Lessons Learned from Sloan Digital Sky Survey Operations

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ABSTRACT

Astronomy is changing. Large projects, large collaborations, and large budgets are becoming the norm. The Sloan Digital Sky Survey (SDSS) is one example of this new astronomy, and in operating the original survey, we put in place and learned many valuable operating principles. Scientists sometimes have the tendency to invent everything themselves but when budgets are large, deadlines are many, and both are tight, learning from others and applying it appropriately can make the difference between success and failure. We offer here our experiences well as our thoughts, opinions, and beliefs on what we learned in operating the SDSS.

Keywords: SDSS, Observatories, Operations, Lessons

1. INTRODUCTION

The Sloan Digital Sky Survey\textsuperscript{1} was an ambitious and largely successful effort to conduct a homogeneous survey of a large piece of the sky — some seven to ten thousand square degrees in five photometric bandpasses, supplemented by extensive optical spectroscopy of $\approx 10^6$ galaxies, $10^5$ quasars, and $10^5$ stellar objects. It was a very coordinated, unified survey involving precise photometry and follow-up spectroscopy on a specifically chosen region of sky, mostly in the northern Galactic cap. Although not meeting its entire set of initial goals during the official five year baseline, the shortcomings were few, the ultimate successes many, and we learned from both. The responsibility for the success lies in many, many talented people who contributed significant parts of their time, energy, and careers in the effort. In addition, the project benefited from an excellent purpose-built telescope\textsuperscript{2} and matching set of unique, state of the art instruments: a large-field imaging camera,\textsuperscript{3} dual multi-object fiber-fed spectrographs,\textsuperscript{4} and an automated photometry telescope with near real-time data capability, along with extensive photometric,\textsuperscript{5–9} astrometric,\textsuperscript{10} and spectroscopic systems and pipelines. The latest data release paper, that for Data Release 6, is Adelman et al. (2008).\textsuperscript{11}

In the hopes that some of this work will be of use beyond its immediate benefit to the SDSS, we attempt here to describe SDSS operations, paying particular attention to the site observing and engineering efforts and the many lessons we learned during the survey. We endeavored to quantitatively measure operations efficiency during the survey and used these metrics to help determine our operational strategies. Boroski et al. (2002)\textsuperscript{12} discuss the development of the SDSS operations baseline in more detail as well as the importance of systems engineering and external reviews in early SDSS commissioning and operations. Not everything in operations can be strictly quantified, however, and we therefore had sometimes to rely on our accumulated experiences, wisdom, and philosophies as well, some of which are promulgated here.
2. GOALS AND SPECIFICATIONS

One of the SDSS’s fundamental strengths was the careful planning and specifying of the survey from the early days of the project. The SDSS’s mission, goals, and requirements were carefully detailed and constructed so that the ultimate survey was an intricate weaving of details, carefully orchestrated to achieve the desired goals. The survey telescope, instruments, and sky coverage, for example, were jointly optimized to efficiently achieve the desired scientific results in terms of both money and time.

This careful specification process gave operations a very strong base from which to proceed. The project’s specifications were translated to form quantitative measurements to evaluate the survey’s state and progress. This pre-defined survey structure allowed us to evaluate proposed changes against stated requirements, keeping the mission focused and on track. While the temptation to continually expand the scientific capacity of our data was large, we did not want to end up with a dataset that became a smaller datasets, each a homogeneous subset of an overall, inhomogeneous dataset. Thus, the deciding principle was that in general, such improvements were made only if they had little or no impact on the original data quality objectives (positively or negatively) and did not affect efficiency too negatively.

Within the SDSS imaging survey, the initially-formulated data quality objectives, as well as the camera and software realizations, were complete enough to prevent many extraneous new capabilities and improvements being tacked on to the survey. The exceptions to this clarity were within the calibration and reduction processes, both of which could be applied to the entire dataset once perfected, thereby assuring continued uniformity. At least in theory. As it turns out, spectroscopic targeting was affected by changing photometric reductions. An object assigned a fiber in one version of the reductions, might not have been in a later version, and vice versa. Thus, there are non-uniformities of varying degrees in the spectroscopic sample selection due to these changes. In addition, if any part of the data is eventually found lacking during final reduction (like additional calibrations), it may be too late to go back and acquire the necessary data or information to fix it. Thus, even data reductions have to be at a fairly complete state early on to fully assess the quality and completeness of the incoming data.

