A Low Cost Distributed Computing Approach to Pulsar Searches at a Small College[1]

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ABSTRACT

We describe a distributed processing cluster of inexpensive Linux machines developed jointly by the Astronomy and Computer Science departments at Haverford College which has been successfully used to search a large volume of data from a recent radio pulsar survey. Analysis of radio pulsar surveys requires significant computational resources to handle the demanding data storage and processing needs. One goal of this project was to explore issues encountered when processing a large amount of pulsar survey data with limited computational resources. This cluster, which was developed and activated in only a few weeks by supervised undergraduate summer research students, used existing decommissioned computers, the campus network, and a script-based, client-oriented, self-scheduled data distribution approach to process the data. This setup provided simplicity, efficiency, and "on-the-fly" scalability at low cost. The entire 570 GB data set from the pulsar survey was processed at Haverford over the course of a ten-week summer period using this cluster. We conclude that this cluster can serve as a useful computational model in cases where data processing must be carried out on a limited budget. We have also constructed a DVD archive of the raw survey data in order to investigate the feasibility of using DVD as an inexpensive and easily accessible raw data storage format for pulsar surveys. DVD-based storage has not been widely explored in the pulsar community, but it has several advantages. The DVD archive we have constructed is reliable, portable, inexpensive, and can be easily read by any standard modern machine.

Subject headings:

1. Introduction and Motivation

Radio pulsars, which are exotic, rapidly spinning collapsed stars, are named for the characteristic radio pulses that make them detectable. Pulsars are not completely understood, but it is

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thought that they form when a massive star explodes and the core collapses into a super-dense star called a neutron star. Extreme electromagnetic fields accelerate charges, and a beam of radio waves is emitted, which is seen as a pulsed source as the pulsar spins. Pulsars were first detected accidentally around 35 years ago (Hewish et al. 1968) and they have since been found with spin periods as fast as 1.56 ms (Backer et al. 1982).

Pulsars are interesting from both astronomical and physical standpoints. Discovering more pulsars aids in the understanding of the underlying Galactic pulsar distribution and population as well as pulsar formation and evolution. Pulsars can also be used as probes of the interstellar medium by observing the effects of radio wave propagation through interstellar plasma. Pulsars are also useful for testing physical theories, such as General Relativity (e.g., Taylor 1994), and the physics of the pulsar emission process. Pulsars provide a rare opportunity to study extreme physics with their tremendous magnetic fields and huge densities. Their extremely regular pulse periods and unusual physical conditions make pulsars excellent tools for observational physics. Complete reviews of pulsars, their properties, and their uses are presented in Manchester & Taylor (1977) and Lyne & Graham-Smith (1998).

In order to find and study pulsars, very large data sets must be searched for their characteristic periodicities. This analysis requires significant computational resources in the form of processing power and data storage capability and data accessibility. At a small college with a limited research budget, these resources may not be readily available, making pulsar data processing difficult or impossible unless alternative options can be explored. The Astronomy and Computer Science departments at Haverford College have jointly developed an inexpensive distributed processing cluster of decommissioned machines running Linux. We aimed to explore the issues encountered when searching for pulsars with old, decommissioned computers in a networked cluster. Our goal was not only to discover new pulsars in the survey, but also to test the feasibility of using such a cluster for large-scale pulsar survey processing in the small college research environment.

The survey, which was conducted in collaboration with the pulsar group at McGill University, targeted 56 unidentified gamma-ray sources from the 3rd EGRET catalog (Hartman et al. 1999) at intermediate Galactic latitudes. The survey used the multibeam receiver (Staveley-Smith et al. 1996) on the Parkes 64-meter radio telescope in Parkes, Australia. This combination of instruments has been very successfully used to find pulsars in previous radio pulsar surveys (Manchester et al. 2001; Morris et al. 2002; Kramer et al. 2003; Crawford et al. 2001; Edwards et al. 2001). It is possible that some of the target gamma-ray sources could be powered by previously unidentified energetic radio pulsars. Radio pulsar counterparts to these sources would not only be interesting systems to study individually (e.g., Roberts et al. 2002), but they would also help resolve outstanding questions about the pulsar emission mechanism and the physical origin of pulsar radiation at different wavelengths (see, e.g., Harding et al. 2004 and references therein). More detailed descriptions of this survey, including the science goals, results, and implications of the survey, are presented elsewhere (Ransom et al. 2003; Roberts et al. 2003).

We discuss the development, deployment, advantages, and disadvantages of our chosen method of parallelization of the computational problem at hand. Our data processing problem, though quite large, is embarrassingly parallel (Wilkinson & Allen 1999), meaning that the task can be easily divided up and tasked to separate client machines for local processing without additional interprocess communication. After consideration of various methods of implementation, we settled on a simple setup that used existing low-cost technologies. The benefits of this approach included ease of adding additional processors, modular design, low cost, and rapid deployment. This set of benefits was well-suited to our small college research program and can serve as a computational model for similar institutions.

We have also constructed an archive of the raw survey data on DVD in order to investigate the feasibility of using DVD as an inexpensive and accessible format for raw data storage for pulsar surveys. DVD-based storage has not been widely explored in the pulsar community for data storage. We describe this archive and the advantages of using DVD for pulsar survey data storage. We also compare the costs of using DVD vs. Digital Linear Tape IV (DLT-IV), a commonly used data storage format in pulsar astronomy.

