# The Pan-STARRS Project: The Next Generation of Survey Astronomy Has Arrived

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**Abstract**

The University of Hawaii Institute for Astronomy is developing a large optical synoptic survey telescope system: the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS). This talk summarizes the Pan-STARRS science goals, the distributed aperture design approach, and the overall project development plan. The overview description of the Pan-STARRS system design comprises the telescope, camera, observing control infrastructure, image processing, image analysis, and archiving of the science data products. The development plan includes the Pan-STARRS PS1 system that will begin its survey mission in mid-2009 as well as the next phases of the project.

## 1. Science Goals and System Requirements

The 2000 Decadal Review report (AANM) reviewing the status and priorities for astronomy highlighted the need for a new 6m class Large Synoptic Survey Telescope to fulfill the need for a new survey system using advances in imaging technologies. The AANM reviewers realized that the exponential growth in wide-field detector technology, *viz.*, a doubling of the number of pixels every 18 months since the inception of astronomical CCD imaging three decades ago, was set to continue into the foreseeable future and would allow, in the current decade, the development of gigapixel scale cameras. Based on this they recommended as its fourth major ground-based (and fifth overall) initiative the construction of a system capable of

> […] surveying the visible sky every week to a much fainter level than can be achieved with existing optical surveys, [. . . ] will open a new frontier in addressing time-variable phenomena in astronomy. This 6.5-m-class optical telescope will detect 90 percent of the near-Earth objects larger than 300 m in diameter within a decade, and will enable assessment of the potential hazard each poses to Earth. It will take a census of some 10,000 of the most primitive bodies in the solar system, located in the Kuiper Belt. It will also contribute to the study of the structure of the universe by observing thousands of supernovae, both nearby and at large redshift, and by measuring the distribution of dark matter through gravitational lensing [1].

The wide-ranging science goals for the University of Hawaii Institute for Astronomy's Panoramic Survey Telescope and Rapid Response System (UH-IfA Pan-STARRS) are intentionally aligned with those given in the AANM report, and can be grouped into the following four major categories:

- A census of the solar system; with emphasis on potentially hazardous asteroids and comets but also providing a greatly increased inventory of objects in the outer solar system.
- Study of the content and formation history of the Milky Way.
- Dark energy (DE) from deep static-sky observations, primarily from weak lensing but also from baryon acoustic oscillations and from the evolution of galaxy cluster abundance.
- Cosmology from "time-domain" astronomical observations; includes DE from measurements of the evolution of the expansion rate from supernovae Ia.

  At the highest level, the measurements proposed are to measure the dark energy equation of state parameter w and its evolution; to measure the phase space density of objects in the solar system, etc.

A more specific idea of the science that can be conducted with Pan-STARRS is illustrated by the 12 "Key Projects" adopted by the PS1 Science Consortium, and international consortium of institutions funding the 3-4 year science mission of the first Pan-STARRS telescope, PS1:

1. Populations of objects in the Inner Solar System
2. Populations of objects in the Outer Solar System - (Beyond Jupiter)

3. Low-Mass Stars, Brown Dwarfs, and Young Stellar Objects
4. Search for Exo-Planets by dedicated Stellar Transit Surveys
5. Structure of the Milky Way and the Local Group
6. A Dedicated Deep Survey of M31
7. Massive stars and supernova progenitors
8. Cosmology Investigations with Variables and Explosive Transients
9. Galaxy Properties
10. Active Galactic Nuclei and High Redshift Quasars
11. Cosmological Lensing
12. Large Scale Structure.