Although well defined in the original survey specifications, the SDSS spectroscopic operational objectives developed much less lucidly than did those for the imaging survey. The main “problem” was that the signal to noise of the gathered spectra was far in excess of what was needed to satisfy the survey’s main objective: red-shift determination. We were also late to develop testable functional requirements for the immense and varied science beyond this objective. The net result was that the ultimate capability of the spectroscopic survey was determined primarily by efficiency — how much could we do and still finish the survey in a reasonable time. Much effort and many misunderstandings could have been avoided had the real value of the spectroscopic survey beyond mere redshifts been initially included and fully specified at the start of the survey.

As with the imaging, we also went through several attempts at determining the best way to calibrate each plate’s spectra during the night. We ended up taking a significant amount of calibration data that ultimately never got used.

Lesson: Have well-specified project objectives which include a scientific motivation, quantitative objective, and a proposed test at the start of the project. Evaluate all activity and proposed changes against these objectives. Fervently avoid mission creep. Plan carefully for data calibration.

3. BASELINES AND TIME-TRACKING

A set of goals and objectives become meaningless if they are not continuously measured and held up for review. This effort of establishing baselines and tracking performance is especially relevant for a time-limited (five-year) project like the SDSS. To this end, we made initial time estimates for all observing operations, including overhead due to instrument change, telescope slewing, centering, focusing, etc. With these estimates, we constructed a survey completion baseline and regularly evaluated this against current progress.

Once survey operations officially started, we soon found that we were not meeting all of our benchmarks. There were some obvious errors in our baselines, but other causes were less easy to identify and needed a more detailed breakdown of both the baseline and the used operational time to track them down. We tried various ways...
to gather the latter data, but the only one that really worked was to develop automatic, accurate time/event-tracking directly into our operational software.\textsuperscript{13} Every primary command automatically recorded its start and stop times in a running log file. We developed additional software to extract these data and compare them to the detailed baseline. With this information in hand, we could then direct our resources towards specific problem areas and rapidly move towards meeting or exceeding our incremental baselines. The data also allowed us to more precisely test our baseline assumptions on nightly weather conditions. The results from regularly monitoring baseline progress, including our improvements in problem areas, allowed us to demonstrate to ourselves and just as importantly, our sponsors, continual progress and improvement.

The spectroscopic survey benefited enormously from this attention to the baseline. Once we had a clear understanding of both the baseline and our data, we realized a fundamental mistake: we had been observing to the baseline exposure time estimate, not required signal to noise ratio. In good conditions, we could achieve the desired signal to noise in less time than was in the baseline. In worse conditions, of course, we needed more time. Once corrected, this realization helped us immensely in understanding our baseline and in providing a quality, uniform spectroscopic data set. Boroski et al. (2002) further discuss the development of the SDSS operations baselines.

Lesson: Establish an expected baseline for all operations. Build automatic task time-tracking into your operations software along with corresponding time-analysis code from the beginning of your project. Continually compare your real efforts to your baseline, but be sure you are comparing against and measuring the right things.

4. SYSTEMS AND DATA TELEMERTY

Just as important as quantifying our operational efficiency was our effort to establish baseline operating parameters for our hardware as well. Many different institutions and people developed and built the SDSS hardware, yet it all had to be maintained, troubleshooting, etc. by local personnel on the engineering and nighttime operations staffs. Establishing how things look when behaving properly, therefore, was just as important as having the ability to see how they are when misbehaving.

We created a very detailed system of data logging using EPICS (Experimental Physics and Industrial Control System\textsuperscript{14}) we called the Telescope Performance Monitor, TPM.\textsuperscript{14} This system monitored many different signals including telescope positions, drive currents, temperatures, etc. It was capable of frequent sampling rates and realtime display of the data as well as archival plots and trend analysis. Time and time again, the TPM proved invaluable in solving problems at the telescope.

During early equipment troubleshooting, we learned three things about our initial implementation of the TPM: 1) not all necessary signals were being (properly) recorded at the appropriate frequencies, 2) the data were not readily accessible for quick analysis and correlation with other data, and 3) it was not always clear which signal was what; that is a signal’s name did not always unambiguously identify its nature. During further system development, therefore, we systematically tested and reviewed each measured signal and created a generic set of data analysis tools to allow the most commonly-performed analysis to proceed quickly. We started documenting the signal names and what each was measuring, but never fully-developed this as much as we could. In the end, therefore, the TPM was of most use only to engineers familiar with a given system’s specific details.