2. Survey Data and Data Processing Details

Each of the 56 unidentified EGRET gamma-ray sources targeted in the survey was observed with the 1400-MHz 13-beam multibeam receiver on the Parkes radio telescope. Owing to the uncertainty in the position of each EGRET source (which typically has an uncertainty of about 1 square degree), full spatial coverage of each source required four multibeam pointings of 13 beams each (see, e.g., Staveley-Smith et al. 1996; Manchester et al. 2001). A total of 3016 beams were recorded at the telescope to be processed in the survey[2]. For each telescope pointing, we used a 35-minute observation time which was sampled at 0.125 ms with 1-bit per sample. 96 contiguous frequency channels of 3 MHz each were recorded, providing a total observing bandwidth of 288 MHz. The observing setup was similar to that described in detail by Manchester et al. (2001) for the Parkes Multibeam Pulsar Survey. Each resulting beam contained 194.8 MB of raw data, corresponding to a total of 573.7 GB of raw survey data to be stored and processed.

When a radio pulse from a distant pulsar travels through space, plasma in the interstellar medium disperses the pulse, causing lower frequency components to be delayed relative to higher frequency components. This dispersion effect, quantified by a dispersion measure (DM), is one indicator of the distance to the pulsar. The DM is the integrated column density of free electrons between Earth and the pulsar (e.g., Manchester & Taylor 1977). To detect a pulsar, one must first correct for dispersion by appropriately phase adjusting each frequency channel. However, if one does not know *a priori* how far away the pulsar is, or if a pulsar signature even exists in the data,

[2]Nine pointings were observed twice, and one pointing was not observed. All other pointings were unique.

the DM to correct for is unknown. The data must therefore be dedispersed at a large number of trial DMs, with each trial separately searched for a pulsar signature. In general, aside from an initial processing overhead, searching in dispersion measure space increases the complexity of the processing linearly by a function of the number of trial dispersion measures. For our search, we dedispersed each data set at 450 trial DMs, ranging from 0 to 700 pc cm^{-3}. This easily encompassed the expected maximum DM for Galactic pulsars in the directions observed (Cordes & Lazio 2002).[3]

After each trial dedispersion, the frequency channels were summed to create a time series. This time series was then Fourier transformed via a Fast Fourier Transform (FFT) to identify strong signal candidates in the resulting power spectrum. The characteristic signal of interest is a wideband, extremely regular series of radio pulses. FFTs are well equipped for finding this type of signal, although radio frequency interference (RFI) can mask these signatures. To mitigate RFI, we filtered our data for certain known interference signals.

The raw data from the survey were originally processed at McGill University using custom pulsar search software (Ransom 2001; Ransom, Eikenberry, & Middleditch 2002). During this first processing run, several new pulsars were discovered, and all previously known pulsars that were spatially coincident with the target sources were redetected. The second pass at processing, which is described here, was conducted at Haverford College and used different software (Lorimer et al. 2000). The analysis at Haverford was primarily done by undergraduates during a ten-week summer research period. The reprocessing of the data aimed to see whether there were pulsars that were missed during the first processing pass. Of particular interest were long period pulsars ($P \gtrsim 20$ ms); fewer than expected were found in the first processing run. We therefore aggregated the data prior to processing to reduce the data size and thus significantly decrease the processing time while still maintaining sensitivity to longer-period pulsars. The data were aggregated into contiguous groups of 4 frequency channels (effectively reducing the resolution from 3 MHz to 12 MHz) and into contiguous groups of 16 time samples (effectively reducing the sampling time from 0.125 ms to 2.0 ms). This reduced the size of each data set by a factor of 64, which greatly eased the computational burden.

According to the Nyquist theorem (Nyquist 1928), we were in principle sensitive to pulsars with periods as fast as 4 ms in the aggregated data, but in practice the sensitivity was degraded for periods below about 20 ms (this is partially due to intra-channel dispersion effects which cannot be corrected for in the processing). This sensitivity degradation is clearly shown in Figure 1, which shows minimum detectable 1400 MHz flux density as a function of pulsar period for a range of assumed pulsar DMs. We redetected all of the new and previously known pulsars which had been found in the first processing run in this period range, thereby demonstrating the effectiveness of this approach.

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[3]One pc, which stands for parsec, is equal to 3.0856×10^{18} cm.

3. Possible Computing Approaches

In order to practically process the large amount of data from the survey, we needed to use multiple processors in a cluster. There were several possible approaches to parallelizing the processing, but the choices were greatly limited by the technology and facilities locally available to us. For the processing at Haverford College, we had seven older 400-MHz Intel Celeron PCs, one new 2.5-GHz Pentium 4 PC, and the Haverford College network at our disposal. We ran Red Hat 9.0 Linux on these machines. We also had access to a number of existing software packages designed for pulsar searching.

Given the available technology, our choice was between implementing a parallel program using a message-passing library, such as MPI/PVM, or writing our own distribution and processing system. While using MPI could enhance performance, it required either writing new MPI-enhanced parallel software or extensive porting of existing software. In either case, this would have been a time consuming task which would have delayed processing in the limited time available. We found that the existing software would compile and run on Red Hat 9.0 and could do all of the needed processing. We decided to implement our own distribution system, which is described in the next section.