Optimizing a design to meet these requirements is a complex systems engineering task, and is beset by problems in obtaining accurate cost and schedule estimates. A critical design choice is the size of the telescope. Since no one has figured out how to provide full adaptive optics over a very wide field of view because of the small isoplanatic angle the image quality is, by and large, determined by the atmosphere rather than the telescope one has to chose between a small number (possibly 1) of large telescopes or multiple telescopes in a 'distributed aperture' system composed of smaller telescopes. In making this decision some relevant engineering considerations are as follows:

- Optics design — large telescopes require fast optics requiring exquisite precision for collimation, alignment and control.
- Telescope costs, risks and delivery time — higher for larger apertures.
- Detector costs — higher for distributed aperture.
- Integration times — the need to be sky-noise, rather than read-noise, limited sets a limit on the speed of the optics, with very slow systems being disfavored if very short exposure times are desired.
- Diffraction effects — disfavors sub-meter scale apertures.
- Partial adaptive optics from on-chip 'OT' fast guiding — possible with small telescopes ($D/r_0 \approx 4$ being optimal), but ineffective with larger telescopes.

Based on these, and other, considerations, the Pan-STARRS project opted for a "distributed aperture" wide field high resolution design concept utilizing four 1.8m (primary mirror) apertures and 7 square degree field of view to meet the AANM requirements. More simply put, combining the images from smaller telescopes is done in such a way to yield the performance of a single larger telescope at a significantly reduced cost. At the time this decision was made, there was considerable uncertainty in the cost figures, particularly in the ability to deliver multiple gigapixel cameras at a reasonable cost. In retrospect, the decision appears well justified.

The measurements described above leads to the following top-level performance requirements:

- Etendue ($50 m^2 deg^2$). Product of collecting area and field of view. Driven by all science programs.
- Image sharpness. Total system FWHM $\leq 0.5''$ (i.e., not including natural atmospheric seeing). Driven by all science programs.
- Wavelength coverage. $400 \leq \lambda \leq 1000$ nm.
- Photometric precision. 1% absolute photometric precision (most bands). Drivers include transient searches, but also critical for all 'static-sky' science requiring photometric redshifts.
- Astrometric precision. $\leq 100$ mas (absolute), $\leq 20$ mas (relative). Driven by primarily by orbit determination and by galaxy science (proper motions and parallaxes).
- Exposure time. $\leq 40$s. Driven by rapid rates of motion of inner solar system objects. "Trailing losses" for moving objects negligible for 30s exposures but much longer exposure times incur a penalty.
- Transient alert time. 30 minutes (goal). Driven by need for rapid follow up for transients.

The technical specifications on which the collecting area and field of view of this concept were based on the requirement to be able to survey the entire available sky in the optical to 24th magnitude once per week. The Pan-STARRS PS4 design has a somewhat smaller collecting area, but, by virtue of the superior image quality provided by sites in Hawaii, nonetheless meets those broad requirements. Other factors affecting the choice of the distributed aperture implementation for Pan-STARRS:

- Integration times — the need to be sky-noise limited, rather than read-noise limited, sets design constraints on the optics to achieve science goals above.
- Diffraction effects — disfavors sub-meter scale apertures.
- Partial adaptive optics from on-chip ‘OT’ fast guiding — possible with small telescopes but ineffective with larger telescopes.
- Multiplicity of images. Many of the major science goals are expected to be limited by systematics rather than by photon counting statistics; this is particularly the case for modern ‘precision cosmology’. In this regard it is a great advantage to have images that are constructed from a very large number of individually shallow images since this tends to average out systematic effects. This favors distributed apertures.
- Flexibility of choice survey modes. With a distributed aperture system, one can choose between width, and therefore speed of sky coverage, and depth by either pointing the telescopes at the same patch of sky or spreading the pointings apart. One also has the potential for simultaneous multi-color imaging.

From a scientific perspective, there are few, if any, major down-sides to the parameters adopted. The read-noise of the detectors turned out to be somewhat higher than initially anticipated. This means that in the bluest band (g-band) where the sky brightness is lowest, read-noise starts to become an issue at 30s exposure time. This has been ameliorated by adjusting exposure times accordingly and efforts to reduce the read-noise are being pursued.