While this EPICS-based system monitored low-level signals, mostly from the telescope and infrastructure, we created another system to monitor instrument and data quality status. The SDSS instruments all had built-in communication channels to relay instrument status and operating conditions. We created master server programs which controlled communication to each instrument and relayed the status bits to another program called the Watcher. The Watcher also talked to the data acquisition computers and did some data analysis of its own to be able to report on the current status of instrument well-being and data quality. When a parameter became out of specification, it sounded an alarm, notifying the appropriate people of the problem. One problem in our implementation of the alarm function was that it only notified people via email and a red button on its software display panel. If no one was reading email or running the display software, or worse, the network was down, alarms would get missed. A better implementation would include other contact methods such as telephone, pagers, etc.

\textsuperscript{1}http://www.aps.anl.gov/epics/
Since an alarm that is always alarming really ends up alarming no one, alarm thresholds were carefully adjusted to meaningful levels during the course of the project. Equally problematic were alarms that indicated problems with no immediate solutions nor required actions. While many such conditions may indeed need to be monitored and addressed, they do not need to be handled the same way as alarms that require immediate action. We never quite fully addressed this problem, but our thought was if there is no action that can or needs to be taken now, don’t alarm. Instead, find some other way to record the problem so that it can be analyzed at some convenient time in the (near) future.

Other ways that alarms got ignored included there being no one clearly responsible for handling the alarm, or no established procedures for how to address the alarm. We therefore tried to establish procedures which described who is responsible for handling the alarms, how to indicate an alarm is being addressed, and finally, what to do to fix the cause of the alarm.

At first, the Watcher merely displayed alarms and informed people of problems. This service was very valuable, but we soon realized we needed more. For example, if the telescope stopped moving during a slew or track, the watch would clearly indicate that the telescope had stopped moving, but not always why it had stopped. Because the SDSS telescope is highly-interlocked to protect it, its instruments, and its users, there were many root causes that might cause the telescope to stop moving. Since the Watcher already had access to all the low-level interlock signals, we added the interlock logic within it, thereby making it possible for the Watcher to indicate the root cause of all interlock-driven problems as well as the problems themselves. Thus, the Watcher became not only a problem notification tool, but also a problem diagnosis tool. It is unclear which mode was most valuable. Both were needed and relied upon extensively.

Lesson: Hardware telemetry is extremely valuable, but make sure the data are accurate, sampled properly, and easy to analyze. Don’t wait until there is a problem with the equipment before you test for problems in your telemetry. Alarm when values get out of specification, but be certain the alarms are heard and not being sent when urgent action is not needed. Ensure alarms have known remedies and response procedures. In complicated systems, computer diagnostics can greatly help debugging and can often pinpoint the low-level root cause of a much higher level symptom. Document what you measure.

5. PERSONNEL AND THE SCIENTIST DILEMMA

Astronomy projects often need very specifically-skilled people to play largely support roles. Scientists are not always needed in all skilled positions, but when they are, they present an additional complication: they usually want to do science. Rewards and professional development need to be included in their work plan. The conflicting needs of the project (support) and the desires of the scientists (science) form what may be referred to as the *scientist dilemma*. The scientist dilemma occurs whenever highly-skilled, scientifically motivated people are needed for support work. This work could be, as in the case discussed here, operations and observations, but the dilemma applies equally well to programmers, data analysts, archivists, etc.

5.1 The Dilemma

The SDSS collaboration realized early on that Ph.D.-level people were going to be required for nightly operations. The telescope, instrument, software, and data systems were complex enough that a high level of skill was demanded to successfully use and develop them. In addition, the nightly observing plan was flexible enough to the current conditions that scientific tradeoffs between different courses of action would need to be evaluated in real time to optimize each night’s observations. We also realized that a stable group of skilled observers could not only hone the operating systems and procedures to improve both efficiency and data uniformity, but could also take over some of the software and hardware development work as well, more finely tuning the initial efforts to fit real observing conditions. This work resulted in continual operational efficiency improvements and left the

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It wasn’t so much the degree itself that was necessary, but several factors that come with it: observing experience, data handling and analysis, scientific context, problem solving, and an exposure to scientific computing environments. It is certainly possible to find these skills and experiences in someone without a Ph.D., but they are more common in those with it.
system in such a state that by the end of the project, Ph.D.-level scientists were no longer required to make operations successful. This result also helped address the endgame issue mentioned in the next section.

