenecks, such as increasing I/O backend capability by adding more disks with higher speeds, are unlikely to keep up with the performance issues due to the costs associated with storage. The problem is further exacerbated by the inefficiency of I/O performance; some applications are unable to achieve a significant fraction of the peak performance of the storage system. This can be due to a variety of factors the complexity of traditional I/O methods, where the developer has to make a heroic effort to optimize the application I/O. This limit on usability directly impacts the possible performance of the application. The OLCF has implemented a multi-point approach to addressing these challenges.

The ADIOS I/O framework was designed with the aforementioned concerns in mind. The ADIOS I/O framework [9] not only addresses the system I/O issues, but also provides an easy-to-use mechanism for the scientific developers to work from I/O skeleton applications. Through the use of an optional metadata file, which describes the output data and enables automatic generation of the output routines, the burden on the user is substantially reduced. ADIOS componentizes different methods of I/O, allowing the user to easily select the optimal method. In concert with data staging, this work exemplifies a next generation framework for I/O.

As common in many next-generation software projects, the the biggest challenge is often one of technology adoption, that is, getting users to change from current I/O implementations to ADIOS. As the ADIOS ecosystem continues to grow, we believe that ADIOS will gain a wider spread acceptance.

ADIOS and our eSiMon dashboard are used by the combustion, climate, nuclear, astrophysics, and relativity communities. In particular we have created a I/O skeleton generation system, using ADIOS, and have applied this in 10 applications, to make it easy for computing centers to analyze I/O performance from many of the leading LCF applications, with virtually no working knowledge of each application on their systems.

ADIOS has worked well with all current users, and have often shown over a 10X improvement of using other I/O implementations; see Figure 2 for I/O performance of the S3D and PMCL3D simulations on the Jaguar system.

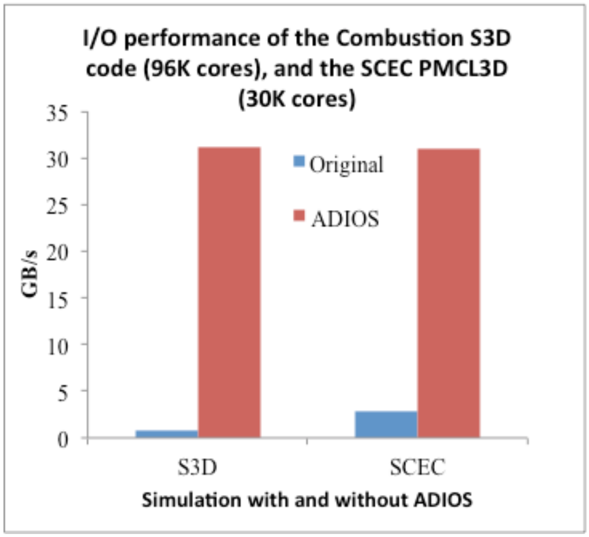

Figure 2. ADIOS performance.

CONCLUSIONS

Oak Ridge Leadership Computing Facility has developed extensive developed key competencies in architecting and administration of large-scale Lustre deployments as well as HPSS archival systems. Lessons learned from past Lustre and HPSS deployments and upgrades help us to better adopt to changing technology and user requirements.

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