The single telescope PS1 system has demonstrated that we can achieve 0.5″ FWHM optics image quality and 0.6″ FWHM for the total system. While somewhat poorer than the PS4 specification, the experience and knowledge gained gives us confidence that 0.4″ optical performance is achievable.

The Pan-STARRS (PS) project has been supported by the USAF since September 2002 for the design and construction of a wide field optical/NIR observatory facility. The PS design features a distributed aperture approach to the telescope design with 1.8m telescopes providing 7 square degree field of view equipped with gigapixel array cameras with on-chip orthogonal transfer (OT) fast guiding. A full-scale single telescope system PS1 is now fully operational on Haleakala and embarking on a 4 year survey mission. PS2 is under construction and will join PS1 and then, in 2013, these, together with two more telescopes, will form the PS4 observatory, to be sited on Mauna Kea replacing the University of Hawaii 88” telescope.

The USAF funding has also supported the development of the image processing pipeline (IPP) and database software (PSPS) to make the image and catalog data usable for science, and for the development of the observatory, telescope and instrumentation software system (OTIS). Under the terms of the grant and cooperative agreement, the US government is free to use designs and SW solutions developed by PS, but the telescopes become the property of the University of Hawaii, and the sponsor will have no call on the use of the telescopes. The University of Hawaii therefore needs to seeks funds to operate the observatory, and possibly to complete the construction, since the funding is provided on a year-by-year basis and the funding to complete the construction of the last two telescope and the 4-telescope enclosure are not, at present, secured.

The PS project has been successful in finding non-USAF sponsorship for the operation of PS1, which is embarking on a 3.5 year mission. The bulk of operations funding are coming from a consortium of academic partners in the US, Germany, the UK and Taiwan, and partial operations funding support is being provided by NASA. It is likely that PS4 operations will be funded in a similar way, possibly with an expansion of the existing consortium. Now that PS1 has shown the success of the design, it is also likely that greater non-institutional private funding may be forthcoming.

The Pan-STARRS system is divided into six subsystems:

- Telescope(s)
- Camera(s)
- Observatory, Telescope and Instrumentation Software (OTIS)
- Image Processing Pipeline (IPP)

- Moving Object Processing Software (MOPS)
- Published Science Products Subsystem (PSPS)

A concept block diagram showing how data and control flows interact is given in Fig. 1.

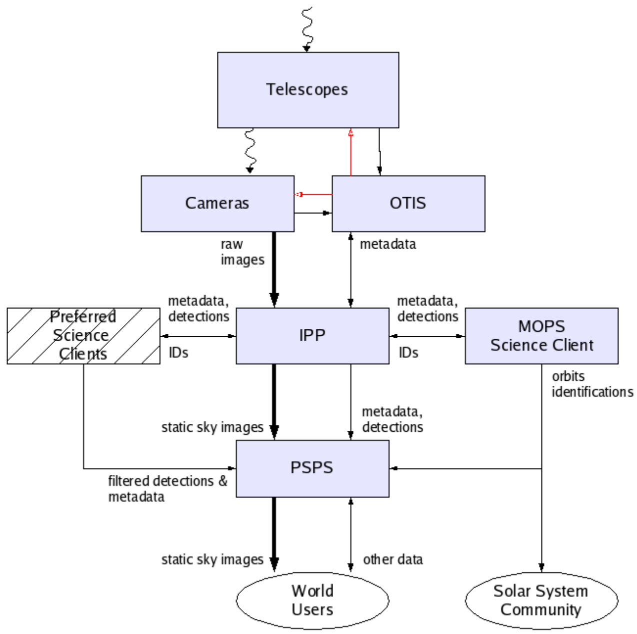


Fig. 1. Block diagram of Pan-STARRS subsystems

## 2. Technical Overview

### 2.1 Telescope and Enclosure

The development of the Pan-STARRS PS1 telescope system has answered most of the critical questions regarding the technical challenges of building and collimating a wide-field telescope of 1.8-m diameter. All five optics required for the PS1 telescope have been built to specifications, mounted in a-thermal cells, and aligned to an accuracy which has provided 0.5" image quality across the entire telescope field of view. The PS1 telescope is currently exceeding its design specification by providing an 8.5 square degree field of view with this image quality. The original specifications called for a 7 square degree field of view. While the original ambitious specifications also called for image quality of 0.4", the current performance is sufficient to guarantee that the telescope will be site-limited for a large majority of its lifetime. We will address below our efforts to improve upon the PS1 performance in the future.