The problem with this approach is that whereas the project wanted Ph.D.-level astronomers to learn and understand the complex operational systems, spend non-observing time improving the systems and performing required auxiliary tasks (instrument calibration, data integrity checks, etc.), decide coherent efficient nightly observing strategies, and operate the telescopes and instruments nightly during observations, most Ph.D-level astronomers want to do (at least some) astronomy — hence the dilemma.

The only way to really address this dilemma is to simply staff accordingly, allowing your professional staff enough time to do their three main tasks: in this case, observing, system verification and development, and scientific research. Without the latter, not only do you not have happy workers willing to devote themselves to the project for its duration, but you also leave them with no career path beyond future, non-scientific support work.

The inevitable argument against this obvious solution to this critical dilemma is money. Hiring more people costs more money. Since projects are usually run with less money than they really need, additional personnel are often deemed an un-obtainable extravagance. There are several arguments against this position, though:

- When you factor in project downtime, intervening overtime, recruitment, relocation, training, etc., replacing an employee is expensive. It can be cheaper to hire an additional employee and keep the ones you have than to constantly have to bring-in new replacements as current employees move on to protect their careers.
- Having skilled observers directly participate in developing operations not only increased project efficiency (thereby decreasing operations costs), but provided staffing in an area that otherwise would need to be staffed additionally.
- And finally, the personnel costs we are discussing here are not really an extravagance. They simply represent the real cost of employing scientists. Scientists come with additional overhead which budgets need to reflect.

Ultimately, the observers were staffed in such a way that roughly half their time could be spent observing, a quarter on systems verification and development, and a quarter on professional development and scientific research. We also created a rotating month away from assigned observatory duties (roughly annually), so dedicated time could be spent either starting a new project or pushing an ongoing one out the door to completion. Correspondingly, we made available a small amount of financial resources for these activities.

The endgame is also an important concern for project staffing. Obviously, it is advantageous to the project to ensure their key people stay until the very end of the project. However, given the time it can take to find jobs in astronomy, people simply will not be able to stay to the project’s very last day if there is no guarantee of some additional employment past it. Staffing plans must therefore be made to provide useful employment for key employees for some time past the project’s end, or otherwise provide for bringing in, or doing without, last minute replacements. Loyalty alone cannot be relied on.

Lesson: Hiring scientists comes at a cost: they must have some time and resources to do science. Replacing staff is a time-consuming, costly affair. It can be cheaper to keep good, happy, staff, than make do with a rotation of less expensive short-timers. Keeping people to the end of a mission necessitates ways of guaranteeing employment past said end.

5.2 The Management Corollary

Scientists are not usually trained as managers and managers are not usually trained as scientists. There are some talented people who can play both roles, but rather than relying on the exception, it is safer to plan for the more commonplace scenario.

Like software engineers, professional managers exist for a reason. They are trained in evaluating personnel, logistics, scheduling, fundraising, etc. — all things not usually found on the transcript of your average scientist. On the other hand, they are not always well-versed on the science of their missions and less able to make well-informed compromises between a project’s logistical and scientific needs. The Large Synoptic Survey Telescope
project\(^1\) is addressing this problem by putting both a trained scientist and an experienced manager in each management box of their organizational chart\(^2\). This approach seems sound and time will tell how well this works, but the important point is to recognize that science leadership and management leadership are two different things and it is rare to find someone sufficiently effective in both.

Similarly, scientists and not usually engineers, and engineers are not usually scientists. This same discussion applies to a variety of possible job titles. Hire people to do what they do best, but help them work together by appropriate levels of management, communication, and training. Management and technical training for those that don’t have it can be quite beneficial.

Finally, in multi-institution projects, rivalries, jealousies, and competitions often arise amongst the different institutions. These things can sometimes actually be beneficial to a project, but at other times, they must be fairly and professionally curtailed before the project derailed itself from within. Project-level management, therefore, needs to strive to be above institutional partisanship. While it is natural and often unavoidable to have project management come directly from an individual member institution, it is important for management to work hard to not appear (and more importantly, to not be) too attached to an individual partner institution.

Lesson: Recognize the strengths and weaknesses of your management and work to temper both. Both technical and logistical leadership are needed throughout the project. Hire the skills you need. Avoid management with strong institutional biases in a multi-institutional project.