4. Computer Cluster Details

The initial pulsar search cluster consisted of a set of 8 PCs running Linux (Red Hat 9.0) and two 180 GB disks. One of the PCs (a 400-MHz Intel Celeron with 128 MB RAM) was a dedicated file server and workstation, but did no actual data processing. Another machine (a 2.5-GHz Pentium 4 with 512 MB RAM) served simultaneously as a secondary file server (data only) and processing client. The remaining six 400-MHz Celerons, with 128 MB RAM each, were dedicated processing clients. In terms of cluster nomenclature, the cluster was not technically a Beowulf because it lacked a dedicated network, and some machines performed multiple user-based tasks. Rather, the cluster can be best described as a semi-dedicated Network of Workstations (NOW) (Culler & Singh 1999) running a data-parallel type algorithm taking advantage of the existing data partitioned 195 MB unaggregated beam structure (Grama et al. 2003).

The cluster was divided into clients and servers, with all control left in the hands of the clients, allowing for self-maintained load balancing. The servers used Network File System (NFS) file servers that were remotely mounted by every client machine. The NFS server hosted a flat database file that contains a list of beams, their current processing status, and location information. It also stored the raw data file for each beam and the results returned by the clients.

Client machines ran scripts written in PERL that parsed the database on the server, found available beams for processing, downloaded them to their local hard drives, and ran a series of pre-existing commands on the local data. Each client processed one beam at a time. This resulted in a nearly linear increase in processing potential as more clients were added, limited only by network load (discussed below). Once a client completed processing, it returned the relevant files to the server and looked for more work to do.

System status and control were achieved through control files on the server. Clients maintained individual log files, status files, and timing files on the server. They also checked certain server-based text files for instructions. This method of control allowed for monitoring and maintenance of the cluster, either through specialized monitoring scripts or a text editor. In this state, the clients allowed for limited error checking and recovery, with the ability to recover from bad data files by marking them as failed and moving on to new data.

Performing the full analysis (all 450 DM trials) on a single aggregated beam with the modern 2.5-GHz Pentium 4 computer took on average about 28 minutes. On one of the older computers (400-MHz Intel Celeron), it took on average approximately 100 minutes (only about a factor of three longer). Of this time, approximately 36 seconds on average was spent downloading the data to the local disk (corresponding to a 5.4 MB/s transfer rate over the local network). This download time was roughly constant for all machines (independent of the processor speed) since the download was limited by the network transfer speed. All other functions in the processing were slower by about a factor of three for the slower machines compared to the modern computer. Figure 2 and Table 1 give more detailed timing information for the cluster.

5. Benefits of Our Cluster Processing Approach

There were several significant benefits in using this cluster processing approach.

1. **Scalability.** Because our cluster was completely maintained by the clients themselves, it was very simple to add an additional client without the need to restart the cluster. One simply remote mounted the NFS drive on a Red Hat 9.0 machine, copied two files to the local drive, created two files and a directory, and edited one configuration line. All other needed files were loaded from the server as needed. With practice, it took less than 5 minutes to get an additional (preinstalled) Red Hat 9.0 machine up and added to the cluster. Additional machines have since been added to the cluster as they have been decommissioned in order to increase the processing capability of the cluster for future projects.

2. **Use of Existing Technology.** Instead of having to rewrite signal-processing software for use with MPI, we were able to use existing software written in both C and Fortran. Specifically, we used the pulsar search packages Seek and Sigproc written by Dunc Lorimer (e.g., Lorimer et al 2000)[4]. Additionally, we used PERL, NFS, and the Linux operating system, all of which are well-tested and freely available products.

[4]See also http://www.jb.man.ac.uk/∼drl.

3. **Simplicity.** For communication, we used plain text files that were edited with either custom scripts or a text editor. This allowed for quick debugging and error detection, as well as convenient control of the cluster remotely over a secure shell. Additionally, since all the scripts were plain text files, making changes simply required editing the script and restarting the client processes.

4. **Efficiency.** Our use of existing technology allowed for rapid development and deployment. The cluster was fully operational and searching for pulsars in a few weeks. This meant that the survey processing could be completed in the ten-week summer research period.

5. **Near-linear Speedup.** We found that, on average, the older 400-MHz Celerons took about 100 minutes to fully process a single beam, while the new 2.5-GHz Pentium 4 took only 28 minutes. Of this processing time, both systems averaged a network download time of just 36 seconds, comprising six tenths of a percent of the total processing time for the older systems and two percent for the newer machine (see Table 1 for additional timing results). Because the download-to-computation time ratio was so small, we would expect a near-linear increase in processing capability as additional computers are added to the cluster. This linear increase should hold until download times start to overlap, at which point processing times would slowly increase. However, the cluster software used dedicated file downloads with scheduling scripts with built-in download staggering to avoid overlapped downloads.

6. **Dependability.** The cluster was maintained using detailed client logs, timing records and monitoring scripts. Errors from incompletely processed data sets were recorded for later reprocessing. The existence of many large data sets, each implying substantial computation time per processing node, motivated the use of self-scheduling (Hummel, Schonberg, & Flynn 1992) at the beam level. Benefits of this approach included ease of implementation, near maximal throughput, and trackable progress.