Unique software has been developed to collimate the PS1 telescope. This has proven to be quite successful. The initial collimation of the PS1 optics took approximately 1 year as we were developing this software. After having recently re-coated the PS1 secondary it has taken us about 1 month to re-collimate the telescope. This effort could have been as short as two weeks if weather had permitted more timely observations.

We have built and delivered astronomical filters of unprecedented size and a mechanism that reliably allows us to interchange these filters in less than 20 seconds. The uniformity and performance of these filters is no longer an open question.

Several changes to the design of the PS1 telescope will be implemented when the PS2 telescope is fabricated. Among these will be changes in the support structure of the first two corrector lenses to allow for more flexibility in the positioning of these optics, a position change in the filter mechanism to help eliminate some ghost images, a re-design of the cable wrap to allow for a more balanced telescope, a re-design of the secondary mirror support to reduce wind vibrations of the secondary mirror, an increase in the force range available to the astigmatism correction system, better metrology fiducials on the telescope structure to reduce the time it takes to achieve initial collimation, and some changes in the polishing specifications of the corrector optics to help reduce flatness variations in the focal plane. This last point requires some further comments.

Variations in the telescope focal plane flatness is one of the main contributions causing us to have missed our goal of PS1 image quality of 0.4" FWHM. Zonal polishing errors in the L2, L3 optics, and perhaps in the filters themselves have contributed to these errors. We do not believe that these errors are insurmountable, but they do require slightly different polishing specifications for the PS2 optics.

In short, while we are sure that there are improvements to be made on the PS1 system, we do not believe that any of these improvements will require major technological developments of any kind. The basic telescope design and our approach to achieving collimation are sound and will be roughly replicated in the PS2 optics. Because of this, we believe that the development risks are low and the costs to the Pan-STARRS telescopes are well understood.

### 2.2 Gigapixel Camera and Readout Electronics

The construction of gigapixel cameras for PS4 is relatively straightforward and costs and schedules can be predicted with high confidence. We have found that our design for the GPC1 on PS1 is quite satisfactory and the changes we are implementing for PS2 are all minor, such as improvement in fill factor by a few percent, and funding alternate vendors for CCDs. We have already ramped up our production of controllers in order to accommodate PS2, WIYN's ODI, and ANU's SkyMapper, so mass production of controllers and acquisition computers is already underway. The cryostat and auxiliary systems are essentially duplicates of GPC1 and a relatively minor portion of the work. The biggest effort and concern is mass production of CCDs to an performance specification analogous to the challenging optical performance specifcation, and exactly how to mount them to follow the focal surface produced by the optics. Our vendor for PS1, MIT Lincoln Laboratory, has a capacity of about a gigapixel camera's worth per two years. MITLL will produce the CCDs for PS2, but we have contracted with Semiconductor Technology Associates to produce CCD wafer through DALSA (a commercial foundry which could fabricate many GPC's worth of CCDs in three months), and the Imaging Technology Laboratory to thin them. ITL has been adding capacity and we believe that they will be able to produced CCDs as fast as Pan-STARRS can use them. Our total cost for a gigapixel camera depends strongly on the yield of CCD production, but now that the engineering expenses are mostly past, we believe that we can produce gigapixel cameras in any quantity desired for less than $5M per copy.