### 5.3 Staffing and Scheduling

Astronomy operations necessitate shift work and scheduling shift work can be difficult. In addition, despite common procedures and training, different observers will inevitably collect the data in different ways, possibly affecting data uniformity and efficiency. Since the SDSS observers worked in pairs, we decided to create a schedule where roughly half the observing nights of each observer were spent with the same partner, and half with the others. This arrangement allowed for each team to develop some cohesiveness and efficiency together as well as to propagate new ideas and procedures to the rest of the team and integrate out any major differences.

In addition to the standard night shifts, we also established an afternoon-evening swing shift position. This position was rotated into, each observer taking a turn in it, and offered a few salient features: 1) it allowed telescope and instrument setup to begin early in the day so any problems could be addressed before observations, 2) it allowed the night staff to come in later than would have otherwise been practical had they needed to do the setup themselves, helping to make the long observing nights more tolerable, 3) it allowed an overlap between the day staff and the observing team to discuss daytime work and other observing-related issues, and almost as important, 4) it allowed the night-working observers an occasional chance to work mostly in daylight.

We realized early on we needed another unique position among the observing staff: a coordinator of some sort. This person could serve as a conduit of information between the observers and the rest of the collaboration, bridging the day/night gaps and providing representation of the observing staff to the rest of the project and the rest of the project to the observing staff. This capability was vital in melding the project’s needs with on-site operations. With emails and project meetings accumulating throughout the day, it could be difficult for the night observers to discover what new information they needed to know from the day’s activity for their upcoming night shift. This coordinator therefore filtered all the day’s information and created a way for the night’s observers to “pull” the information they needed at the start of each shift. This person also worked some night shifts, but only half as many as the rest of the team, to spend remaining hours in daytime work, accessible to the rest of the collaboration and at least the first half of the night time shifts\(^3\).

Lesson: Schedule operations staff so they can establish rapport and efficiency with each other, but allow for cross-pollination of new ideas and procedures. Create some part-time daytime positions amongst the night staff\(^4\). It is probably worth noting that the lead author of this paper held this coordinator position during the SDSS-I survey and came to view it as vital to the success of the project, greatly helping with project communications and establishing uniform operations procedures. Thus, many of the lessons stated here come from the viewpoint of this position, although additional experiences at other organizations and discussions and input from other project members contribute as well.
staff to provide vital overlap and communication with the local day crew and the project at large. A single coordinator, or “lead observer” served us well as a single voice for and conduit between the observing staff and the rest of the collaboration.

6. PRODUCT DELIVERY AND HANDOVER

While the SDSS may have employed highly-skilled observers and telescope engineers on site, most of the project’s developers were off-site. Thus, when a new system was delivered to the site, it had to be taken care of by the site staff, and usually not by the system developers. Each delivered system should therefore have had a handover document establishing the required deliverables (documentation, spares, procedures, training, etc.) before the developer was allowed to disavow responsibility for it. As it turns out, though, the SDSS never formally established this approach and we therefore often relied on developers for continued system support, sometimes well after they were on to other projects. Also, local staff often spent more time than might otherwise have been necessary when working with these systems. In rare cases, we simply went without desired changes to a system because we could find no way to implement them ourselves.

Lesson: Establish formal handover procedures for all deliverable systems. Strive to take complete ownership (it may not always be possible) of a system on-site once delivered.

7. SOFTWARE AND VERSION CONTROL

We start this section first with the lesson.

Lesson: Software is difficult. It takes time. It often takes trained professionals to get done right. It requires user input and evaluation throughout development. Plan for an active software life after delivery.

7.1 Development

When computers were expensive and not very powerful, most things were done in hardware, or not at all. These days, though, with incredible amounts of power available on our laps and desks, software does so much more than it used to, but too often, only old-style resources and requirements are allocated to the effort. Software needs requirements, management, and a testing plan, just like hardware. Ideally, it should test the limits of the hardware from the beginning and be integrated into hardware and other software acceptance testing and baseline measurements.

We solve problems in software because it is usually more flexible and quicker to develop than are hardware solutions. These advantages, though, often lead to the temptation to purposefully not define a full set of requirements from the start, relying on software’s nature as a fast, flexible solution to provide a last minute product appropriate to its task. While there are controlled versions of this approach often referred to as extreme programming, which can indeed be beneficial, allowing software requirements to change with time as a project progresses nearly always guarantees that it will be the last thing done. If you mean to take an extreme programming or agile approach to software development, by all means, do so. It can be a quite useful powerful approach. But if you are simply allowing the rest of the project to eventually define your software in order to save time at the start by not fully specifying a set of requirements, be aware that this means your software will probably be over budget and behind schedule, practically by definition.