7. **Cost.** The costs of developing the cluster were kept low, since Red Hat 9.0 (Linux), PERL, and NFS are all free products, as are Seek and Sigproc. Additionally, we were able to use older decommissioned computers, readily available from computer labs and other sources. A cursory analysis of prices on eBay in July 2003 showed bulk lots of older computers available. For example, fifty 350-MHz Pentium II machines were selling for for $3500 ($70 per machine), and twenty-five 500-MHz Pentium III machines were selling for $3000 ($120 per machine). Either of these lots would offer significantly more raw processing power than the equivalent cost in new machines for our purpose. Our cluster cost us $360 for two 180 GB hard drives and $835 for the new Pentium 4 machine. The older Celerons were scavenged, and we used the available campus network for networking. The approximate cost of the entire cluster was $1200, not including the additional hidden costs of using the college network, lab space, and power. Student stipend costs are also not included in this figure. Developing the cluster at low cost was an important consideration since research funds were limited.

6. Drawbacks of Our Cluster Processing Approach

The problems we encountered with our cluster were primarily easily fixed coding flaws or manageable technical issues. The largest problem was also one of our benefits: the lack of a central management server. While this provided for excellent modularity and ease of development, it also made the cluster harder to maintain and check for errors during processing. Still, we found that the trade off for rapid development was worthwhile. We were able to start the data processing in a couple of weeks because we did not need to write server or signal processing software.

Other issues we encountered included troublesome remote file locking (we settled this by using three separate file locking mechanisms simultaneously) and coding issues. Additionally, network security was a concern because we used the campus network for client-server communication instead of a dedicated network. This required that we keep all computers up-to-date and secure. This is an intrinsic problem with NOW-type architectures (Culler & Singh 1999).

Our approach worked very well for an embarrassingly parallel data processing and distribution problem with large data sets (such as the pulsar search described here), but it would be inappropriate for problems requiring interprocess communication. For such problems, a language with a richer set of communication primitives, such as MPI, would be more appropriate.

7. Motivation for a DVD Archive of the Raw Survey Data

We have also constructed a DVD archive of the raw survey data that were processed with the cluster in order to investigate the feasibility of using DVD as an inexpensive and easily accessible format for raw data storage for pulsar surveys. The DVD format has not yet been widely explored in the pulsar community, but it has several advantages. The archive we have made is reliable, portable, inexpensive, and easily read on any standard modern machine with a DVD-ROM drive. The archive is presently available for extraction of specific data from the survey if needed for reprocessing at any time in the future.

The raw survey data were originally recorded and stored on DLT-IV tape at the Parkes telescope. DLT-IV is the standard medium used for pulsar data recording at several observatories (including Parkes). DLT systems are used because they can record vast amounts of data in real time at the telescope. DLT-IV tape media can hold up to 35 GB of uncompressed raw data per tape. The main motivation for using DLT, aside from its real time data acquisition capability, is convenience in data consolidation, since a relatively small number of DLT tapes can often hold all the data for a given pulsar survey project. However, this particular convenience comes at a significant cost. DLT 8000 tape drives, which are required to read the tapes, sell for approximately \$2300[5], a sizable investment for research programs at small colleges which have very limited research

[5]All prices quoted in this paper are from June 2003 unless otherwise specified.

budgets. These drives are required not only for writing the data (for instance, at the telescope) and for making backups of the data, but also for reading the data from tape before data processing can even begin. Furthermore, the DLT-IV storage medium itself costs about $65 per tape. Since the medium is magnetic and sequentially organized (i.e., implying a single point of failure), the tapes can be subject to wear and catastrophic failure through repeated usage as well as from unregulated environmental conditions (e.g., heat and humidity). With a single point of failure, an entire tape is lost. In some cases, this can correspond to entire days of telescope time being lost. The failure rate of DLT-IV tapes in the Parkes Multibeam Pulsar Survey (Manchester et al. 2001; Morris et al. 2002; Kramer et al. 2003) was a few percent, which, for a large pulsar survey, adds significantly to the expense of the project when re-observation costs are factored in. At a small college such as Haverford, the usefulness of a DLT drive would also be limited since its use is so specialized. A DVD writer/reader is more generically useful for other research projects in departments across the college, particularly if the drive is external and can be easily moved to different machines and locations.

Since DVD drives are now available on standard modern computers, a DVD archive can be easily accessed for reprocessing at a later time. No specialized drive is needed, making the data very portable across many platforms (Linux, Windows, Mac) and accessible to researchers who do not have the funds for specialized peripherals, such as DLT drives. The DVDs themselves are also easily transported and can be copied and shipped in the mail with little cost or worry about failure. DVDs are also not as susceptible to changes in environmental conditions which affect reliability. For instance, no environmentally controlled room is required for storage, and DVDs are not subject to wear through contact during many tape passes.

DVD writers can be purchased for about $400, which is very affordable for observatories or research groups that are charged with maintaining, copying, or disseminating raw pulsar data. DVD media are also inexpensive and can be obtained for a cost of less than $1.50 per disc. Table 2 outlines the cost structure for storing the EGRET survey raw data on DVD vs. DLT-IV tape. Archiving the data on DVD is significantly less expensive.