### 2.3 Image Processing Pipeline

The Pan-STARRS Image Processing Pipeline (IPP) is required to perform real-time analysis of the full data stream coming from the camera and telescope, to archive the raw images and output data products, to generate instrumental response corrections, and to perform the astrometric and photometric calibration of the resulting dataset. The IPP performs a series of analysis steps on every individual image, as well as image stacking and image differencing. The single-image analysis stage corrects the detector response, detects and characterizes the astronomical objects in the images, and performs an initial astrometric and photometric calibration. Collections of images are stacked to improve the depth and the fill in the gaps. Image differencing, with PSF-matching, is performed between individual pairs of images, pairs of stacks or combinations.

A high-quality object analysis is performed on the deep stacks, including simultaneous multi-band chi-square source detection and PSF-convolved galaxy model fitting. The repeated and overlapping observations are used to generate improved astrometric and photometric calibrations of the images; the same process results in a high-quality astrometric and photometric reference catalog, along with proper-motion and parallax measurements across the sky.

For PS1, the major technical challenges included the high-level of precision demanded of the analysis system, the large data volume and rates, and the requirement for the delivered system to be capable of meeting the long-term needs of PS4. We considered re-use of existing data analysis systems (eg, SDSS and Terapix), but found that they were not sufficient to meet a combination of these needs.

The Pan-STARRS project had from the start very aggressive requirements for accuracy and quality of the data analysis. The science goals drive the calibration accuracy requirements of 10 milli-arc-seconds for astrometry and 10 milli magnitudes for photometry. The weak-lensing science project, among others, drives the need for extremely well characterized point-spread-functions for all images, including the stacked images. The IPP is designed from top to bottom to track an extensive amount of meta-data describing the images, the processing steps, and the detected objects. We developed improved techniques for PSF modeling, for PSF-matching of images combined in stacks, and for PSF-convolved galaxy model fitting, based on existing implementations of the analysis steps.

In good weather, the PS1 generates roughly 500 science images per night, or nearly 1.5TB. The IPP is required to process these images to the level of pair-wise differences within the 12 hour night-time. The IPP computing cluster uses a collection of 'whitebox' rack-mount computers for both storage and processing. The system assigns specific chips from the camera and specific chunks of the sky to individual computers, and targets all processing to the corresponding storage machine. This design dramatically reduces the network bandwidth impact, but requires special software for both the storage and computing management. The simple, modular design allows the cluster to grow in stages as the archived data volume grows, and to add additional processing power as needed.

**2.4 Observatory, Telescope and Instrumentation Software**

The PS1 Observatory, Telescope, and Instrument Software (OTIS) system is a completely integrated software package for operating the PS1 observatory. PS1 is not analogous to any existing telescope, and has several unique aspects.

First is the unprecedented requirement to maintain sub-arc-second image quality over a 3 degree field of view. Active control of collimation, alignment, focus, and primary mirror figure continuously to this accuracy and over the entire field of view of the 1.4 Gigapixel camera has been a significant challenge and has required new techniques for finding and implementing models for mirror and camera control and real time data analysis of very large images. This also requires detailed thermal sensing and control of the environment. The observatory and telescope must be operated entirely remotely (for cost saving reasons) and this means a significant amount of auxiliary instrumentation and meteorological sensors to make the most of the available clear time, as well as power and network watch-dogs, and the availability of remote personal to access all heartbeat functions within the camera and the telescope.

The other significant OTIS capability is to schedule the observations to meet the goals of the scientific program with all of its complicated cadences and revisiting requirements ranging from 15 minutes to six months. With exposures as short as 30 seconds, we have demonstrated observing efficiencies as high as 65 percent by careful parallel and serial staging of camera and telescope intermediate tasks. Perhaps the biggest challenge has been to distill and present detailed information across the entire field of view rapidly when the images themselves are simply too large to inspect by hand. Perhaps the greatest challenge of extending all of this to multiple telescopes and cameras will be the human interface to diagnose and maintain performance and scheduling in real time. OTIS has been developed in concert with the commissioning of the telescope and camera, and consists of half a million lines of code. As a prototype, it is a functioning and impressive real time system. We have learned to take great advantage of browser technology, but this has evolved as the system has grown. We would expect for PS4 and beyond, to re-design certain aspects to make the best use of ongoing browser technology for display and control for remote operations, while building new tools for visualization of data and scheduling tasks.