Many astronomers have significant experience with data reduction software; fewer, with operations software. The two are fundamentally different, however, and skills at one do not necessarily translate to the other. The SDSS was fortunate to have some extremely talented programmers, but few were really experienced in operations software and few would call themselves professional programmers. As such, they often had other priorities besides code ease of use and maintenance, efficiency, and general ability to function properly in a complex, interactive, time-critical environment. In addition, while they did a reasonable job of predicting the future model of operations and its environment, less thought was given to how to correct the software once parts of the model were inevitably proven wrong by real operations. Plans were made for software delivery, but not for its continued maintenance and development. Through a devoted effort of some original developers, newly-allocated

**See, for example, [http://www.extremeprogramming.org](http://www.extremeprogramming.org)**
resources, and contributions by the observers, the operations software did become reasonably complete and efficient, but the path there was often painful. The salary of an experienced, on-site programmer prepared to handle the real-word changes/improvements necessary in the “delivered” code, would probably have been paid for several times over by increased productivity and efficiency in operations throughout the project.

7.2 Version Control

Proper source and binary version control is essential for smooth operations and problem tracking, both realtime and post-mortem. Some SDSS developers used version control systems religiously, some sometimes, and others, not at all. Initially. Software management and problem tracking/solving took a huge step forward once we initiated a mandatory version control policy. All software version numbers were reported in the appropriate night logs and FITS headers automatically, making the identification of problem data caused by software bugs much more straightforward than it would have been otherwise.

We used the widely-available cvs package for source code version control, and the less-widely known, but equally valuable FermiLab product, ups/upd†† for binary control. Both packages allowed us to always know what version of the software was running when, to quickly revert versions when necessary, and to record what changes were made to each version. These practices were absolutely necessary for effective software management and data quality assurance.

The version control creed became so deep in the SDSS culture that even our procedures and documentation were version controlled. In this way, we could trace changes to the procedures and correlate them with data taken on any given night as well as allow all the observers the freedom to edit and improve them, all in a documented, controllable manner.

7.3 A Time for Testing

The observers ultimately controlled the procedures/documentation repository as well as the binaries that were being run at any given time. They tested new builds of code only on non-survey, bright time engineering nights. The developers proposed tests for their new changes and the observers tried to augment those with their own regression tests (although this system was never as fully-developed as it should/could have been). Developers tried to be available during testing, should there be a fix needed.

A new version of code was only declared “current” and used during the science run when it passed all its tests during the scheduled engineering time. If it did not pass, the previous software version remained current and the developer could work on fixes for the next engineering time. Because the survey did not operate during the peak of the monthly full moon time, we created two opportunities for software testing, one at the end of each monthly run before the bright time and one at the beginning of the next, just after.

These engineering nights might take away from potential science time in other projects, but they could still be worth the loss. The set schedule allowed for clear start and stop dates for operational and hardware changes and provided opportunities to regularly test the observing systems for potential problems before they became too large.

Since our engineering night tests could sometimes leave bugs un-discovered in the new software, we relied on our binary version control system discussed earlier to allow the flexibility to revert to an older version during the night if a fatal bug was found. Only under rare circumstances (critical bugs that could not be reverted out of and negatively impacted data quality or operating efficiency) were new versions of code tested outside of engineering time. Bugs that were discovered during science nights, but that could be worked around, were. They were then (hopefully) addressed the following engineering cycle.

Lesson: Software is hard. Budget time and resources adequately. Allow and plan for end-user involvement in the specifications as well as post-delivery support and further development. Integrate software version control project-wide and provide ample testing time outside of standard operations. Do not operate with un-tested changes. Allow a mechanism for reverting software versions. Software engineers exist for a reason. Use them, but guide them with scientists and end-users.

†† http://www.fnal.gov/docs/products/ups/
8. WRITTEN PROCEDURES

We quickly learned that it was very important to have well-written, thorough operational procedures. These served several purposes:

- Help ensure uniformity in procedures (hence data) across observers.
- Serve as memory aids for rarely-done, or not recently performed tasks.
- Help speed training of new observers.
- Document existing procedures for evaluation by other project members in light of their own areas of expertise.