8. DVD Archive Details

The complete EGRET survey consisted of 3016 distinct beams of 194.8 MB each, totaling 573.7 GB of raw data to be archived on DVD. In constructing the DVD archive, each pointing was remotely read off DLT tape from a drive located at McGill University, split into 13 separate beams, then transferred over the internet to a local machine in our cluster at Haverford. The 13 split beams of raw data from a single pointing were then written to a single DVD along with a plain text file describing the contents of the DVD (including a listing of the 13 beam positions). An example of one of these text files is presented in Figure 3. Each disc in the DVD archive contains about 2.5 GB of data, corresponding to an efficiency of use of the storage space of about 53%. This made the archive more manageable than it would be if we had split pointings across discs. A complete index of the DVD archive is accessible via the world wide web[6]. Information about each EGRET target source is also presented on this page, as is observing information about each individual pointing. The individual beam position (in both J2000 celestial coordinates and Galactic coordinates) for every beam in the survey is also listed on this web page, making identification of the relevant DVDs and extraction of the data for reprocessing easy.

In making the DVD archive, we compiled a comparison of the costs of using DVD vs. DLT-IV tape for storing our survey data (Table 2). Even when using the DVD storage space inefficiently for the sake of ease of data management (53% of space used vs. 75% for the 22 DLT-IV tapes in the EGRET survey), the cost per GB of storage for DVD is still better by a factor of about four ($0.55/GB vs. $2.48/GB for DLT-IV). The figure improves to a factor of six in favor of DVD if both DVD and DLT storage space are used 100% efficiently. If one includes the auxiliary costs of creating and maintaining the survey in both cases, then the total cost of creating the archive (including a DVD writer, DVD carrying case, and a DLT 8000 drive) would be cheaper by a factor of five in the case of DVD ($760 for DVD vs. $3730 for DLT)[7].

DVD is the more reliable, portable, and inexpensive storage medium for long-term archiving of raw pulsar survey data. These benefits are offset only by the relatively small storage capability of each individual DVD (currently a maximum of 4.7 GB), which is an important issue if individual observations produce data files in excess of this limit. However, the small storage capability of DVD also has an advantage in terms of the amount of data lost in the event of failure. A DVD writer could be purchased for about $400 and installed at any observatory for immediate backup of pulsar data and for easy dissemination (copying and mailing) of archived data to researchers who are off-site.

9. Results, Conclusions, and Possible Future Work

All 3016 beams from the radio pulsar survey of 56 unidentified EGRET sources, corresponding to 573.7 GB of raw survey data, were processed with the networked Linux cluster developed by the Astronomy and Computer Science departments at Haverford College. Most of this work was conducted by undergraduates during a ten-week summer research period. We redetected all of the new and previously known pulsars found in the first processing run conducted at McGill University in the period range to which we were sensitive ($P \gtrsim 20$ ms). This demonstrates the feasibility of this processing approach. We conclude that the computer cluster and method of analysis described here can serve as a useful model for scientific computation in the small college environment in which there are limited resources. We hope to modify the existing cluster software for use in other computationally intensive data processing or modeling projects at Haverford. The DVD archive of

[6]http://cs.haverford.edu/pulsar

[7]This does not include the cost of student labor to burn the DVDs for the archive.

the raw survey data that we have constructed is reliable, portable, inexpensive, and easily read on any standard modern machine. The archive data are available for future extraction and reprocessing by members of the pulsar community. We conclude that for pulsar surveys in which individual files can be organized not to exceed 4.7 GB (such as the survey described here), DVD is an attractive alternative format to DLT for data storage.

For the continued development of the cluster, we may seek to revise existing software for improved performance and reliability, perhaps though decentralized error checking and recovery and through analysis of cluster timing results with the intent of finding and removing bottlenecks. Furthermore, the existing signal processing and pulsar search software which was used could be modified. One possibility would be to add an “out-of-core” FFT so that analysis could be performed on larger data sets using these machines with their significant memory limitations, as well as completely RAM-based processing, perhaps with a RAM disk. Preliminary tests have shown a 10% speedup with the use of a RAM disk. We plan to continue to add additional machines to the cluster, which is a simple and easy way to extend to power of the cluster. The addition of more workstations, both in the vicinity of the cluster and over the campus network, will increase the processing output and allow us to test cluster scalability. The possibility exists in the future to re-engineer our cluster to use a SETI@home-style, large-scale distribution system (Anderson et al. 2002). Another area of interest involves exploring the impact of various scheduling, error detection and recovery policies on bother performance and dependability. These might include guided self-scheduling (Polychronopoulos & Kuck 1987), factoring (Hummel, Schonberg, & Flynn 1992), and speculation-based policies (Huang, Kalbarczyk, & Iyer 1998).

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REFERENCES

Anderson, D. P. et al. 2002, Communications of the ACM, 45, 56

Backer, D. C., Kulkarni, S. R., Heiles, C., Davis, M. M., & Goss, W. M. 1982, Nature, 300, 615

Cordes, J. M. & Lazio, T. J. W. 2002, astro-ph/0207156

Crawford, F. 2000, Ph.D. thesis, Massachusetts Institute of Technology

Crawford, F., Kaspi, V. M., Manchester, R. N., Lyne, A. G., Camilo, F., & D'Amico, N. 2001, Astrophysical Journal, 553, 367

Culler, D. E. & Singh, J. P. 1999, Parallel Computer Architecture (San Francisco: Morgan Kaufmann Publishers)

Edwards, R. T., Bailes, M., van Straten, W., & Britton, M. C. 2001, Monthly Notices of the Royal Astronomical Society, 326, 358