Detailed performance analysis, based on real-world experience with PS1 observations, suggest that these science goals can best be fulfilled with a 'wedding cake' model for the surveys with the largest fraction of time devoted to a ‘3π’ survey and with progressively smaller net amounts of time being devoted to medium-deep and ultra-deep surveys of progressively smaller area. These observations are to be carried out using 5 broad-band filters g, r, i, z and y with exposure times chosen to obtain similar effective depth and short enough to avoid serious performance ‘trailing losses’ for rapidly moving near-earth objects. In addition, it is proposed to survey the ‘sweet-spots’; relatively small areas of the ecliptic visible at low solar elongation which are only visible at the start and end of the nights, but which are rich sources of potentially hazardous asteroids. These may be observed through a broader filter that provides greater efficiency for detecting neutral colored objects. These observations must be carried out according to a carefully designed schedule or ‘cadence’.

For example, the cadence for the deep fields must be chosen in order to provide well-sampled light curves for supernovae and other transients. Another feature of the schedule is to provide observations in pairs with a separation in time of order tens of minutes in order to provide discrimination between moving objects and stationary transients. The stream of images coming from the telescopes must be processed in the following way in order to facilitate the stated science goals; a collection of images taken in the same filter (possibly concurrently or sequentially) will be combined to form a current image of a patch of sky and a PSF matched template image of the static sky will then be subtracted to make difference images from which will be measured fluxes and positions of transient, variable and moving objects (with discrimination of the latter objects from the former as described above). The non-static objects detected in the difference image are then masked in the current image and the result accumulated into the static-sky image. The fundamental image-level measurements then are of the surface brightness of both the static and variable components of the sky. From these image-data products are derived catalogs of objects consisting of positions and flux-densities and positions for point-like objects and, in addition to magnitudes, shape information, e.g., fits to analytical models and central second moments for galaxies. From these basic catalog-level measurements are derived further quantities such as parallaxes and proper motions for stars, orbits for moving objects, and photometric redshifts and weak lensing shear estimates for galaxies.

### 2.5 Published Science Products Subsystem

With the wealth of data that a digital sky survey will generate comes the challenge of presenting that data to the user community. When we started the Pan-STARRS project the largest astronomical databases were the 2MASS catalog at IPAC and the SDSS catalog. Both of these data collections weighed in at approximately 1 billion rows with roughly 2 TBytes of data. At the beginning of the PS1 development we decided to concentrate our development efforts on the relational database that provides the attributes that describe the sources found in the images. We decided that developing the technology for this purpose was much more in need of development than software for serving images which has become fairly common place in fields like geospatial satellite imaging.

During the design phases of PS1 it became immediately clear that we would have a system generating over 2 Tbytes of image data and several hundred gigabytes of catalog measurements every night. We estimated that in its operational mission PS1 would collect about 130 billion detections of some 5.5 billion distinct astronomical sources. Further, that the catalog information alone from PS1 would required about 30 Tbytes of disk storage in its first year, and nearly 100 TBytes over the lifetime of the project. Previous surveys like 2MASS and SDSS were snapshots – data was taken, reduced, and loaded into the database. The dynamic nature of the PS1 surveys presents the database with another challenge, namely continually updating the current data collect to incorporate new observations that are important in probing the time history of the sky. The PS1 development team, working with the database group at the Johns Hopkins University’s Department of Physics and Astronomy, and with researchers at Microsoft’s Research and SQL Server divisions have developed a system that we are confident will serve to both hold the data collected from PS1 and the 300 members of the PS1 Science Consortium who are eager to use it.

What is not so clear at this time is how the system for PS1 will scale to handle the data volume of PS4. One year of PS4 operation will equal or exceed the entire set of data catalog products produced over the 3.5 year PS1 mission. Equal to the challenge of handling this data volume will be serving it to a larger user community.