These procedures continued to be developed and modified throughout the entire survey. In addition, we found there were also a lot of little tidbits of information we called folklore which didn’t seem to fit in any strictly-defined procedure. We thus created a web-based system to allow the easy addition and editing of these small bits of information. They were broadly categorized into many different areas and like the standard procedures, were completely searchable for easier retrieval. Sometimes, these bits of folklore became so numerous or complex that we could then gather them together and form a formal procedure to replace the folklore category. This mechanism turned out to be a good way to document valuable information that seemingly had no other place for storage.

Lesson: Procedures and documentation written by the developers is a start, but for real utility, they need to be continually modified and improved by those actually using them. A version-controlled documentation repository provided this facility for us. Finding places for small bits of information that don’t make a manual or procedure by themselves can be quite important.

9. COMMUNICATION AND BUG REPORTING

As with most human endeavors, communication in any astronomical project is very important. More specifically, open and abundant communication is very important. Sometimes this idea runs contrary to people’s inclinations, but like many in the business world have discovered (eg. [http://blog.redfin.com], Schwartz 2005), we found talking openly about our problems and weaknesses as well as our successes and strengths actually helped, not hurt, the project. Firstly, it built a sense of trust and honesty among our participants and the outside world. And secondly, it opened us up to insights and solutions from a much larger body of people than might otherwise have been involved. And finally, it kept the collaboration involved and informed about the project.

Open communications means everyone should feel free to discuss problems, solutions and other concerns. Hiding problems behind private mailing lists, closed doors, and secret communiqué only increases the morale-zapping rumor mill and decreases the number of possible solutions that can be offered. The SDSS produced free, detailed, public nightlogs from the observers, offered a plethora of archived mailing lists for all aspects of the project, held regular (often weekly) phone meetings to discuss operations, controls, engineering, data reduction and distribution, etc., and held bi-annual general collaboration and engineering planning meetings which allowed for significant face to face time amongst the participants. Project management routinely traveled from site to site in the collaboration, meeting people in their home space, and learning the environment in which the team’s members operated. We encouraged wide participation in both the bi-annual meetings, including people involved in operations and data reduction/quality in addition to the project engineers, scientists and management. Such attendance helped place the project, workload, and any coming changes into context.

The nightlogs, mail archive, meetings, and an openly-accessible problem reporting system all worked together to establish good communications throughout the project. Within the atmosphere this effort created, people could freely discuss problems as things to be solved not as things requiring blame to be placed. If a mistake was made, the system allowed that mistake to be made and thus the system could be improved to help prevent future similar mistakes. Blame became less of an issue as positive steps to solve problems became more of one.
The mail archive and problem reporting system made finding past occurrences of problems easier. Providing a project-level mail archive also meant each project member was relieved of the responsibility of maintaining their own file system for the myriad of project emails. They could subscribe to the lists they wanted to, avoiding the rest, thus keeping the flow of relevant information relatively high. The archive allowed us to locate old messages, search for past events, and even scan critical lists for information without having to wade through our own (usually overflowing) mail queue.

Open communication also pertains to data rights. As a community, we’ve taken practically all approaches possible with respect to data rights and each has its strengths and weaknesses. We tend, however, to lean towards public data rights as soon as possible, for the following reasons:

- We are in the science business. Disseminating our results is part of what we do. Science progresses more quickly when data are released sooner.

- In today’s large projects, community support is vital for continued funding and operations. Such support is easier to gather when giving something freely in return.

- The temptation to keep data exclusive as a benefit to the project’s members is large, but there will always be an insider edge regardless of the data rights themselves. Insiders will understand the structure, quality, and limitations of the data better than anyone else. You also do not want to restrict your insiders’ ability to do science by restricting their possible set of collaborators.

- These new databases are large, complex affairs\(^1\). Having more public data access helps them develop more quickly. The SDSS had a period of exclusive data rights for the collaboration prior to each data release. Until late in the project, however, the data were not as easily accessible during this proprietary period as they were in the public releases. This scenario is simply a reflection of the complexity of data releases. It is most efficient not to split your resources into developing proprietary and public data release systems.