Grama, A., Gupta, A., Karypis, G., & Kumar, V. 2003, Introduction to Parallel Computing. Second Edition (England: Pearson Education Limited)

Harding, A. K., Gonthier, P. L., Grenier, I. A., & Perrot, C. A. 2004, Advances in Space Research, 33, 571

Hartman, R. C. et al. 1999, Astrophysical Journal Supplement, 123, 79

Hewish A., Bell S. J., Pilkington J. D. H., Scott P. F., & Collins R. A., 1968, Nature, 217, 709

Huang, Y., Kalbarczyk, Z., & Iyer, R. K. 1998, in Proceedings of the 30th Conference on Winter Simulation, 475

Hummel, S. F., Shonberg, E., & Flynn, L. E. 1992, Communications of the ACM, 35, 90

Kramer, M. et al. 2003, Monthly Notices of the Royal Astronomical Society, 342, 1299

Lorimer, D. R., Kramer, M., Müller, P., Wex, N., Jessner, A., Lange, C., & Wielebinski, R. 2000, Astronomy & Astrophysics, 358, 169

Lyne, A. G. & Graham-Smith, F. 1998, Pulsar Astronomy (Cambridge: Cambridge University Press)

Manchester, R. N. & Taylor, J. H. 1977, Pulsars (San Francisco: Freeman)

Manchester, R. N. et al. 2001, Monthly Notices of the Royal Astronomical Society, 328, 17

Morris, D. J. et al. 2002, Monthly Notices of the Royal Astronomical Society, 335, 275

Nyquist, H. 1928., AIEE Trans., 47, 617

Polychronopoulos, C. D., & Kuck, D. J. 1987, IEEE Transactions on Computers, 36, 1425

Ransom, S. M. 2001, Ph.D. thesis, Harvard Univ.

Ransom, S. M., Eikenberry, S. S., & Middleditch, J. 2002, Astronomical Journal, 124, 1788

Ransom, S. M., Livingstone, M. A., Hessels, J. W. T., Roberts, M. S. E., Tam, C., Kaspi, V. M., & Crawford, F. 2003, American Astronomical Society, HEAD Meeting, 35, #20.10

Roberts, M. S. E., Hessels, J. W. T., Ransom, S. M., Kaspi, V. M., Freire, P. C. C., Crawford, F., & Lorimer, D. R. 2002, Astrophysical Journal Letters, 577, L19

Roberts, M. S. E., Ransom, S. M., Hessels, J. W. T., Livingstone, M. A., Tam, C., Kaspi, V. M., & Crawford, F. 2003, IAU Symposium 218: Young Neutron Stars and Their Environments, Sydney, Australia, 156

Staveley-Smith, L. et al. 1996, Publications of the Astronomical Society of Australia, 13, 243

Taylor, J. H. 1994, Reviews of Modern Physics, 66, 711

Wilkinson, B. & Allen, M. 1999, Parallel Programming (New Jersey: Prentice Hall)