### 3. Summary

It is now nearly a decade since the last decadal review proposed a Large Synoptic Survey Telescope capable of repeatedly surveying the sky to 24th magnitude per week. That system, which would revolutionize many areas of modern astronomy, has not yet been realized, but the gigapixel camera technology on which the concept was based has been and is now in operation on the Pan-STARRS PS1 telescope. Figs. 2-5 illustrate the realization of the Pan-STARRS concept and the reality of the PS1 survey system.

The PS4 system is the most cost effective and rapid means to advance the goals of wide field survey astronomy. As well as probing the mysteries of dark energy and the formation of the universe and the solar system, it will be highly effective for providing sources for follow up with other upcoming facilities. The PS2/PS4 route has the great advantage that data will become available soon; this is critical since development of the science-specific analysis tools rely on real data for testing — no amount of computer simulations will suffice for this. It provides a test-bed for, and development path towards, even larger facilities, whatever shape or form that these may take. The alternative, sadly, is that wide field imaging will remain in the dark-ages where it has languished since the advent of CCDs and a generation of astronomers will be denied access to a valuable resource that is clearly within reach.

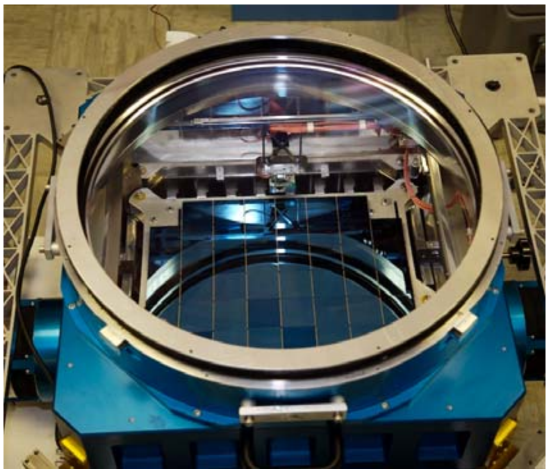

Fig. 2. The Pan-STARRS Gigapixel camera for PS1, the world’s largest digital camera at 1.4 billion pixels (left), and PS1 opening up at twilight in advance of a night of observing (right).

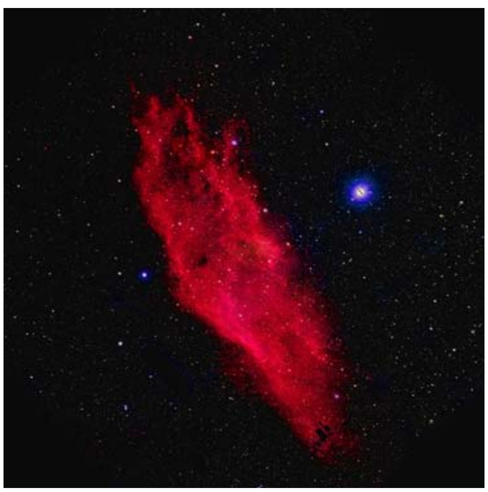

Fig. 3. Each of these PS1 images, the California Nebula on the left and the Rosette Nebula on the right, comprises about 90% of the total area of the gigapixel camera field of view.

Fig. 4. These extractions from PS1 images, galaxies M81on the left and M51/NGC5195 on the right, each comprise an area of about 1/60 of the total area of the gigapixel camera field of view.

Fig. 5. This extraction from a PS1 image of the Perseus cluster of galaxies, comprises an area of less than ½ of 1% of the total area of the gigapixel camera field of view.

Acknowledgements: The design and construction of the Panoramic Survey Telescope and Rapid Response System by the University of Hawaii Institute for Astronomy is funded by the United States Air Force Research Laboratory (AFRL, Albuquerque, NM) through Cooperative Agreement number FA9451-06-2-0338.

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