For bug/problem reporting, we used a modified version of the GNU GNATS\(^2\) system. This system allowed us to set up a variety of broad problem categories, each with individually-assigned notification lists and auto-notification of status changes to the submitter (this feedback is important to help show the submitter that something is happening). Any member of the collaboration could sign up for any category’s notification list and all could see whichever problem reports they desired. We modified the stock GNU system to include a Scheduling category where we could place a problem report in various approved or un-approved states. We found this modification allowed us to continue to promote problem reporting by everyone, but gave us more control on the priorities of addressing them. Just because someone filed a problem report doesn’t necessarily mean people should drop all they’re doing to address it. During the active development phases of the project, we held regular meetings to review and prioritize problem reports and their solutions, usually with input from the problem submitters.

Lesson: Fostering open, free communications invests everyone in the project, provides for easier problem troubleshooting, and involves more people in the solutions than might otherwise be. Email along with phone and video conferences are important components of this effort, but do not adequately substitute for general face to face meetings. Searchable, common archives of communications serve many important objectives and become valuable resources of information. Establish a culture of problem solving, not blame placing. Build a sense of community and involvement. Evaluate your data rights policy carefully. Proprietary rights are not as obviously beneficial as they may seem. Openly learn from your mistakes.

10. STABILITY VS. CHANGE

A survey or other long term project values stability. Research science, however, values continuous change and evolutionary improvements. Balancing these two motivations was one of the most difficult and time-consuming

\(^1\)So we should also add a note here to budget for this effort carefully. Just like software development, data distribution will take significant time and resources and is not easily handled by an informal effort.

\(^2\)http://www.gnu.org/software/gnats/
aspects of the SDSS. While we can’t offer a short recipe for providing this balance, we instead offer a few points for consideration.

- A full understanding of the scientific necessity and operational impact of a proposed change is vital for evaluating its worth.

- There are almost always unseen impacts from change. Tread carefully and thoroughly. The regression tests you already put in place will serve you well here.

- If a change is decided upon, don’t be afraid to change back if things don’t go well. Corollary: make it easy to change back after initiating a change.

Establishing a series of change control boards at different levels of the project can help maintain both focus and a cross-discipline outlook when evaluating change proposals. It also lengthens the timescale needed to enact a change. At early levels of the project, this characteristic can be a detriment, but later on, it can be a definite benefit.

11. CONCLUSIONS

The SDSS was by no means the first such successful large project in this new era of astronomy, but it was arguably one with the most significant impact relative to its cost. This success was due to several simultaneous efforts, most of which are discussed here: choosing and maintaining specific, clear, and interesting objectives (Sections 2 and 10), careful attention to project metrics and efficiencies (Section 3 and 4), a large, cooperative collaboration of dedicated people (Sections 5 and 9), and efficient hardware, software, and procedures designed to work together from the start (Sections 1, 4, 6, 7, and 8).

Astronomy’s new projects must maintain and inspire both their collaboration participants and their funders. They must attract top talent and keep them with the project. They must avoid fatal miscalculations that could cost long delays and increasingly larger amounts of money. While the SDSS did not invent the ideas presented here, it did at least end up applying them reasonably well and we believe the key points will be relevant to many future projects trying hard to ensure their early success.

We discussed many issues in this paper, but the three areas we believe are most key are:

- **Addressing the scientist dilemma**: You simply cannot hire scientists into 100% service positions and expect either to reap their full benefit or keep them. Scientists are not always the best managers and the best managers are not always scientists. Your project needs both. There are various solutions to these problems, but they cannot be ignored.

- **Software**: We expect more and more out of our software which in turn does more and more for us. Even small efficiency increases made through software that is repeatedly run can benefit the bottom line immensely. The field of software engineering developed because the days of a single person in front of a keyboard and screen turning out high quality innovative software solutions in a few days are largely over. Software needs should be carefully evaluated from the beginning, including getting user input, providing documentation and handover material, maintenance, and testing. Plan ahead for continued software development after delivery.

- **Communication**: As in any human endeavor, excellent communications are vital for astronomical projects. A temptation is often present to downplay and hide potentially negative news and to keep valuable information private, both in an attempt to increase one’s own value to the project and the project’s value to the community. Both these temptations must be overcome. Your collaboration exists for a reason — trust them, use them, *include* them. The better people are informed, the more involved they become and the more they contribute. Establish a teamwork culture of solving problems together, not one of assigning blame or assuring job security through information hoarding. Evaluate your data distribution policy carefully.
The suggestions and solutions presented here may not work for every project in every situation. The issues they address, however, are universal and any successful project will have to address them to ensure its success. We hope that if nothing else, this work will help raise these important issues and inspire you to find your own solutions that keep astronomy growing and flourishing deep into this new era.

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