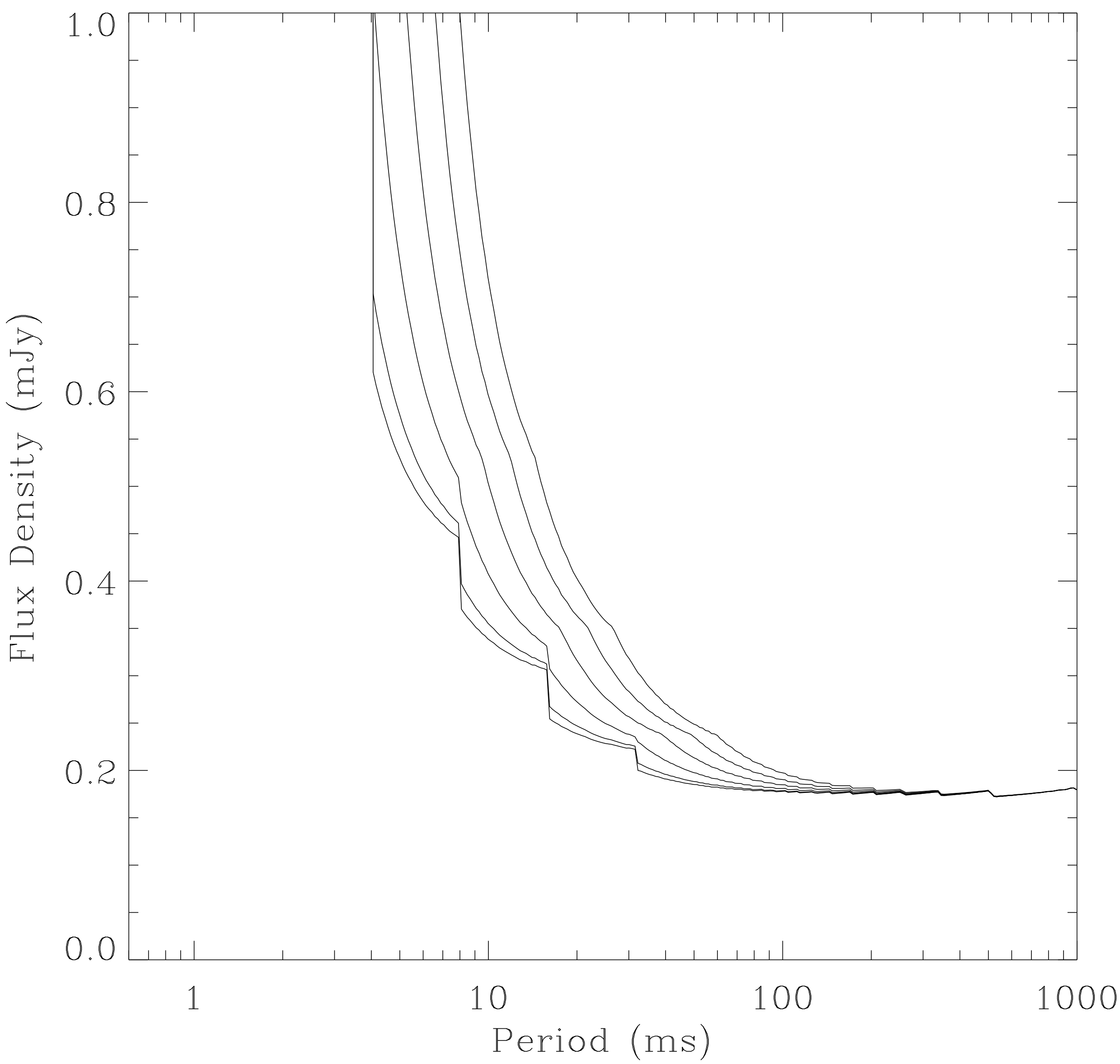

Fig. 1.— Minimum detectable 1400 MHz flux density as a function of pulsar period for the EGRET survey described here. The six curves correspond to assumed DM values of 0, 20, 40, 60, 80, and 100 pc cm^{-3} (in order from left to right). An intrinsic duty cycle of 5% for the pulsed emission is assumed in the sensitivity calculation. For pulsar periods faster than about 20 ms, the sensitivity to pulsations is sharply degraded. The details of the sensitivity calculation are outlined in Crawford (2000) and Manchester et al. (2001). This plot applies to the aggregated (resampled) data processed at Haverford College using the computer cluster described here.

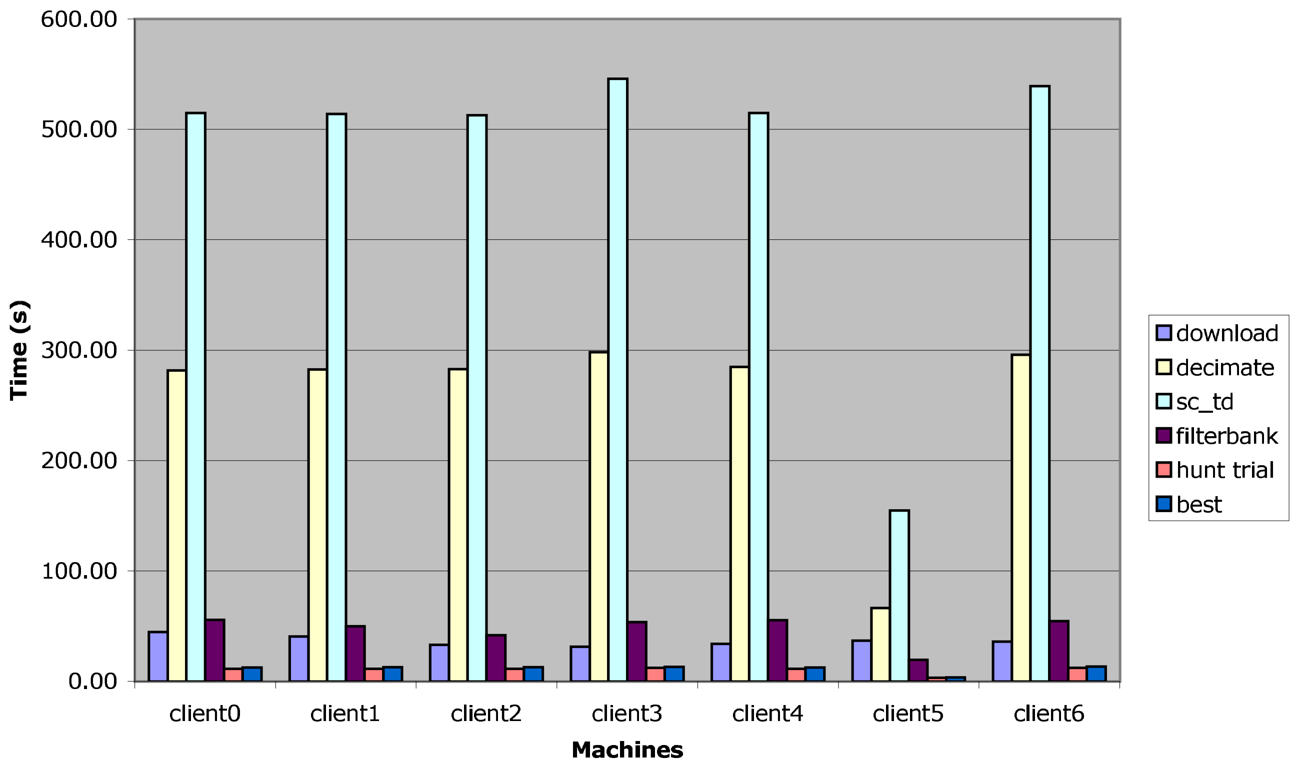

Fig. 2.— Timing statistics for the seven client machines in the initial processing cluster. The average times for function completion are shown for six 400-MHz Intel Celerons and one 2.5-GHz Pentium 4 (client5). *Download* is the initial data transfer process, *decimate* is the data aggregation process, *sc_td* and *filterbank* put the raw data into a readable format, *hunt trial* runs through a single DM trial and computes a 2^{20} point FFT on the dedispersed time series (this step was repeated 450 times in the processing using different trial DMs), and *best* picks out the most promising pulsar candidates at the end of the processing. The total processing time for client5 was faster by about a factor of three than the other machines. Table 1 lists additional cluster timing results.

```
Parkes P406 EGRET Pulsar Survey Raw Data DVD Archive

Author: Fronefield Crawford <crawford@alum.mit.edu>
see http://cs.haverford.edu/pulsar for more information

Pointing Name:

EGU010_3

Entry in pmobs.db:

@# P406   G1649ceg    3.534  17.699 o EGU010 004 52469.452 egunid 40 020714_105010
   4102   0.125000 1516.500 -3.000 13 2100

Beam Positions:

FILE              RAJ         DECJ         l       b

EGU010_3_01.pkmb 16:50:29.13 -16:06:53.77 3.534 17.699
EGU010_3_02.pkmb 16:51:25.81 -16:32:36.56 3.312 17.263
EGU010_3_03.pkmb 16:49:24.53 -16:31:30.52 3.026 17.664
EGU010_3_04.pkmb 16:48:28.13 -16:05:45.77 3.249 18.101
EGU010_3_05.pkmb 16:49:32.71 -15:41:10.10 3.757 18.135
EGU010_3_06.pkmb 16:51:33.47 -15:42:15.86 4.042 17.732
EGU010_3_07.pkmb 16:52:30.16 -16:07:57.56 3.818 17.297
EGU010_3_08.pkmb 16:53:28.42 -16:33:50.10 3.596 16.855
EGU010_3_09.pkmb 16:50:21.12 -16:57:36.67 2.800 17.224
EGU010_3_10.pkmb 16:47:21.90 -16:30:30.54 2.734 18.068
EGU010_3_11.pkmb 16:47:30.66 -15:39:48.18 3.471 18.543
EGU010_3_12.pkmb 16:50:37.08 -15:16:10.90 4.272 18.171
EGU010_3_13.pkmb 16:53:35.62 -15:43:06.90 4.331 17.327

Legend:

EGUXXX_Y_ZZ.pkmb

XXX = tape number
Y   = file number (NOT necessarily the same as the original file on DLT tape)
ZZ  = beam number

Notes:

This pointing has already been split into 13 separate beams (files)
using Scott Ransom's split_parkes_beams program.
```

Fig. 3.— Example plain text description file included on each DVD archive disc. This file, which was automatically generated using a custom PERL script, describes the details of the particular pointing observation archived on the DVD. Each disc contains a single multibeam pointing (13 beams), corresponding to about 2.5 GB of storage space used on the disc.

Table 1. Cluster Data Processing Times.

Function	client0	client1	client2	client3	client4	client5[a]	client6
download (sec)	44.5	40.6	33.2	31.4	33.9	36.7	35.9
decimate (sec)	281.7	282.4	282.9	298.2	284.7	66.4	295.8
sc_td (sec)	514.9	513.8	512.9	545.9	514.8	154.7	539.3
filterbank (sec)	55.7	49.8	41.6	53.6	55.5	19.5	54.4
hunt trial (sec)[b]	11.3	11.4	11.4	12.1	11.4	3.2	12.1
best (sec)	12.3	12.9	12.7	13.1	12.6	3.6	13.3
total (min)[c]	99.9	100.3	100.4	106.7	100.8	28.3	106.5

Note. — Average times for completion of computational functions in the processing of a single beam of the aggregated pulsar data. See also Figure 2 for an explanation and graphical representation of the functions.

[a]2.5-GHz Pentium 4 processor, which also served as a secondary data server. All other machines were 400-MHz Intel Celerons.

[b]Average time for completion of a single trial dedispersion and subsequent FFT. A total of 450 DM trials were separately searched in hunt. The average time to complete all DM trials and FFTs for a single beam using hunt is therefore found by multiplying the listed number by 450.

[c]Average time to fully process a single aggregated beam (includes all 450 hunt trials).

Table 2. Cost Comparison for Archiving the EGRET Survey on DVD vs. DLT-IV Tape.

Storage Medium	DVD	DLT-IV	DVD/DLT Ratio
Number of media used for storage	233 discs	22 tapes	10.59
Cost per medium unit	\$1.36	\$65	0.02
Media writer/reader cost	\$400	\$2300	0.17
Other costs	\$45[a]	\$0	
Maximum storage capacity per medium unit	4.7 GB	35 GB	0.13
Fraction of storage capacity used per medium unit	0.53	0.75	0.70
Archive cost per GB (assuming maximum storage capacity)	\$0.29/GB	\$1.86/GB	0.16
Actual archive cost per GB	\$0.55/GB	\$2.48/GB	0.22
Total archive cost	\$760	\$3730	0.20

Note. — All prices from June 2003.

[a]DVD storage case, which holds 264 discs.